WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the September/October 2022 issue of *CERN Courier.*

Born at CERN in the late 1980s for the design of state-of-the-art accelerators, “Molflow” has become the industry standard for ultra-high vacuum simulations. The open-source code is used, among others, by satellite firms, fusion researchers, synchrotron X-ray facilities and the space sector – with a recent collaboration between CERN and NASA initiated to develop contamination-free vacuum equipment for its Mars 2020 and SPHEREx missions (p25).

The knowledge transfer from particle physics to other fields is a theme of this issue. We explore the status of the future space-based gravitational-wave detector LISA (p51), with which the CERN vacuum group has recently entered a collaboration, and of SLAC’s upgraded X-ray free-electron laser, LCLS-II, which rests on a collaborative effort involving Fermilab, JLab, DESY, KEK and other centres. Cutting-edge accelerator technologies are also the engine for next-generation radiotherapy tools (p9), while IAEA’s first International Conference on Accelerators for Research and Sustainable Development (p23) highlighted the numerous applications of accelerators in wider society.

Also in the new issue: nuclear clocks (p32); forward physics at CMS (p45); high-efficiency klystrons (p9); Webb’s first images (p11); a bumper meeting-reports section (p18), how to become a CERN guide (p55); Science for Peace (p49); and much more.

To sign up to the new-issue alert, please visit:
http://comms.iop.org/k/iop/cerncourier

To subscribe to the magazine, please visit:
https://cerncourier.com/p/about-cern-courier

EDITOR: MATTHEW CHALMERS, CERN
DIGITAL EDITION CREATED BY IOP PUBLISHING

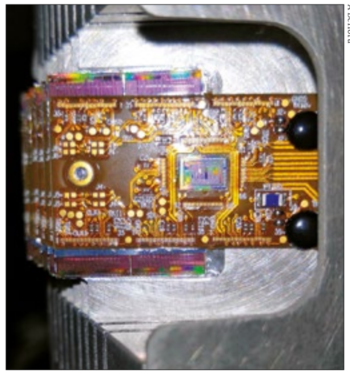
CERNCOURIER
September/October 2022 cerncourier.com Reporting on international high-energy physics

IN THIS ISSUE

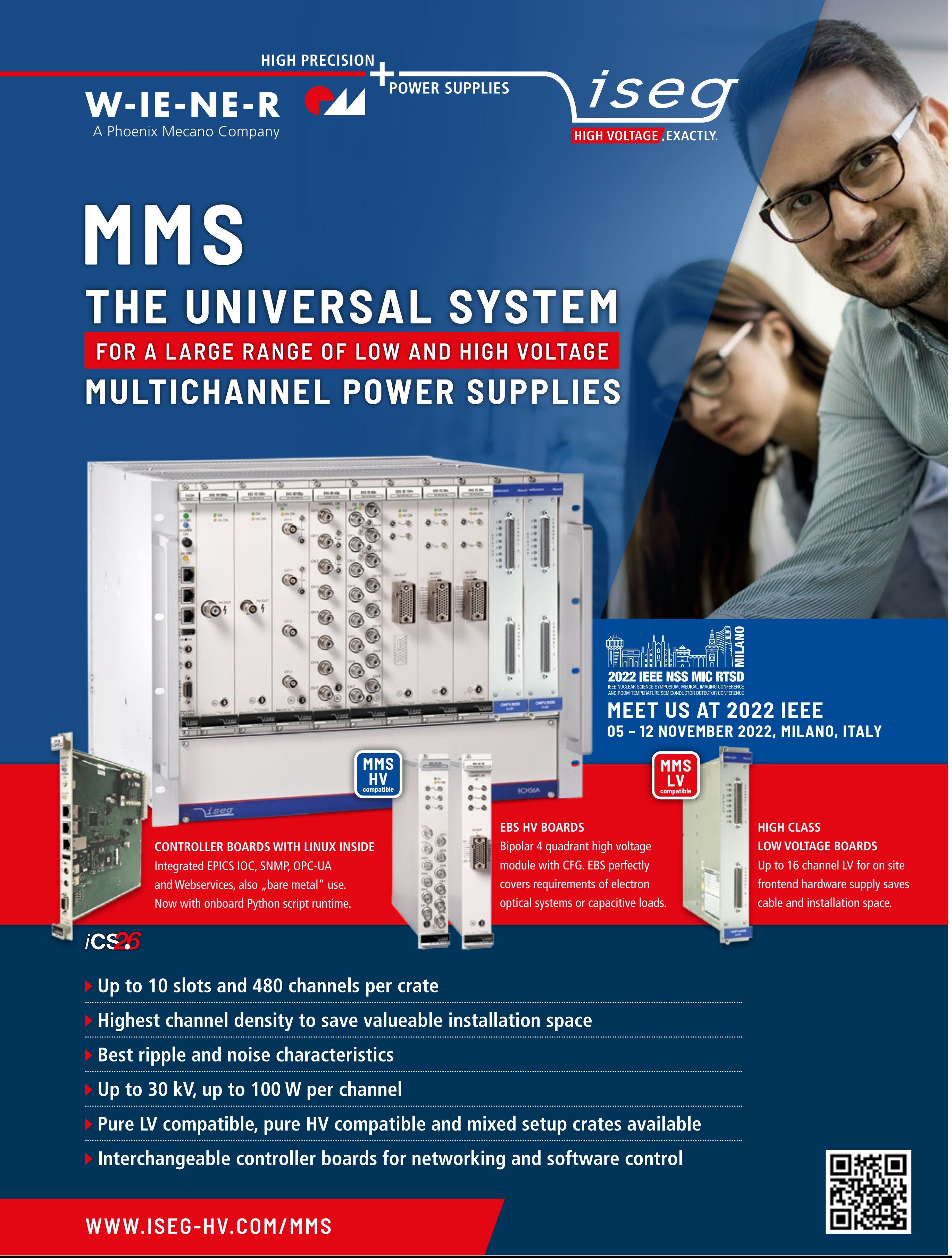
Volume 62 Number 5 September/October 2022

To the stars *First JWST images show distant stars and galaxies with unprecedented resolution.* **11**

Timely *Ultra-precise nuclear clocks offer tests of fundamental physics.* **32**



Exclusive *CMS spectrometer opens the door to a new physics domain.* **45**



FROM THE EDITOR

Intersections with other sciences

Matthew Chalmers
Editor

CERN is best known for exploring the fundamental laws and constituents of the universe. Many people also know it as the place where the web was invented. Far fewer are aware of its increasing role in transferring knowledge, gained through the development of advanced accelerator, detector, computing and other technologies, to different laboratories and fields.

"Molflow" – the open-source molecular-flow simulator that lies behind the image on the cover of this issue (showing the synchrotron-radiation flux density in the interaction region of SuperKEKB) – is a prime example. Born in the late 1980s for the design of state-of-the-art accelerators, it has become the industry standard for ultra-high vacuum simulations, and is used by satellite manufacturers, fusion experiments and synchrotron X-ray facilities, among others (p25). Molflow is increasingly being noticed by the space sector, and is the basis of a recently established collaboration between CERN and NASA's Jet Propulsion Laboratory. NASA's Mars 2020 mission, for instance, relies on contamination-free vacuum equipment to be able to search for signs of ancient microbial life, while its future near-infrared space observatory SPHEREx requires a decontamination strategy to keep its optics free from performance-degrading molecular accumulations. Molflow is also being used by ESA to analyse data from the LISA Pathfinder mission. Such relationships are not just one-way: the NASA team has already boosted aspects of Molflow, for example, and made feature requests that are now available in the public versions of the code.

As our interview with LISA scientist Stefano Vitale shows (p51), the links between CERN and the gravitational-wave community are growing ever stronger, both scientifically and technologically. LISA has recently entered a new collaboration with the CERN vacuum group, for example, while collaboration agreements on vacuum and cryogenics technology for the proposed Einstein Telescope are at an advanced stage. Along with LIGO and Advanced Virgo, plus several other astrophysical facilities, the two future gravitational-wave observatories are CERN-recognised experiments.

The links between CERN and the gravitational-wave community are growing ever stronger

Vacuum synergies *NASA's Mars 2020 Perseverance rover in its Atlas V rocket payload.*

Nowhere are the contributions of particle physics to other fields better illustrated than X-ray light sources, which serve tens of thousands of users per year, ranging from biologists and chemists to materials scientists and paleontologists. On p39, project leaders for SLAC's upgraded X-ray free-electron laser, LCLS-II, which is centred on a new superconducting linac, describe how its success lies in a multi-centre collaborative effort involving high-energy physics labs in the US, Europe and Japan.

Cutting-edge accelerator technologies are also the engine for next-generation radiotherapy tools, as an ambitious new proposal for a laser-hybrid accelerator demonstrates (p9). Indeed, as explored in-depth during IAEA's first International Conference on Accelerators for Research and Sustainable Development (p23), tens of thousands of accelerators around the world help treat cancer, create radiopharmaceuticals, preserve food, monitor the environment, strengthen materials, understand fundamental physics, study the past and even disclose crimes – with numerous new applications being explored.

Welcome back

The summer conference season saw a welcome return to in-person events. The energy and enthusiasm among 1200 participants present at ICHEP22 (p18) was palpable, and the start of LHC Run 3 (p7) and 10th anniversary of the Higgs-boson discovery (p21) have put extra wind in the sails. Also in this issue: nuclear clocks (p32); forward physics at CMS (p45); high-efficiency klystrons (p9); Webb's first images (p11); becoming a CERN guide (p55); Science for Peace (p49); and much more.

Reporting on international high-energy physics

CERN Courier is distributed to governments, institutes and laboratories affiliated with CERN, and to individual subscribers. It is published six times per year. The views expressed are not necessarily those of the CERN management.

IOP Publishing

Editor Matthew Chalmers
Associate editor Kristiane Bernhard-Novotny
Editorial assistant Bryan Pérez Tapia
Astrowatch contributor Arshia Ruina
Archive contributor Peggie Rimmer

E-mail cern.courier@cern.ch

Advisory board Peter Jenni, Christine Sutton, Claude Amsler, Philippe Bloch, Roger Forty, Mike Lamont, Joachim Kopp

Laboratory correspondents
Argonne National Laboratory Tom LeCompte
Brookhaven National Laboratory Achim Franz
Cornell University D G Cassel
DESY Laboratory Till Mundzeck
Fermilab Kurt Riesselmann
Forschungszentrum Jülich Markus Buescher
GSI Darmstadt I Peter
IHEP, Beijing Lijun Guo
INFN Antonella Varaschin
Jefferson Laboratory Kandice Carter
Lawrence Berkeley Laboratory Spencer Klein
Los Alamos National Lab Rajan Gupta
NCSL Ken Kingery
Nikhef Robert Fleischer
Orsay Laboratory Anne-Marie Lutz
PSI Laboratory P-R Kettle
Saclay Laboratory Elisabeth Locci
UK STFC Stephanie Hills
SLAC National Accelerator Laboratory Melinda Baker
SNOLAB Samantha Kuula
TRIUMF Laboratory Marcello Pavan

Produced for CERN by IOP Publishing Ltd
2 The Distillery, Glassfields, Avon Street Bristol BS2 0GR
Tel +44 (0)117 929 7481

Head of Media Jo Allen
Head of Media Business Development Ed Jost
Content and production manager Ruth Leopold
Technical illustrator Alison Tovey
Advertising and recruitment sales Chris Thomas

Advertisement production Katie Graham
Marketing and circulation Emma Hughes, Jessica Pratten

Advertising
Tel +44 (0)117 930 1026 (for UK/Europe display advertising) or +44 (0)117 930 1164 (for recruitment advertising); e-mail sales@cerncourier.com

General distribution
Courrier Adressage, CERN, 1211 Geneva 23, Switzerland; e-mail courrier-adressage@cern.ch

Published by CERN, 1211 Geneva 23, Switzerland
Tel +41 (0) 22 767 61 11

Printed by Warners (Midlands) plc, Bourne, Lincolnshire, UK

ISSN 0304-288X

NEWS ANALYSIS

LHC

Run 3 physics gets under way

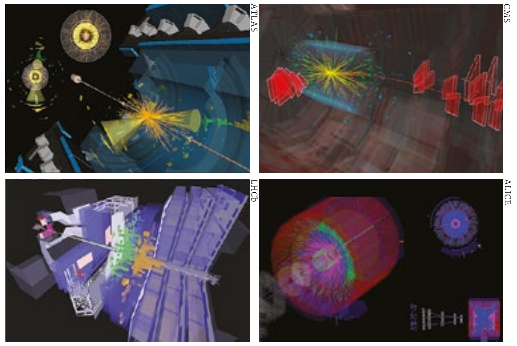
At 4.47 p.m. on Tuesday 5 July, applause broke out in the CERN Control Centre as LHC operators declared Stable Beams. After more than three years of upgrade and maintenance work across the machine and experiments, ALICE, ATLAS, CMS and LHCb started recording their first proton–proton collisions at an unprecedented energy of 13.6 TeV.

LHC Run 3 is set to last until December 2025. In addition to a slightly higher centre-of-mass energy than Run 2, the machine will operate at an increased average luminosity thanks to larger proton intensities and smaller transverse beam sizes. New or upgraded detectors and improved data readout and selection promise the experiments their greatest physics harvests yet. ATLAS and CMS each expect to record more collisions during Run 3 than in the two previous runs combined, while LHCb and ALICE hope for three and 50 times more data, respectively. Two new forward experiments, FASER and SND@LHC (*CERN Courier* July/August 2021 p7), also join the LHC-experiment family.

While pilot beams circulated in the LHC for a brief period in October 2021, the countdown to LHC Run 3 began in earnest on 22 April, when two beams of protons circulated in opposite directions at their injection energy of 450 GeV. Since then, operators have worked around the clock to ensure the smooth beginning of the LHC's third run, which was livestreamed to the media on the afternoon of 5 July. True to form, the machine added drama to proceedings: a training quench that morning generated enough heat to warm up several magnets well above their operating temperature. The cryogenics team sprang into action, managing to recuperate operational conditions just in time for the live event, watched by more than 1.5 million people.

Since then, the intensity of the beams has been increased in carefully monitored steps. As the *Courier* went to press, 900 bunches each containing around 120 billion protons were circulating, with 2748 bunches expected by September. "Run 3 is going to be a game-changer for us," says operations group leader Rende Steerenberg. "In Run 2, we exploited the LHC in its 'normal' hardware configuration as constructed. Now, after the injectors have been adapted, we can push the brightness and the intensity of the beams much more. Run 3 is also an important stepping-stone to the High-Luminosity LHC upgrade."


CERN



In tune *Cheering the start of Run 3 physics in the CERN Control Centre on 5 July (top), as (bottom, clockwise) ATLAS, CMS, ALICE and LHCb recorded their first proton–proton collisions at 13.6 TeV.*

Schedule change

In March, the CERN management announced a change to the LHC schedule. Long Shutdown 3 will now start in December 2025, one year later than in the previous baseline, and last for three instead of 2.5 years. Production schedules across the LHC's lifetime will remain unaffected, while the change will allow work for the HL-LHC to be completed with appropriate schedule margins. The extended year-end technical stop (EYETS) is now scheduled to take place in 2024/2025 and to last for 17 weeks, while the two preceding EYETSs will be of the standard length of 13 weeks beam-to-beam.

Every time we start a new run, it's always a new adventure

The preferred scenarios and duration of ion runs during Run 3 remain to be confirmed, but are likely to take place in four week-long periods towards the end of each year. While the majority of the LHC's heavy-ion runs employ lead ions, a novel addition to the Run 3 programme will be a short period of collisions between oxygen ions in 2024. As with the first xenon runs in 2017, colliding ions with masses that are intermediate between protons and lead allows the experiments to scan important physics regimes relevant to the study of high-energy QCD.

"Every time you make a step in energy, even if it's not that large, and a step in the amount of data, you open up new physics opportunities," said CERN Director-General Fabiola Gianotti. "And every time we start a new run, it's always a new adventure. You have to recalibrate the detectors and the accelerator, so it's always uncharted territory and always a big emotion."

