WELCOME

CERN Courier – digital edition

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_3Sn) 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_3Sn have been mastered. The first use of Nb_3Sn conductor in accelerator magnets will be the High-Luminosity LHC (HL-LHC), for which the first Nb_3Sn dipole and quadrupole magnets have recently been tested successfully at CERN and in the US. As our cover feature describes, the demonstration of Nb_3Sn 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_3Sn 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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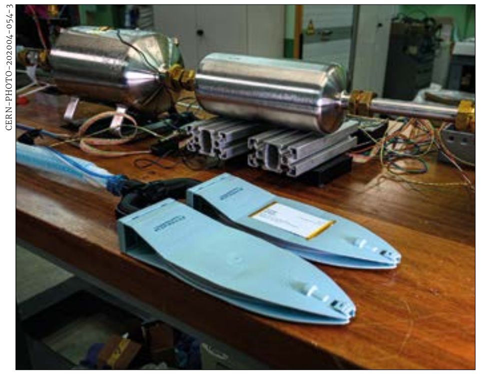

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FROM THE EDITOR

Accelerating science – and medicine

Matthew Chalmers
Editor

Two dipole magnets, currently hooked up to test rigs in CERN's SM18 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 (Nb_3Sn). The 5.5 m-long magnets will be positioned at Point 7, 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 Nb_3Sn 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 versions. Following initial tests of the 11 T 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 130 T/m and reaching a peak-field of 11.4 T at the conductor (p7).

As this month's cover feature explains (p34), the demonstration of Nb_3Sn 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. Nb_3Sn is so far the only conductor that experts are confident is capable of sustaining such fields (up to 16 T) – the baseline field of the dipoles for the hadron–hadron mode of the proposed Future Circular Collider (FCC). The Nb_3Sn programme is also relevant for a future muon collider, featured on p41 of this issue.

The Nb_3Sn magnet technology for the HL-LHC is also a stepping stone to future hadron colliders

CERN and the US labs are achieving impressive results in driving up the performance of Nb_3Sn conductor 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 study, 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 14.1 T at 4.5 K at Fermilab. These and the recent HL-LHC milestones bode well for the future of the field.

S Hertzog/CERN

Milestones *Nb_3Sn dipole magnets being tested at CERN.*

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 structure of the SARS-CoV-2 virus; studies that would have taken several years with conventional lab-based X-ray sources can now be done in a matter of days (p29). Accelerators are also vital for sustaining Europe's neutron-science programme – as argued in this month's Viewpoint (p49).

This accelerator-themed issue was meant to be distributed at the 2020 International Particle Accelerator Conference at GANIL, France, which, though cancelled, may take place in a virtual format due to the global COVID-19 situation. On this note, with almost all laboratories involved in the HL-LHC currently in teleworking mode, there could be some delays in the project schedule. But the decades-long technological march towards higher energies continues to advance.

Reporting on international high-energy physics

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NEWS ANALYSIS

ACCELERATORS

HL-LHC quadrupole successfully tested

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 focusing magnet ready for installation in an accelerator. The 4.2 m-long, 150 mm-single-aperture device is based on the superconductor niobium-tin (Nb$_3$Sn) and is 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 Nb$_3$Sn dipole magnet, and the milestones are soon to be followed by tests of other 7.2 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 continued: "This full-length, accelerator-ready magnet performance record is a real textbook case for international collaboration: since the very beginning the three 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 6.5 TeV operation, are made from the superconductor niobium-titanium (Nb-Ti). As the transport properties of Nb-Ti are limited for fields beyond 10–11 T at 1.9 K, HL-LHC magnets call for a move to Nb$_3$Sn, which remains superconducting for much higher fields. Although Nb$_3$Sn has been studied for decades and is already in widespread use in solenoids for nuclear magnetic resonance – not to mention underpinning the large coils presently being manufactured that will be used to contain and control the plasma in the ITER fusion experiment – it is more challenging than Nb-Ti to work with. Once formed, the Nb$_3$Sn compound becomes brittle and strain-sensitive and therefore much harder than niobium-titanium alloy to process into cables to be wound with the accuracy required to achieve the performance and field quality of state-of-the-art accelerator magnets.

Brookhaven National Laboratory

High field *The advanced quadrupole magnet being prepared for a test at Brookhaven National Laboratory.*

This is a real textbook case for international collaboration in the accelerator domain

The purpose of a quadrupole magnet is to produce a field gradient in the radial direction with respect to the beam, allowing charged-particle beams to be focused. Researchers at Fermilab, Brookhaven National Laboratory and Lawrence Berkeley National Laboratory are to provide a total of 16 quadrupole magnets for the interaction regions of the HL-LHC, which is due to operate from 2027. The recent test was carried out at Brookhaven in January, when the team operated the 8 tonne quadrupole magnet continuously at a nominal field gradient of around 130 T/m and a temperature of 1.9 K for five hours. Eight longer quadrupole magnets each with an equivalent "cold mass" of two US 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, Nb$_3$Sn 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, 60 mm-twin-aperture dipole magnet and achieved a nominal bore field of 11.2 T at 1.9 K (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 Nb$_3$Sn conductors to much higher fields, as would be needed for future hadron colliders beyond the LHC (see p34).

Before being judged fully operational and ready to be installed in 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.

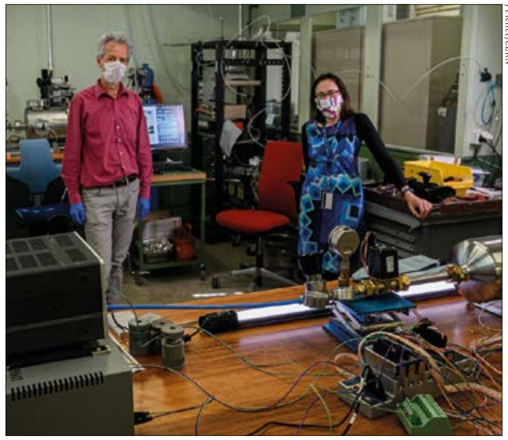
Physicists develop stripped-down ventilator

As part of the global response to the COVID-19 pandemic, a team led by physicists and engineers from the LHCb collaboration has proposed a design for a novel ventilator. The High Energy Ventilator (HEV) is based on components that are simple and cheap to source and, although the system needs to be verified 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.

Most people infected with the COVID-19 virus recover without requiring special treatment, but in some cases the disease can cause severe breathing difficulties and pneumonia. For such patients, the availability of ventilators that deliver oxygen to the lungs while removing carbon dioxide could be the difference between life and death. Even with existing suppliers ramping up production, the rapid rise in COVID-19 infections is causing a global shortage of ventilators. Multiple efforts are therefore being mounted by governments, industry and academia to meet the demand, with firms that normally operate in completely different sectors, such as Airbus, Dyson and General Motors, diverting resources to the task.

HEV was born out of discussions in the LHCb VELO group when lead designer Jan Buytaert of CERN realised that the systems which are routinely used to supply and control gas at desired temperatures and pressures in particle-physics detectors are well matched to the techniques required to build and operate a ventilator. The driving pressure of ventilators – which must be able to handle situations of rapidly changing lung behaviour and potential collapse – is a crucial factor for patient outcomes. The HEV team therefore aimed to produce a patient-safety-first design with precise pressure control, providing internationally recommended operation modes.

As the HEV team comprises physicists, rather than medics, it was vital to get the relevant input from the very start, explains HEV collaborator Paula Collins of CERN. "Here we have benefited enormously from the experience and knowledge of CERN's HSE [Occupational Health & Safety and Environmental Protection] group for medical advice, conformity with applicable legislation



Prototyping *Jan Buytaert and Paula Collins with the HEV prototype in the LHCb VELO lab at CERN on 6 April.*

Systems in particle-physics detectors are well matched to the techniques required to build and operate a ventilator

and health-and-safety requirements, and the working relationship with local hospitals. The team is also greatly supported from other CERN departments, in particular for electronic design and the selection of the best components for gas manipulation. We were also very encouraged to find that it was possible in a short space of time to set up an online chat group of experienced anaesthesiologists and respiratory experts from Australia, Belgium, Switzerland and Germany, which sped up the design considerably."

Keeping it simple

The HEV concept comprises electro-valves, a 10 litre buffer container, a pressure regulator and several pressure and flow sensors. Embedded components – currently Arduino and Rasbperry Pi – are being used to meet portability requirements. The unit's 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 serious intensive care, explains Collins: "It incorporates 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 failsafe mechanisms based on CERN's long experience in this area, with online training to be developed." The first stage of prototyping, which was achieved at CERN on 27 March, demonstrated that the HEV principle is sound and allows the ventilator to operate within the required ranges of pressure 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 Bowcock of the University of Liverpool. "It is aimed at deployment round the world, and in places that do not necessarily have state-of-the-art facilities."

Complementary designs

The HEV ventilator complements another recent proposal initiated by physicists in the Global Argon Dark Matter Collaboration. The Mechanical Ventilator Milano (MVM) is optimised to permit 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 and the US, with an initial goal to produce up to 1000 units in each of the three countries while the interim certification process is ongoing.

Sharing several common ideas with 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 Particles Physics in Portugal. All designs are evolving quickly and require further development before they can be deployed in hospitals.

"It is difficult to conceive a project that goes all the way and includes all the bells and whistles needed to get it into the hospital, but this is our firm goal," says Collins. "After one week we had a functioning demonstrator, after two weeks we tested on a medical mechanical lung, and we are now prototyping under clinical supervision. We find ourselves in a unique and urgent situation where there are many proposals on the market, but we don't know now which ones will in the end make a difference, so everything that could be viable should be pursued."

Further reading

J Buytaert *et al.* 2020 arXiv:2004.00534.
C Galbiati *et al.* 2020 arXiv:2003.10405.
A Pereira *et al.* 2020 arXiv:2004.00310.

European strategy update postponed

During its 197th session, which took place for the first time by videoconference on 19–20 March, the CERN Council addressed the impact of the current COVID-19 situation on the update of the European strategy for particle physics (ESPPU).

The ESPPU got under way in September 2017, when the CERN Council appointed a European Strategy Group (ESG) to organise the process. Following two years of discussions with the high-energy physics and related communities (*CERN Courier* November/December 2019 p8), culminating in a week-long drafting session in January, the ESG reported convergence on recommendations. These were due to be submitted for final approval at an extraordinary session of the CERN Council on 25 May in Budapest, Hungary, before being publicly released.

Acknowledging that the COVID-19 outbreak affects the everyday lives of a significant fraction of the global population, the CERN Council has now agreed that it would not be appropriate to release the ESG update (and an accompanying deliberation document) to a wider audience, nor for the Council to make any further comment on the contents of the documents for the time being. The Budapest event has been replaced by a new extraordinary Council session, to be held by videoconference on the same date, at which delegates will discuss how to proceed.

In these exceptional circumstances it is not the right time to release the strategy

"In these exceptional circumstances it is not the right time to release the strategy, and discussing with various stakeholders in the Member States will take more time," says Ursula Bassler, president of the CERN Council. "Even though this will come as a disappointment to many physicists after all the effort put into the ESPPU, everyone can understand, that in this situation, the process will last longer."

CERN establishes coronavirus task force

In March, CERN established a task force to collect and coordinate ideas from the 18,000-strong global CERN community to help fight the COVID-19 pandemic. The CERN-against-COVID-19 group (against-covid-19.web.cern.ch) aims to work closely with experts in healthcare, drug development, epidemiology and emergency response to help ensure effective and well-coordinated action from high-energy physicists. The laboratory has also offered its support to the World Health Organization, with which it has had a collaboration agreement since 2011.

The initiative has attracted a large number of suggestions at various stages of development. In addition to listing proposals for ventilators (see previous page), efforts so far range from the use of CERN's computing resources and 3D printing of components for medical equipment, to the production of sanitiser gel (pictured) and Perspex shields and visors for emergency-response teams.

Clean hands *Benoit Teissandier prepares sanitiser gel in the CERN chemistry laboratory.*

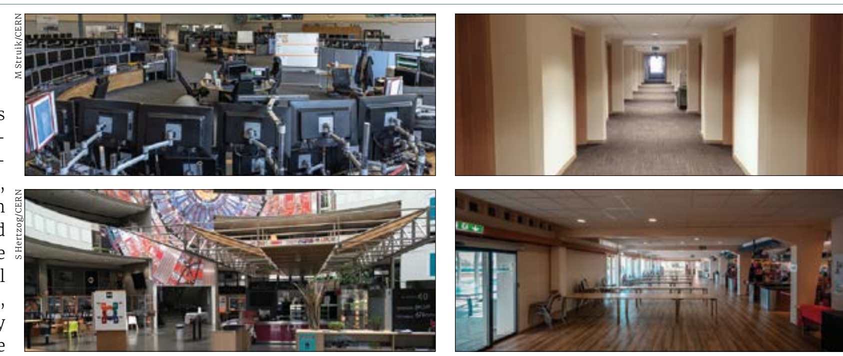
Another platform, Science Responds (science-responds.org), led by researchers in the US and loosely modelled on the HEP Software Foundation, has been established to facilitate interactions between COVID-19 researchers and the broader science community.

"It's not about going out there and doing things because we think we know best," says Beniamino Di Girolamo of CERN, who is chair of the CERN-against-COVID-19 task force. "But about offering our services and waiting to hear from the experts as to how we may be able to help."

Empty spaces, but physics continues

As the *Courier* went to press, CERN was about to enter its sixth week of shut-down in line with Stage 3 of the epidemic-preparedness plan. Since 20 March, activities at CERN have largely been limited to those essential for safety and security, with approximately 300 people working on site as opposed to several thousand during normal times. Also, having carefully reviewed the feasibility of running its diverse student and trainee programmes in light of the evolution of the COVID-19 pandemic, CERN has postponed the start dates for students and traineeships, and was forced to cancel its flagship summer-student programmes for this year.

While CERN's corridors and cafeterias lie almost empty, the vast majority of personnel and users are teleworking, and numerous measures have been put in place to help with continuity. Video conferences have become the new norm, with high levels of participation being witnessed across experiments and departments. For many physicists working on data analysis in the large LHC collaborations, remote working is not so unusual. However, many activities relating to the experiment upgrades and other work taking place on CERN's accelerator complex during long-shutdown two have temporarily been put on hold.



Silent CERN *(clockwise from top left) The CERN Control Centre, the Theory Department, Restaurant 1 and Building 40, captured during the current lock-down phase.*

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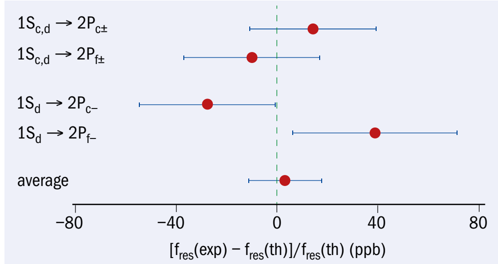
Antimatter

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 antihydrogen atoms. The results, published in *Nature* in February, bring further scrutiny to comparisons between antimatter and ordinary matter, which, if found to behave differently, would challenge CPT symmetry and shake the foundations of the Standard Model.

In 1947, US physicist Willis Lamb and his colleagues observed an incredibly small shift in the n = 2 energy levels of hydrogen in a 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 1955.

The ALPHA team creates antihydrogen atoms by binding antiprotons delivered by CERN's Antiproton Decelerator (AD) with positrons. The antiatoms are then confined in a magnetic trap in an ultra-high vacuum, and illuminated with a laser to measure their spectral response. 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 antihydrogen atom for the first time. The ALPHA team previously used this approach to measure other quantum effects in antihydrogen, the most recent being a measurement of the Lyman-alpha (1S–2P) transition in 2018 (*CERN Courier* October 2018 p9).



In line *The measured frequencies for the 1S–2P transitions in antihydrogen, f_{res}(exp), compared with those theoretically expected for hydrogen, f_{res}(th), with error bars corresponding to 1σ. All are consistent with hydrogen, and their average gives a combined test of CPT invariance at the level of 16 parts per billion.*

The splitting of the n = 2 energy level of hydrogen is a separation between the $2P_{3/2}$ and $2P_{1/2}$ 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 $2S_{1/2}$ and $2P_{1/2}$ levels, also in the absence of a magnetic field, and is the result of the effect on the electron of quantum fluctuations associated with virtual photons.

In its new study, the ALPHA team determined the fine-structure splitting and the Lamb shift by inducing transitions between the lowest (n = 1) energy level of antihydrogen and the $2P_{3/2}$ and $2P_{1/2}$ levels in the presence of a 1 T magnetic field. Using the value of the frequency of a previously measured transition (1S–2S), the team was able to infer the values of the fine-structure splitting and the Lamb shift. The results were found to be consistent with theoretical predictions of the splittings in normal hydrogen, within the experimental uncertainties of 2% for the fine-structure splitting and 11% 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 ALPHA spokesperson Jeffrey Hangst.

The seminal measurements of antihydrogen's spectral structure that are now possible follow more than 30 years of effort by the low-energy antimatter community at CERN (*CERN Courier* March 2018 p30). The first antihydrogen atoms were observed at CERN's LEAR facility in 1995 and, in 2002, the ATHENA and ATRAP collaborations produced cold (trappable) antihydrogen at the AD, opening the way to precision measurements of antihydrogen'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 0.8 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.