- For full coverage of the physics targets at LHC Run 3, please see the May/June 2022 issue of *CERN Courier*.

CERN

Council decides new measures for Russia and Belarus

At its 208th meeting on 16 June, the CERN Council announced further measures in response to the continuing illegal military invasion of Ukraine by the Russian Federation with the involvement of the Republic of Belarus. The Council declared that it intends to terminate CERN's International Cooperation Agreements (ICAs) with both countries at their expiration dates in 2024. However, the situation will continue to be monitored carefully and the Council stands ready to take any further decision in the light of developments in Ukraine.

CERN's ICAs normally run for five years and are tacitly renewed for the same period unless a written notice of termination is provided by one party to the other at least six months prior to the renewal date. The ICA with the Russian Federation expires in December 2024, and that with the Republic of Belarus in June 2024.

The latest measures follow those already adopted at an extraordinary meeting of the Council on 8 March, and at the Council's regular session on 25 March. In addition to the promotion of initiatives to support Ukrainian collaborators and Ukrainian scientific activity in high-energy physics, these measures

CERN-PHOTO-202206-111-1

Open council *Delegates from CERN's Member States during the open meeting of the June Council.*

included the suspension of Russia's Observer status and the decision not to engage in new collaborations with Russia and its institutions until further notice (*CERN Courier* May/June 2022 p7).

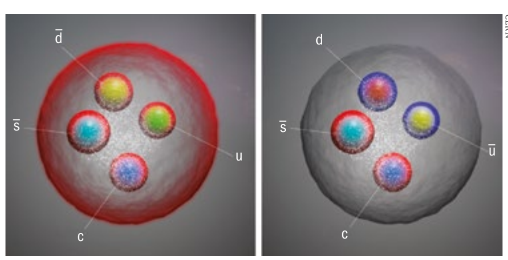
The Council also decided in June to review CERN's future cooperation with the Joint Institute for Nuclear Research (JINR) well in advance of the expiration of the current ICA in January 2025. This follows measures adopted at the previous Council sessions to suspend the Observer status of JINR and the participation of CERN scientists in all JINR scientific committees, and vice versa, until further notice. The Council reaffirmed that all decisions taken to date, along with the actions undertaken by the CERN management, which have had a marked impact on the involvement of the Russian Federation and the Republic of Belarus in the scientific programme of the organisation, remain in force.

Ukraine joined CERN as an Associate Member State in 2016 and Ukrainian scientists have long been active in many of the laboratory's activities. Russian scientists also have a long and distinguished involvement with CERN, and Russia was granted Observer status in recognition of its contributions to the construction of the LHC. At the June Council meeting, the Member States reiterated their denunciation of the continuing illegal military invasion, recalling that the core values of CERN (p49) have always been based upon scientific collaboration across borders as a driver for peace, and stressing that the aggression of one country against another runs counter to these values.

Hadron spectroscopy

Exotic hadrons brought into order by LHCb

With so many new hadronic states being discovered at the LHC (67 and counting, with the vast majority seen by LHCb), it can be difficult to keep track of what's what. While most are variations of known mesons and baryons, LHCb is uncovering an increasing number of exotic hadrons, namely tetraquarks and pentaquarks. A case in point is its recent discovery, announced at CERN on 5 July, of a new strange pentaquark (with quark content $c\bar{c}uds$) and a new tetraquark pair: one constituting the first doubly charged open-charm tetraquark ($c\bar{s}u\bar{d}$) and the other a neutral isospin partner ($c\bar{s}\bar{u}d$). The situation has prompted the LHCb collaboration to introduce a new naming scheme. "We're creating 'particle zoo 2.0'," says Niels Tuning, LHCb physics coordinator. "We're witnessing a period of discovery similar to the 1950s, when a 'zoo' of hadrons ultimately led to the quark model of conventional hadrons in the 1960s."



CERN

Brand new *LHCb's latest tetraquarks, illustrated here as single units of tightly bound quarks, go by the names $T^{a}_{c\bar{s}0}(2900)^{0}$ and $T^{a}_{c\bar{s}0}(2900)^{++}$ in the new naming scheme.*

While the quark model allows the existence of multiquark states beyond two- and three-quark mesons and baryons, the traditional naming scheme for hadrons doesn't make much allowance for what these particles should be called. When the first tetraquark candidate was discovered at the Belle experiment in 2003, it was denoted by "X" because it didn't seem to be a conventional charmonium state. Shortly afterwards, a similarly mysterious but different state turned up at BaBar and was denoted "Y". Subsequent exotic states seen at Belle and BESIII were dubbed "Z", and more recently tetraquarks discovered at LHCb were labelled "T".

Complicating matters further, the subscripts added to differentiate between the various states lack consistency. For example, the first known tetraquark states contained both charm and anticharm quarks, so a subscript "c" was added. But the recent discoveries of tetraquarks and pentaquarks containing a single strange quark require an extra subscript "s". On top of all of that, explains LHCb's Tim Gershon, who initiated the new naming scheme, tetraquarks discovered by LHCb in 2020 contain a single charm quark. "We couldn't assign the subscript 'c' because we've always used that to denote states containing charm and anticharm, so we didn't know what symbols to use," he explains. "Things were starting to become a bit confusing, so we thought it was time to bring some kind of logic to the naming scheme. We have done this over an extended period, not only within LHCb but also involving other experiments and theorists in this field."

The new scheme could make it easier to spot patterns that might have been missed before

Helpfully, the new proposal labels all tetraquarks "T" and all pentaquarks "P", with a set of rules regarding the necessary subscripts and superscripts. In this scheme, the two different spin states of the open-charm tetraquarks discovered by LHCb in 2020 become $T_{cs0}(2900)^{0}$ and $T_{cs1}(2900)^{0}$ instead of $X_0(2900)^{0}$ and $X_1(2900)^{0}$, for example, while the latest pentaquark is denoted $P^{\Lambda}_{\psi s}(4338)^{0}$. The collaboration hopes that the new scheme, which can be extended to six- or seven-quark hadrons, will make it easier for experts to communicate while also helping newcomers to the field.

Importantly, it could make it easier to spot patterns that might have been missed before, perhaps shedding light on the central question of whether exotic hadrons are compact tightly bound multi-quark states or more loosely bound molecular-like states. The new LHCb scheme might even help researchers predict new exotic hadrons, just as the multiplets arising from the quark model made it possible to predict new mesons and baryons such as the Ω^-.

"Before this new scheme it was almost like a Tower of Babel situation where it was difficult to communicate," says Gershon. "We have created a document that people can use as a kind of dictionary, in the hope that it will help the field to progress more rapidly."

Further reading

LHCb Collab. 2022 arXiv:2206:15233.

Accelerators

CERN and Canon demonstrate efficient klystron

The radio-frequency (RF) cavities that accelerate charged particles in machines like the LHC are powered by devices called klystrons. These electro-vacuum tubes, which amplify RF signals by converting an initial velocity modulation of a stream of electrons into an intensity modulation, produce RF power in a wide frequency range (from several hundred MHz to tens of GHz) and can be used in pulsed or continuous-wave mode to deliver RF power from hundreds of kW to hundreds of MW. The close connection between klystron performance and the power consumption of an accelerator has driven researchers at CERN to develop more efficient devices for current and future colliders.

The efficiency of a klystron is calculated as the ratio between generated RF power and the electrical power that is delivered from the grid. Experience with many thousands of such devices during the past seven decades has established that at low frequency and moderate RF power levels (as required by the LHC), klystrons can deliver an efficiency of 60–65%. For pulsed, high-frequency and high peak-RF power devices, efficiencies are about 40–45%. The efficiency of RF power production is a key element of an accelerator's overall efficiency. Taking the proposed future electron–positron collider FCC-ee as an example: by increasing klystron efficiency from 65 to 80%, the electrical power savings over a 10-year period could be as much as 1 TWhr. In addition, reduced demand on the electrical power storage capacity and cooling and ventilation may further reduce the original investment cost.

In 2013 the development of high-efficiency klystrons started at CERN within the Compact Linear Collider study as a means to reduce the global energy consumed by the proposed collider. Thanks to strong support by management, this evolved into a project inside the CERN RF group. A small team of five people, led by Igor Syratchev, developed accurate computer tools for klystron simulations and in-depth analysis of the beam dynamics, and used them to evaluate effects that limit klystron efficiency. Finally, the team proposed novel technological solutions (including new bunching methods and higher order harmonic cavities) that can improve klystron efficiency by 10–30% compared to commercial analogues. These new technologies were applied to develop new high-efficiency klystrons for use in the high-luminosity LHC (HL-LHC), FCC-ee and the CERN X-band high-gradient facilities, as well as in medical and industrial accelerators.

Canon ETD, Japan

RF boost *The first commercial prototype of a high-efficiency 8 MW, 12 GHz "E37117" klystron.*

Some of the new tube designs are now undergoing prototyping in close collaboration between CERN and industry.

The first commercial prototype of a high-efficiency 8 MW X-band klystron developed at CERN was built and tested by Canon Electron Tubes and Devices in July this year. Delivering an expected power level with an efficiency of 53.3% measured at their factory in Japan, it is the first demonstration of the technological solution developed at CERN that showed an efficiency increase of more than 10% compared to commercially available devices. In terms of RF power production, this translates to an overall increase of 25% using the same wall-plug power as the model currently working at CERN's X-band facility. Later this year the klystron will arrive at CERN and replace Canon's conventional 6 MW tube. The next project in progress aims to fabricate a high-efficiency version of the LHC klystron, which, if successful, could be used in the HL-LHC.

"These results give us confidence for the coming high-efficiency version of the LHC klystrons and for the development of FCC-ee," says RF group leader Frank Gerigk. "It is also an excellent demonstration of the powerful collaboration between CERN and industry."

Applications

Exploring a laser-hybrid accelerator for radiotherapy

A multidisciplinary team in the UK has received seed funding to investigate the feasibility of a new facility for ion-therapy research based on novel accelerator, instrumentation and computing technologies. At the core of the facility would be a laser-hybrid accelerator dubbed LhARA: a high-power pulsed laser striking a thin foil target would create a large flux of protons or ions, which are captured using strong-focusing electron-plasma lenses and then accelerated rapidly in a fixed-field alternating-gradient accelerator. Such a device, says the team, offers enormous clinical potential by providing more flexible, compact and cost-effective multi-ion sources.

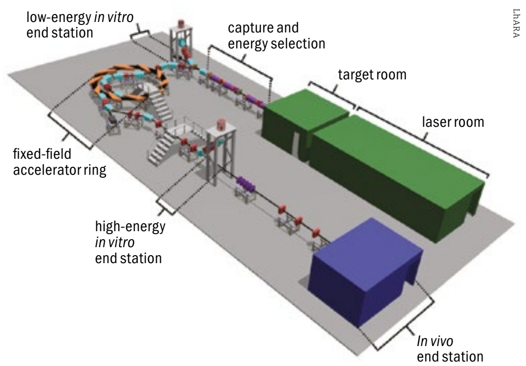
High-energy X-rays are by far the most common radiotherapy tool, but recent decades have seen a growth in particle-beam radiotherapy. In contrast to X-rays, protons and ion beams can be manipulated to deliver radiation doses more precisely than conventional ▷

CERNCOURIER
Volume 62 Number 5 September/October 2022
IOP Publishing

radiotherapy, sparing surrounding healthy tissue. Unfortunately, the number of ion treatment facilities is few because they require large synchrotrons to accelerate the ions. The Proton–Ion Medical Machine Study undertaken at CERN during the late 1990s, for example, underpinned the CNAO (Italy) and MedAustron (Austria) treatment centres that helped propel Europe to the forefront of the field – work that is now being continued by CERN's Next Ion Medical Machine Study (*CERN Courier* July/August 2021 p23).

"LhARA will greatly accelerate our understanding of how protons and ions interact and are effective in killing cancer cells, while simultaneously giving us experience in running a novel beam," says LhARA biological science programme manager Jason Parsons of the University of Liverpool. "Together, the technology and the science will help us make a big step forward in optimising radiotherapy treatments for cancer patients."

A small number of laboratories in Europe already work on laser-driven sources for biomedical applications. The



LhARA

Ambitious *Schematic showing the layout of the proposed Laser-hybrid Accelerator for Radiobiological Applications (LhARA).*

LhARA collaboration, which comprises physicists, biologists, clinicians and engineers, aims to build on this work to demonstrate the feasibility of capturing and manipulating the flux created in the laser-target interaction to provide a beam that can be accelerated rapidly to the desired energy. The laser-driven source offers the opportunity to capture intense, nanosecond-long pulses of protons and ions at an energy of 15 MeV, says the team. This is two orders of magnitude greater than in conventional sources, allowing the space-charge limit on the instantaneous dose to be evaded.

In July, UK Research and Innovation granted £2 million over the next two years to deliver a conceptual design report for an Ion Therapy Research Facility (ITRF) centred around LhARA. The first goal is to demonstrate the feasibility of the laser-hybrid approach in a facility dedicated to biological research, after which the team will work with national and international partnerships to develop the clinical technique. While the programme carries significant technical risk, says LhARA co-spokesperson Kenneth Long from Imperial College London/STFC, it is justified by the high level of potential reward: "The multidisciplinary approach of the LhARA collaboration will place the ITRF at the forefront of the field, partnering with industry to pave the way for significantly enhanced access to state-of-the-art particle-beam therapy."

ASTROWATCH

Webb opens new era in observational astrophysics

The keenly awaited first science-grade images from the James Webb Space Telescope were released on 12 July – and they did not disappoint. Thanks to Webb's unprecedented 6.5 m mirror, together with its four main instruments (NIRCam, NIRSpec, NIRISS and MIRI), the $10 billion probe marks a new dawn for observational astrophysics.

The past six months since Webb's launch from French Guiana have been devoted to commissioning, including alignment and calibration of the mirrors and bringing temperatures to cyrogenic levels to minimise noise from heat radiated from the equipment (*CERN Courier* March/April 2022 p7). Unlike the Hubble Space Telescope, Webb does not look at ultraviolet or visible light but is primarily sensitive to near- and mid-infrared wavelengths. This enables it to look at the farthest galaxies and stars, as early as a few hundred million years after the Big Bang.

Wealth of information

Pictured here are some of Webb's early-release images. The first deep-field image (top) covers the same area of the sky as a grain of sand held at arm's length, and is swarming with galaxies. At the centre is a cluster called SMACS 0723, whose combined mass is so high that its gravitational field bends the light of objects that lie behind it (resulting in arc-like features), revealing galaxies that existed when the universe was less than a billion years old. The image was taken using NIRCam and is a combination of images at different wavelengths. The spectrographs, NIRSpec and NIRISS, will provide a wealth of information on the composition of stars, galaxies and their clusters, offering a rare peak into the earliest stages of their formation and evolution.

Stephan's Quintet (bottom left) is a visual group of five galaxy clusters that was first discovered in 1877 and remains one of the most studied compact galaxy groups. The actual grouping involves only four galaxies, which are predicted to eventually merge. The non-member, NGC 7320, which lies about 40 million light years from Earth rather than 290 million for the actual group, is seen on the left, with vast regions of active star formation in its numerous spiral arms.

A third stunning image, the Southern Ring nebula (bottom right), shows a dying

NASA/ESA/CSA/STScI

Stunning *Top: Webb's first deep field, a lensing galaxy cluster (NIRCam image). Left: Stephan's Quintet, an interacting galaxy cluster (NIRCam + MIRI composite). Right: Southern Ring, a planetary nebula (NIRCam).*

star. With its reservoirs of light elements already exhausted, it starts using up any available heavier elements to sustain itself – a complex and violent process that results in large amounts of material being ejected from the star in intervals, visible as shells.

These images are just a taste, yet not all Webb data will be so visually spectacular. By extending Hubble's observations of distant supernovae and other standard candles, for example, the telescope should enable the local rate of expansion to be determined more precisely, possibly shedding light on the nature of dark energy. By measuring the motion and gravitational lensing of early objects, it will also survey the distribution of dark matter, and might even hint at what it's made of. Using transmission spectroscopy, Webb will also reveal exoplanets in unprecedented detail, learn about their chemical compositions and search for signatures of habitability.

CERNCOURIER
VOLUME 62 NUMBER 5 SEPTEMBER/OCTOBER 2022
IOP Publishing

NEWS DIGEST

Magnet MQXFA05 entering the vertical cryostat at BNL.

Niobium–tin's resilience tests
A full-size, US-produced quadrupole magnet for the High-Luminosity LHC has passed a critical endurance test, marking another step towards confirming the viability of Nb_3Sn magnet technology. The higher current supported by niobium–tin is key to increase the energies of colliders, but the alloy is more brittle and harder to work with than the niobium–titanium currently used. In tests at Brookhaven over the past two years, the 4.2 m-long magnet (which was tested in vertical position and was not equipped with the outer stainless-steel shell required to complete the cold mass) endured five thermal cycles, during which it was cooled from room temperature to 1.9 K, with no degradation in performance. During the most recent thermal cycles in April and May this year, the magnet also underwent 50 provoked quenches and emerged as good as new. The tests also showed that the magnet can maintain its peak field of 11.4 T up to 4.5 K, providing a margin of operation far exceeding the requirements imposed by collision-debris heat coming from the ATLAS and CMS experiments.

XENON1T excess fades
An unexpected excess of events in the XENON1T dark-matter experiment at Gran Sasso that was reported in 2020 (*CERN Courier* September/October 2020 p8) has disappeared. While the collaboration could not rule out a more conventional explanation resulting from trace amounts of tritium in the ultra-pure detector volume, it also interpreted the events as being compatible with the existence of a new 2.3 keV-mass particle. Now, based on a blinded analysis of the first low-energy electronic-recoil data from XENONnT, which is an order of magnitude more sensitive to rare events, no excess was seen. The results exclude the collaboration's previous new-physics interpretation and set stringent new limits on solar axions, an enhanced neutrino magnetic moment, and bosonic dark matter (arXiv:2207.11330).

CERN tech in space
On 13 July, the first CERN-driven satellite – a 1 kg device designed to study the effects of cosmic radiation on electronics – was successfully launched, along with five other cubesats, on a Vega-C rocket from French Guiana. Carrying a miniature version of RadMon, a radiation monitoring device deployed in the LHC, CELESTA orbits at an altitude of almost 6000 km, in the centre of the inner Van Allen belt where radiation levels are at their highest. A radiation model of CELESTA was tested at CERN's mixed-field irradiation facility

The CELESTA prototype in the CHARM irradiation facility.

CHARM and, if successful, its Space RadMon technology could act as a predictive maintenance tool for the renewal of satellites.

LUX-ZEPLIN debuts
After just 60 "live" days of data-taking, the LUX-ZEPLIN (LZ) experiment at SURF, South Dakota has already claimed the title of the world's most sensitive dark-matter detector. The 1500 m-deep, low-background experiment, which is centered on a dual-phase time projection chamber in a cryostat filled with 10 tonnes of liquid xenon, started its hunt for Weakly Interacting Massive Particles (WIMPs) in December. With no signal seen, the data place stringent limits on WIMP-nucleon, WIMP-neutron, and WIMP-proton cross sections for WIMP masses above 9 GeV. The most

The photomultiplier array chamber of the LUX-ZEPLIN experiment.

stringent limit for WIMP masses is set at 30 GeV, excluding cross sections above $5.9\times10^{-48}\,cm^2$ at 90% confidence (arXiv:2207.03764). The LZ team plans to record 1000 live days of data, corresponding to a factor of 17 more exposures than the first science run.

Abrupt change in magic nucleus
Despite the complexity of nuclei, evidence suggests that around particular "magic" numbers corresponding to full nuclear shells, nuclear properties are governed by a single unpaired nucleon. The constancy of the electromagnetic properties of indium isotopes, for example, indicates that a single unpaired proton hole can provide their identity. To investigate the validity of this simple picture, Adam Vernon and colleagues used precision laser spectroscopy at ISOLDE's CRIS experiment to measure the magnetic dipole moment of different indium isotopes. They found that the moment undergoes a surprisingly abrupt change at magic number 82, indicating that, whereas the single-particle picture indeed dominates at N = 82, it does not for previously studied isotopes. The findings shed light on how seemingly simple single-particle phenomena naturally emerge from complex interactions among protons and neutrons (*Nature* **607** 260).

AWAKE self-modulates
The AWAKE collaboration at CERN has taken a key step towards a workable plasma-wakefield accelerator. AWAKE uses proton bunches from the SPS to create plasma waves in a 10 m-long rubidium plasma cell, upon which a subsequent beam of electrons can "surf" to reach high energies in a single stage. Since the proton bunch is long compared to the plasma–electron wavelength, the scheme relies on the seeded self-modulation of the entire proton bunch to reach larger accelerating gradients. The team has now shown that such self-modulation can be seeded by the wakefields driven by a preceding electron bunch. It marks the first milestone of AWAKE Run 2, which aims to accelerate a witness bunch to GeV energies while preserving the initial quality (*Phys. Rev. Lett.* **129** 024802).

Gallium anomaly remains
New results from the Baksan Experiment on Sterile Transitions (BEST) further confirm the so-called gallium anomaly: a deficit in the number of electron neutrinos emitted from radioactive sources as seen by the SAGE and GALLEX experiments, one possible explanation for which is oscillations between electron and "sterile" neutrino states. Based on the same concept as SAGE, the team placed a ^{51}Cr electron–neutrino source at the centre of two nested Ga volumes and measured the production rate of ^{71}Ge via charged-current reactions. Finding a 20–24% lower rate than expected, the results are in agreement with the previously reported gallium anomaly. If interpreted in the context of neutrino oscillations, says the team, the results are consistent with $\nu_e \rightarrow \nu_s$ oscillations with a relatively large squared mass difference ($>0.5\,eV^2$) and mixing $\sin^2 2\theta \sim 0.4$. Other explanations, for example concerning the determination of relevant cross sections, are also being investigated. (*Phys. Rev. C* **105** 065502; *Phys. Rev. Lett.* **128** 232501).

CERNCOURIER
VOLUME 62 NUMBER 5 SEPTEMBER/OCTOBER 2022
IOP Publishing

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

CMS

Jet-energy corrections blaze a trail

Understanding hadronic final states is key to a successful physics programme at the LHC. The quarks and gluons flying out from proton–proton collisions instantly hadronise into sprays of particles called jets. Each jet has a unique composition that makes their flavour identification and energy calibration challenging. While the performance of jet-classification schemes has been increased by the fast-paced evolution of machine-learning algorithms, another, more subtle, revolution is ongoing in terms of precision jet-energy corrections.

CMS physicists have taken advantage of the data collected during LHC Run 2 to observe jets in many different final states and systematically understand their differences in detail. The main differences originate from the varying fractions of gluons making up the jets and the different amounts of final-state radiation (FSR) in the events, causing an imbalance between the leading jet and its companions. The gluon uncertainty was constrained by splitting the Z+jet sample by flavour, using a combination of quark–gluon likelihood and b/c-quark tagging, while FSR was constrained by combining the missing-E_T projection fraction (MPF) and direct balance (DB) methods. The MPF and DB methods have been well established at the LHC since Run 1: while in the DB method the jet response is evaluated by comparing the reconstructed jet momentum directly to the momentum of the reference object, the MPF method considers the response of the whole hadronic activity in the event, recoiling versus the reference object. Figure 1 shows the agreement achieved with the Run 2 data after carefully accounting for these biases for samples with different jet-flavour compositions.

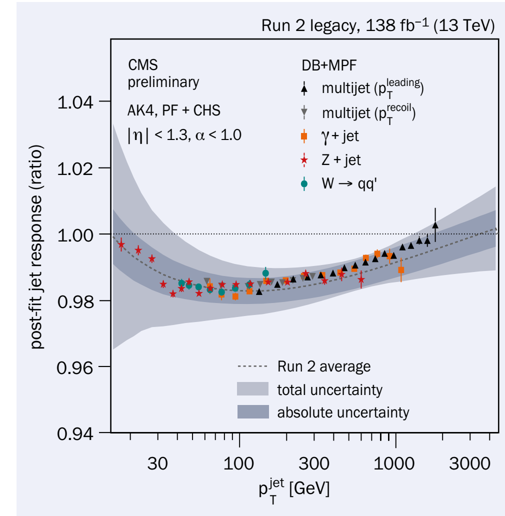


Fig. 1. *The measurement of particle-flow jet to particle-jet momentum ratio (or response) with multiple different final states, combining two complementary techniques (DB+MPF) to explicitly account for biases from initial- and final-state radiation. The ratio between data and simulation is shown after accounting for systematic biases in a global fit.*

Source: CERN-CMS-DP-2021-033

Precise jet-energy corrections are critical for some of the recent high-profile measurements by CMS, such as an intriguing double dijet excess at high mass (*CERN Courier* May/June 2022 p15), a recent exceptionally accurate top-quark mass measurement (*CERN Courier* July/August 2022 p8), and the most precise extraction of the strong coupling constant at hadron colliders using inclusive jets.

The expected increase of pileup in Run 3 and at the High-Luminosity LHC will pose additional challenges in the derivation of precise jet-energy corrections, but CMS physicists are well prepared: CMS will adopt the next-generation particle-flow algorithm (PUPPI, for PileUp Per Particle Id) as the default reconstruction algorithm to tackle pileup effects within jets at the single-particle level.

Jets can be used to address some of the most intriguing puzzles of the Standard Model (SM), in particular: is the SM vacuum metastable, or do some new particles and fields stabilise it? The top-quark mass and strong-coupling-constant measurements address the former question via their interplay with the Higgs-boson mass, while dijet-resonance searches tackle the latter.

Underlying these studies are the jet-energy corrections and the awareness that each jet flavour is unique.

Further reading

CMS Collab. 2021 CERN-CMS-DP-2021-033.
CMS Collab. 2021 CERN-CMS-DP-2021-001.
CMS Collab. 2022 CMS-PAS-TOP-20-008.

ATLAS

Low-pileup data pin down top-quark production

The top quark – the heaviest known elementary particle – differs from the other quarks by its much larger mass and a lifetime that is shorter than the time needed to form hadronic bound states. Within the Standard Model (SM), the top quark decays almost exclusively into a W boson and a b quark, and the dominant production mechanism in proton–proton (pp) collisions is top-quark pair ($t\bar{t}$) production.

Measurements of $t\bar{t}$ production at various pp centre-of-mass energies at the LHC probe different values of Bjorken-x, the fraction of the proton's longitudinal momentum carried by the parton participating in the initial interaction. In particular, the fraction of $t\bar{t}$ events produced through quark–antiquark annihilation increases from 11% at 13 TeV to 25% at 5.02 TeV. A measurement of the $t\bar{t}$ production cross-section thus places additional constraints on the proton's parton distribution functions (PDFs), which describe the probabilities of finding quarks and gluons at particular x values. ▷

In November 2017, the ATLAS experiment recorded a week of pp-collision data at a centre-of-mass energy of 5.02 TeV. Although the main motivation of this 5.02 TeV dataset is to provide a proton reference sample for the ATLAS heavy-ion physics programme, it also provides a unique opportunity to study top-quark production at a previously unexplored energy in ATLAS. The majority of the data was recorded with a mean number of two inelastic pp collisions per bunch crossing compared to roughly 35 collisions during the 13 TeV runs. Due to much lower pileup conditions, the ATLAS calorimeter cluster noise thresholds were adjusted accordingly, and a dedicated jet-energy scale calibration was performed.

Now, the ATLAS collaboration has released its measurement of the $t\bar{t}$ production cross-section at 5.02 TeV in two final states. Events in the dilepton channel were selected by requiring opposite-charge pairs of leptons, resulting in a small, high-purity sample. Events in the single-lepton final states were separated into subsamples with different signal-to-background ratios, and a multivariate technique was used to further separate signal from background events. The two measurements were combined, taking the correlated systematic uncertainties into account.

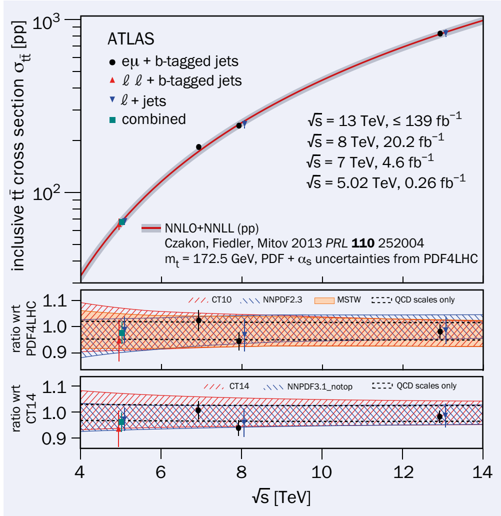


Fig. 1. *ATLAS measurements of the $t\bar{t}$-production cross section as a function of centre-of-mass energy compared to the SM prediction, with measurements made at the same energy slightly offset for clarity. The middle and lower panels show the ratios of measurements and predictions from different parton-distribution functions.*

Source: arXiv:2207.01354.

The measured cross section in the dilepton channel (65.7 ± 4.9 pb) corresponds to a relative uncertainty of 7.5%, of which 6.8% is statistical. The single-lepton measurement (68.2 ± 3.1 pb), on the other hand, has a 4.5% uncertainty that is primarily systematic. This measurement is slightly more precise than the single-lepton measurement at 13 TeV, despite the much smaller (almost a factor of 500!) integrated luminosity. The combination of the two measurements gives 67.5 ± 2.6 pb, corresponding to an uncertainty of just 3.9%.

The new ATLAS result is consistent with the SM prediction and with a measurement by the CMS collaboration, though with a total uncertainty reduced by almost a factor of two. It thus improves our understanding of the top-quark production at different centre-of-mass energies and allows an important test of the compatibility with predictions from different PDF sets (see figure 1). The result also provides a new measurement of high-x proton structure and shows a 5% reduction in the gluon PDF uncertainty in the region around x = 0.1, which is relevant for Higgs-boson production. Moreover, the measurement paves the way for the study of top-quark production in collisions involving heavy ions.

Further reading

ATLAS Collab. 2022 arXiv:2207.01354.
ATLAS Collab. 2020 *Phys. Lett. B* **810** 135797.
CMS Collab. 2022 *JHEP* **04** 144.

LHCb

LHCb digs deeper in CP-violating charm decays

To explain the large matter–antimatter asymmetry in the universe, the laws of nature need to be asymmetric under a combination of charge-conjugation (C) and parity (P) transformations. The Standard Model (SM) provides a mechanism for CP violation, but it is insufficient to explain the observed baryon asymmetry in the universe. Thus, searching for new sources of CP violation is important.

The non-invariance of the fundamental forces under CP transformation can lead to different rates between a particle and an antiparticle decay. The CP violation in the decay of a particle is quantified through the parameter A_{CP}, equal to the relative difference between the decay rate of the process and the decay rate of the CP-conjugated process. Three years ago, the LHCb collaboration reported the first observation of CP violation in the decay of charmed hadrons by measuring the difference between the time-integrated A_{CP} in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays, ΔA_{CP}. This difference was found to lie at the upper end of the SM expectation, prompting renewed interest in the charm-physics community. There is now an ongoing effort to understand whether this signal is consistent with the SM or a sign of new physics.