Next for the ALPHA 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 comparisons between matter and antimatter," says Hangst.

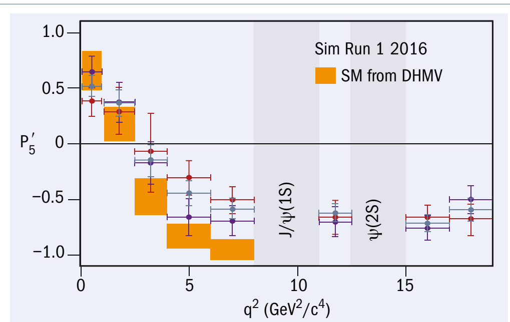
Further reading

ALPHA Collab. 2020 *Nature* **578** 375.

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 at CERN on 10 March, Eluned Smith of RWTH Aachen University presented an updated analysis of the angular distributions of $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decays based on around twice as many events as used for the collaboration's previous measurement (*CERN Courier* May 2015 p8). The result reveals a mild increase in overall tension



Angular puzzle *The distribution of the angular variable P_5' as a function of the mass squared of the muon pair, q^2. The results from Run 1 (red), those from the additional 2016 dataset only (purple), and those from both LHCb datasets (grey) are shown, along with the SM predictions (orange).*

with the Standard Model (SM) prediction, though, at 3.3σ, more data are needed to confirm or rule out the effect.

The $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decay is a promising system with which to explore physics beyond the SM. A flavour-changing neutral-current process, it involves a quark transition (b → s) that is forbidden at the lowest perturbative order in the SM, and therefore occurs only around once for every million B decays. The decay proceeds instead via higher-order penguin and box processes, which are sensitive to the presence of new, heavy particles. Such particles would enter in competing processes and could significantly change the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decay rate and the angular distribution of its final-state particles. Measuring angular distributions as a function of the invariant mass squared (q^2) of the muon pair is of particular interest because it does not depend heavily on hadronic modelling uncertainties.

Potentially anomalous behaviour in an angular variable called P_5' came to light in 2013, when LHCb reported a 3.7σ local deviation with respect to the SM in one q^2 bin, based on 1 fb^{-1} of data. In 2015, a global fit of different angular distributions of $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decays using the total Run-1 data sample of 3 fb^{-1} reaffirmed the puzzle, showing discrepancies of 3.4σ (later reduced to 3.0σ when using new theory calculations). In 2016, the Belle experiment at KEK in Japan performed its own angular analysis of this decay using data from electron–positron collisions and found a small (2.1σ) deviation in the same direction and in the same q^2 region as the LHCb anomaly.

The latest LHCb result includes additional Run-2 data collected during 2016, corresponding to a total integrated luminosity of 4.7 fb^{-1}. It shows that the local tension of P_5' in two q^2 bins between 4 and 8 GeV^2/c^4 reduces from 2.8 and 3.0σ, as observed in the previous analysis, to 2.5 and 2.9σ, but LHCb notes that a global fit to several angular observables increases the overall tension with the SM from 3.0 to 3.3σ. The results of the fit also find better overall agreement with predictions of new-physics models that contain additional vector or axial-vector contributions. However, the collaboration also makes it clear that the discrepancy could be due to an unexpectedly large hadronic effect that is not accounted for in the SM predictions.

"We as a community have been eagerly waiting for this measurement and LHCb has not disappointed," says theorist Jure Zupan of the University of Cincinnati. "The new measurements have moved closer to the SM predictions in the angular observables so that the combined significance of the excess remained essentially the same. It is thus becoming even more important to understand and scrutinise the SM predictions and claimed theory errors."

The latest result makes LHCb's continued measurements of lepton-flavour universality even more important, says Zupan. In recent years, LHCb has found that the ratio of the rates of muonic and electronic B decays departs from the SM prediction, suggesting a violation of the key SM principle of lepton-flavour universality. Though not individually statistically significant, the measurements are theoretically very clean, and the most striking departure – in the variable known as R_K – concerns B decays that proceed via the same b → s transition as $B^0 \rightarrow K^{*0}\mu^+\mu^-$. This has led physicists to speculate that the two 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 anomalies (*CERN Courier* May/June 2019 p33).

We as a community have been eagerly waiting for this measurement and LHCb has not disappointed

An update on R_K based on additional Run-2 data is hotly anticipated, and the collaboration is also planning to add data from 2017–2018 to the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ angular analysis. LHCb also recently brought the decays of beauty baryons, which also depend on b → s transitions, to bear on the subject.

"We have not seen evidence of new physics, but neither were the B physics anomalies ruled out," says Zupan of the LHCb result. "The wait for the clear evidence of new physics continues."

Further reading

LHCb Collab. 2020 arXiv:2003.04831.

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IOP Publishing

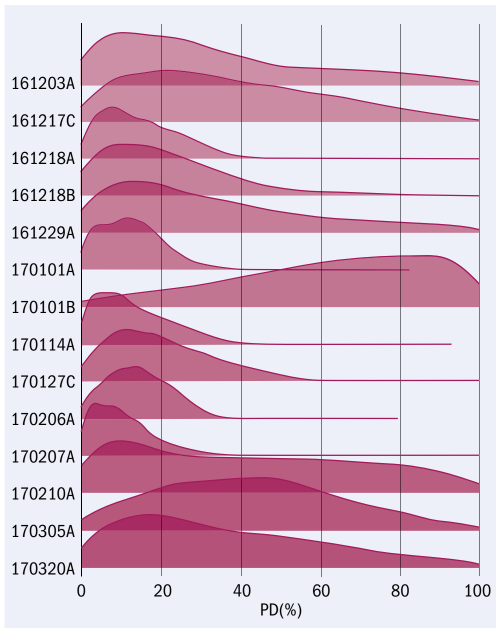
Astrowatch

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). GRBs consist of intense bursts of gamma rays which, for periods ranging from hundreds of milliseconds to hundreds of seconds, outshine any other source 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.



New tool *Probability distributions for the likely degree of polarisation (PD) of various GRBs inferred from POLAR data, indicating that the emission is lowly polarised or unpolarised for the vast majority of events. This would imply that magnetic fields are not important in these bright explosions, but detailed studies paint a more complicated picture.*

Difficult measurements

The reason that 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 photon, 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.

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

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 2016 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. For example, the polarisation is found to be low when looking at the full GRB emission, but when studying it over short time intervals, a strong hint of high polarisation is found with a rapidly changing polarisation angle during the GRB event. This rapid evolution of the polarisation angle, which is yet to be explained by the theoretical community, smears out the polarisation when looking at the full GRB. In order to fully understand the evolution, which could give hints of an evolution of a magnetic field, finer time-binning and more precise measurements are needed, which require more statistics.

POLAR-2

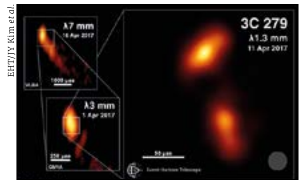
Two future instruments capable of providing such detailed measurements are currently being developed. The first, POLAR-2, is the follow-up of the POLAR mission and was recently recommended to become a CERN-recognised experiment. POLAR-2 will be an order of magnitude more sensitive (due to larger statistics and lower systematics) than its predecessor and therefore should be able to answer most of the questions raised by the recent POLAR results. The experiment will also play an important role in detecting extremely weak GRBs, such as those expected from GW events. POLAR-2, which will be launched in 2024 to the under-construction China Space Station, could well be followed by a similar but slightly smaller instrument called LEAP, which recently progressed to the final stage of a NASA selection process. If successful, LEAP would join POLAR-2 in 2025 in orbit on the International Space Station.

Apart from dedicated GRB polarimeters, progress is also being made at other upcoming instruments such as NASA's Imaging X-ray Polarimetry Explorer and China-ESA's enhanced X-ray Timing and Polarimetry mission, which aim to perform the first detailed polarisation measurements of a range of astrophysical objects in the X-ray region. While the first measurements from POLAR have been published recently, and more are expected soon, the 2020s should see the start of a new type of astrophysics, which adds yet another parameter to multi-messenger exploration.

Further reading

S Zhang *et al.* 2019 *Nat. Astron.* **3** 258.

NEWS DIGEST



EHT/J Y Kim et al.

Event Horizon Telescope image of a jet produced by a supermassive black hole.

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, blazar 3C 279, in hitherto unseen detail (pictured), revealing an unexpected twisted shape and perpendicular features that could be interpreted as the poles of the accretion disk. Variation observed over consecutive days could be due to rotation of the accretion disk and shredding and infall of material, say the team (*Astron. Astrophys.* doi: 10.1051/0004-6361/202037493). Meanwhile, following up on leads from NASA's Chandra X-ray Observatory and ESA's X-ray Multi-Mirror Mission, the Hubble Space Telescope has found the first strong evidence for the existence of an intermediate-mass (10^2–10^5 solar masses) black hole – previously a missing link in the evolution of stellar to supermassive black holes (*ApJL* **892** L25).

First physics for Belle II
A little over a year since Belle II began taking data at the SuperKEKB collider in Japan, the collaboration has published its first physics analysis, using data from the Belle II pilot run in 2018: a search for invisibly decaying Z′ bosons, which would constitute evidence for physics beyond the Standard Model (SM). The team scoured four months of data for the Z′ in the process $e^+e^- \to \mu^+\mu^- Z'$ and for a lepton-flavour violating Z′ in $e^+e^- \to e^\pm\mu^\mp Z'$, by looking for missing energy recoiling against the two clean lepton tracks. No excess of events was found, yielding preliminary sensitivity to the coupling g′ in the so-called L_μ–L_τ extension of the SM. This model, wherein the Z′ couples only to muon and tau-lepton flavoured SM particles and the dark sector, also has the potential to explain anomalies in $b \to s\mu^+\mu^-$ decays reported by LHCb (*CERN Courier* May/June 2019 p33) and the muon g–2 anomaly, claims the team (*Phys. Rev. Lett.* **124** 141801).

Neutron STAR measurements
The STAR collaboration at Brookhaven's Relativistic Heavy-Ion Collider has measured the binding of the lightest strange nucleus to be stronger than previously thought (*Nat. Phys.* **16** 409). Hypertriton is the bound state of a tritium nucleus – a triton – where one neutron has been replaced by a lambda hyperon. STAR measured its binding energy, defined to be the mass of its components, a deuteron and a lambda hyperon, less the measured mass of the nucleus, to be 0.41 ± 0.12 (stat.) ± 0.11 (syst.) MeV. Previous measurements in the 1970s were consistent with zero. 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 forms. The collaboration also found no evidence for a mass difference between hypertriton and antihypertriton: a test of CPT symmetry.

Dyons elude MoEDAL
In 1969, Julian Schwinger extended Dirac's concept of the magnetic monopole by speculating that particles might carry both electric and magnetic charges (*Science* **165** 3895), and today "dyons" are often a feature of grand unified theories. The MoEDAL collaboration at CERN has now conducted the first collider search for dyons using a subdetector system consisting of almost a tonne of aluminium (arXiv:2002.00861). The 2400 bars were exposed to 13 TeV proton–proton collisions at the LHC between 2015 and 2017, and then scanned using a SQUID magnetometer to look for the presence of trapped magnetic charge belonging to dyons. The researchers ruled out the existence of dyons that carry a magnetic charge ranging up to six units of a fundamental magnetic charge (the Dirac charge) and an electric charge up to 200 times the electron's charge, for dyons with a mass between 830 and 3180 GeV.

VECC

The Superconducting Cyclotron.

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 of superconducting cyclotrons operating worldwide. A similar machine to those 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.

Xi excitations puzzle
The LHCb collaboration has observed a system of three narrow peaks in the invariant mass of $\Lambda_c^+ K^-$ pairs, interpreted as the decays of new excited Ξ_c^0 (csd) states at 2923, 2939 and 2965 MeV (arXiv:2003.13649, submitted to *Phys. Rev. Lett.*). The Λ_c^+ baryons were reconstructed in their decays into $pK^-\pi^+$. The $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ are observed for the first time. The $\Xi_c(2965)^0$ is close to a previously known state, the $\Xi_c(2970)^0$, but its measured mass and width differ significantly from existing Belle and BABAR results. Further studies are required to clarify the situation.

New measure of neutron EDM
The nEDM collaboration at the Paul Scherrer Institute in Switzerland has published the most sensitive measurement so far of the electric dipole moment of the neutron (nEDM), 0.0 ± 1.1 (stat.) ± 0.2 (syst.) $\times 10^{-26}$ e cm, by watching for shifts in the Larmor precession frequency of ultracold neutrons proportional to an applied electric field (*Phys. Rev. Lett.* **124** 081803). A nonzero nEDM would be evidence of the violation of time-reversal symmetry, therefore also suggesting the violation of CP, if CPT symmetry holds. As the nEDM due to CP violation in the CKM matrix is estimated to be of the order of just 10^{-32} e cm, the PSI result places an even more stringent upper limit on the as-yet inexplicably small amount of CP violation in QCD: the so-called strong CP problem.

Not from a lab
Researchers in the US, the UK and Australia have dismissed speculation that SARS-CoV-2 might have originated from a laboratory in Wuhan (*Nat. Med.* doi: 10.1038/s41591-020-0820-9). Genetic data irrefutably show that SARS-CoV-2 is not derived from any previously used virus backbone, say the authors, who compared its genome to SARS-CoV, which originated in a food market in Guangdong in April 2003.

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ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

ATLAS

Tau pairs speed search for heavy Higgs bosons

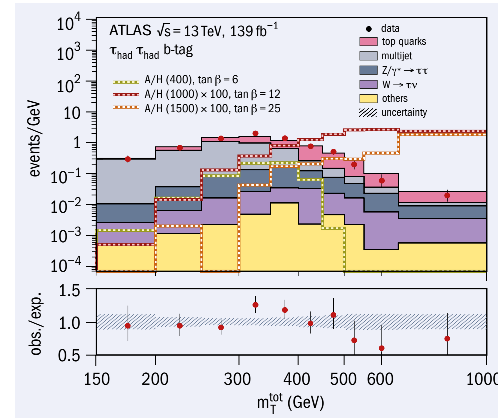


Fig. 1. *The distribution of the final discriminant in the analysis, obtained after a fit under the background-only hypothesis, with three signal models overlaid. This particular analysis category requires two hadronically decaying tau leptons and at least one b-tagged jet.*

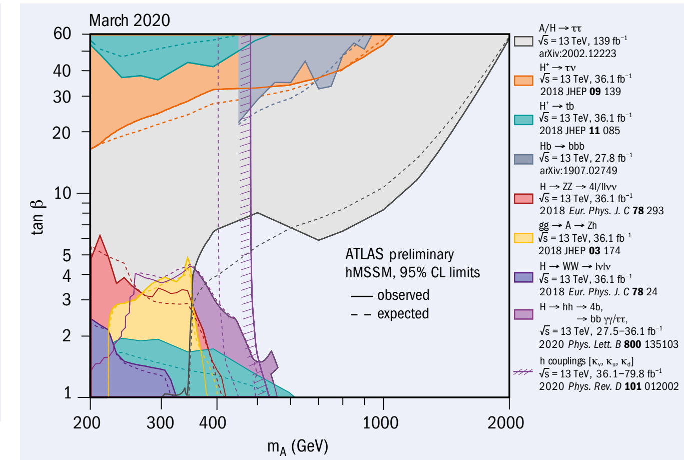


Fig. 2. *Excluded regions in the hMSSM scenario, overlaying various ATLAS searches for heavy neutral and charged Higgs bosons. The A/H→ττ search (light grey) excludes a wide range of values for high and intermediate values of tan β.*

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 supersymmetric 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 (139 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 values (for example when the heavy Higgs boson is radiated by a b-quark produced in the collision of two gluons), the data are further categorised based on the presence or absence of additional b-jets. One of the challenges of the analysis is the misidentification of backgrounds with hadronic jets as tau candidates. These backgrounds are estimated from data by measuring the misidentification probabilities and applying them to events in control regions representative of the event selection. The final discriminant is on the quantity m_T^{tot}, which is built from the combination of the transverse masses of the two tau-lepton decay products (figure 1).

The new ATLAS search requires the presence of two oppositely charged tau-lepton candidates

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 → ττ exclusion 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

ATLAS Collab. 2020 arXiv:2002.12223.
ATLAS Collab. 2020 ATL-PHYS-PUB-2020-006.

Control systems for big Science, today

In the last decade, control system development has become an established engineering discipline and less of a scientific endeavour that was at times characterised by the "not-invented-here" viewpoint.

At the turn of the century, very little ready-made and off-the-shelf equipment was available for control systems. The handful of physics labs that had demanding requirements were not commercially interesting to equipment vendors and the control system engineers were still mostly the scientists themselves. Today, a larger number of experimental projects and advancements in computing have allowed the widespread standardisation of control system components and the adoption of good practises and solutions from industry.

During this time, control system packages and frameworks have also matured through community collaboration. The growing control system integration market in science has also attracted industry players in much larger numbers. This has reduced control system budgets from being 10% of the machine's budget to even less than 5%. Today's challenge is, therefore, no longer how to implement a control system with state-of-the-art technology, but how to do it cheaper and quicker, without sacrificing quality.

In this article, I will outline some of the main points that you must consider when implementing a control system for a modern machine.