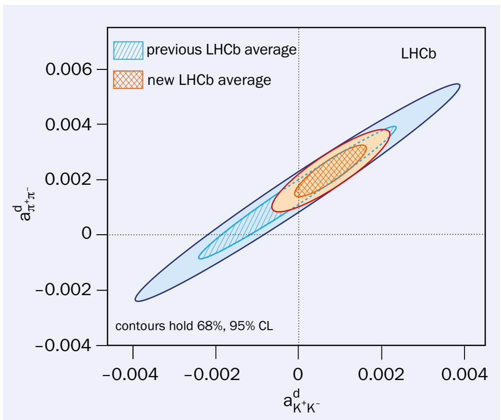


Fig. 1. *Preliminary plot of the contours showing the measurement of the direct CP asymmetry for the decays $D^0 \to \pi^+\pi^-$ versus $D^0 \to K^+K^-$. The new measurement of $a_d(D^0 \to K^+K^-)$ improves the precision significantly and leads to evidence that $a_d(D^0 \to \pi^+\pi^-)$ is different from zero. The inner (outer) ellipses show the 1 (2)σ contours.*

Source: LHCb-PAPER-2022-024.

At the 41st ICHEP conference in Bologna on 7 July (p18), the LHCb collaboration announced a new measurement of the individual time-integrated CP asymmetry in the $D^0 \to K^-K^+$ decay using the data sample collected during LHC Run 2. The measured value, $A_{CP}(K^-K^+) = [6.8 \pm 5.4\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4}$, is almost three times more precise than the previous LHCb determination obtained with Run 1 data. This was possible thanks not only to a larger data sample but also by including additional control channels $D_s^+ \to K^-K^+\pi^+$ and $D_s^+ \to K_S^0K^+$. Together with the previous control channels, $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to K_S^0\pi^+$, these decays allow the ▷ separation between tiny signals of CP asymmetries from the much larger bias due to the asymmetric meson production and instrumental effects.

The combination of the measured values with the previously obtained ones of $A_{CP}(K^-K^+)$ and ΔA_{CP} by LHCb allowed the determination of the direct CP asymmetries in the $D^0 \to \pi^-\pi^+$ and $D^0 \to K^-K^+$ decays: $[23.2 \pm 6.1] \times 10^{-4}$ and $[7.7 \pm 5.7] \times 10^{-4}$, respectively, with correlated uncertainties (ρ = 0.88). This is the first evidence of direct CP violation in an individual charm–hadron decay ($D^0 \to \pi^-\pi^+$), with a significance of 3.8σ.

The measured value is almost three times more precise than the previous LHCb determination obtained with Run 1 data

The sum of the two direct asymmetries, which is expected to be equal to 0 in the limit of s–d quark symmetry (called U-spin symmetry), is equal to $[30.8 \pm 11.4] \times 10^{-4}$. This corresponds to a departure from U-spin symmetry of 2.7σ. In addition, this result is essential to the theory community in the quest to clarify the theoretical picture of CP-violation in the charm system. Since the measurement is statistically limited, its precision will improve with the larger dataset collected during Run 3.

Further reading

LHCb Collab. 2022 LHCb-PAPER-2022-024.

ALICE

J/ψ photoproduction in hadronic PbPb collisions

Photon-induced reactions are regularly studied in ultra-peripheral nucleus–nucleus collisions (UPCs) at the LHC. In these collisions, the accelerated ions, which carry a strong electromagnetic field, pass by each other with an impact parameter (the distance between their centres) larger than the sum of their nuclear radii. Hadronic interactions between nuclei are therefore strongly suppressed. At LHC energies, the photoproduction of charmonium (a bound state of charm and anti-charm quarks) in UPCs is sensitive to the gluon distributions in nuclei over a wide low Bjorken-x range. In particular, in coherent interactions, the photon emitted by one of the nuclei couples to the other nucleus as a whole, leaving it intact, while a J/ψ meson is emitted with a characteristic low transverse momentum (p_T) of about 60 MeV, which is roughly of the order of the inverse of the nuclear radius.

Surprisingly, in 2016 ALICE measured an unexpectedly large yield of J/ψ mesons at very low p_T in peripheral, not ultra-peripheral, PbPb collisions at a centre-of-mass energy of 2.76 TeV. The excess with respect to expectations from hadronic J/ψ-meson production was interpreted as the first indication of coherent photoproduction of J/ψ mesons in PbPb collisions with nuclear overlap. This effect comes with many theoretical challenges. For instance, how can the coherence condition survive in the photon–nucleus interaction if the latter is broken up during the hadronic collision? Do only the non-interacting spectator nucleons participate in the coherent process? Can the photoproduced J/ψ meson be affected by interactions with the formed and fast-expanding quark–gluon plasma (QGP) created in nucleus–nucleus collisions? Recent theoretical developments on the subject are based on calculations for UPCs in which the J/ψ meson photoproduction-cross section is computed as the product of an effective photon flux and an effective photonuclear cross section for the process γPb → J/ψPb, with both terms usually modified to account for the nuclear overlap.

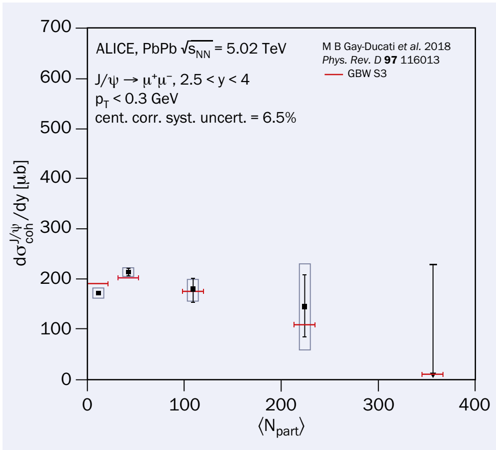


Fig. 1. *J/ψ photoproduction-cross section as a function of the mean number of nucleons participating in hadronic PbPb interactions, <N_{part}>, at a centre-of-mass energy of 5.02 TeV. The results are compared with theory predictions from a UPC-like calculation accounting for the nuclear overlap.*

Source: arXiv:2204.10684

The ALICE experiment has recently measured the coherently photoproduced J/ψ mesons in PbPb collisions at a centre-of-mass energy of 5.02 TeV, using the full Run 2 data sample. The measurement is performed at forward rapidity (2.5 < y < 4) in the dimuon decay channel. For the first time, a significant (> 5σ) coherently photoproduced J/ψ-meson signal is observed even in semi-central PbPb collisions. In figure 1, the coherently photoproduced J/ψ cross section is shown as a function of the mean number of nucleons participating in the hadronic interaction (<N_{part}>). In this representation, the most central head-on PbPb collisions correspond to large <N_{part}> values close to 400. The photoproduced J/ψ cross section does not exhibit a strong dependence on collision centrality (i.e. on the amount of nuclear overlap) within the current experimental precision. A UPC-like model (the red line in figure 1) reproduces the semi-central PbPb data if a modified photon flux and photonuclear cross section to account for the nuclear overlap are included.

To clarify the theory behind this experimental observation of coherent J/ψ photoproduction, the upcoming Run 3 data will be crucial in several aspects. ALICE expects to collect a much larger data sample, thereby measuring a statistically significant signal in most central collisions. At midrapidity, the larger data sample and the excellent momentum resolution of the detector will allow for p_T-differential cross-section measurements, which will shed light on the role of spectator nucleons for the coherence condition. By extending the coherently photoproduced J/ψ cross-section measurement towards most central PbPb collisions, ALICE will study the possible interaction of these charmonia with the QGP. Photoproduced J/ψ mesons could therefore turn out to be a completely new probe of the charmonium dissociation in the QGP.

Further reading

ALICE Collab. 2022 arXiv:2204.10684.

CERNCOURIER
VOLUME 62 NUMBER 5 SEPTEMBER/OCTOBER 2022
IOP Publishing

FIELD NOTES

Reports from events, conferences and meetings

41st International Conference on High-Energy Physics

High-energy interactions in Bologna

Involving around 1500 participants, 17 parallel sessions, 900 talks and 250 posters, ICHEP2022 (which took place in Bologna from 6 to 13 July) was a remarkable week of physics, technology and praxis. The energy and enthusiasm among the more than 1200 delegates who were able to attend in person was palpable. As the largest gathering of the community since the beginning of the pandemic – buoyed by the start of LHC Run 3 and the 10th anniversary of the Higgs-boson discovery – ICHEP2022 served as a powerful reminder of the importance of non-digital interactions.

ICHEP

Welcome back *Discussions at ICHEP showed the field to be in a fascinating period.*

Roberto Tenchini's (INFN Pisa) heroic conference summary began with a reminder: it is 10 years since ICHEP included a session titled "Standard Model", the theory being so successful that it now permeates most sessions. As an example, he highlighted cross-section predictions tested over 14 orders of magnitude at the LHC. Building on the Higgs@10 symposium at CERN on 4 July, the immense progress in understanding the properties and interactions of the Higgs boson (including legacy results with full Run 2 statistics in two papers by ATLAS and CMS published in *Nature* on 4 July) was centre stage. CERN Director-General Fabiola Gianotti gave a sweeping tour of the path to discovery and emphasised the connections between the Higgs boson and profound structural problems in the SM. Many speakers highlighted the concomitant role of the Higgs boson in exploring new physics, dashing notions that future precision measurements are "business as usual". Chiara Mariotti (INFN Torino) pointed out that only 3% of the total Higgs data expected at the LHC has been analysed so far.

Hot topics

Another hot electroweak topic was CDF's recent measurement of the mass of the W boson, as physicists try to understand what could cause it to lie so far from its prediction and from previous measurements. Andrea Rizzi (Pisa) confirmed that CMS is working hard on a W-mass analysis that will bring crucial information, on a time-scale to be decided. Patience is king

ICHEP2022 served as a powerful reminder of the importance of non-digital interactions

with such a complex analysis, he said: "we are really trying to do the measurement the way we want to do it."

CMS presented a total of 85 parallel talks and 28 posters, including new searches related to b-anomalies with taus, and the most precise measurement of $B_s \to \mu^+\mu^-$. Among new results presented by ATLAS in 71 parallel talks and 59 posters were the observation of a four charm-quark state consistent with one seen by LHCb, joint-polarisation measurements of the W and Z bosons, and measurements of the total proton–proton cross section and the ratio of the real vs imaginary parts of the elastic-scattering amplitude. ATLAS and CMS also updated participants on many searches for new particles, in particular leptoquarks. Among highlights were searches by ATLAS for events with displaced vertices, which could be caused by long-lived particles, and by CMS for resonances decaying to Higgs bosons and pairs of either photons or b quarks, which show interesting excesses. "*Se son rose fioriranno*!" said Tenchini.

The sigmas are rather higher for exotic hadrons. LHCb presented the discovery of a new strange pentaquark (with a minimum quark content ccuds) and two tetraquarks (one corresponding to the first doubly charged open-charm tetraquark with csud), taking the number of hadrons discovered at the LHC so far to well over 60, and introducing a new exotic-hadron naming scheme for "particle zoo 2.0" (p8). LHCb also reported the first evidence for direct CP violation in the charm system (p16) and a new precise measurement of the CKM angle γ. Vladimir Gligorov (LPNHE) described how, in addition to the flavour factories LHCb and Belle II, experiments including ATLAS, CMS, BESIII, NA62 and KOTO will be crucial to enable the next level of understanding in quark mixing. Despite no significant new results having been presented, the status of tests of lepton flavour universality (LFU) in B decays by LHCb generated lively discussions, while Toshinori Mori (Tokyo) described exciting prospects for LFU tests in charged-lepton flavour experiments, in particular MEG-II, which has just started operations at PSI, and the upcoming Mu2e and MUonE experiments.

Moving to leptons that are known to mix, neutrinos continue to play very important roles in understanding the smallest and largest scales, said Takaaki Kajita (Tokyo) via a link from the IUPAP Centennial Symposium taking place in parallel at ICTP Trieste. Status reports on DUNE, Hyper-K, JUNO, KM3NeT and SNB showed how these detectors will help constrain the still poorly-known PNMS matrix that describes leptonic mixing, while new results from NOvA and STEREO further reveal anomalous behaviour. Among the major open questions in neutrino physics summed-up by theorist Joachim Kopp (Mainz and CERN) were: how do neutrinos interact? What explains the oscillation anomalies? And how do supernova neutrinos oscillate?

Several plenary presentations showcased the increasing complementarity with astroparticle physics and cosmology, with the release of the first-science images from the James Webb Space Telescope on 12 July adding spice (p11). Multiband gravitational-wave astronomy across 12 or more orders of magnitude in ▷

frequency will bloom in the next decade, predicted Giovanni Andrea Prodi (Trento), while larger datasets and synchronisation of experiments offer a bright future in all messengers, said Gwenhael De Wasseige (Louvain): "We are just at the beginning of the story." The first results from the Lux-Zeplin experiment were presented, setting the tightest limits on spin-independent WIMP–nucleon cross-sections for WIMP masses above 9 GeV (p13), while the increasingly crowded plot showing limits from direct searches for axions illustrate the vibrancy and shifting focus of dark-matter research. Indeed, among several sessions devoted to the exploration of high-energy QCD in heavy-ion, proton–lead and proton–proton collisions, Andrea Dainese (INFN Padova) described how the LHC is not only a collider of nuclei but an (anti-)nuclei factory relevant for dark-matter searches.

The unique ability of theorists to put numerous results and experiments in perspective was on full display. We should all renew the enthusiasm that built the LHC, and be a lot more outspoken about the profound ideas we explore, urged Veronica Sanz (Sussex); after all, she said, "we are searching for something that we know should be somewhere." A timely talk by Gavin Salam (Oxford) summarised the latest understanding of QCD effects relevant to the muon g-2 and W-mass anomalies and also to future Higgs-boson measurements, concluding that, as we approach high precision, we should expect to be confronted by conceptual problems that we could, so far, ignore.

Accelerators (including a fast-paced summary of the HL-LHC niobium-tin magnet programme from Lucio Rossi), detectors (68 talks and posters revealing an increasingly holistic approach to detector design), computing (highlighting a period of rapid evolution thanks to optimisation, modernisation, machine-learning algorithms and increasing hardware diversity), industry, diversity and outreach were addressed in detail. A highly acclaimed outreach event in Bologna's Piazza Maggiore on the evening of 12 July

The unique ability of theorists to put numerous results and experiments in perspective was on full display

saw thousands of people listen to Fabiola Gianotti, Guido Tonelli, Gian Giudice and Antonio Zoccoli discuss the implications of the Higgs-boson discovery.

Only the narrowest snapshot of proceedings is possible in such a short report. What was abundantly clear from ICHEP2022 is that, following the discovery of the Higgs boson and as-yet no new particles beyond the SM, the field is in a fascinating and challenging period where confusion is more than matched by confidence that new physics must exist. The strategic direction of the field was addressed in two wide-ranging round-table discussions where laboratory directors and senior physicists answered questions submitted by participants. Much discussion concerned future colliders, and addressed a perceived worry in some quarters that the field is entering a period of decline. For anyone following the presentations at ICHEP2022, nothing could be further from the truth.

Matthew Chalmers *editor.*

13th International Particle Accelerator Conference

IPAC back in full force

The 13th International Particle Accelerator Conference (IPAC'22), which took place in Bangkok from 12 to 17 June, marked the return of an in-person event after two years due to the COVID pandemic. Hosted by the Synchrotron Light Research Institute, it was the first time that Thailand has hosted an IPAC conference, with around 800 scientists, engineers, technicians, students and industrial partners from 37 countries in attendance. The atmosphere was understandably electric. Energy and enthusiasm filled the rooms, as delegates had the chance to meet with colleagues and friends from around the world.

Synchrotron Light Research Institute

Face-to-face *IPAC'22 was a symbol of our return to normal scientific activities.*

The conference began with a blessing from princess Maha Chakri Sirindhorn, who attended the two opening plenary sessions. The scientific programme included excellent invited and contributed talks, as well as outstanding posters, highlighting scientific achievements worldwide. Among them were the precise measurement of the muon's anomalous magnetic dipole moment (g-2) at Fermilab, and the analysis at synchrotron light sources of soil samples obtained from near-Earth asteroid 162173 Ryugu by the Hayabusa2 space mission, which gave a glimpse into the origin of the Solar System.

In total, 88 invited and contributing talks on a wide array of particle accelerator-related topics were presented. These covered updates of new collider projects such as the Electron Ion Collider (EIC), proposed colliders (FCC, ILC and CEPC), as well as upgrade plans for existing facilities such as BEPCII and SuperKEKB, and new photo-source projects such as Nano-Terasu and Siam Photon Source II. A talk about the power efficiency of accelerators drew a lot of attention given increasing global concern about sustainability. Accelerator-based radiotherapy continued to be the main topic in the accelerator application category, with a special focus on designing an affordable and low-maintenance linac for deployment in low- and middle-income countries and other challenging environments (*CERN Courier* January/February 2022 p30).

Raffaella Geometrante (KYMA) hosted a popular industry session on accelerator technology. Completely revamped from past editions, its aim was to substantially improve the dynamics between laboratories and industry, while also addressing other topics on accelerator innovations and disruptive technologies.

An engaging outreach talk "Looking into the past with photons" highlighted how synchrotron radiation has become an indispensable tool in archaeological and paleontological research, enabling investigations of the relationship between past civilisations in different corners of the world. A reception held during an evening boat cruise along the Chao Phraya River took participants past majestic palaces and historic temples against a backdrop of traditional Thai music and performances.

IPAC'22 was a successful and memorable conference, seen as a symbol of our return to normal scientific activities and face-to-face interaction. It was also one of the most difficult IPAC conferences to organise – prohibiting or impeding participation from several regions, particularly China and Taiwan, as the world begins to recover from the most prevalent health-related crisis in a century. It was mentioned in the opening session that many breakthroughs in combating the coronavirus pandemic were achieved with the use of particle accelerators: the molecular structure of the virus, which is essential information for subsequent rational drug design, was solved at synchrotron light sources.

Prapong Klysubun *SLRI,* **Hitoshi Tanaka** *RIKEN and* **Porntip Sudmuang** *SLRI.*

FCC Week 2022

A word from FCC Week

More than 500 participants from over 30 countries attended the annual meeting of the Future Circular Collider (FCC) collaboration, which is pursuing a feasibility study for a visionary post-LHC research infrastructure at CERN. Organised as a hybrid event at Sorbonne University in Paris from 30 May to 3 June, the event demonstrated the significant recent progress en route to the completion of the feasibility study in 2025, and the technological and scientific opportunities on offer.

In their welcome talks, Ursula Bassler (CNRS) and Philippe Chomaz (CEA), chair of the FCC collaboration board, stressed France's long-standing participation in CERN and reaffirmed the support of French physicists and laboratories in the different areas of the FCC project. CERN Director-General Fabiola Gianotti noted that the electron–positron stage, FCC-ee, could begin operations within a few years of the end of the HL-LHC – a crucial step in keeping the community engaged across different generations – while the full FCC programme would offer 100 years of trail-blazing physics at both the energy and intensity frontiers. Beyond its outstanding scientific case, FCC requires coordinated R&D in many domains, such as instrumentation and engineering, raising opportunities for young generations to contribute with fresh ideas. These messages echoed those in other opening talks, in particular by Jean-Eric Paquet, director for research and innovation at the European Commission, who highlighted FCC's role as a world-scale research infrastructure that will allow Europe to maintain its leadership in fundamental research.


FCC Week

Accelerating discussions *Participants from diverse fields attended the Paris event.*

A new era

Ten years after the discovery of the Higgs boson, the ATLAS and CMS collaborations continue to establish its properties and interactions with other particles. The discovery of the Higgs boson completes the Standard Model but leaves many questions unanswered; a new era of exploration has opened that requires a blend of large leaps in precision, sensitivity and eventually energy. Theorist Christophe Grojean (DESY) described how the diverse FCC research programme (*CERN Courier* May/June 2022 p23) offers an extensive set of measurements at the electroweak scale, the widest exploratory potential for new physics, and the potential to address outstanding questions such as the nature of dark matter and the origin of the cosmic matter–antimatter asymmetry.

In recent months, teams from CERN have worked closely with external consultants and CERN's host states to develop a new FCC layout and placement scenario (*CERN Courier* May/June 2022 p27). Key elements include the effective use of the European electricity grid, the launch of heat-recovery projects, cooling, agriculture and industrial use – as well as cutting-edge data connections to rural areas. Parallel sessions at FCC Week focused on the design of FCC-ee, which offers a high-luminosity Higgs and electroweak factory. Tor Raubenheimer (SLAC) showed it to be the most efficient lepton collider for energies up to the top-quark mass threshold and highlighted its complementarity to a future FCC-hh. Profiting from the FCC-ee's high technological readiness, ongoing R&D efforts aim to maximise the efficiency and performance while optimising its environmental impact and operational costs. Many sessions were dedicated to detector development, where the breadth of new results showed that the FCC-ee is much more than a scaled-up version of LEP. It would offer unprecedented precision on Higgs couplings, electroweak and flavour variables, the top-quark mass, and the strong coupling constant, with ample discovery potential for feebly interacting particles. Participants also heard about the FCC-ee's unique ability in ultra-precise centre-of-mass energy measurements, and the need for new beam-stabilisation and feedback systems.

High-temperature superconductor (HTS) magnets are among key FCC-ee technologies under consideration for improved energy efficiency, also offering significant potential societal impact. They could be deployed in the FCC-ee final-focus sections, around the positron-production target, and even in the collider arcs. Another major focus is ensuring that the 92 km-circumference machine's arc cells are effective, reliable and easy to maintain, with a complete arc half-cell mockup planned to be constructed by 2025. The exploration of existing and alternative technologies for FCC-ee is supported by two recently approved projects: the Swiss accelerator R&D programme CHART, and the EU-funded FCCIS design study. The online software requirements for FCC-ee are dominated by an expected physics event rate of ~200 kHz when running at the Z pole. Trigger and data acquisition systems sustaining comparable data rates are already being developed for the HL-LHC, serving as powerful starting points for FCC-ee.

Looking to the future

Finally, participants reviewed ongoing activities toward FCC-hh, an energy-frontier 100 TeV proton–proton collider to follow FCC-ee by exploiting the same infrastructure. FCC-hh studies complement those for FCC-ee, including the organisation of CERN's high-field magnet R&D programme and the work of the FCC global conductor-development programme. In addition, alternative HTS technologies that could reach higher magnetic fields and higher energies while reducing energy consumption are being explored for FCC's energy-frontier stage. The challenges of building and operating this new infrastructure and the benefits that can be expected for society and European industry were also discussed during a public event under the auspices of the French Physical Society.

The FCC programme builds on the large, stable global community that has existed for more than 30 years at CERN and in other laboratories worldwide. The results presented during FCC Week 2022 and ongoing R&D activities will inspire generations of students to learn and grow. Participants from diverse fields and the high number of junior researchers who joined the meeting underline the attractiveness of the project. Robust international participation and long-term commitment to deliver ambitious projects are key for the next steps in the FCC feasibility study.

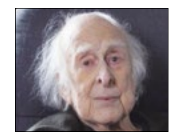
Panos Charitos *CERN.*

Higgs@10: Scientific Symposium

A(nother) day to remember

On the morning of 4 July 2012, Joe Incandela for CMS and Fabiola Gianotti for ATLAS presented results confirming the observation of a new elementary particle. Precisely 10 years later, with somewhat shorter queues, around 500 people packed into the same room to celebrate this momentous event in the history of particle physics. Many hundreds more connected remotely, while similar celebrations were held around the globe. The symposium marking the 10th anniversary of the Higgs-boson discovery was a veritable Higgs feast that immersed participants in the history of the discovery, the latest results from ATLAS and CMS in understanding the Higgs-boson's properties and interactions, and the potential of future precision measurements at the LHC and beyond. For those who were unable to be there, the *Courier* provides a bite-sized digest.

"I am an opportunist, in one way an extremely successful one. Weinberg and I were working along similar lines with similar attitudes. I wish you well for your celebrations and regret that I can't be with you in person."



Peter Higgs winner of the 2013 Nobel Prize in Physics.

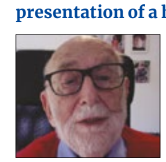
"It was an overwhelming time for us. It took time to understand what had happened. I especially remember the excitement among the young researchers."
Rolf Heuer former CERN Director-General.

"It took 14 years to build the LHC. At one point we had 1000 dipoles, each costing a million Swiss francs, stored on the surface, throughout rain and snow."
Lyn Evans former LHC project director.

"The first two years of measuring Standard Model physics were essential to give us confidence in the readiness of the two experiments to search for new physics."
Peter Jenni founding ATLAS spokesperson.

"A key question for CMS was: can tracking be done in a congested environment with just a few points, albeit precise ones? It was a huge achievement requiring more than 200 m² of active silicon."
Michel Della Negra founding CMS spokesperson.

"I remember on 4 July 2012 a magnificent presentation of a historical discovery. I would also like to celebrate the life of Robert Brout, a great physicist and important man."



François Englert winner of the 2013 Nobel Prize in Physics.

"The gist of the theory behind the Higgs boson would easily compete with the most far-fetched conspiracy theory, yet it seems nature chose it."
Eliezer Rabinovici president of the CERN Council.

"The structure of the vacuum is intimately connected to how the Higgs boson interacts with itself. To probe this phenomenon at the LHC we can study the production of Higgs-boson pairs."
André David CMS experimentalist (CERN).

"Collaboration between experiment and theory is even more necessary now to find any hints for BSM physics."
Reisaburo Tanaka ATLAS experimentalist (Université Paris-Saclay).

"Precision Higgs physics is a telescope to high-scale physics, so I'm looking forward to the next 10 years of discovery."

Sally Dawson theorist (BNL).

"Theory accuracy will be even more important to make the best of the HL-LHC data, especially in the case in which no evidence of new physics will show up… This is also crucial for the Monte Carlo tools used in the analyses."
Massimiliano Grazzini theorist (University of Zurich).

"After 10 years we've measured the five main production and five major decay mechanisms of the Higgs boson."

Kerstin Tackmann ATLAS experimentalist (DESY).

"What we know so far – Mass: known to 0.11%. Width: closing in on SM value of $3.2^{+2.5}_{-1.7}$ MeV (plus evidence of off-shell Higgs production). Spin 0: spin 1 & 2 excluded at 99.9% CL. CP structure: in accordance with SM CP-even hypotheses."
Marco Delmastro ATLAS experimentalist (CNRS/IN2P3 LAPP).

"We have learned much about the 125 GeV Higgs boson since its discovery. The LHC Run 3 starts tomorrow: ready for the next decade of Higgs-boson exploration!"
Adinda de Wit CMS experimentalist (University of Zurich).

"The Higgs boson is linked to profound structural problems in the Standard Model. It is therefore an extraordinary discovery tool that calls for a broad experimental programme at the LHC and beyond."

Fabiola Gianotti CERN Director-General.

"Elusive non-resonant pairs of Higgs bosons are the prime experimental signature of the Higgs-boson self-coupling. We are all eager to analyse Run 3 data to further probe HH events!"
Arnaud Ferrari ATLAS experimentalist (Uppsala University).

"New physics can affect differently the different fermion generations. We have to precisely measure the couplings if we want to understand the Higgs boson's nature."
Andrea Marini CMS experimentalist (CERN).

"From its potential invisible, forbidden, and exotic decays to the possible existence of scalar siblings, the Higgs boson plays a fundamental role in searches for physics beyond the Standard Model."
Roberto Salerno CMS experimentalist (CNRS/IN2P3 – LLR & École polytechnique).

"An incredible collaborative effort has brought us this far. But there is much more to come, especially during Long Shutdown 3, with HL-LHC paving the way from Run 3 to ultimate performance. Interesting times ahead to say the least!"

Mike Lamont CERN director for accelerators and technology.

"The hard work and creativity in reconstruction and analysis techniques are already evident since the last round of projections. Imagine what we can do in the next 20 years!"
Elizabeth Brost ATLAS experimentalist (BNL).

"The Higgs is the first really new elementary particle we've seen. We need to study it to death!"
Nima Arkani-Hamed theorist (IAS).

HiggsDiscovery@10

UK event celebrates Higgs@10

Marking 10 years since the discovery of the Higgs boson, a two-day workshop held at the University of Birmingham on 30 June and 1 July brought together ATLAS and CMS physicists who were involved in the discovery and subsequent characterisation of the Higgs boson. Around 75 physicists, in addition to members of the public who attended a colloquium, celebrated this momentous discovery together with PhD students, early-career researchers and members of IOP's history of physics group. In an informal atmosphere, participants recalled and gave insights on what had taken place, spicing it with personal stories that placed the human dimension of science under the spotlight.

K Nikolopoulos

Higgstory *Participants of the HiggsDiscovery@10 symposium in Birmingham.*

The story of the Higgs-boson search was traced from the times of LEP and the Tevatron. Participants were reminded of the uncertainty and excitement during the final days of LEP: the hints of an excess of events at around 115 GeV and the ensuing controversy surrounding the decision to either stop the machine or extend its data-taking further. For the Tevatron, the focus was more on the relentless race against time until the LHC could provide an overwhelming dataset. It was considered plausible that the Tevatron could observe the Higgs boson first, leading CERN to delay a scheduled break in LHC data-taking following its 2011 run.

The timeline of the design, construction and commissioning of the LHC experiments was presented, with a particular focus on the excellent performance achieved by ATLAS and CMS since the beginning of Run 1. The parallel role of theory and the collaboration among theorists and experimentalists was also discussed. Speakers from the experiments involved in the Higgs-discovery analyses provided personal perspectives on the events leading up to the 4 July 2012 announcement.

With his unique perspective, former CERN Director-General Chris Llewellyn-Smith described the early discussions and approval of the LHC project during a well-attended public symposium. He recalled his discussions with former UK prime minister Margaret Thatcher, the role of the ill-fated US Superconducting Super Collider and the "byzantine politics" that led to the LHC's approval in 1994. Most importantly, he emphasised that the LHC was not inevitable: scientists had to fight to secure funding and bring it to reality. Former ATLAS spokesperson David Charlton reflected on the preparation of the experiments, the LHC startup in 2008 and subsequent magnet problems that delayed the physics runs until 2010, noting the excellent performance of the machine and detectors that enabled the discovery to be made much earlier than expected.

The workshop could not have been complete without a discussion on what happened after the discovery. Precision measurements of the Higgs-boson couplings, observation of new decay and production modes, as well as the search for Higgs-boson pair-production were described, always with a focus on the challenges that needed to be overcome. The workshop closed with a look to the future, both in terms of experimental prospects of the High-Luminosity LHC and theory.

C Anastopoulos *University of Sheffield*, **K Nikolopoulos** *University of Birmingham* and **N Rompotis** *University of Liverpool*.

Detectors

Flying high with silicon photomultipliers

The ever maturing technology of silicon photomultipliers (SiPMs) has a range of advantages over traditional photomultiplier tubes (PMTs). As such, SiPMs are quickly replacing PMTs in a range of physics experiments. The technology is already included in the LHCb SciFi tracker and is foreseen to be used in CMS's HGCAL, as well as in detectors at proposed future colliders. For these applications the important advantages of SiPMs over PMTs are their higher photo-detection efficiencies (by roughly a factor of two), their lower operating voltage (30–70 V compared to kV's) and their small size, which allows them to be integrated in compact calorimeters. For space-based instruments – such as the POLAR-2 gamma-ray mission, which aims to use 6400 SiPM channels (see image) – a further advantage is the lack of a glass window, which gives SiPMs the mechanical robustness required during launch. There is, however, a disadvantage with SiPMs: dark current, which flows when the device is not illuminated and is greatly aggravated after exposure to radiation.