Photo by Yulia Buchatskaya on Unsplash (DESY, Hamburg)

Basic or multiple control system packages

Traditionally, the first decision that the project manager and control system engineer makes is which control system package to use. Luckily, today's most popular control system packages are quite mature and with a wide enough scope that you will be able to finish your project whatever your choice.

Nevertheless, some scientific facilities, such as big physics machines, use more than one control system. In our experience, it is better to avoid mixing and matching several control system packages, if at all possible. In general, we believe that you should clearly define the functionalities and requirements for the interfaces. And don't forget about documentation and maintenance of the systems. It is usually best to adopt established best practises and learn from the experience of previous similar projects.

Machine protection and timing systems

A reliable, fast and flexible machine-protection system (MPS) is a critical safety feature that prevents damage to the machine or harm to its users, primarily when it works at high energies. A completely flexible MPS implementation does not yet exist for big science but, based on requirements from many projects, its ideal features are known. One feature is the reconfiguration of the MPS depending on the working mode of the machine. Clients also desire integration with the timing and control systems, allowing for quick reconfiguration and post-mortem analysis. New MPS designs allow responses in the range of microseconds where the speed of light becomes one of the constraints.

New demanding physics machines require complex timing systems. Features such as virtual accelerators, timing super-cycles and event acknowledgements are becoming more common. It is now almost agreed that existing – bespoke – timing solutions cannot provide all the necessary functionality. But these solutions can be employed as the underlying transmission layer, to which customisation can be added. Put simply: one can purchase the transport layer, whereas the machine-specific application layer must be individually adapted for each project.

Focus on development and standardisation

Building any complex system from many components is always a daunting engineering task but control system development has an even more complicated cycle: define specifications, architecture, design, prototyping, test procedures; then implement, write documentation, test, debug and gain site acceptance. Project managers are increasingly aware of the development process itself, so more things require focus. Control system engineers must 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 replaces development as the most prominent aspect of a control system project. So 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 increasingly an engineering discipline and less of a scientific one.

ABOUT THE AUTHOR
Rok Šabjan is currently the Technical Advisor and Sales Director for the Scientific domain at Cosylab and is also one of the co-founders of the company. Rok has a bachelor's in physics and an executive MBA, with fields of expertise including EPICS, control system architecture and integration, project management and consulting.
In his free time, Rok likes to spend time with his family, read, hike and play inline hockey.

CMS

First sight of the running of the top-quark mass

The coupling between quarks and gluons depends strongly on the energy scale of the process. The same is true for the masses of the quarks. This effect – the so-called "running" of 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, SLC and HERA, though the running of the top-quark mass has hitherto 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 at a centre-of-mass energy of 13 TeV, recorded by the CMS detector in 2016. The top quark's mass was determined as a function of the invariant mass of the top quark–antiquark system (the energy scale of the process), by comparing differential measurements of the system's production cross section with theoretical predictions. In the vast majority of the cases, top quarks decay into a W boson and a 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 determined using a maximum-likelihood fit to multi-differential distributions of final-state observables, allowing the precision of 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 RGE, within 1.1 standard deviations, and a hypothetical no-running scenario is excluded at above 95% confidence level.

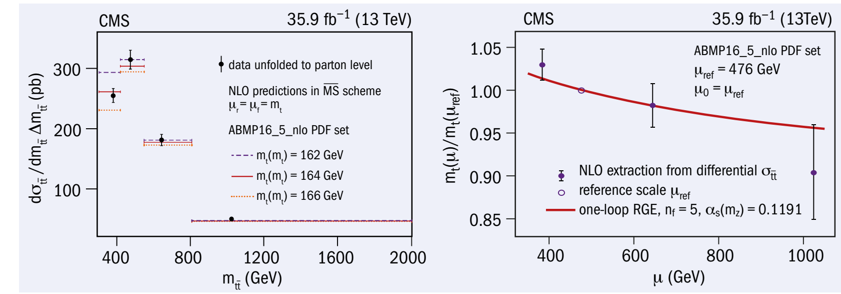


Fig. 1. *Left: the cross section for top-quark pair production as a function of the invariant mass of the system. The data are unfolded to the parton level and compared to next-to-leading-order theoretical predictions at different values of the top-quark mass. Right: the observed running of the top-quark mass compared to the solution of the RGEs at one-loop precision.* μ_{ref} *= 476 GeV (purple circle) is the mean of the second mass bin.*

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 calibrations and the modelling of the top-quark production in the simulation. Further progress will not only require a significant effort in improving the calibrations of the final-state objects, but also substantial theoretical developments.

Further reading
CMS Collab. 2020 *Phys. Lett. B* **803** 135263.

ALICE

ALICE extends quenching studies to softer jets

Jets are the most abundant high-energy objects produced in collisions at the LHC, and often contaminate searches for new physics. In heavy-ion collisions, however, these collimated showers of hadrons are not a background but one of the main tools to probe the deconfined state of strongly interacting matter known as the quark–gluon plasma.

ALICE is actively working to further constrain theoretical predictions in both pp and Pb–Pb collisions

There are many open questions about the structure of the quark–gluon plasma: What are the relevant degrees of freedom? How do high-energy quarks and gluons interact with the hot QCD medium? Do factorisation and universality hold in this extreme environment? To answer these questions, experiments study how jets are modified in heavy-ion collisions, where, unlike in proton–proton collisions, they may interact with the constituents of the quark–gluon plasma. Since jet production and interactions can be computed in perturbative QCD, comparing theoretical calculations to measurements can provide insight to the properties of the quark–gluon plasma.

In this spirit, the ALICE collaboration has measured the inclusive jet production yield in both Pb–Pb and proton–proton (pp) collisions at a centre-of-mass energy of 5.02 TeV. Jets were reconstructed from a combination of information from the ALICE tracking detectors and electromagnetic calorimeter for a variety of jet radii R. The detectors' excellent performance with soft tracks was exploited to allow the measurements to cover the lowest jet transverse momentum ($p_{T,jet}$) region measured at the LHC, where jet modification effects are predicted to be strongest. The measured jet yields in Pb–Pb collisions exhibit strong suppression compared to pp collisions, consistent with theoretical expectations that jets lose energy as they propagate through the quark–gluon plasma (figure 1). For relatively narrow R = 0.2 jets, the data show stronger suppression at lower p_T, jet than at higher $p_{T,jet}$, suggesting that lower $p_{T,jet}$ jets lose a larger fraction of their energy. Additionally, the data show no significant R dependence of the suppression within the uncertainties of the measurement, which places constraints on the angu- ▷

lar distribution of the "lost" energy.

Several theoretical models, spanning a range of physics approximations from jet–medium weak-coupling to strong-coupling, were compared to the data. The models are able to generally describe the trends of the data, but several models exhibit hints of disagreement with the measurements. These data complement existing jet measurements from ATLAS and CMS, and take advantage of ALICE's high-precision tracking system to provide additional constraints on jet-quenching models in heavy-ion collisions at low p_T. Moreover, these measurements can be used in combination with other jet observables to extract properties of the medium such as the transverse momentum diffusion parameter, which describes the angular broadening of jets as they traverse the quark–gluon plasma, as a function of the medium temperature and the jet p_T.

The "reference" measurements in pp collisions contain important QCD

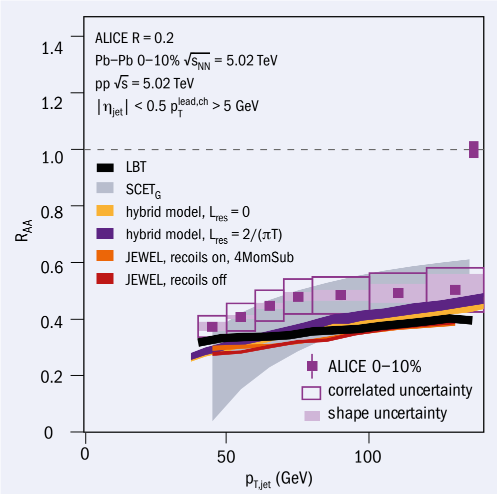


Fig. 1. *The ratio of jet yields in Pb–Pb collisions relative to pp collisions (appropriately scaled) compared to four theoretical predictions.*

physics themselves. This new set of measurements was performed systematically from R = 0.1 to R = 0.6, in order to span from small R, where hadronisation effects are large, to large R, where underlying event effects are large. These data can be used to constrain the perturbative structure of the inclusive jet cross section, as well as hadronisation and underlying event effects, which are of broad interest to the high-energy physics community.

Going forward, ALICE is actively working to further constrain theoretical predictions in both pp and Pb–Pb collisions by exploring complementary jet measurements, including jet substructure, heavy-flavour jets, and more. With a nearly 10 times larger Pb–Pb data sample collected in 2018, upcoming analyses of the data will be important for connecting observed jet modifications to properties of the quark–gluon plasma.

Further reading

ALICE Collab. 2020 *Phys. Rev. C* **101** 034911.

LHCb

New SMOG on the horizon

Fig. 1. *Half of the SMOG2 storage cell (black), attached to its wake-field suppressor (black, right) and the VELO RF foil (grey, left).*

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 Overlap with Gas (SMOG), which injected noble gases into the vacuum vessel of LHCb's vertex detector (VELO) at a low rate with the initial goal of calibrating luminosity measurements. The new system has several advantages, including the ability to reach effective area densities (and thus luminosities) up to two orders of magnitude higher for the same injected gas flux.

SMOG2 is a gas target confined within a 20 cm-long aluminium storage cell that is mounted at the upstream edge of the VELO, 30 cm from the main interaction point, and coaxial with the LHC beam (figure 1). The storage-cell technology allows a very limited amount of gas to be injected in a well defined volume within the LHC beam pipe, keeping the gas pressure and density profile under precise control, and ensuring that the beam-pipe vacuum level stays at least two orders of magnitude below the upper threshold set by the LHC. With beam–gas interactions occurring at roughly 4% of the proton–proton collision rate at LHCb, the lifetime of the beam will be essentially unaffected. The cell is made of two halves, attached to the VELO with an alignment precision of 200 µm. Like the VELO halves, they can be opened for safety during LHC beam injection and tuning, and closed for data-taking. The cell is sufficiently narrow that as small a flow as 10^{-15} particles per second will yield tens of pb^{-1} of data per year. The new injection system will be able to switch between gases within a few minutes, and in principle is capable of injecting not just noble gases, from helium up to krypton and xenon, but also several other species, including H_2, D_2, N_2, and O_2.

SMOG2 will open a new window on QCD studies and astroparticle physics at the LHC, performing precision measurements in poorly known kinematic regions. Collisions with the gas target will occur at a nucleon–nucleon centre-of-mass energy of 115 GeV for a proton beam of 7 TeV, and 72 GeV for a Pb beam of 2.76 TeV per nucleon. Due to the boost of the interacting system in the laboratory frame and the forward geometrical acceptance of LHCb, it will be possible to access the largely unexplored high-x and intermediate Q^2 regions.

Combined with LHCb's excellent particle identification capabilities and momentum resolution, the new gas target system will allow us to advance our understanding of the gluon, antiquark, and heavy-quark components of nucleons and nuclei at large-x. This will benefit searches for physics beyond the Standard Model at the LHC, by improving our knowledge of the parton distribution functions of both protons and nuclei, particularly at high-x, where new particles are most often expected, and will inform the physics programmes of proposed next-generation accelerators such as the Future Circular Collider. The gas target will also allow the dynamics and spin distributions of quarks and gluons inside unpolarised nucleons to be studied for the first time at the LHC, a decade before corresponding measurements at much higher accuracy are performed at the Electron-Ion Collider in the US. Studying particles produced in collisions with light nuclei, such as He, and possibly N and O, will also allow LHCb to give important inputs to cosmic-ray physics and dark-matter searches. Last but not least, SMOG2 will allow LHCb to perform studies of heavy-ion collisions at large rapidities, in an unexplored energy range between the SPS and RHIC, offering new insights into the QCD phase diagram.

Further reading

LHCb Collab. 2018 LHCb-PUB-2018-015.
LHCb Collab. 2019 LHCB-TDR-020.

FIELD NOTES

Reports from events, conferences and meetings

FCC Physics and Experiments Workshop

Circular colliders eye Higgs self-coupling

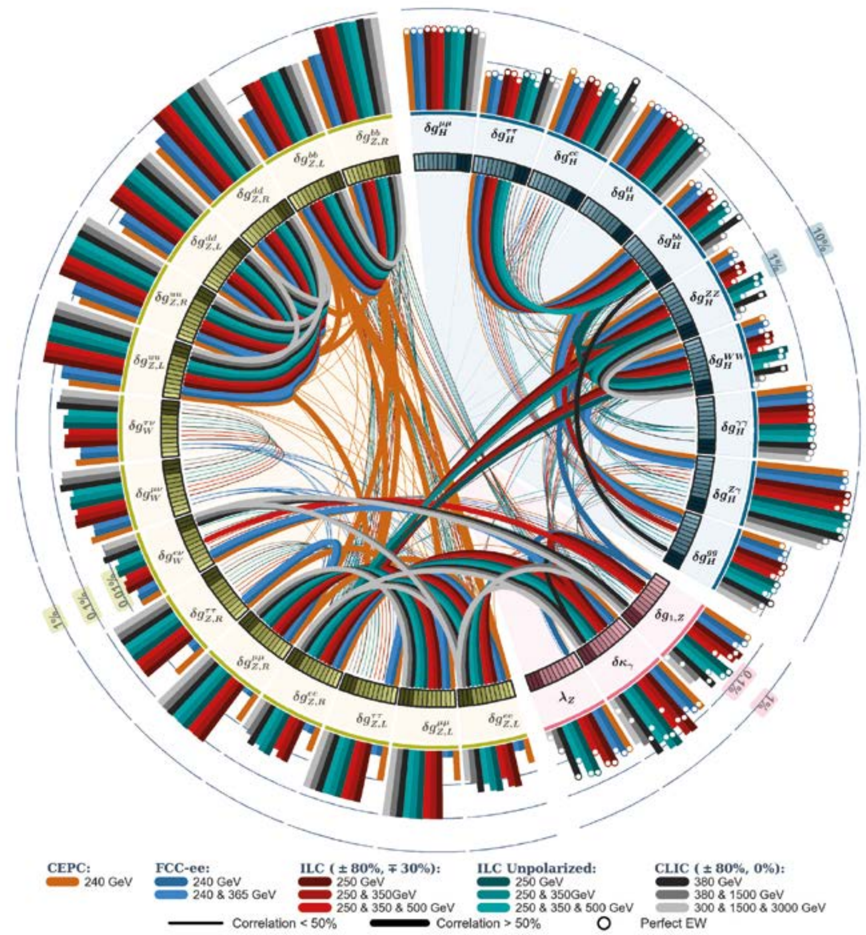
Physics beyond the Standard Model must exist, to account for dark matter, the smallness of neutrino masses and the dominance of matter over antimatter in the universe; but we have no real clue of its energy scale. It is also widely recognised that new and more precise tools will be needed to be certain 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 an 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 5×10^{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. To reach the required precision at the Z-pole, three-loop calculations of quantum electroweak corrections must include all the heavy Standard Model particles ($W^\pm$, Z, H, t).

In parallel, a significant focus of the meeting was on detector designs for FCC-ee, with the aim of forming experimental proto-collaborations by 2025. The design of the interaction region allows for a beam vacuum tube of 1 cm radius in the experiments – a very promising condition for vertexing, lifetime measurements and the separation of bottom and charm quarks from light-quark and gluon jets. Elegant solutions have been found to bring the final-focus magnets close to the interaction point, using either standard quadrupoles or a novel ▷



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 (connections) and achievable precisions (outer 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.)*

magnet design using a superposition of off-axis ("canted") solenoids. Delegates discussed solutions for vertexing, tracking and calorimetry during a Z-pole run at FCC-ee, where data acquisition and trigger electronics would be confronted with visible Z decays at 70 kHz, all of which would have to be recorded in full detail. A new subject was π/K/p identification at energies from 100 MeV to 40 GeV – 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 delivery of luminosity for little extra power consumption, but construction costs and compatibility with a possible subsequent hadron collider must be determined. A bolder idea discussed at the workshop aims to improve both luminosity (by a factor of 10) and energy reach (perhaps up to 600 GeV), by turning FCC-ee into a 100 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: $e^+e^- \rightarrow H$, sitting exactly at a 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 (4.2 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.

Physicists cannot refrain from investigating improvements

The ability to precisely probe the self-coupling of the Higgs boson is the keystone of the FCC physics programme. As said above, 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-hh would be able to access Hμμ, Hγγ, HZγ and Htt couplings at sub-percent precision. Further study of double Higgs production at FCC-hh shows that a measurement of the Higgs self-coupling could be done with 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 constituted the highlight of the workshop.

Alain Blondel *LPNHE Paris, CERN and the University of Geneva, and* **Panagiotis Charitos** *CERN.*

QUARK MATTER 2019

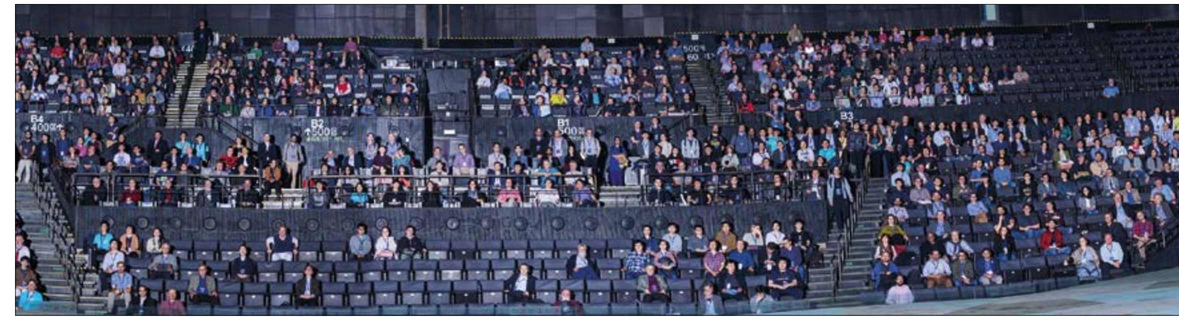
LHC and RHIC heavy ions dovetail in Wuhan

QM2019

The 28th International 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 early universe, matter is a quark–gluon plasma (QGP), in which quarks and gluons are not confined within hadrons. In the recent editions of Quark Matter, much attention has also been devoted to the study of emergent QCD phenomena in high-multiplicity proton–proton and proton–nucleus collisions, which resemble the collective effects seen in nucleus–nucleus collisions and pose the intriguing question of whether a QGP can also form in "small-system" collisions.

Colourful physics *The latest edition of the International Conference on Ultrarelativistic Nucleus–Nucleus Collisions, Quark Matter 2019, took place in Wuhan in November.*

The large data sample from the Pb–Pb period of LHC Run 2 in 2018 allowed ALICE, ATLAS, CMS and LHCb to study rare probes of the QGP, such as jets and heavy quarks, with unprecedented precision. New constraints on the energy loss of partons when traversing the high-density medium were presented, pushing the limits of jet measurements to lower transverse momenta and larger radii: jet modifications are now measured in the transverse momentum range from 40 to 1000 GeV and in the jet radius (resolution parameter) range 0.2 to 1. The internal structure of jets was studied not only by the LHC experiments, but also by the PHENIX and STAR collaborations at the 25-times lower RHIC collision ▷



QM2019

energy. LHC and RHIC measurements are complementary as they cover a broad range of QGP temperatures and differ in the balance of quark- and gluon-initiated jets, with the former dominating at RHIC and the latter dominating at the LHC.

Fundamental understanding *More than 800 participants discussed the latest results of the heavy-ion programmes at the LHC and RHIC.*

Measurements in the sectors of heavy quarks and rarely-produced light nuclei (such as deuterons, ^{3}He and hypertriton, a pnΛ bound state) also strongly benefited from the large recent samples recorded at the LHC. In particular, their degree of collective behaviour could be studied in much greater detail. The family of QGP probes in the heavy-quark sector has been extended with new members at the LHC by first observations of the X(3872) exotic hadron and of top-antitop quark production. In the sector of electromagnetic processes, new experimental observations were presented for the first time at the conference, including the photo-production of dileptons in collisions with and without hadronic overlap, and light-by-light scattering. These effects are induced by the interaction of the strong electromagnetic fields of the two Pb nuclei (Z = 82) passing close to each other (*CERN Courier* January/February 2020, p17).

New information

In nuclear collisions, the fluid-dynamical flow of the QGP leaves an imprint in the azimuthal distribution of soft particles as the initial geometry of the collision is translated to flow through pressure gradients. Its experimental trace is multi-particle angular correlations between low-momentum particles, even at large rapidity separations. In non-central nucleus–nucleus collisions that have an elliptical initial geometry, the resulting azimuthal modulation of particle momentum distribution is called elliptic flow. New information on collective behaviour and on the dynamics of heavy-quark interactions in the QGP was added by a first measurement of the D-meson momentum distribution down to zero momentum in Pb–Pb collisions at the LHC, and by new measurements of the elliptic flow of D mesons and muons from charm and beauty decays, as well as bound states of heavy quarks (charmonia and bottomonia). These measurements suggest a stronger degree of collective behaviour for light than heavy quarks, and further constrain estimates of the QGP viscosity. Such estimates also require an understanding of heavy-quark hadronisation, which was discussed in the light of new results at RHIC and the LHC, which indicate an increased production of charmed baryons with respect to mesons, at low momentum in both pp and nucleus–nucleus collisions, when compared to expectations from electron–positron collisions.

The LHC and RHIC together cover a broad range of quark–gluon-plasma temperatures

Dynamical origins

While there is strong evidence for the production of QGP in nuclear collisions, the situation is much less clear in the collisions of small systems. The momentum correlations and azimuthal modulations that characterise the large nuclear collisions were also observed in smaller collision systems, such as p–Pb at the LHC, p–Au, d–Au and ^{3}He–Au at RHIC, and even pp. The persistence of these correlations in smaller collision systems, down to pp collisions where it is unlikely that an equilibrated system could be created, may offer an inroad to understand how the collective behaviour of the QGP arises from the microscopic interaction of its individual constituents. New measurements on multi-particle correlations were presented and the dynamical origin of the collectivity in small systems was discussed. Small expanding QGP droplets, colour connections of overlapping QCD strings, and final-state rescattering at partonic or hadronic level are among the possible mechanisms that are proposed to describe these observations. While many of the signs characteristic of the QGP are seen in small-system collisions, parton energy loss (in the form of jet or large-momentum hadron modifications) remains absent in the measurements carried out to date.

The field is now looking forward to future programmes at the LHC and RHIC, which were extensively reviewed at the conference. At the LHC, the heavy-ion injectors and the experiments are currently being upgraded. In particular, the heavy-ion-dedicated ALICE detector is undergoing major improvements, with readout and tracker upgrades that will provide larger samples and better performance for heavy-flavour selection. Run 3 of the LHC, which is scheduled to start in 2021, will provide integrated luminosity increases ranging from one order of magnitude for the data samples based on rare triggers to two orders of magnitude for the minimum-bias (non-triggered) samples. At RHIC, the second beam-energy-scan programme is now providing the STAR experiment with higher precision data to search for the energy evolution of QGP effects, and the new sPHENIX experiment aims at improved measurements of jets and heavy quarks from 2023. Low-energy programmes at the CERN SPS, NICA, FAIR, HIAF and J-PARC, which target a systematic exploration of heavy-ion collisions with high baryon density to search for the onset of deconfinement and the predicted QCD critical point, were also discussed in Wuhan, and the updated plans for the US-based Electron-Ion Collider (EIC), which is foreseen to be constructed at Brookhaven National Laboratory, were presented. With ep and e-nucleus interactions, the EIC will provide unprecedented insights into the structure of the proton and the modification of parton densities in nuclei, which will benefit our understanding of the initial conditions for nucleus–nucleus collisions.

Andrea Dainese *INFN Padova,* **Aleksi Kurkela** *CERN and Stavanger University, and* **Michael Weber** *SMI Vienna.*

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VI COSMOLOGY AND THE QUANTUM VACUUM

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 for scalar fields and gauge theories. Joseph Buchbinder gave a review of one-loop effective action in supersymmetric gauge theories. Conformal quantum gravity and quantum electrodynamics in de Sitter space were presented by Enrique Alvarez (Madrid) and Drazen Glavan (Brussels), respectively.

S Odintsov

String inspiration *Ekaterina Pozdeeva (Skobeltsyn Institute of Nuclear Physics, Moscow) discusses the stability of de Sitter solutions in "Gauss-Bonnet" gravity.*

Even more attention was paid to theoretical cosmology. The evolution of the early and/or late universe in different theories of modified gravity was discussed by several delegates, with Enrique Gaztanaga (Barcelona) expressing an interesting point of view on the inflationary universe, arguing for two early inflationary periods.

Martiros Khurshudyan and I discussed modified-gravity cosmology with the unification of inflation and dark energy, and wormholes, building on work with Emilio Elizalde. Wormholes are usually related with exotic matter, however, they may in alternative gravity be caused by modifications to the gravitational equations of motion. Iver Brevik (Trondheim) gave an excellent introduction to viscosity in cosmology. Rather exotic wormholes were presented by Sergey Sushkov (Kazan), while black holes in modified gravity were discussed by Gamal Nashed (Cairo). A fluid approach to the dark-energy epoch and the addition of four forms (antisymmetric tensor fields with four indices) to late universe evolution was given by Diego Saez (Vallodolid) and Mariam Bouhmadi-Lopez (Bilbao), respectively. Novel aspects of non-standard quintessential inflation were presented by Jaime Haro (Barcelona).

Many interesting talks were given by young participants at this meeting. The exchange of ideas between cosmologists on the one side and quantum-field-theory specialists on the other will surely help in the further development of rigorous approaches to the construction of quantum gravity. It also opens the window onto a much better account of quantum effects in the history of the universe.

Sergey Odintsov *Institute of Space Sciences, Barcelona.*

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 5 October 2019. In this first round, 12 undergraduates at the University of Hamburg joined 11 students from Yerevan State University to form eight small teams. Each team worked its way through an experiment under the supervision of experts from both nations, interacting with physicists in a laboratory setting for the first time in many cases. 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.

Working together *German and Armenian undergraduates teamed up to tackle accelerator-physics experiments in Yerevan.*

CANDLE Institute

CANDLE is a proposed third-generation synchrotron-radiation facility in Armenia. As a first step towards its realisation, AREAL, an ultrafast laser-driven electron accelerator, has been constructed. The next steps are S-band linac acceleration up to 20–50 MeV and the generation of coherent and tunable THz-radiation in an undulator.

Joerg Rossbach *University of Hamburg.*

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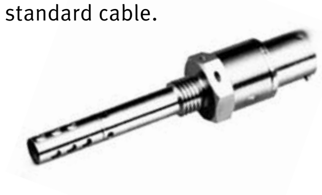

We also manufacture cryogenic assemblies for temperatures down to 1.5K.

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

Magnetic assemblies

Magnetic sensors in a fusion experiment. In the "configuration" column, m × n means the number of the sensors in the poloidal and toroidal direction, respectively, and single numbers indicate the numbers of the sensors along poloidal or toroidal paths, except for Rogowski coils for Halo current.

Type of sensor	Configuration	Physical quantity	Main purpose
Magnetic probe winding wire; TCprobe)	23×1	Bθ, (poloidalfield), low frequency	Plasma equilibrium reconstruction and control
	23×1	Bθ,	Plasma equilibrium reconstruction and control
Magneticprobe (metalized ceramic; new ATprobe)	18×6	Low frequency	3D MHD, RWM identification
	18×6	B_r (radial field)	
	32×1+1×9	δBθ, high frequency	(High frequency) MHD instabilities (identification of poloidal and toroidal mode number)
Rogowski coil	4sets	I_p (plasma current)	Plasma equilibrium reconstruction and control
Flux loop	34	Ψ (poloidal flux)	Plasma equilibrium reconstruction and control
Diamagnetic loop	3sets	$Ψ_c$ (diamagnetic flux)	Plasma stored energy
Saddle loop	(3×6)×2	B_r	Non-rotating modes, RWM
Rogowski coil	48	I_h (halo current)	Halo current distribution
Rogowski coil	2	I_v (vessel current)	Eddy current on VV

Magnetic measurements conducted using these sensors serve the following three purposes: plasma equilibrium reconstruction and control, MHD identification, and disruption study.

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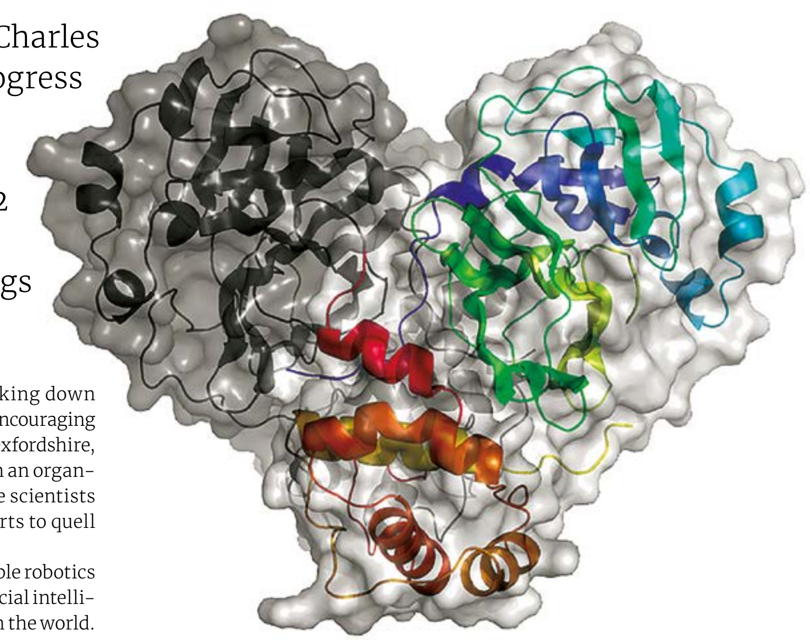
SYNCHROTRONS ON THE CORONAVIRUS FRONTLINE

Accelerator physicist Tessa Charles describes the impressive progress being made by synchrotron X-ray facilities to solve the structure of the SARS-CoV-2 virus – a first step towards the development of new drugs and vaccines.



Unlocking the puzzle *Representation of 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.)*

At a time when many countries are locking down borders, limiting public gatherings and encouraging isolation, the Diamond Light Source in Oxfordshire, UK, has been ramping up its activities, albeit in an organised and controlled manner. The reason: these scientists are working tirelessly on drug-discovery efforts to quell COVID-19.

It is a story that requires fast detectors, reliable robotics and powerful computing infrastructures, artificial intelligence, and one of the brightest X-ray sources in the world. And it is made possible by international collaboration, dedication, determination and perseverance.

Synchrotron light sources are particle accelerators capable of producing incredibly bright X-rays by forcing relativistic electrons to accelerate on curved trajectories. Around 50 facilities exist worldwide, enabling studies over a vast range of topics. Fanning out tangentially from Diamond's 562 m-circumference storage ring are more than 30 beamlines equipped with instrumentation to serve a multitude of user experiments. The intensely bright X-rays (corresponding to a flux of around 9×10^{12} photons per second) are necessary for determining the atomic structure of proteins, including the proteins that make up viruses. As such, synchrotron light sources around the world are interrupting their usual operations to work on mapping the structure of the SARS-CoV-2 virus.

Knowing the atomic structure of the virus is like knowing how the enemy thinks. A 3D visualisation of the building blocks of the structure at an atomic level would allow scientists to understand how the virus functions. Enzymes, the molecular machines that allow the virus to replicate, are key to this process. Scientists at Diamond are exploring the binding site of one enzyme, the main SARS-CoV-2 protease, which is responsible for the breakdown of proteins into smaller pieces. A drug that binds to this enzyme's active site would 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.

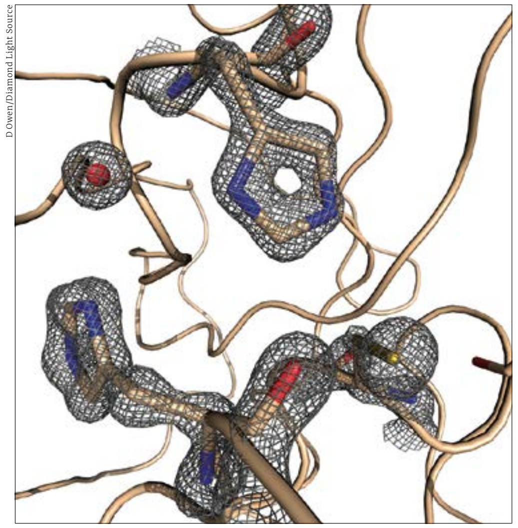
Call to arms

On 26 January, Diamond's life-sciences director, Dave Stuart, received a phone call from structural biologist Zihe 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.

THE AUTHOR

Tessa Charles
University of Melbourne.

Shedding light *An aerial view of the UK's Diamond Light Source (left) and one of its transfer lines in the foreground and storage ring in the background (right), where ultra-relativistic electrons circulate and produce intense synchrotron radiation.*



Twists and turns *A close-up view of some residues in the active site of the SARS-CoV-2 protease (an enzyme), where the sticks represent the protein molecules and the mesh represents the electron density.*

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 Lukacik 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.

The same amount of data collected with a lab-based X-ray source would have taken approximately 10 years

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." These first diffraction patterns of the SARS-CoV-2 virus were recorded with a resolution of 0.19 nm – high enough resolution to see the position of all of the chemical groups that allow the protease to do its work.

By 19 February, through constant adjustments and learning, the team knew they could grow good-quality crystals quickly. It was time to bring in more colleagues. The XChem team at Diamond joined the mission to set up fragment-based screening – whereby a vast library of small molecules ("fragments") are soaked into crystals of the viral protease. These fragments are significantly smaller and functionally simpler than most drug molecules and are a powerful approach to selecting candidates for early drug discovery. By 26 February, 600 crystals had been mounted and the first fragment screen launched. In parallel, the team had been making a series of samples to send to a company in Oxford called Exscientia, which has set up an AI platform designed to expedite candidates in drug discovery.