University of Geneva

Compact *A SiPM array inside a probe station for the future POLAR-2 mission, which aims to study gamma-ray bursts in detail.*

In order to strengthen the community and make progress on this technological issue, a dedicated workshop was held at CERN in a hybrid format from 25 to 29 April. Organised by the University of Geneva and funded by the Swiss National Science Foundation, the event attracted around 100 experts from academia and industry. The participants included experts in silicon radiation damage from the University of Hamburg who showed both the complexity of the problem and the need for further studies. Whereas the non-ionising energy loss concept used to predict radiation damage in silicon is linearly correlated to the degradation of semiconductor devices in a radiation field, this appears to be violated for SiPMs. Instead, dedicated measurements for different types of SiPMs in a variety of radiation fields are required to understand the types of damage and their consequences on the SiPMs' performance. Several such measurements, performed using both proton and neutron beams, were presented at the April workshop, while plans were made to coordinate such efforts in the future, for example by performing tests of one type of SiPMs at different facilities followed by identical analysis of the irradiated samples. In addition, an online platform to discuss upcoming results was established.

The damage sustained by radiation manifests itself mainly in the form of an increased dark current. As presented at the workshop, this increase can cause a vicious cycle because the increased current can cause self-heating, which further increases the highly temperature-dependent dark current. These issues are of great importance for future space missions as they influence the power budget, causing the scientific performance to degrade over time. Data from the first SiPM-based in-orbit detectors, such as the SIRI mission by the US Naval Research Lab, the Chinese-led GECAM and GRID detectors, and the Japanese–Czech GRBAlpha payload, were presented. It is clear that although SiPMs have advantages over PMTs, the radiation, which is highly dependent on the satellite's orbit, can cause a significant degradation in performance that limits low-earth orbit missions to several years in space. Based on these results, a future Moon mission has decided against the use of SiPMs and reverted to PMTs.

Solutions to radiation damage in SiPMs were discussed at length

Solutions to radiation damage in SiPMs were also discussed at length. These are mainly in the form of speeding up the annealing of the damage by exposing SiPMs to hotter environments for short periods. Additionally, cooling of the SiPM during data taking will not only decrease the dark current directly, but could also reduce the radiation damage itself, although further research on this topic is required.

Overall, the workshop indicated that significant further studies are required to predict the impact of radiation damage on future experiments.

Merlin Kole *University of Geneva*.

International Conference on Accelerators and Sustainable Dvelopment

Accelerating a better world

Tens of thousands of accelerators around the world help create radiopharmaceuticals, treat cancer, preserve food, monitor the environment, strengthen materials, understand fundamental physics, study the past and even disclose crimes.

A first of its kind international conference, Accelerators for Research and Sustainable Development: From Good Practices Towards Socioeconomic Impact was organised by the International Atomic Energy Agency (IAEA) at its headquarters in Vienna from 23 to 27 May. It was held as a hybrid event attended by around 500 scientists from 72 IAEA member states. While focusing mainly on applications of accelerator science and technology, the conference was geared towards accelerator technologists, operators, users, entrepreneurs and other stakeholders involved in applications of accelerator technologies as well as policy makers and regulators.

"The far-reaching capabilities of accelerator technology help countries progress towards sustainable development," said IAEA director general Rafael Mariano Grossi in his opening address. "IAEA's work with accelerators helps to fulfil a core part of its 'Atoms for Peace and Development' mandate." He also highlighted how accelerator technology plays a critical role in two IAEA initiatives launched over the past year: Rays of Hope, aimed at improving access to radiotherapy and cancer care in low- and middle-income countries, and NUTEC plastics, supporting countries in addressing plastic waste issues in the ocean and on land. Finally, he described IAEA plans to establish an accelerator of its own: a state-of-the-art ion-beam facility in Seibersdorf, Austria that will support research and help educate and train scientists.

IAEA

Hub *The IAEA serves as a hub for the diverse use of accelerator technologies.*

The conference included sessions dedicated to case studies demonstrating socioeconomic impact as well as best practices in effective management, safe operation, and the sustainability of present and future accelerator facilities. It showcased the rich diversity in types of accelerators – from large-scale synchrotrons and spallation neutron sources, or medical cyclotrons and e-beam irradiators used for industrial applications, to small-scale electrostatic accelerators and compact-accelerator-based neutron sources – and included updates in emerging accelerator technologies, such as laser-driven neutron and X-ray sources and their future applications. Six plenary sessions featuring 16 keynote talks captured the state of the art in various application domains, accompanied by 16 parallel and two poster sessions by young researchers.

During the summary and highlights session, important developments and future trends were presented:

- Large-scale accelerator facilities under development across the world – notably FAIR in Germany, SPIRAL-2 in France, FRIB in the US, RIBF in Japan, HIAF in China, RAON in Korea, DERICA in Russia and MYRRHA in Belgium – boost the development of advanced accelerator technologies, which are expected to deliver high-impact socio-economical applications. Substantial interdisciplinary research programmes are foreseen from their beginning, and the IAEA could play an important role by strengthening the links and cooperation between all parties.
- Recent technology developments in Compact-Accelerator Neutron Sources (CANS) or High-Power CANS (HiCANS) are very promising. Among many projects, ERANS at RIKEN in Japan aims to realise a low-cost CANS capable of providing 10^{12} n/s for applications in materials research and ERANS-III a transportable CANS for testing the structure of bridges. On the HiCANS front, the French SONATE project aims to reach neutron flux levels comparable to the ageing fleet of low- and medium-power research reactors at least for some applications.
- CANS technology is promising for tools to fight cancer, for example via the boron neutron capture therapy (BNCT) method. Japan leads the way by operating or constructing 10 such in-hospital-based facilities, with only a few other countries, e.g. Finland, considering similar technologies. Recent developments suggest that accelerator-based BNCT treatments will soon be more acceptable. IAEA could play an important coordinating role, and as a technology bridge to developing countries to enable more widespread adoption.

CERNCOURIER
Volume 62 Number 5 September/October 2022
IOP Publishing

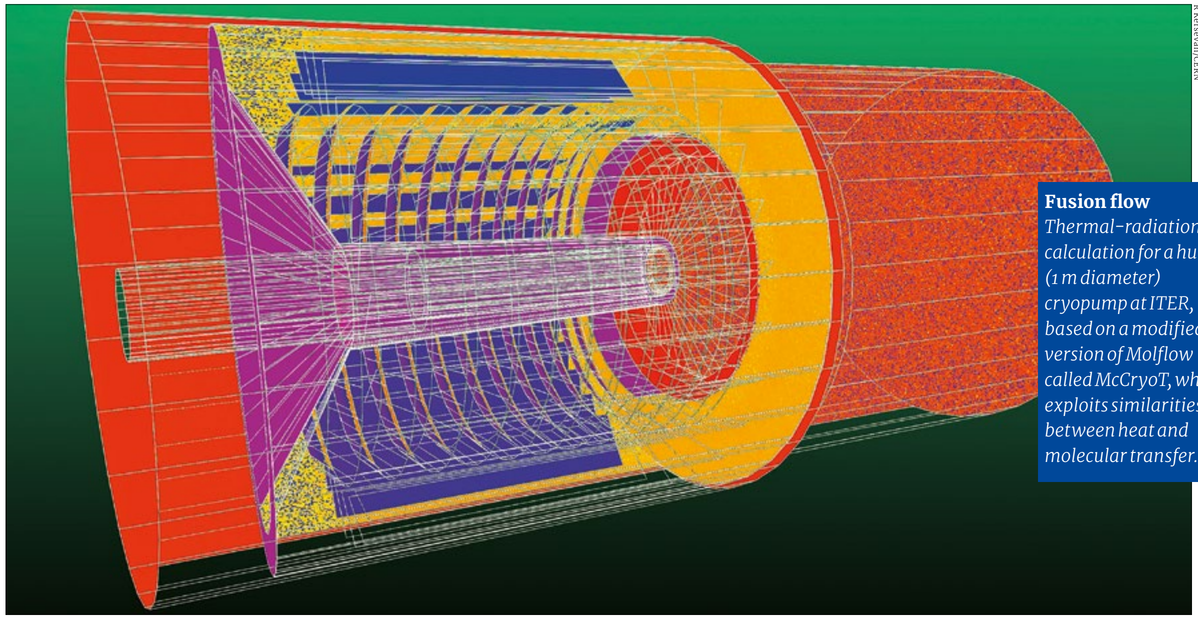
- The role of accelerators in preserving cultural heritage objects and in detecting forgeries is becoming more vital, especially in countries that do not have the required capabilities. Ion-beam analysis and accelerator mass-spectrometry techniques are of particular relevance, and, again, the IAEA can assist by coordinating actions to disseminate knowledge, educating the relevant communities and possibly centralising the demands for expertise.
- The IAEA could simplify the supply of accelerator technologies between the different member states, enabling the installation and operation of facilities in low- and middle-income countries, for example by structuring the scientific and technical accelerators communities, and educating young researchers and technicians via dedicated training schools.
- One of IAEA's projects is to establish a state-of-the-art ion beam facility in Austria. This will enable applied research and provision of analytical services, as well as help educate and train scientists on the diverse applications of ion beams (including the production of secondary particles such as neutrons) and will enhance collaborations with both developed and developing countries.
- Ion-beam analysis (IBA) together with accelerator-mass spectroscopy (AMS) techniques are unique, reliable and cost-effective for environmental monitoring and climate-change-related studies, for example in characterising environmental samples, and investigating isotope ratio studies for chronology and environmental remediation AMS facilities with smaller footprints have increased their distribution worldwide, resulting in accessible and affordable measurements for interdisciplinary research, while other IBA techniques offer efficient analytical methods to characterise the chemical composition of particles from air pollution.
- Materials science and accelerators are now moving ahead hand-in-hand, from characterisation to modification of technologically important materials including semiconductors, nano-materials, materials for emerging quantum technologies and materials relevant to energy production. Testing materials with accelerator-based light and heavy-ion beams remains a unique possibility in the case of fusion materials and offers much faster radiation-damage studies than irradiation facilities at research reactors. Equally important is the accelerator-assisted creation of gaseous products such as hydrogen and helium that allows the testing of radiation resilience in unmoderated neutron systems such as fast fission and fusion reactors.
- New developments in electron-beam accelerators for industrial applications were also mentioned, in particular their application to pollution control. E-beam system technologies are also widely employed in food safety. Reducing spoilage by extending the shelf-life of foods and reducing the potential for pathogens in and on foods will become major drivers for the adoption of these technologies, for which a deeper understanding of the related effects and resistance against radiation is mandatory.

Accelerator technologies evolve very quickly, presenting a challenge for regulatory bodies to authorise and inspect accelerator facilities and activities. This conference demonstrated that thanks to recent technological breakthroughs in accelerator technology and associated instrumentation, accelerators are becoming an equally attractive alternative to other sources of ionising radiation such as gamma irradiators or research reactors, among other conventional techniques. Based on the success of this conference, it is expected that the IAEA will start a new series of accelerator-community gatherings periodically from now on every two to three years.

Sotirios Charisopoulos, Danas Ridikas, Celina Horak *and* **Valeriia Starovoitova** *IAEA.*

TRACING MOLECULES AT THE VACUUM FRONTIER

CERN's Molflow software has become the de-facto industry standard for ultra-high-vacuum simulations. Roberto Kersevan and Marton Ady describe how it is now enabling space research and other branches of science to develop their own applications.



R Kersevan/CERN

Fusion flow
Thermal-radiation calculation for a huge (1 m diameter) cryopump at ITER, based on a modified version of Molflow called McCryoT, which exploits similarities between heat and molecular transfer.

In particle accelerators, large vacuum systems guarantee that the beams travel as freely as possible. Despite being one 25-trillionth the density of Earth's atmosphere, however, a tiny concentration of gas molecules remain. These pose a problem: their collisions with accelerated particles reduce the beam lifetime and induce instabilities. It is therefore vital, from the early design stage, to plan efficient vacuum systems and predict residual pressure profiles.

Surprisingly, it is almost impossible to find commercial software that can carry out the underlying vacuum calculations. Since the background pressure in accelerators (of the order 10^{-9}–10^{-12} mbar) is so low, molecules rarely collide with one other and thus the results of codes based on computational fluid dynamics aren't valid. Although workarounds exist (solving vacuum equations analytically, modelling a vacuum system as an electrical circuit, or taking advantage of similarities between ultra-high-vacuum and thermal radiation), a CERN-developed simulator "Molflow", for molecular flow, has become the de-facto industry standard for ultra-high-vacuum simulations.

Instead of trying to analytically solve the surprisingly difficult gas behaviour over a large system in one step, Molflow is based on the so-called test-particle Monte Carlo method. In a nutshell: if the geometry is known, a single test particle is created at a gas source and "bounced" through the system until it reaches a pump. Then, repeating this millions of times, with each bounce happening in a random direction, just like in the real world, the program can calculate the hit-density anywhere, from which the pressure is obtained.

The idea for Molflow emerged in 1988 when the author (RK) visited CERN to discuss the design of the Elettra light source with CERN vacuum experts (see "From CERN to Elettra, ESRF, ITER and back" panel). Back then, few people could have foreseen the numerous applications outside particle physics that it would have. Today, Molflow is used in applications ranging from chip manufacturing to the exploration of the Martian surface, with more than 1000 users worldwide and many more downloads from the dedicated website.

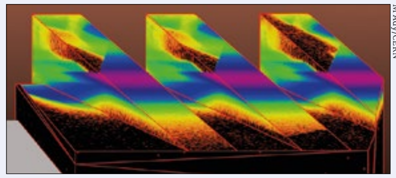
THE AUTHORS
Roberto Kersevan *and* **Marton Ady** *CERN.*

CERNCOURIER
VOLUME 62 NUMBER 5 SEPTEMBER/OCTOBER 2022
IOP Publishing

From CERN to Elettra, ESRF, ITER and back

Molflow emerged in 1988 during a visit to CERN from its original author (RK), who was working at the Elettra light source in Trieste at the time. CERN vacuum expert Alberto Pace showed him a computer code written in Fortran that enabled the trajectories of particles to be calculated, via a technique called ray tracing. On returning to Trieste, and realising that the CERN code couldn't be run there due to hardware and software incompatibilities, RK decided to rewrite it from scratch. Three years later the code was formally released. Once more, credit must be given to CERN for having been the birthplace of new ideas for other laboratories to develop their own applications.

Molflow was originally written in Turbo Pascal, had (black and white) graphics, and visualised geometries in 3D – even allowing basic geometry editing and pressure plots. While today such features are found in every simulator, at the time the code stood out and was used in the design of several accelerator facilities, including the Diamond Light Source, Spallation Neutron Source, Elettra, Alba and others – as well as for the analysis of a gas-jet experiment for the PANDA experiment at GSI Darmstadt. That said, the early code had its limitations. For example, the upper limit of user memory (640 kB for MS-DOS) significantly limited the number of polygons used to describe the geometry, and it was single-processor.



M Ady/CERN

Synchrotron simulation *Molflow simulation of the synchrotron-radiation power density on a "crotch absorber", which protects downstream UHV vacuum chambers in a storage ring.*

In 2007 the original code was given a new lease of life at the European Synchrotron Radiation Facility in Grenoble, where RK had moved as head of the vacuum group. Ported to C++, multi-processor capability was added, which is particularly suitable for Monte Carlo calculations: if you have eight CPU cores, for example, you can trace eight molecules at the same time. OpenGL (Open Graphics Library) acceleration made the visualisation very fast even for large structures, allowing the usual camera controls of CAD editors to be added. Between 2009 and 2011 Molflow was used at ITER, again following its original author, for the design and analysis of vacuum components for the international tokamak project.

In 2012 the project was resumed at CERN, where RK had arrived the previous year. From here, the focus was on expanding the physics and applications: ray-tracing terms like "hit density" and "capture probability" were replaced with real-world quantities such as pressure and pumping speed. To publish the code within the group, a website was created with downloads, tutorial videos and a user forum. Later that year, a sister code "Synrad" for synchrotron-radiation calculations, also written in Trieste in the 1990s, was ported to the modern environment. The two codes could, for the first time, be used as a package: first, a synchrotron-radiation simulation could determine where light hits a vacuum chamber, then the results could be imported to a subsequent vacuum simulation to trace the gas desorbed from the chamber walls. This is the so-called photon-stimulated desorption effect, which is a major hindrance to many accelerators, including the LHC.