As of early March, 1500 crystals and fragments have been analysed. Owen attributes the team's success so far to the incredible amounts of data they could collect and analyse quickly. With huge numbers of data sets, they could pin down the parameters of the viral protease with a high degree of confidence. And with the synchrotron light source they were able to create and analyse the diffraction patterns rapidly. The same amount of data collected with a lab-based X-ray source would have taken approximately 10 years. At Diamond, they were able to collect the data in a few days of accumulated beamtime.

Rapid access

Synchrotron light sources all over the world have been granting priority and rapid access to researchers to support their efforts in discovering more about the virus. Researchers at the Advanced Photon Source in Argonne in the US, and at Elettra Sincrotrone in Trieste, Italy, are also trying to identify molecules effective against COVID-19, in an attempt to bring us closer to an effective vaccine or treatment. Researchers at PETRA III, a synchrotron light source at DESY in Germany, are examining several thousand existing drugs to access whether they are effective against the virus. COVID-19 research is also being conducted at BESSY II at Helmholtz-Zentrum Berlin, ANSTO's Australian Synchrotron, and light sources all over the world have announced rapid-access schemes for research directly related to COVID-19. The community as a whole has a platform called www.lightsources.org where scientists can have a birds-eye view of calls for proposals and access.

In addition to allowing the structure of tens of thousands of biological structures to be elucidated – such as that of the ribosome, which was recognised by the 2009 Nobel Prize in Chemistry – light sources have a strong pedigree in solving the structure of viruses. Development of common anti-viral medication that blocks the actions of the virus in the body, such as Tamiflu or Relenza, also relied upon synchrotrons to reveal their atomic structure.

Mapping the SARS-CoV-2 protease structures bound to small chemical fragments, the Diamond team demonstrated a crystallography- and fragmentation-screen tour de force. The resulting and ongoing work is a crucial first step in developing a drug. Forgoing the usual academic route of peer-review, the Diamond team have made all of their results openly and freely available to help inform public heath response and limit the spread of the virus, with the hope that this can fast-track effective treatment options.

Knowing the atomic structure of the virus is like knowing how the enemy thinks

This work is continuing. The researchers at Diamond are testing hundreds of compounds each week, and with each step they learn something new about the virus and how to target it. ●

TAMING THE SUPERCONDUCTORS OF TOMORROW

The imminent deployment of accelerator magnets based on the superconductor Nb_3Sn 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 7.7 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 Future Circular Collider design study (FCC), both at CERN, together with studies and programmes outside Europe, such as the Super proton–proton Collider in China (SppC) or the past studies of a Very Large Hadron Collider at Fermilab and the US-DOE Muon Accelerator Program (see p7). This requires that we turn to other superconducting materials and novel magnet technology.

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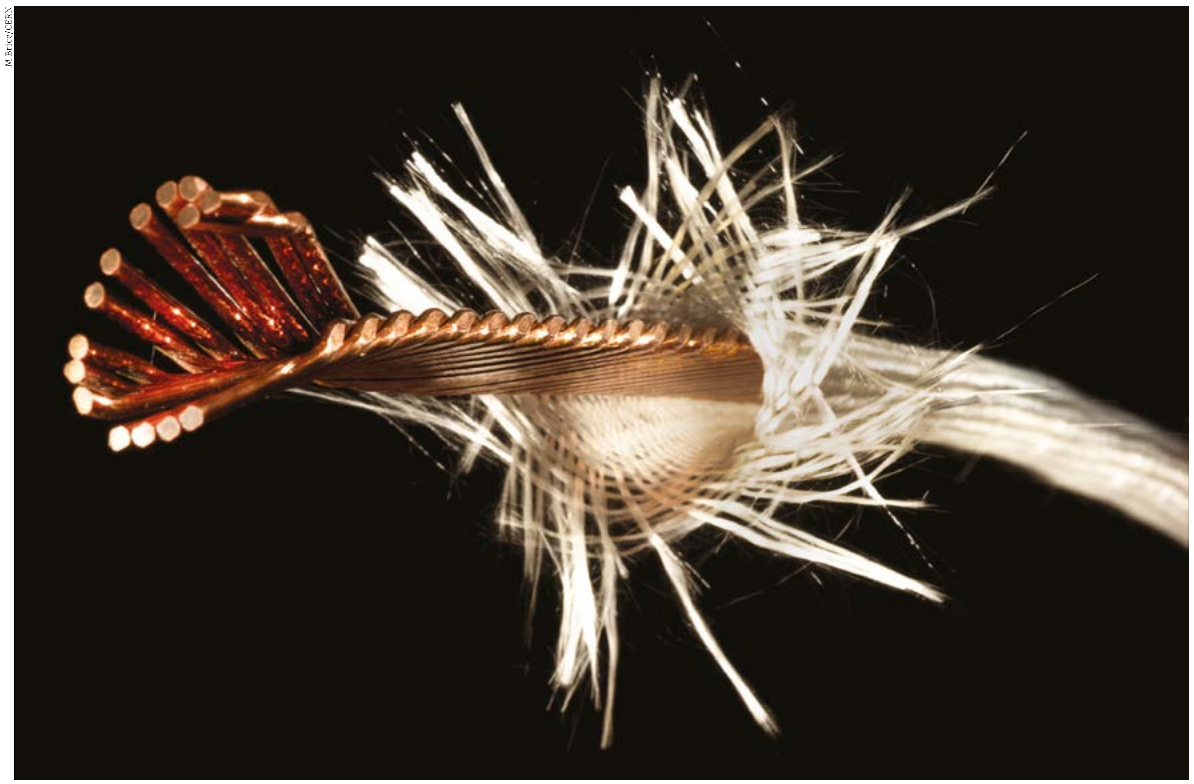
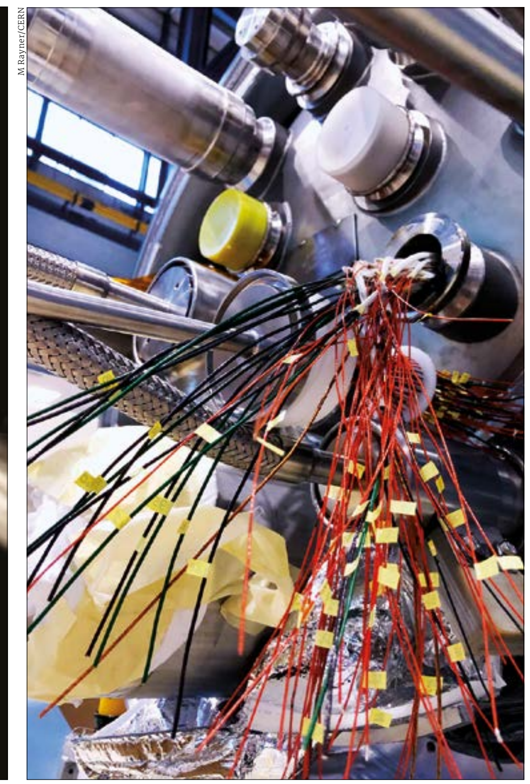
M Brice/CERN



Wired *A Nb_3Sn cable, showing the single strands and the glass-fibre insulation, partially unwrapped.*

M Rayner/CERN



Development *One of the 11 T niobium–tin dipoles for the HL-LHC, pictured at CERN's Large Magnet Facility in January.*

The HL-LHC springboard

To reach its main objective, to increase the levelled LHC luminosity at ATLAS and CMS, and the integrated luminosity by a factor of 10, the HL-LHC requires very large-aperture quadrupoles, with field levels at the coil in the range of 12 T 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_3Sn, which was discovered in 1954. Nb_3Sn has a critical field of about 30 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_3Sn 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_3Sn was one of the candidate materials considered for the LHC in the late 1980s and mid 1990s.

CERN-PHOTO-202002-038-5

Power couple *Nb_3Sn 11 T dipoles for the HL-LHC undergoing tests at CERN's SM18 facility in February.*

Already at that time it was demonstrated that accelerator magnets could be built with Nb_3Sn, 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_3Sn 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_3Sn technology is sufficiently mature to satisfy the challenging field levels required by the HL-LHC.

A difficult recipe

The present manufacturing recipe for Nb_3Sn 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 Cu 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 precursor elements react chemically and form the desired Nb_3Sn 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.

Magnet experts are now convinced that Nb_3Sn technology is sufficiently mature to satisfy the challenging field levels required by the HL-LHC

The above process, though conceptually simple, has a number of technical difficulties that call for top-of-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 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 tooling 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 leave much 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_3Sn 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 dipoles (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 to the development of high-field magnets for future accelerators: not only will it be the first demonstration of Nb_3Sn 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.

Fermilab

Cos-theta 1 *The MDP "cos-theta 1" dipole accelerator magnet at Fermilab, which achieved a field of 14.1 T (the highest ever achieved for such a device at an operational temperature of 4.5 K) in 2019.*

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 dipole. Are these field levels realistic? And based on which technology?

Looking at the dipole fields produced by Nb_3Sn 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 2018 "FRESCA2" – a large-aperture (100 mm) dipole developed over the past decade through a collaboration between CERN and CEA-Saclay in the framework of the European Union project EuCARD – attained a record field of 14.6 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 MDPCT1 (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_3Sn 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 p38), produced a 16.36 T central field at 1.9 K and a 16.5 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 16.3 T (see p7). These results send a positive signal for the feasibility of next-generation hadron colliders.

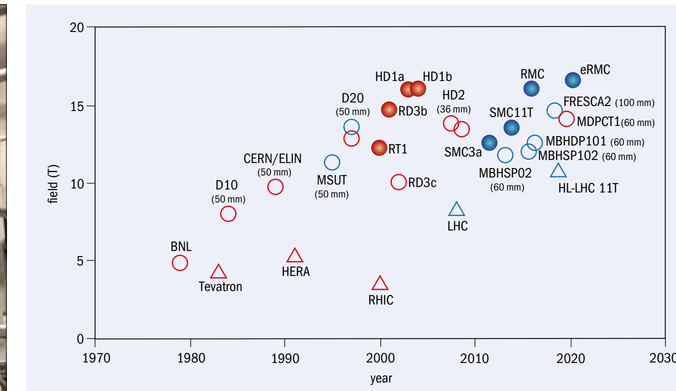


Fig. 1. *Record fields attained with Nb_3Sn dipole magnets of various configurations and dimensions, and either at liquid (4.2 K, red) or superfluid (1.9 K, blue) helium temperature. Solid symbols are short (< 1 m) demonstrator "racetracks" with no bore, while open symbols are short models and long magnets with bore. For comparison, superconducting colliders past and present are shown as triangles.*

A field of 16 T seems to be the upper limit that can be reached with a Nb_3Sn accelerator magnet. Indeed, though the conductor performance can still 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 field grows, requiring an increasing amount of material to carry a given current. The effect becomes dramatic when approaching a significant fraction of the critical field. Akin to Nb-Ti in the region of 8 T, a further field increase with Nb_3Sn beyond 16 T would require an exceedingly large coil and an impractical amount of conductor. Reaching the ultimate performance of Nb_3Sn, which will be situated between the present 12 T and the expected maximum of 16 T, still requires much work. The technology issues identified by the ongoing work on the HL-LHC magnets are exacerbated by the increase in field, electromagnetic force and stored energy. Innovative industrial solutions will be needed, and the conductor itself brought to a level of maturity comparable to Nb-Ti in terms of performance, quality and cost. This work is the core of the ongoing FCC magnet-development programme that CERN is pursuing in collaboration with laboratories, universities and industries worldwide.

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

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Racetrack demo
A Nb_3Sn demonstrator racetrack dipole magnet with no bore developed at CERN in the framework of the Future Circular Collider study, which reached a record peak field of 16.5 T in February.


J Perez/CERN

As the limit of Nb_3Sn 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 Nb_3Sn 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 100 T and above. And 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 NMR 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.

The potential of high-temperature super-conductivity to make a quantum leap is enormous

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 Nb_3Sn 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 are 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 Nb_3Sn. 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 likely take place in steps – exploring 12 T territory first, while seeking the solutions to the challenges of ultimate Nb_3Sn performance towards 16 T – and could take as long as a decade. For China's SppC, 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 MgB_2 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. ●

● *This is an updated version of an article published recently in a special supplement about magnet technology:* cerncourier.com/p/in-focus/magnet-technology.

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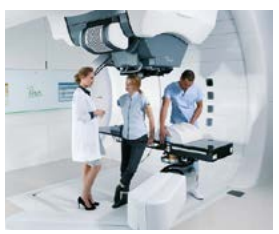

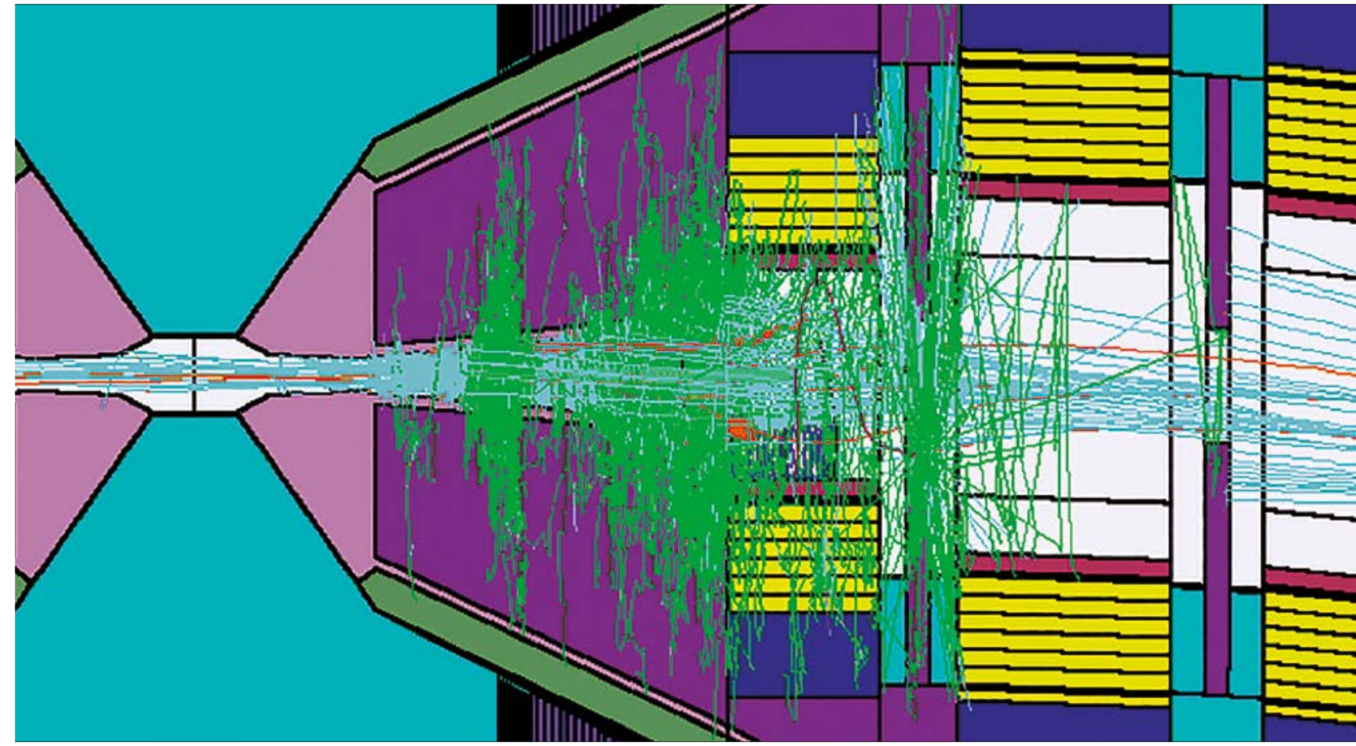

Background reduction *A model of the machine–detector interface for a muon collider. The interaction point is on the left. The principal detector components are not visualised (teal region). The geometry, material distributions and magnetic fields are optimised to protect components from the high levels of beam-induced background, such as muon decays, which induce electromagnetic showers (green). (Credit: N V Mokhov)*

SKETCHING OUT A MUON COLLIDER

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–

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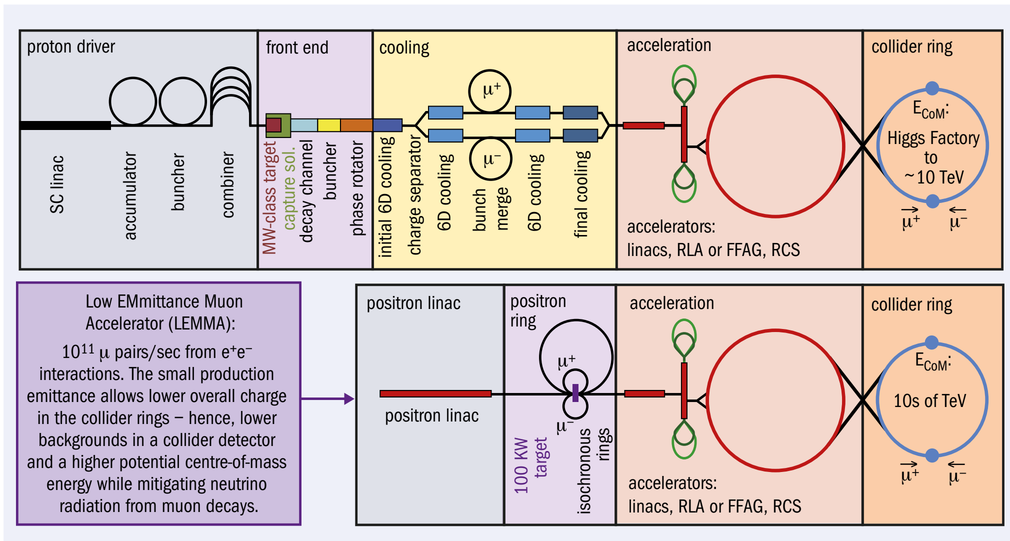

Fig. 1. *Schematic layouts of the two muon-collider concepts: the proton-driven scheme explored by MAP (top) and the more recent LEMMA proposal (bottom).*

Positron Collider (CEPC) in China. FCC-ee offers very high luminosities 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 principal 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 passage 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 a 3 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.

Beating the lifetime

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 muons produced 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.

The unique potential of a multi-TeV muon collider deserves a strong commitment to fully demonstrate its feasibility

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 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 and 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 quadrilinear 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 determina-

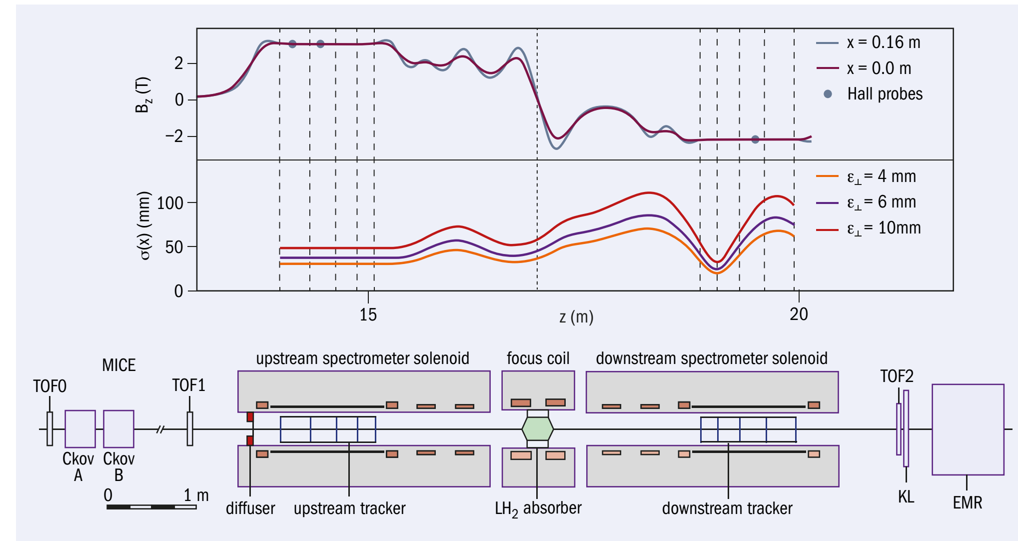

Fig. 2. *A sketch of the MICE apparatus. The modelled field B_z is shown on the beam axis (black line) and at 160 mm from the axis (green line) in the horizontal plane. The readings of Hall probes situated at 160 mm from the beam axis are also shown. Vertical lines indicate the positions of the tracker stations (dashed) and the absorber (dotted). The nominal r.m.s. beam width σ(x) is calculated assuming a nominal input beam and using linear beam-transport equations. The beams have minimum size and hence maximum divergence inside the focus coil, to maximise cooling.*

tion 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 10^4 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 126 GeV (the Higgs pole) to measure the Higgs-boson line-shape. The specifications for such a machine are demanding as it requires knowledge of the beam-energy spread at the level of a few parts in 10^5.

Half a century of ideas

The idea of a muon collider was first introduced 50 years ago by Gersh Budker and then 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 2007. 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, condition, accelerate and store intense beams of muons for a muon collider on the Fermilab site. Although MAP was wound down in 2014, it generated a reservoir of expertise and enthusiasm that the current international effort on physics, machine and detector studies can not do without.

So far, two concepts have been proposed for a muon collider (figure 1). The first design, developed by MAP, is to shoot a proton beam into a target to produce pions, many of which decay into muons. This cloud of muons (with positive and negative charge) is captured and an ionisation cooling system of a type first imagined by Budker rapidly cools the muons from the showers to obtain a dense beam. The muons are 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.

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 Emittance Muon Accelerator (LEMMA) 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 of the electron and positron in the centre-of-mass frame are small, so little transverse momentum can be generated). The challenge with LEMMA 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 produced would be circulated about 1000 times, limited by the muon lifetime, in a ring collecting muons produced from as many positron

It was only when the Muon Accelerator Program was formally approved in 2011 in the US that a systematic effort started

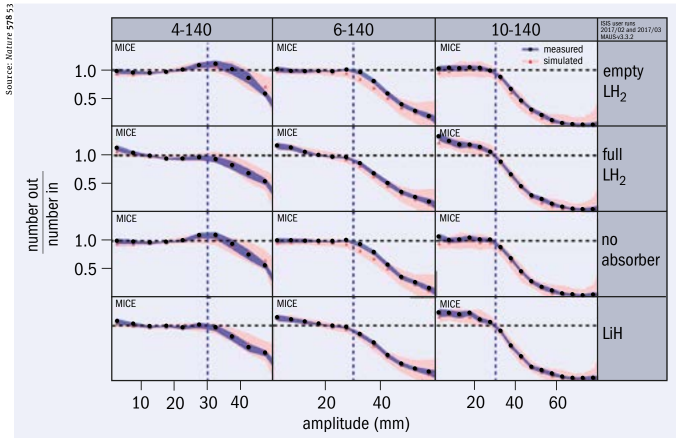

Fig. 3. *Muons that pass through MICE are seen to migrate from high to low amplitudes (a measure of the distance of a particle from the centre of transverse phase space), with an enhancement of the number at low amplitudes providing evidence of ionisation cooling. The effect in a single absorber is stronger for high initial-emittance beams (10 mm) than for lower and intermediate configurations (4 and 6 mm). The results are shown for beams with a momentum of 140 MeV/c.*

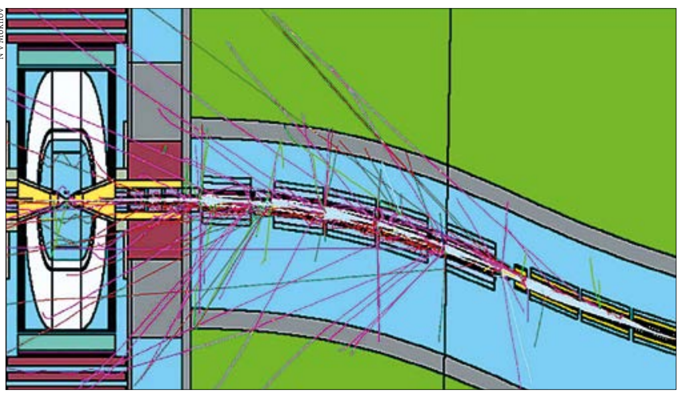

Fig. 4. *A model with tungsten nozzles (yellow) on each side of the interaction point and tungsten (purple) masks in interconnect regions. The collider sub-detectors and iron-concrete shielding around the magnets are also shown, along with particle tracks (> 1 GeV) for several decays of both muon beams.*

bunches as possible before they are accelerated and collided in a fashion similar to the proton-driven scheme of MAP. The low emittance of the LEMMA beams potentially allows the use of lower muon currents, easing the challenges of operating a muon collider due to the remnants of the decaying muons. The initial LEMMA scheme offered limited performance in terms of luminosity, and further studies are required to optimise all parameters of the source before capture and fast acceleration. With novel ideas and a dedicated expert team, LEMMA could potentially be shown to be competitive with the MAP scheme.

Concerning the ambitious muon ionisation-cooling complex (figure 2), which is the key challenge of MAP's proton-driven muon-collider scheme, the Muon Ionization Cooling Experiment (MICE) collaboration recently published results demonstrating the feasibility of the technique (*CERN Courier* March/April 2020 p7). Since muons produced from proton interactions in a target emerge in a rather undisciplined state, MICE set out to show that their transverse phase-space could be cooled by passing the beam through an energy-absorbing material and accelerating structures embedded within a focusing magnetic lattice – all before the muons have time to decay. For the scheme to work, the cooling (squeezing the beam in transverse phase space) due to ionisation energy loss must exceed the heating due to multiple Coulomb scattering within the absorber. Materials with low multiple scattering and a long radiation length, such as liquid hydrogen and lithium hydride, are therefore ideal.

MICE, which was based at the ISIS neutron and muon source at the Rutherford Appleton Laboratory in the UK, was approved in 2005. Using data collected in 2018, the MICE collaboration was able to determine the distance of a muon from the centre of the beam in 4D phase space (its so-called amplitude or "single-particle emittance") both before and after it passed through the absorber, from which it was possible to estimate the degree of cooling that had occurred. The results (figure 3) demonstrated 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 Geant4-based simulation, validating the designs of ionisation cooling channels for an eventual muon collider. The next 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 full "6D" cooling. This effort could profit from tests at Fermilab of accelerating cavities that can operate in a very high magnetic field, and also from the normal-conducting cavity R&D undertaken for the CLIC study, which pushed accelerating gradients to the limit.

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 are needed to minimise 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 10.5 T would allow the muons to survive about 2000 turns. Such magnets, which are about 20% more powerful than those in the LHC, could be built from niobium-tin (Nb_3Sn) as used in the new magnets for the HL-LHC (see p34).

The electrons and positrons produced when muons decay pose an additional challenge for the magnet design. The decay products will hit the magnets and can lead to a quench (whereby the magnet suddenly loses its superconductivity, rapidly releasing an immense amount of stored energy). It is therefore important to protect the magnets. The solutions considered include the use of large-aperture magnets in which shielding

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. The ring that accelerates 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 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 superconducting and fast-ramping normal-conducting bends have been explored by the MAP collaboration. In these designs, the energy in the fields of the fast-ramping bends will be very high, so it is important that the energy is recuperated for use in a subsequent accelerating cycle. This requires a very efficient energy-recovery system which extracts the energy after each cycle and reuses it for the next one. Such a system, called POPS ("power for PS"), is used to power the magnets of CERN's Proton Synchrotron. The muon collider, however, requires more stored energy and much higher power flow, which calls for novel solutions.

High occupancy

Muon decays also induce the presence of a large amount of background in the detectors at a muon collider – a factor that 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 therefore strongly depend on the machine lattice and the configuration of the interaction point, which in turn depends on the collision energy. The background particles (mainly photons, electrons and neutrons) may be produced tens of metres upstream of the interaction point. To mitigate the effects of the beam-induced background inside the detector, tungsten shielding cones, called nozzles, are proposed in this configuration and their opening angle has to be optimised for a specific beam energy, which affects the detector acceptance (see figure 4). Despite these mitigations, a large particle flux reaches the detector, causing 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 4D silicon sensors that allow exploitation of the time distribution will be needed to remove a significant fraction of the background hits.

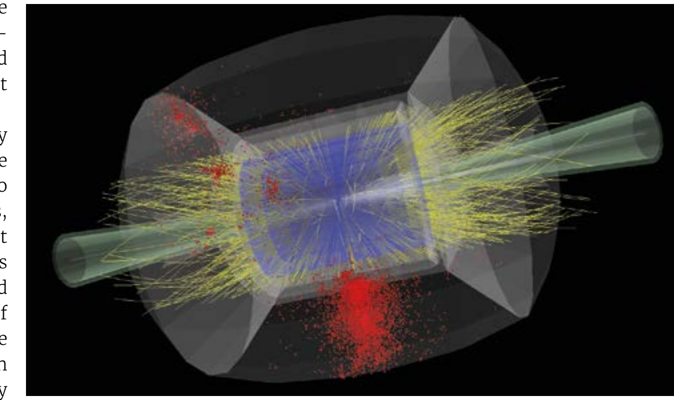

Fig. 5. *A simulation indicates that Higgs-boson decays to a b-quark pair can be reconstructed at a muon collider despite the harsh environment: the two b-jets are identifiable (red dots) among the beam-induced background.*

Energy expansion

It was recently demonstrated, by a team supported by INFN and Padova University in collaboration with MAP researchers, that state-of-the-art detector technology for tracking and jet reconstruction would make one of the most critical measurements at a muon collider – the vector-boson fusion channel $\mu^+\mu^- \to (W^*W^*)\nu\bar{\nu} \to H\nu\bar{\nu}$, with $H \to b\bar{b}$ – feasible in this harsh environment, with a high level of precision, competitive to other proposed machines (figure 5). A muon collider could in principle expand its energy reach to several TeV with good luminosity, allowing unprecedented exploration in direct searches and high-precision tests of Standard Model phenomena, in particular the Higgs self-couplings.

The technology for a muon collider also underpins a so-called neutrino factory, in which beams of equal numbers of electron and muon neutrinos are produced from the decay of muons circulating in a storage ring – in stark contrast to the neutrino beams used at T2K and NOvA, and envisaged for DUNE and Hyper-K, which use neutrinos from the decays of pions and kaons from proton collisions on a fixed target. In such a facility it is straightforward to tune the neutrino-beam energy because the neutrinos carry away a substantial fraction of the muon's energy. This, combined with the excellent knowledge of the beam composition and energy spectrum that arises from the precise knowledge of muon-decay characteristics, makes a neutrino factory an attractive place to measure neutrino oscillations with great precision and to look for oscillation phenomena that are outside the standard, three-neutrino-mixing paradigm. One proposal – nuSTORM, an entry-level facility proposed 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.

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Muon-based facilities have the potential to provide lepton–antilepton 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 interaction probability is tiny, the total flux of neutrinos is sufficiently high in a very small area in the collider plane to produce localised radiation that can reach a fraction of natural-radiation levels. Beam wobbling, whereby the lattice is modified periodically so that the neutrino flux pointing to Earth's surface is spread out, is one of the promising solutions to alleviate the problem, although it requires further studies.

The muon collider would be a unique lepton-collider facility at the high-energy frontier

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

D Alesini *et al.* 2019 arXiv:1905.05747.
N Bartosik *et al.* 2020 arXiv:2001.04431.
M Chiesa *et al.* 2020 arXiv:2003.13628.
J P Delahaye *et al.* 2019 arXiv:1901.06150.
MICE Collaboration 2020 *Nature* **578** 53.
Muon Accelerators for Particle Physics (MUON) Special issue of *J. Instrum* (https://iopscience.iop.org/journal/1748-0221/page/extraproc46).

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.

Helmut Schober *is director of the Institut Laue-Langevin and chair of the League of advanced European Neutron Sources.*

Reactor neutrons *The Institut Laue-Langevin in Grenoble.*

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 50% 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 II 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 rest 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.

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

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 building large scientific facilities such as ESS, or FAIR in Germany, takes so long, despite significant strategic planning (e.g. via ESFRI) and sophisticated project management. 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 that agility. The Chinese Spallation Neutron Source has just reached its design goal of 100 kW, and the Spallation Neutron Source in Oak Ridge, Tennessee, is actively pursuing plans for a second target station.

We therefore need to look to next-generation sources such as Compact Accelerator driven Neutron Sources (CANS). Contrary to spallation sources that produce neutrons by bombarding heavy nuclei with high-energy protons, CANS rely on nuclear processes that can be triggered by proton bombardment in the 5 to 50 MeV range. While these processes are less efficient than spallation, they allow for a more compact target and moderator design. Examples of this scheme are SONATE, currently under development at CEA-Saclay and the High Brilliance Source being pursued at Jülich. CANS must now be brought to maturity, requiring carefully planned business models to identify how they can best reinforce the ecosystem of neutron science.

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 strategic evaluation 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 researchers will rise to the challenge and carve a route to a greener future through world-leading neutron science.

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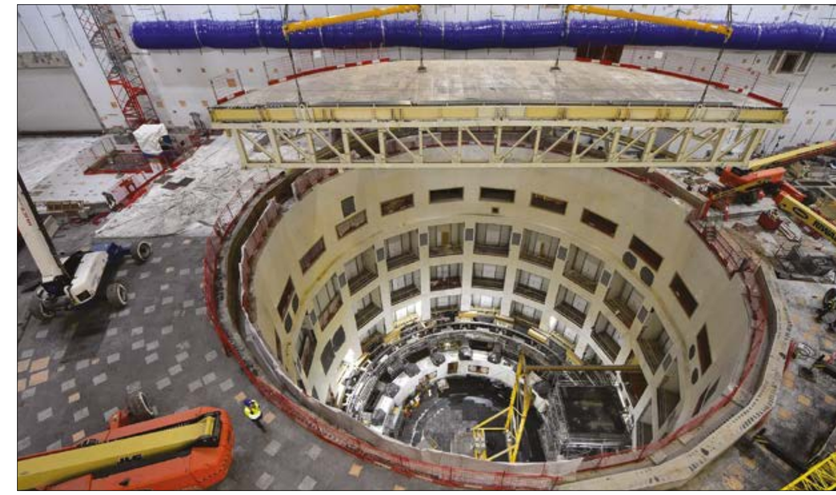
OPINION REVIEWS

A unique exercise in scientific diplomacy

ITER: The Giant Fusion Reactor – Bringing a Sun to Earth

By Michel Claessens

Springer



ITER

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 criss-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 prejudices. 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.