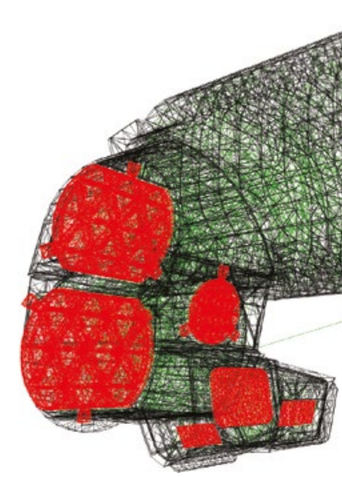
Molflow and Synrad have been downloaded more than 1000 times in the past year alone, and anonymous user metrics hint at around 500 users who launch it at least once per month. The code is used by far the most in China, followed by the US, Germany and Japan. Switzerland, including users at CERN, places only fifth. Since 2018, the roughly 35,000-line code has been available open-source and, although originally written for Windows, it is now available for other operating systems, including the new ARM-based Macs and several versions of Linux.

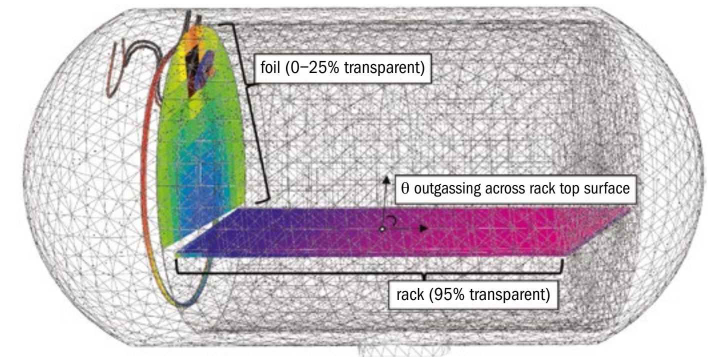
Molflow in space

While at CERN we naturally associate ultra-high vacuum with particle accelerators, there is another domain where operating pressures are extremely low: space. In 2017, after first meeting at a conference, a group from German satellite manufacturer OHB visited the CERN vacuum group, interested to see our chemistry lab and the cleaning process applied to vacuum components. We also demoed Molflow for vacuum simulations. It turned out that they were actively looking for a modelling tool that could simulate specific molecular-contamination transport phenomena for their satellites, since the industrial code they were using had very limited capabilities and was not open-source.

A high-quality, clean mirror for a space telescope, for example, must spend up to two weeks encapsulated in the closed fairing from launch until it is deployed in orbit. During this time, without careful prediction and mitigation, certain volatile compounds (such as adhesive used on heating elements) present within the spacecraft can find their way to and become deposited on optical elements, reducing their reflectivity and performance. It is therefore necessary to calculate the probability that molecules migrate from a certain location, through several bounces, and end up on optical components. Whereas this is straightforward when all simulation parameters are static, adding chemical processes and molecule accumulation on surfaces required custom development. Even though Molflow could not handle these processes "out of the box", the OHB team was able to use it as a basis that could be built on, saving the effort of creating the graphical user interface and the ray-tracing parts from scratch. With the help of CERN's knowledge-transfer team, a collaboration was established with the Technical University of Munich: a "fork" in the code was created; new physical processes specific to their application were added; and the code was also adapted to run on computer clusters. The work was made publicly available in 2018, when Molflow became open source.

One year later, the Contamination Control Engineering (CCE) team from NASA's Jet Propulsion Laboratory (JPL) in California reached out to CERN in the context of its three-stage Mars 2020 mission. The Mars 2020 Perseverance Rover, built to search for signs of ancient microbial life, successfully landed on the Martian surface in February 2021 and has collected and cached samples in sealed tubes. A second mission plans to retrieve the cache canister and launch it into Mars orbit, while a third would locate and capture the orbital sample and return it to Earth. Each spacecraft experiences and contributes to its own contamination environment through thruster operations, material outgassing and other processes. JPL's CCE team performs





Molflow in space *Above: a vacuum-chamber simulation performed for NASA's Mars 2020 mission. Left: designing a decontamination solution for NASA's SPHEREx mission, due for launch in 2024. (Credit: JPL Contamination Control Engineering)*

the identification, quantification and mitigation of such contaminants, from the concept-generation to the end-of-mission phase. Key to this effort is the computational physics modelling of contaminant transport from materials outgassing, venting, leakage and thruster plume effects.

Contamination consists of two types: molecular (thin-film deposition effects) and particulate (producing obscuration, optical scatter, erosion or mechanical damage). Both can lead to degradation of optical properties and spurious chemical composition measurements. As more sensitive space missions are proposed and built – particularly those that aim to detect life – understanding and controlling outgassing properties requires novel approaches to operating thermal vacuum chambers.

Just like accelerator components, most spacecraft hardware undergoes long-duration vacuum baking at relatively high temperatures to reduce outgassing. Outgassing rates are verified with quartz crystal microbalances (QCMs), rather than vacuum gauges as used at CERN. These probes measure the resonance frequency of oscillation, which is affected by the accumulation of adsorbed molecules, and are very sensitive: a 1 ng deposition on 1 cm^2 of surface de-tunes the resonance frequency by 2 Hz. By performing free-molecular transport simulations in the vacuum-chamber test environment, measurements by the QCMs can be translated to outgassing rates of the sources, which are located some distance from the probes. For these calculations, JPL currently uses both Monte Carlo schemes (via Molflow) and "view factor matrix" calculations (through in-house solvers). During one successful Molflow application (see "Molflow in space" image, top) a vacuum chamber with a heated inner shroud was simulated, and optimisation of the chamber geometry resulted in a factor-40 increase of transmission to the QCMs over the baseline configuration.

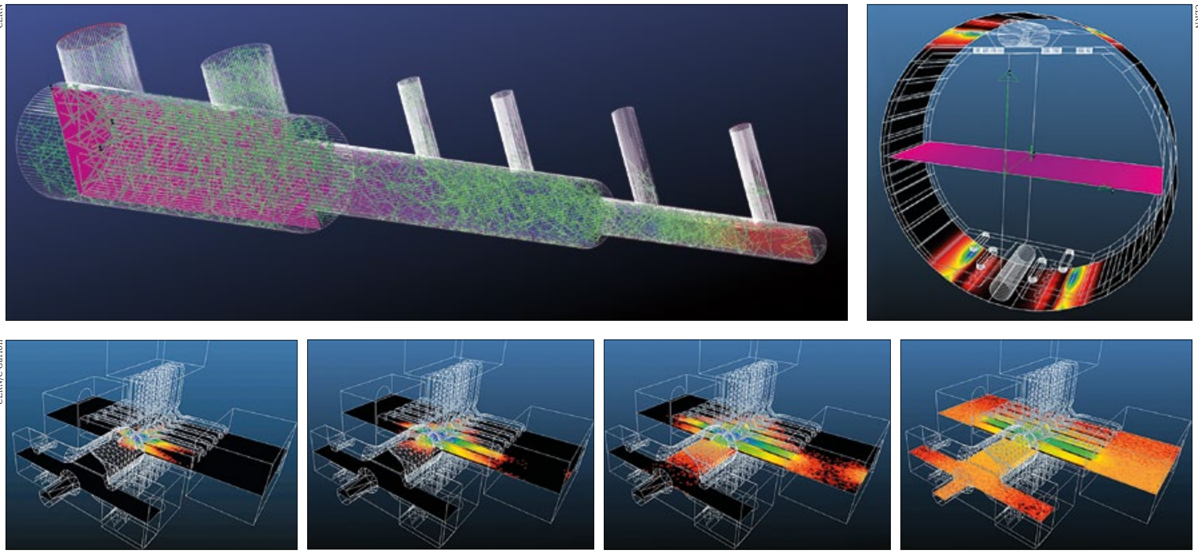
From SPHEREx to LISA

Another JPL project involving free molecular-flow simulations is the future near-infrared space observatory SPHEREx (Spectro-Photometer for the History of the Universe and Ices Explorer). This instrument has cryogenically cooled optical surfaces that may condense molecules in vacuum and are thus prone to significant performance degradation from the accumulation of contaminants, including water. Even when taking as much care as possible during the design and preparation of the systems, some elements, such as water, cannot be entirely removed from a spacecraft and will desorb from materials persistently. It is therefore vital to know where and how much contamination will accumulate. For SPHEREx, water outgassing, molecular transport and adsorption were modelled using Molflow against internal thermal predictions, enabling a decontamination strategy to keep its optics free from performance-degrading accumulation (see "Molflow in space" image, left). Molflow has also complemented other NASA JPL codes to estimate the return flux (whereby gas particles desorbing from a spacecraft return to it after collisions with a planet's atmosphere) during a series of planned fly-bys around Jupiter's moon Europa. For such exospheric sampling missions, it is important to distinguish the actual collected sample from return-flux contaminants that originated from the spacecraft but ended up being collected due to atmospheric rebounds.

It is the ability to import large, complex geometries (through a triangulated file format called STL, used in 3D printing and supported by most CAD software) that makes Molflow usable for JPL's molecular transport problems. In fact, the JPL team "boosted" our codes with external post-processing: instead of built-in visualisation, they parsed the output file format to extract pressure data on individual facets (polygons representing a surface cell), and sometimes even changed input parameters programmatically – once again working directly on Molflow's own file format. They also made a few feature requests, such as adding histograms showing how many times molecules bounce before adsorption, or the total distance or time they travel before being adsorbed on the surfaces. These were straightforward to implement, and because JPL's scientific interests also matched those of CERN users, such additions are now available for everyone in the public versions of the code. Similar requests have come from experiments employing short-lived radioactive beams, such as those generated at CERN's ISOLDE beamlines. Last year, against all odds during COVID-related restrictions, the JPL team managed to visit CERN. While showing the team around

Molflow has complemented NASA JPL codes to estimate the return flux during a series of planned fly-bys around Jupiter's moon Europa

CERNCOURIER
Volume 62 Number 5 September/October 2022
IOP Publishing



High-energy applications *Top left: transmission probability calculation between two ports (red) of a gas-injection device. Top right: simulation of a slice of LHC beam pipe that has two surfaces: an outer "cold bore" at 1.9 K and a warmer 20 K inner beam-screen that catches the heat caused by beam- and radiation-induced processes, and contains pumping holes that enable particles to pass between the surfaces. Bottom: time-dependent simulation of a pressure wave due to an electric spark in an RF cavity for CLIC, creating a burst of molecules in the tiny cavity that may interfere with the following electron bunch.*

the site and the chemistry laboratory, they held a seminar for our vacuum group about contamination control at JPL, and we showed the outlook for Molflow developments.

Our latest space-related collaboration, started in 2021, concerns the European Space Agency's LISA mission, a future gravitational-wave interferometer in space (see p51). Molflow is being used to analyse data from the recently completed LISA Pathfinder mission, which explored the feasibility of keeping two test masses in gravitational free-fall and using them as inertial sensors by measuring their motion with extreme precision. Because the satellite's sides have different temperatures, and because the gas sources are asymmetric around the masses, there is a difference in outgassing between two sides. Moreover, the gas molecules that reach the test mass are slightly faster on one side than the other, resulting in a net force and torque acting on the mass, of the order of femtonewtons. When such precise inertial measurements are required, this phenomenon has to be quantified, along with other microscopic forces, such as Brownian noise resulting from the random bounces of molecules on the test mass. To this end, Molflow is currently being modified to add molecular force calculations for LISA, along with relevant physical quantities such as noise and resulting torque.

Our latest space-related collaboration concerns the European Space Agency's LISA mission

Sky's the limit

Molflow has proven to be a versatile and effective computational physics model for the characterisation of free-molecular flow, having been adopted for use in space exploration and the aerospace sector. It promises to continue to intertwine different fields of science in unexpected ways. Thanks to the ever-growing gaming industry, which uses ray tracing to render photorealistic scenes of multiple light sources, consumer-grade graphics cards started supporting ray-tracing in 2019. Although intended for gaming, they are programmable for generic purposes, including science applications. Simulating on graphics-processing units is much faster than traditional CPUs, but it is also less precise: in the vacuum world, tiny imprecisions in the geometry can result in "leaks" or some simulated particles crossing internal walls. If this issue can be overcome, the speedup potential is huge. In-house testing carried out recently at CERN by PhD candidate Pascal Bahr demonstrated a speedup factor of up to 300 on entry-level Nvidia graphics cards, for example.

Another planned Molflow feature is to include surface processes that change the simulation parameters dynamically. For example, some getter films gradually lose their pumping ability as they saturate with gas molecules. This saturation depends on the pumping speed itself, resulting in two parameters (pumping speed and molecular surface saturation) that depend on each other. The way around this is to perform the simulation in iterative time steps, which is straightforward to add but raises many numerical problems.

Finally, a much-requested feature is automation. The most recent versions of the code already allow scripting, that is, running batch jobs with physics parameters changed step-by-step between each execution. Extending these automation capabilities, and adding export formats that allow easier post-processing with common tools (Matlab, Excel and common Python libraries) would significantly increase usability. If adding GPU ray tracing and iterative simulations are successful, the resulting – much faster and more versatile – Molflow code will remain an important tool to predict and optimise the complex vacuum systems of future colliders. ●

CERNCOURIER
VOLUME 62 NUMBER 5 SEPTEMBER/OCTOBER 2022
IOP Publishing

FROM ATOMIC TO NUCLEAR CLOCKS

Peter Thirolf, Benedict Seiferle and Lars von der Wense describe how recent progress in understanding thorium's nuclear structure, and new upcoming results, could enable an ultra-accurate nuclear clock with applications in fundamental physics.

For the past 60 years, the second has been defined in terms of atomic transitions between two hyperfine states of caesium-133. Such transitions, which correspond to radiation in the microwave regime, enable state-of-the art atomic clocks to keep time at the level of one second in more than 300 million years. A newer breed of optical clocks developed since the 2000s exploit frequencies that are about 10^5 times higher. While still under development, optical clocks based on aluminium ions are already reaching accuracies of about one second in 33 billion years, corresponding to a relative systematic frequency uncertainty below 1×10^{-18}.

To further reduce these uncertainties, in 2003 Ekkehard Peik and Christian Tamm of Physikalisch-Technische Bundesanstalt in Germany proposed the use of a nuclear instead of atomic transition for time measurements. Due to the small nuclear moments (corresponding to the vastly different dimensions of atoms and nuclei), and thus the very weak coupling to perturbing electromagnetic fields, a "nuclear clock" is less vulnerable to external perturbations. In addition to enabling a more accurate timepiece, this offers the potential for nuclear clocks to be used as quantum sensors to test fundamental physics.

Clockwork

A clock typically consists of an oscillator and a frequency-counting device. In a nuclear clock (see "Nuclear clock schematic" figure), the oscillator is provided by the frequency of a transition between two nuclear states (in contrast to a transition between two states in the electronic shell in the case of an atomic clock). For the frequency-counting device, a narrow-band laser resonantly excites the nuclear-clock transition, while the corresponding oscillations of the laser light are counted using a frequency comb. This device (the invention of which was recognised by the 2005 Nobel Prize in Physics) is a laser source whose spectrum consists of a series of discrete, equally spaced frequency lines. After a certain number of oscillations, given by the frequency of the nuclear transition, one second has elapsed.

The need for direct laser excitation strongly constrains applicable nuclear-clock transitions: their energy has to be low enough to be accessible with existing laser technology, while simultaneously exhibiting a narrow linewidth. As the linewidth is determined by the lifetime of the excited nuclear state, the latter has to be long enough to allow for highly stable clock operation. So far, only the metastable (isomeric) first excited state of ^{229}Th, denoted ^{229m}Th, qualifies as a candidate for a nuclear clock, due to its exceptionally low excitation energy.