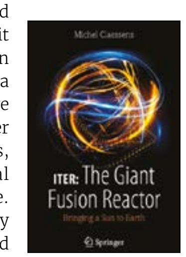
Why don't we more resolutely pursue a technology that could contribute to the production of carbon-free energy? ITER's path has been plagued by rivalries between strong personalities, and difficult technical and political decisions, though, in retrospect, few domains of science and technology have received 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. Travelling through history, the author shows that when politicians take decisions of high inspiration, as at the famous fireside 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.

Opened up *ITER's lid was removed on 2 April – the Tokamak pit is nearly ready for its first machine component.*

Price tag

Was the 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 met a single knowledgeable person who did 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 directorate 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 mangers 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 afforda-



ble cost to the environment, and based on abundant and widely distributed fuel.

Though Claessens notes that there is almost no intrinsic innovation in ITER, he shows how the project has nevertheless pushed tokamak technology beyond its apparent limits by a sheer increase in size, though he neglects some key points, such as the incredible stored energy of the superconducting magnets. An incident similar to that suffered by the LHC in 2008 would be a logistical nightmare for ITER, as it contains more than three times the stored energy of the entire LHC and its detectors in an incomparably smaller volume. Comparisons with CERN are a feature of the book, and a point of pride for high-energy physicists – clearly, CERN has set the standard for high-tech international collaboration, and ITER has tried to follow its example (*CERN Courier* October 2014 p45). Having begun my career as a plasma scientist, I have seen the connections between the laboratories first-hand: they range from Robert Aymar, a former CERN director-general and a recognised father of ITER, to Arnaud Devred, who was head of superconductor procurement at ITER before recently being installed as deputy group leader of CERN's magnets division.

Michel Claessens' book explores different points of view without fanaticism

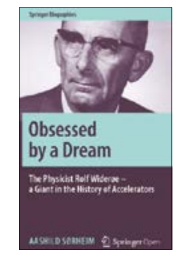
I recommend Michel Claessens' well written and easy-to-read book. It is passionate and informative, and explores different points of view without fanaticism. Interestingly, his conclusion is not scientific or political, but socio-philosophical in nature: ITER will be built because it can be, he says, according to a principle of "technological necessity".

Lucio Rossi *CERN.*

Obsessed by a Dream: The Physicist Rolf Widerøe – a Giant in the History of Accelerators

By Aashild Sørheim

Springer



The betatron is an early type of MeV-range electron accelerator that uses the electric field induced by a varying magnetic field to accelerate electrons, or beta particles. It operates like a transformer with the secondary winding replaced by a beam of electrons circulating in a vacuum tube. It was invented by pioneering Norwegian accelerator physicist Rolf Widerøe when a student in 1925. Since the construction failed at the time, he had to find another theme for his thesis, and so in 1927 he constructed the first linear accelerator (50 keV), before later proposing the principle of colliding beams to fully exploit the energy of accelerated particles. Through these innovations, Rolf Widerøe decisively influenced the course of high-energy physics, with betatrons shaping the landscape in the early days, and linear accelerators and colliding beams becoming indispensable tools today.

Aashild Sørheim, a professional writer, now presents a new biography of this visionary engineer, who had a seminal impact on accelerator physics. Her book covers Widerøe's whole life, from 1902 to 1996, and from his childhood in a well-to-do family in Oslo, to his retirement in Switzerland. Certainly, many who read Pedro Waloscheck's 1994 biography, *The Infancy of Particle Accelerators: Life and Work of Rolf Widerøe*, will be curious as to how this new book will complement the former. Sørheim's new offering is based on new documentary evidence, the result of painstaking sifting through archives, and a large number of interviews. She has opened new perspectives through her interviews, and the access she has gained in several countries to hitherto restricted archives has provided a wealth of new material and insights, in particular in relation to the Second World War. Sørheim's book focuses not on physics or technology, but on Widerøe himself, and the social and political environment in which he had to find his way. In particular, it gravitates to the question of his motivation to work in Germany in the troubled years from 1943 to 1945, when he constructed a betatron, the accelerator that he had invented two decades earlier while a student in Karlsruhe.

Occupied Oslo

In the most interesting parts, the book provides background information about the entanglement of science, industrial interests and armament, and in particular the possible reasons for the "recruitment" of Rolf Widerøe in occupied Oslo in the spring of 1943 by three German physicists mandated by the German Air Force, who insinuated that willingness to cooperate might well help to improve the conditions of his brother Viggo, who was in prison in Germany for helping Norwegians escape to England. The apparent motivation was that a powerful betatron could produce strong enough X-rays to neutralise allied bomber pilots. Although leading German scientists quickly discovered this to be nonsense, the betatron project was not interrupted.

The book describes the difficult working conditions in Hamburg, and the progress towards a 15 MeV betatron. Among the key players was Widerøe's assistant Bruno Touschek, who was finally arrested by the Gestapo in 1945 as his mother was Jewish. It was during this time that Widerøe patented his idea to use colliding beams to maximise the energy available, against the advice of Touschek, who found the idea too trivial to publish. It was the Touschek though, who in 1961 first used this principle in ADA, the e^+e^- ring in Frascati, which was the first collider ever built.

Widerøe faced official prosecution on the ludicrous charge of having helped develop V2 rockets

After Widerøe's return to Oslo in March 1945, when the betatron was operational and the advancing English army made a study of a 200 MeV betatron illusionary, he faced official prosecution on the ludicrous main charge of having helped develop V2 rockets, explains Sørheim. Released from prison after 47 days, he got away without trial, but had to pay a substantial fine. Unemployed, seeing no basis for pursuing his dream of further developing betatrons in his home country, and with the stigma of a collaborator in the understandably overheated atmosphere of the time, he moved his family to Switzerland in 1946. One chapter, strangely put near the beginning of the book, describes how Widerøe then became a successful leader of the betatron construction at Brown-Boveri in Switzerland, a respected lecturer at the ETH in Zurich and a promoter of radiation therapy until late into his retirement. He was a CERN consultant in the early days, and worked with Odd Dahl and Frank Goward in Brookhaven in 1952 where they became acquainted with the alternating-gradient focusing principle that was then boldly proposed to the CERN Council as basis for the design of the 25 GeV Proton Synchrotron.

The book leaves the reader somehow overwhelmed by the amount of material presented, the non-chronological presentation, and the many repetitions of the same facts, conveying the impression that the author had difficulty in putting the information in a coherent order. However, the many interviews and new documentary evidence, including a hitherto unknown letter from his brother Viggo, open novel perspectives on this extraordinary engineer and scientist who, besides receiving many honours abroad, finally also received recognition in his home country, after a lengthy reconciliation process.

Kurt Hübner *formerly of CERN (now retired).*

PEOPLE CAREERS

Opening doors with a particle-physics PhD

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


L Esteveny/CERN

Transition *Former LHCb user Alexandra Martín Sánchez, now a project manager in scientific computing at energy firm EDF, standing in front of her old office at CERN.*

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 $B^0 \to DK^{*0}$ 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 ICHEP 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 I 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 fairly 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.*

Appointments and awards

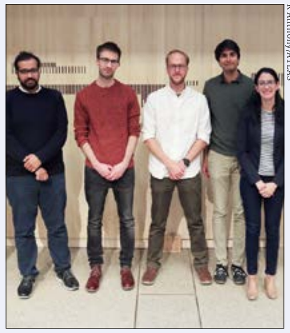
Rossi receives Wideröe Prize
Lucio Rossi of CERN, who is project leader for the High-Luminosity LHC, is the recipient of the European Physical Society Accelerator Group IPAC'20 Rolf Wideröe Prize for outstanding work in the accelerator field. Rossi was recognised "for his pioneering role in the development of superconducting magnet technology for accelerators and experiments, its application to complex projects in high-energy physics including strongly driving industrial capability, and for his tireless effort in promoting the field of accelerator science and technology". The award was due to be presented on 14 May during this year's International Particle Accelerator Conference (IPAC'20), which has been cancelled due to the situation with coronavirus.


CERN

Wu-Ki Tung Award for Early Career Research
Theorist Valerio Bertone of CEA Paris-Saclay, has been granted the 2019 Wu-Ki Tung Award for Early Career Research on QCD, "for innovative contributions to the precise determination of parton distributions and fragmentation functions, and for the development of cutting-edge software to perform global PDF fits". The $5000 award, given annually to a young physicist performing either experimental or theoretical research on QCD, was established by the CTEQ (Collaborative Theoretical and Experimental studies of QCD) collaboration in 2014 to honour the legacy of Wu-Ki Tung, one of the leading researchers on QCD and the founder of CTEQ.


V Bertone

ATLAS 2019 thesis awards
Selected from a total of 35 nominations, the six winners of the ATLAS 2019 thesis awards were announced on 27 February. Pictured, from left to right, are: Ahmed Tarek Abouelfadl Mohamed (Paris-Diderot University); Stephen Burns Menary (University of Manchester); Daniel Joseph Antrim (University of California, Irvine); Khilesh Pradip (University of Pennsylvania); and Elodie Deborah Resseguie (University of Pennsylvania). Not pictured: Karri Folan Di Petrillo (Harvard University). The ATLAS collaboration has almost 1200 PhD students, and theses awarded can cover any area of ATLAS physics, including detector development, operations, software and performance studies, and physics analysis.


K Anthony/ATLAS

National Order of the Lion
Fama Diagne Sène, first director of the library at Alioune Diop University of Bambey, 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 Sène 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–UNIGE Workshop on Innovations in Scholarly Communication.


S Bennett/CERN

First Stephen Hawking Fellows announced
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 Manchester), will research the properties, such as superfluidity and superconductivity, of neutron stars and plans to undertake a detailed public-engagement programme targeted at underrepresented groups.

Martin Archer (Imperial College London) will carry out research into the interplay between Earth's magnetic field and the solar wind, while also producing virtual-reality experiences and a "magnetospheric drum kit" to be used in creating works for performance.

Francesca Chadha-Day (King's College London) will use astronomical observations to search for axion-like particles, and will communicate her research through stand-up comedy.

Andrei Constantin (University of Oxford) will conduct mathematical research to help map string theory to elementary particles, linked with a range of outreach activities including talks to local schools.

Ömer Gürdoğan (University of Southampton) will focus on scattering amplitudes in quantum field theory and conduct outreach activities including art exhibitions.

Scott Melville (University of Cambridge) will work on effective field theories and their application to problems in gravity and cosmology, and give public talks.

Francesco Muia (University of Cambridge) will explore the catastrophic processes that produced gravitational waves during 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.

Stefan Schacht (University of Manchester) aims to build on the recent observation by LHCb of CP violation in the charm system to explore the matter–antimatter asymmetry, and plans to establish an outreach programme for particle physics at the annual Bluedot Festival.

UKRI will support up to 50 postdoctoral scientists through the Stephen Hawking Fellowships scheme, with further calls to be launched in due course.

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Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

For our location in Zeuthen we are seeking:

Postdocs for Photo Injector Test Facility PITZ in Zeuthen

DESY

DESY is one of the world's leading research centres for photon science, particle and astroparticle physics as well as accelerator physics. More than 2400 employees work at our two locations Hamburg and Zeuthen in science, technology and administration.

The Photo Injector Test Facility PITZ in Zeuthen (near Berlin) develops high brightness electron sources for Free-Electron Lasers (FELs) like FLASH and European XFEL. The research program at PITZ concentrates on optimization of the electron beam quality for pulsed photo injectors and developments towards future CW electron sources, as well as on applications of high brightness electron beams.

The position

3 Postdoc positions are available at PITZ for the following tasks (More details can be found under https://pitz.desy.de/jobs):

- Participate in the upgrade of the photocathode laser systems and develop innovative concepts and techniques for the diagnostics of high-quality laser and electron beams. Perform numerical simulations to support the accelerator R&D program at PITZ towards applications of high brightness electron beams: job offer **APP0005/2020**
- Further developments of tools for detailed characterization of the electron beam phase space. Perform accurate modeling and numerical simulations of electron beam measurements using scintillating screens. Develop, test and support software packages for automatization and optimization of electron beam measurements: job offer **APP0006/2020**
- Perform numerical simulations and experimental studies of semiconductor photocathode (Cs2Te, CsK2Sb) photoemission in high gradient RF guns, including particle dynamics in the material and in vacuum during the emission process. The goal is to better understand and improve the photocathodes and the photoemission dynamics to minimize the cathode emittance: job offer **APP0007/2020**

Requirements

Please find more details in the specific announcements mentioned above.

- Excellent university degree in accelerator physics or semiconductor surface physics with PhD
- Strong background in beam dynamics simulations of space charge dominated beams; familiar with numerical simulations (e.g. ASTRA, GEANT) and high level scripting languages (like Python, Matlab); good programming skills
- Knowledge/skills in experimental characterization of photocathodes and photoemission or of particle beams using image processing
- Very deep knowledge of accelerator physics and accelerator technology or very good knowledge in laser technology
- Very good knowledge of English is required and knowledge of German is of advantage
- Participate in the operation of PITZ for accelerator R&D

Please mark in your application for which of the 3 positions you are applying.

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

The positions are initially limited to 2 years.

Salary and benefits are commensurate with those of public service organisations in Germany. Classification is based upon qualifications and assigned duties. Handicapped persons will be given preference to other equally qualified applicants. DESY operates flexible work schemes. DESY is an equal opportunity, affirmative action employer and encourages applications from women. Vacant positions at DESY are in general open to part-timework. During each application procedure DESY will assess whether the post can be filled with part-time employees.

We are looking forward to your application via our application system:
www.desy.de/onlineapplication

Deutsches Elektronen-Synchrotron DESY
Human Resources Department |
Code: **APP0005/2020 - APP0006/2020 - APP0007/2020**
Notkestraße 85 | 22607 Hamburg Germany
Phone: +49 40 8998-3392 http://www.desy.de/career

Deadline for applications: Until the positions are filled.
Reviewing of the applications will start on May 11th, 2020.

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

For our location in Hamburg we are seeking:

Scientist for the Low Level RF Controls of the European XFEL (LLRF)

DESY

DESY is one of the world's leading research centres for photon science, particle and astroparticle physics as well as accelerator physics. More than 2400 employees work at our two locations Hamburg and Zeuthen in science, technology and administration.

The group MSK is responsible for the controls, feedback regulations and synchronization of the particle accelerators at DESY. We are an international team of technicians, engineers and scientists who develop, install and operate complex instruments for the European X-Ray Free-Electron Laser.

The position

- Further development of high precision field control of the superconducting cavities at the European XFEL
- Coordination of LLRF systems operation with the XFEL machine operation group
- Quality control towards optimal operation of the LLRF system and investigations of RF trips
- Operation anlysis and further development of the field regulation and automation algorithms
- Documentation and maintenance of the LLRF systems

Requirements

- PhD degree in Physics, Electronics or Computer Science or equivalent qualification
- Several years experience in RF control of superconducting particle accelerators
- Advanced understanding of the system architecture and operation of particle accelerators
- Skills in automation and system control
- Computer science skills in Linux, Python, Firmware and Software
- Strong motivation and pragmatism towards problem solving as well as highly proficient English skills

For further information please contact Julien Branlard +49-40-8998-1599.

The position is limited to 3 years.
Salary and benefits are commensurate with those of public service organisations in Germany. Classification is based upon qualifications and assigned duties. Handicapped persons will be given preference to other equally qualified applicants. DESY operates flexible work schemes. DESY is an equal opportunity, affirmative action employer and encourages applications from women. Vacant positions at DESY are in general open to part-timework. During each application procedure DESY will assess whether the post can be filled with part-time employees.

We are looking forward to your application via our application system:
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Deutsches Elektronen-Synchrotron DESY
Human Resources Department | Code: **MMA020/2020**
Notkestraße 85 | 22607 Hamburg Germany
Phone: +49 40 8998-3392
http://www.desy.de/career

Deadline for applications: Until the position is filled.

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

KIT
Karlsruhe Institute of Technology

Karlsruhe Institute of Technology (KIT) – The Research University in the Helmholtz Association creates and imparts knowledge for the society and the environment. It is our goal to make significant contributions to mastering the global challenges of humankind in the fields of energy, mobility, and information. For this, about 9,300 employees of KIT cooperate in a broad range of disciplines in research, academic education, and innovation.

In KIT Division V – Physics and Mathematics – at the Institute for Beam Physics and Technology (IBPT) and at the KIT Department of Physics a new

Professorship (W3) for Laser-based Particle Accelerators

is to be filled at the earliest date possible. The professorship is associated with leading a department of IBPT. The recruitment takes place in the suspension model in accordance with Art. 15 § 2 KIT Act ("Beurlaubungs-modell gemäß § 15 Abs. 2 KIT-Gesetz").

We are looking for an experienced scientist to advance and represent the research area of compact accelerator technologies at KIT. A focus will be laser-based technologies, investigations of the underpinning beam dynamics optimization of the corresponding laser systems and system reliability of novel compact facilities in experiment and simulation. The appointed professor is expected to develop the scientific profile of the IBPT's "Accelerator R&D and Operation I" department and to participate in the Helmholtz Association of German Research Centres' programme-oriented funding, in particular in the programme "Matter and Technologies". In addition to new accelerator technologies, research topics and tasks in the programme include methods of beam control and diagnosis as well as the design and operation of the institute's accelerator test facilities.

KIT offers an outstanding interdisciplinary environment at the interface of the engineering and natural sciences. The incumbent will cooperate closely with colleagues of the Accelerator Technology Platform (ATP) at KIT. He/she raises third-party funds from national and international sources and actively supports the transfer of scientific/technical results into applications. In academic education, candidates are expected to actively participate in existing and newly established German and English study programs offered by the KIT Department of Physics.

The candidate has an outstanding scientific record in the field of laser-based particle acceleration, excellent teaching skills and leadership experience. Further prerequisites are experience in the operation of large-scale facilities, in application-oriented research and in the acquisition of third-party funds. Experience in technology transfer is desirable.

KIT aims to increase diversity at the academic management level and in particular the proportion of female professors and therefore welcomes applications from women. KIT promotes the compatibility of family and career and offers support within the scope of its Dual Career Program. Applicants with a disability having the same qualification are given preferential consideration. According to § 47 Landeshochschulgesetz (LHG) of the State of Baden-Württemberg, a completed university degree, pedagogical aptitude, which as a rule must be demonstrated by experience in teaching or training, and a special aptitude for scientific work, which as a rule is demonstrated by the quality of a doctorate, are required.

Kindly send your application including the usual documents (i.e., a CV, research plan, statements of previous and anticipated teaching activities and a list of publications) before **May 11th, 2020** (preferably in electronic form as a single pdf document) to: Dekanat der KIT-Fakultät für Physik, Karlsruher Institut für Technologie (KIT), 76128 Karlsruhe, Germany, email: **dekanat@physik.kit.edu.**

For further information about this position please contact Prof. Dr. Anke-Susanne Müller, email: **anke-susanne.mueller@kit.edu.**

Zertifikat seit 2010 audit berufundfamilie

KIT – The Research University in the Helmholtz Association

KIT
Karlsruher Institut für Technologie

Karlsruhe Institute of Technology (KIT) – The Research University in the Helmholtz Association – creates and imparts knowledge for the society and the environment. It is our goal to make significant contributions to mastering the global challenges of humankind in the fields of energy, mobility, and information. For this, about 9,300 employees of KIT cooperate in a broad range of disciplines in research, academic education, and innovation.

The KIT Department of Physics, part of Division V – Physics and Mathematics – invites applications for a

Professorship (W3) in Experimental Particle Physics

at the Institute of Experimental Particle Physics (ETP).

We are looking for an outstanding scientist with a research focus on experimental particle physics, in particular in the areas of precision measurements and searches for physics beyond the Standard Model, and on algorithm development and detector technologies. The successful candidate is expected to strengthen and expand the KIT activities at the Belle II experiment. We welcome your participation in the preparation of future collider experiments.

KIT provides an excellent environment for research in particle and astroparticle physics. ETP has long-term involvements in the large-scale projects CMS and Belle II. The infrastructure at ETP includes a semiconductor laboratory, workshops and computer clusters. Close ties exist with the Tier-1 computing centre GridKa. Research at ETP is mainly funded by the BMBF, the DFG and the Helmholtz Association.

ETP is part of the KIT Centre Elementary Particle and Astroparticle Physics (KCETA) and is involved in further large-scale projects such as the Pierre Auger Observatory, IceCube, KATRIN and XENON. Close collaborations exist with strong theory groups working on particle and astroparticle phenomenology. The Karlsruhe School of Elementary Particle and Astroparticle Physics: Science and Technology (KSETA) provides access to an excellent pool of Ph.D. students.

The appointed professor will be part of the ETP board of directors and assume responsibilities in the academic self-administration. The candidate is required to teach at all levels of the undergraduate and graduate curriculum (eventually in German) and to supervise bachelor, master and Ph.D. students. A Habilitation degree or equivalent scientific and teaching qualifications are required.

KIT is pursuing the strategic goal of substantially increasing gender balance and diversity of its faculty. As an equal opportunity employer, KIT explicitly encourages applications from women as well as from all others who will bring additional diversity to the university's research and teaching. KIT provides support for dual career couples and families. Applicants with disabilities will be preferentially considered if suitably qualified. The terms of employment are listed in § 47 Landeshochschulgesetz (LHG) of the State of Baden-Württemberg.

Qualified candidates should submit before **15.06.2020** a curriculum vitae, list of publications, as well as research and teaching statements to: **Dekanat der KIT-Fakultät für Physik, Karlsruher Institut für Technologie (KIT), 76128 Karlsruhe, Germany,** preferably as a single pdf document by email to **dekanat@physik.kit.edu.** For further information about this position please contact Prof. Dr. Thomas Müller, email: thomas.muller@kit.edu, or Prof. Dr. Margarete Mühlleitner, email: margarete.muehlleitner@kit.edu.

KIT – The Research University in the Helmholtz Association

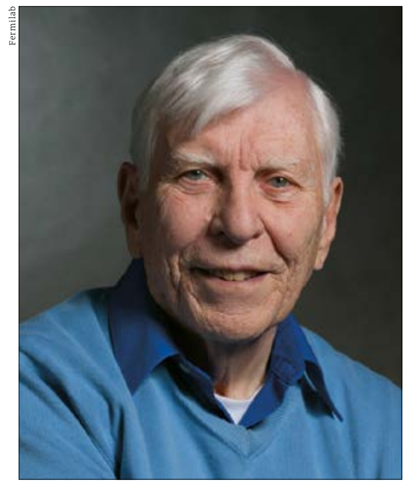
PEOPLE OBITUARIES

Alvin Tollestrup 1924–2020

Remembering a visionary physicist

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 Lab's Bevatron to measure a rare decay mode of the K^+ meson.

Alvin asked me to help design, build and test a new type of particle detector called a spark chamber. In retrospect it was remarkable that he was willing to risk the success of his experiment on the creation of new technology. He also asked me to design a transport system of magnetic lenses that would capture as many K mesons as possible. I did my calculations on an IBM 709 at UCLA – Alvin checked them by tracing rays at his drafting table. When the beam design was completed and the chain of magnets was in place on the accelerator floor, Alvin threaded a single wire through them from the thin window of the accelerator to our hut.


Fermilab

Alvin Tollestrup led the design of the superconducting magnets for the Tevatron.

Zen master

I had no idea what he was doing, or why. Around Alvin the Zen master, I didn't say much or ask many questions. After turning the magnets on and running current through the wire, the wire snapped to attention, tracing the path a K would follow from where it left the accelerator to where its decays would be observed. Calculations – how much current was required in the wire – followed by testing, were Alvin's modus operandi.

When run-time arrived a couple of months later, the proton beam was steered into a tungsten target behind the thin window through which the Ks would pass. We waited for the scintillation counters to start clicking wildly, but nothing happened. Eventually, having calmly persuaded the operators to shut the machine down, Alvin took a pair of long tongs and pressed a small square of dental film against the radioactive target. When developed, it showed a faintly illuminated edge at the top of the target: the Bevatron surveyors had placed the target one inch below its proper position, a big mistake. But there was no panic or finger pointing, just measurement and appropriate action. That was Alvin's style, always diplomatic with management, never asking for something without sufficient reason, and persistent.

The virtuosity required to create new accelerators sometimes exceeds what is necessary to run the resulting Nobel prize-winning experiments

Alvin was my first thesis advisor. When he taught me how to think about my measurements, he also taught me how to analyse and judge the measurements of others. This was essential in understanding which of the many "discoveries" of hadrons in the early 1960s were believable. Without his influence, I never would have discovered quarks (aces), whose existence was later definitively confirmed in deep-inelastic scattering experiments.

More than a dozen years later, true to his belief that users of accelerators should improve them, Alvin left Caltech for Fermilab, where he would create the first large-scale application of superconductivity. Physics at Fermilab at that time was limited by the energy (200 GeV) of the 6.3 km-circumference Main Ring. Alvin made essential contributions to the design, testing and commissioning of superconducting magnets to replace the Main Ring's copper ones – doubling the energy. The new machine, to be known as 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 Segrè 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 discover a flaw in an experiment which, once fixed, validated the V–A theory of the weak interactions.

Alvin did not suffer fools gladly, but outside of work he created a community of collaborators, an extended family. He fed and entertained us. His pitchers of martinis and platters of whole hams were memorable. Legendary tightrope performer Karl Wallenda is quoted as saying, "Life is on the wire. The rest is waiting." Alvin showed us how to have fun while waiting, and shared a long and phenomenal life with us, both off – and especially on – the high wire.

George Zweig *Research Laboratory of Electronics MIT.*

Marcello Cresti 1928–2020

A passion for the elementary and cosmic

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

Born in Grosseto, Cresti 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 1954 at the high-altitude cosmic-ray observatory on the slopes of the Marmolada mountain, he developed and used a setup including two Wilson chambers in a magnetic field. In 1955 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 in the absence of neutrinos in Λ decays.

In 1958 Marcello returned to Padua, where he designed and built the first electrostatic separator in Europe to work with an antiproton beam at CERN, and created the hardware and software structures to enable automatic measuring


Cresti family

Marcello Cresti at the Max Planck Institute for Physics in Göttingen in 1955 with the "G1" – one of the first automatic calculators.

and analysis of bubble-chamber film. Relevant results were obtained on antiproton annihilations and meson resonances.

In 1975/1976 Marcello created a low-energy antiproton beam with excellent monochromaticity and collimation at CERN, and measured the antineutron mass with, 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 1965, Marcello was the dean of the science faculty from 1981 to 1984 and rector of the university from 1984 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 passion: cosmic rays. From 1989, with his group in Padua and a group from Pisa, he designed and carried out an experiment – CLUE – aimed at the detection of high-energy cosmic gamma rays; this started the Italian astrophysical 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.

Tatiana Fabergé 1930–2020

A CERN institution and force of nature

Tatiana (Tania) Fabergé, the head secretary of the CERN theoretical physics department from 1957 until her retirement in 1995, passed away peacefully on 13 February, shortly before reaching 90.

Tania was the great-granddaughter of Peter Carl Fabergé, jeweller to the 19th-century Russian Imperial Family. Born stateless to exiled parents in Geneva, she trained in design and worked in the family tradition for a few years. Then, in 1957, teams of CERN theorists from Copenhagen and Geneva were merged to form, on the new 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 10 department leaders and 10 Directors-General while she was at CERN. During this time she welcomed thousands of visitors to the theory group, and generously helped them settle in at CERN. With her robust sense of humour and colourful character that nobody could ever forget, she was a CERN institution and a force of nature, setting the friendly tone that has long been a


CERN

Tatiana Fabergé in her realm.

hallmark of the theoretical secretariat.

Tania was a talented artist and actress, whose theatrical appearances in many theory Christmas pantomimes were highly appreciated. Outside the lab, for many years Tania helped administer physics schools on the Adriatic coast of what was then Yugoslavia. Her home in Versonnex 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 trotted the globe for many years, connecting with far-flung 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.

Marie-Noëlle Fontaine, Nanie Perrin *and* **John Ellis** *CERN.*

Robert Klapisch 1932–2020

A life dedicated to science and solidarity

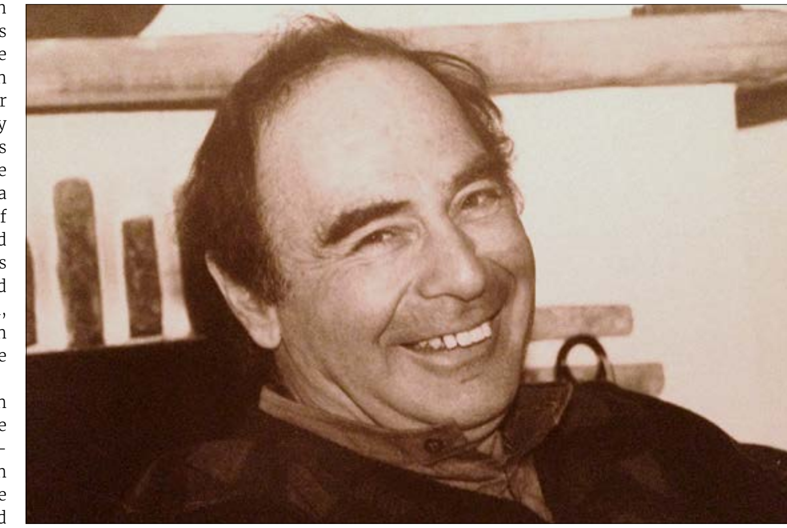
Robert Klapisch, a former director of research at CERN, passed away on 21 March. Robert was a tireless worker, not only passionate about the field of fundamental physics, covering both nuclear and particle physics, but also ever eager to hear about innovative developments in any scientific field. His motto was always: progress 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 at every turn. The many facets of his personality made Robert an endearing friend and a highly appreciated colleague. Open-minded, supportive of others, committed, loyal and with an irresistible *joie de vivre*, he was a fine example of a human being.

Robert was born on 26 December 1932 in Cachan, France. After studying at the École supérieure de physique et de chimie industrielles ESPCI in Paris, he went straight on to join the CNRS in 1956. At the Radium Institute he became proficient in mass spectrometry and precision isotopic separation under the supervision of his mentor, René Bernas. Later, Robert became the director of CSNSM (Centre de spectrométrie nucléaire et de spectrométrie de masse) and transformed it into an 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 spectroscopy on accelerator beams, notably at CERN's Proton Synchrotron (PS) and then at ISOLDE. At this brand-new online isotope separator, the team also carried out the first ever laser spectroscopy, which, when combined with mass spectroscopy, enabled unprecedented studies of exotic short-lived nuclei. This work allowed them to make significant advances in the fields of astrophysics (nucleosynthesis of rare light elements) and nuclear physics (exotic nuclei). These techniques are still used at ISOLDE today.

Robert served as director of research at CERN from 1981 to 1987, a period in which the research programme at the SPS proton–antiproton collider was in full swing. The crowning glory of this programme was the discovery of the W and Z bosons in 1983 and the award of the Nobel Prize in Physics to Carlo Rubbia and Simon van der Meer the following year. During his mandate, Robert gave the study of antimatter a decisive boost with the construction of the LEAR antiproton ring and the start-up of a rich and diverse physics programme. He also launched the relativistic heavy-ion collision programme that led to the discovery of a new state of matter at high temperatures, the quark–gluon plasma.


CERN

Robert Klapisch carried out pioneering research using online mass spectroscopy and also worked to encourage sustainable development.

Robert gave the study of antimatter a decisive boost with the construction of the LEAR antiproton ring

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 2004 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 2019, 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 to encourage sustainable development in countries around the Mediterranean and in Africa by transferring 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 some 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.*

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IOP Publishing

BACKGROUND

Notes and observations from the high-energy physics community

Straight to video

Virtual success *Danielle Speller of Yale presents CUORE's latest results on neutrinoless double-beta decay at the APS virtual April meeting.*

As COVID-19 keeps labs and universities in lockdown, and videoconferencing becomes even more ubiquitous than before, in our globalised field of virtual perma-jetlag, an intriguing phenomenon is being noticed, at least anecdotally: a greater enthusiasm for meetings. Though further data are needed to confirm the effect, teams both big and small are seeing a higher than usual participation in presentations and colloquia.

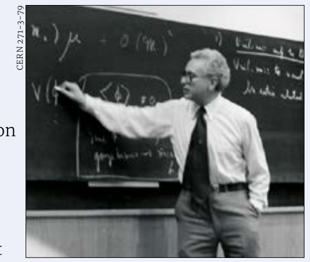
Although nothing can replace the cut and thrust, especially for young researchers, of eyeballing your inquisitor, or cornering an expert over coffee, conferences are adapting quickly. The April APS meeting, originally due to be held in Washington, DC, was in full swing virtually as the *Courier* went to press, with 7000 participants tuning in – 5800 more than the number who had registered to attend – and an almost full programme. Organisers of IPAC 2020, due to take place at GANIL from 10 to 15 May, LHCP in Paris (25 to 30 May) and Neutrino 2020 in Chicago (22 to 27 June) are also working out virtual formats on the same dates. If the current videoconferencing competence continues, physicists' pangs of guilt at their disquieting carbon footprints may become increasingly difficult to ignore in the post-pandemic world.

550,000 **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**

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^{31} 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.

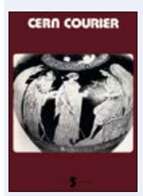


CERN 271-3-79

Murray Gell-Mann describes ideas on the "grand unification" of strong, weak and electromagnetic forces at CERN in 1979.

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, much heavier 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^{31} 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.

Media corner

"The scientific case for the future of experiments in particle physics – accelerator-based or not – is strong... Scientific merits 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** 369).

"The increase [in the brilliance of light sources] by a factor of about 10^{22} 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.

"Weinberg's paper is a bit of lightning in the dark. All of a sudden a titan in the field is suddenly working again on these problems."

Theorist ***Anthony Zee*** quoted in *Quanta Magazine* (30 March) about a recent preprint by Steven Weinberg (arXiv:2001.06582) addressing the mysterious hierarchy of fermion masses.

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

Panagiotis Barkoutsos of IBM Research quoted in *Physics World* (3 April) on a collaboration between IBM and CERN openlab to explore quantum computing in high-energy physics.

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