The existence of the isomeric state was conjectured in 1976 from gamma-ray spectroscopy of ^{229}Th, and its excitation energy has only recently been determined to be 8.19 ± 0.12 eV (corresponding to a vacuum-ultraviolet wavelength of 151.4 ± 2.2 nm). Not only is it the lowest nuclear excitation among the roughly 184,000 excited states of the 3300 or so known nuclides, its expected lifetime is of the order of 1000 s, resulting in an extremely narrow relative linewidth ($\Delta E/E\sim10^{-20}$) for its ground-state transition (see "Unique transition" figure). Besides high resilience against external perturbations, this represents another attractive property for a thorium nuclear clock.

Networks of ultra-precise synchronised nuclear clocks could enable a search for ultra light dark matter

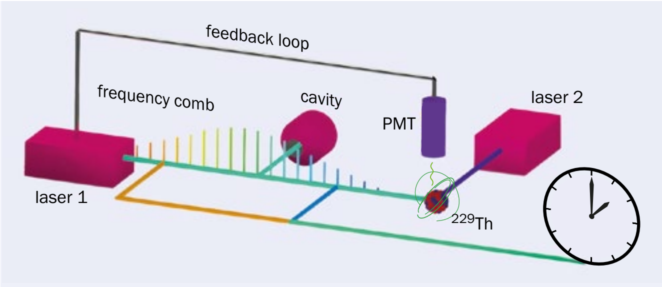
Achieving optical control of the nuclear transition via a direct laser excitation would open a broad range of applications. A nuclear clock's sensitivity to the gravitational redshift, which causes a clock's relative frequency to change depending on its absolute height, could enable more accurate global positioning systems and high-sensitivity detections of fluctuations of Earth's gravitational potential induced by seismic or tectonic activities. Furthermore, while the few-eV thorium transition emerges from a fortunate near-degeneracy of the two lowest nuclear-energy levels in ^{229}Th, the Coulomb and strong-force contributions to these energies differ at the MeV level. This makes the nuclear-level structure of ^{229}Th uniquely sensitive to variations of fundamental constants and ultralight dark matter. Many theories predict variations of the fine structure constant, for example, but on tiny yearly rates. The high sensitivity provided by the thorium isomer could allow such variations to be identified. Moreover, networks of ultra-precise synchronised clocks could enable a search for (ultra light) dark-matter signals.

Two different approaches have been proposed to realise a nuclear clock: one based on trapped ions and another using doped solid-state crystals. The first approach starts from individually trapped Th ions, which promises an unprecedented suppression of systematic clock-frequency shift and leads to an expected relative clock accuracy of about 1×10^{-19}. The other approach relies on embedding ^{229}Th atoms in a vacuum-ultraviolet (VUV) transparent crystal such as CaF_2. This has the advantage of a large

On time *An artist's rendition of a nuclear optical clock, which promises a relative accuracy of about 1×10^{-19}.*

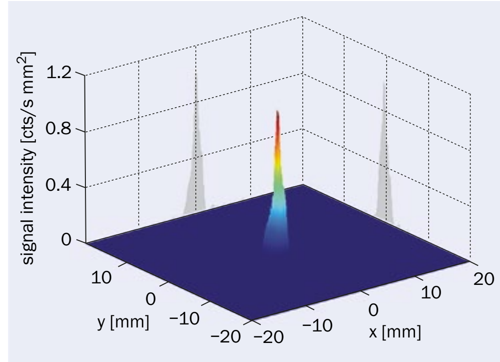
THE AUTHORS
Peter Thirolf *and* **Benedict Seiferle** *Ludwig-Maximilians-Universität Munich, Germany, and* **Lars von der Wense** *JILA, University of Colorado Boulder, US.*

CERNCOURIER
VOLUME 62 NUMBER 5 SEPTEMBER/OCTOBER 2022
IOP Publishing



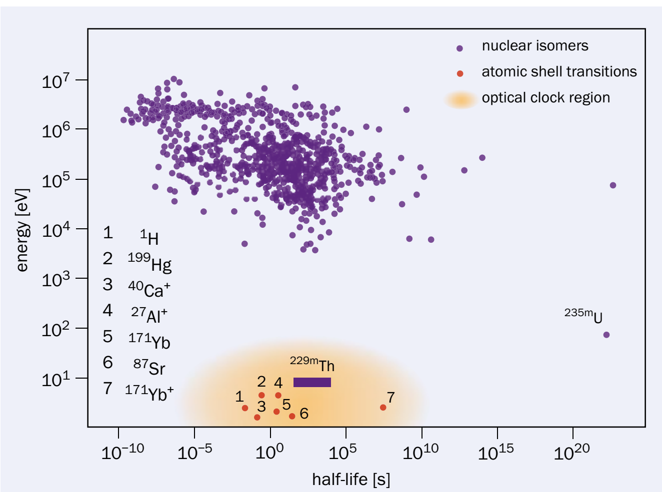
Source: Physik Journal 19 6

Nuclear clock schematic *A cavity-stabilised frequency comb (generated by laser 1) is adjusted to the nuclear excitation of ^{229}Th. The excitation is detected by continuous monitoring of the hyperfine splitting of an atomic shell transition (laser 2). In the case of a nuclear excitation, this will change due to the different nuclear spins of ground and excited states. When laser 2 is in resonance with the shell transition, photons will be detected at the photomultiplier tube (PMT) and laser 1 will be stabilised to the nuclear transition via a feedback loop. The frequency of the exciting mode of the frequency comb can be counted precisely and serves as the clock signal.*



Source: Nature 533 47

Isomeric signal *Detection of the isomer's decay via internal conversion (IC), showing the signal of the first direct detection of the ^{229m}Th decay. The plot shows the IC electron signal of ^{229m}Th^{3+} ions, which were collected with low kinetic energy directly on the surface of a position-sensitive MCP detector.*



Source: Nature 533 47

Unique transition *Isomeric nuclear levels (purple circles) exhibit typical energies from a few 10 keV to several MeV. Only two low-energy (< 1 keV) nuclear isomers are known: ^{229m}Th (8.19 eV, purple bar) and ^{235m}U (76.7 eV). Due to the long radiative lifetime of ^{235m}U (of the order 10^{22} s), only ^{229m}Th qualifies for a direct laser excitation and thus for the realisation of a nuclear clock. In addition, selected clock transitions are included (red circles), which are already in use for optical atomic clocks.*

concentration ($>10^{15}$/cm^3) of Th nuclei in the crystal, leading to a considerably higher signal-to-noise ratio and thus a greater clock stability.

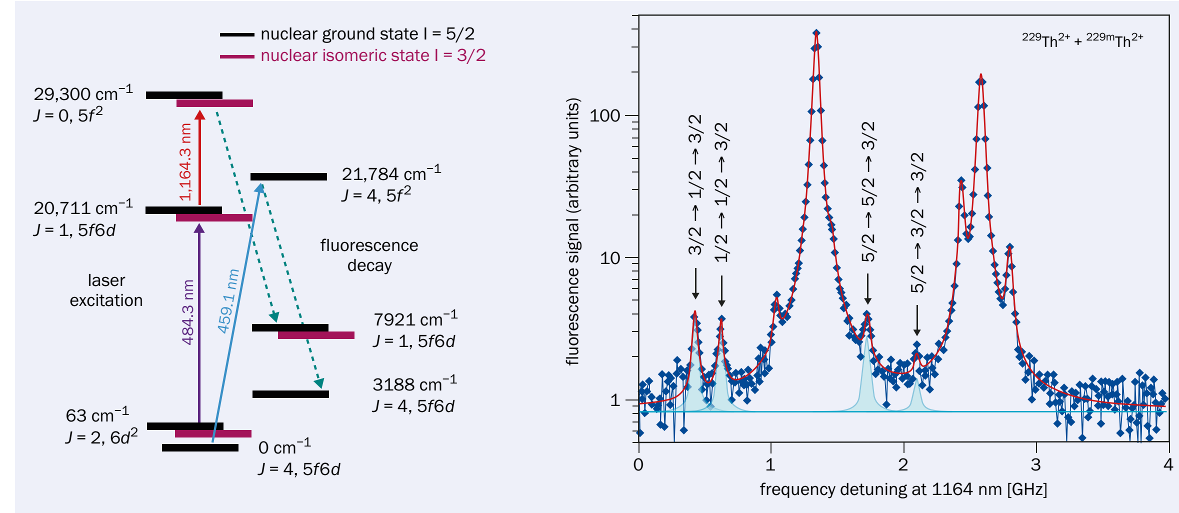
Precise characterisation

A precise characterisation of the thorium isomer's properties is a prerequisite for any kind of nuclear clock. In 2016 the present authors and colleagues made the first direct identification of ^{229m}Th by detecting electrons emitted from its dominant decay mode: internal-conversion (IC), whereby a nuclear excited state decays by the direct emission of one of its atomic electrons (see "Isomeric signal" figure). This brought the long-term objective of a nuclear clock into the focus of international research.

Currently, experimental access to ^{229m}Th is possible only via radioactive decays of heavier isotopes or by X-ray pumping from higher-lying rotational nuclear levels, as shown by Takahiko Masuda and co-workers in 2019. The former, based on the alpha decay of ^{233}U (2% branching ratio), is the most commonly used approach. Very recently, however, a promising new experiment exploiting β^- decay from ^{229}Ac was performed at CERN's ISOLDE facility led by a team at KU Leuven. Here, ^{229}Ac is online-produced and mass-separated before being implanted into a large-bandgap VUV-transparent crystal. In both population schemes, either photons or conversion electrons emitted during the isomeric decay are detected.

In the IC-based approach, a positively charged ^{229m}Th ion beam is generated from alpha-decay daughter products recoiling off a ^{233}U source placed inside a buffer-gas stopping cell. The decay products are thermalised, guided by electrical fields towards an exit nozzle, extracted into a longitudinally 15-fold segmented radiofrequency quadrupole (RFQ) that acts as an ion guide, phase-space cooler and optionally a beam buncher, followed by a quadrupole mass separator for beam purification. In charged thorium isomers, the otherwise dominant IC decay branch is energetically forbidden, leading to a prolongation of the lifetime by up to nine orders of magnitude.

Operating the segmented RFQ as a linear Paul trap to generate sharp ion pulses enables the half-life of the thorium isomer to be determined. In work performed by the present authors in 2017, pulsed ions from the RFQ were collected and neutralised on a metal surface, triggering their IC decay. Since the long ionic lifetime was inaccessible due to the limited ion-storage time imposed by the trap's vacuum conditions, the drastically reduced lifetime of neutral isomers was targeted. Time-resolved detection of the low-energy conversion electrons determined the lifetime to be 7 ± 1 µs.



Source: Nature 556 321

Hyperfine splitting *Left: the two-step excitation scheme for Doppler-free spectroscopy of ^{229}Th^{2+}. The 29,300 cm^{-1} line is excited by two lasers (purple and red) and fluorescence is registered. A third laser (blue) is used to control the number of ions stored in the Paul trap for normalisation purposes. Right: two-step excitation resonances of the ^{229}Th nuclear isomer hyperfine splitting are displayed in cyan, showing the relative strengths and frequency range of the isomeric and ground-state resonances. The first laser is stabilised at around 260 MHz detuning with respect to the ^{229}Th HFS centre and the second laser is scanned. The unlabelled peaks correspond to the ground state.*

Excitation energy

Recently, considerable progress has been made in determining the ^{229m}Th excitation energy – a milestone en route to a nuclear clock. In general, experimental approaches to determine the excitation energy fall into three categories: indirect measurements via gamma-ray spectroscopy of energetically low-lying rotational transitions in ^{229}Th; direct spectroscopy of fluorescence photons emitted in radiative decays; and via electrons emitted in the IC decay of neutral ^{229m}Th. The first approach led to the conjecture of the isomer's existence and finally, in 2007, to the long-accepted value of 7.6 ± 0.5 eV. The second approach tries to measure the energy of photons emitted directly in the ground-state decay of the thorium isomer.

The first direct measurement of the thorium isomer's excitation energy was reported by the present authors and co-workers in 2019. Using a compact magnetic-bottle spectrometer equipped with a repulsive electrostatic potential, followed by a microchannel-plate detector, the kinetic energy of the IC electrons emitted after an in-flight neutralisation of Th ions emitted from a ^{233}U source could be determined. The experiment provided a value for the excitation energy of the nuclear-clock transition of 8.28 ± 0.17 eV. At around the same time in Japan, Masuda and co-workers used synchrotron radiation to achieve the first population of the isomer via resonant X-ray pumping into the second excited nuclear state of ^{229}Th at 29.19 keV, which decays predominantly into ^{229m}Th. By combining their measurement with earlier published gamma-spectroscopic data, the team could constrain the isomeric excitation energy to the range 2.5–8.9 eV. More recently, led by teams at Heidelberg and Vienna, the excited isomers were implanted into the absorber of a custom-built cryogenic magnetic micro-calorimeter and the isomeric energy was measured by detecting the temperature-induced change of the magnetisation using SQUIDs. This produced a value of 8.10 ± 0.17 eV for the clock-transition energy, resulting in a world-average of 8.19 ± 0.12 eV.

Besides precise knowledge of the excitation energy, another prerequisite for a nuclear clock is the possibility to monitor the nuclear excitation on short timescales. Peik and Tamm proposed a method to do this in 2003 based on the "double resonance" principle, which requires knowledge of the hyperfine structure of the thorium isomer. Therefore, in 2018, two different laser beams were collinearly superimposed on the ^{229}Th ion beam, initiating a two-step excitation in the atomic shell of ^{229}Th. By varying both laser frequencies, resonant excitations of hyperfine components both of the ^{229}Th ground state and the ^{229m}Th isomer could be identified and thus the hyperfine splitting signature of both states could be established by detecting their de-excitation (see "Hyperfine splitting" figure). The eventual observation of the ^{229m}Th hyperfine structure in 2018 not only will in the future allow a non-destructive verification of the nuclear excitation, but enabled the isomer's magnetic dipole and electrical quadrupole moments, and the mean-square charge radius, to be determined.

Roadmap towards a nuclear clock

So far, the identification and characterisation of the thorium isomer has largely been driven by nuclear physics, where techniques such as gamma spectroscopy, conversion-electron spectroscopy and radioactive decays offer a description in units of electron volts. Now the challenge is to refine our knowledge of the isomeric excitation energy with laser-spectroscopic precision to enable optical control of the nuclear-clock transition. This requires bridg-

Recently, a promising new experiment exploiting β– decay from ^{229}Ac was performed at CERN's ISOLDE facility

CERNCOURIER
VOLUME 62 NUMBER 5 SEPTEMBER/OCTOBER 2022
IOP Publishing

ing a gap of about 12 orders of magnitude in the precision of the ^{229m}Th excitation energy, from around 0.1 eV to the sub-kHz regime. In a first step, existing broad-band laser technology can be used to localise the nuclear resonance with an accuracy of about 1 GHz. In a second step, using VUV frequency-comb spectroscopy presently under development, it is envisaged to improve the accuracy into the (sub-)kHz range.

Another practical challenge when designing a high-precision ion-trap-based nuclear clock is the generation of thermally decoupled, ultra-cold ^{229}Th ions via laser cooling. $^{229}Th^{3+}$ is particularly suited due to its electronic level structure, with only one valence electron. Due to the high chemical reactivity of thorium, a cryogenic Paul trap is the ideal environment for laser cooling, since almost all residual gas atoms will freeze out at 4 K, increasing the trapping time into the region of a few hours. This will form the basis for direct laser excitation of ^{229m}Th and will also enable a measurement of the not yet experimentally determined isomeric lifetime of ^{229}Th ions. For the alternative development of a compact solid-state nuclear clock it will be necessary to suppress the ^{229m}Th decay via internal conversion in a large band-gap, VUV transparent crystal and to detect the γ decay of the excited nuclear state. Proof-of-principle studies of this approach are currently ongoing at ISOLDE.

Laser-spectroscopy activities on the thorium isomer are also ongoing in the US, for example at JILA, NIST and UCLA

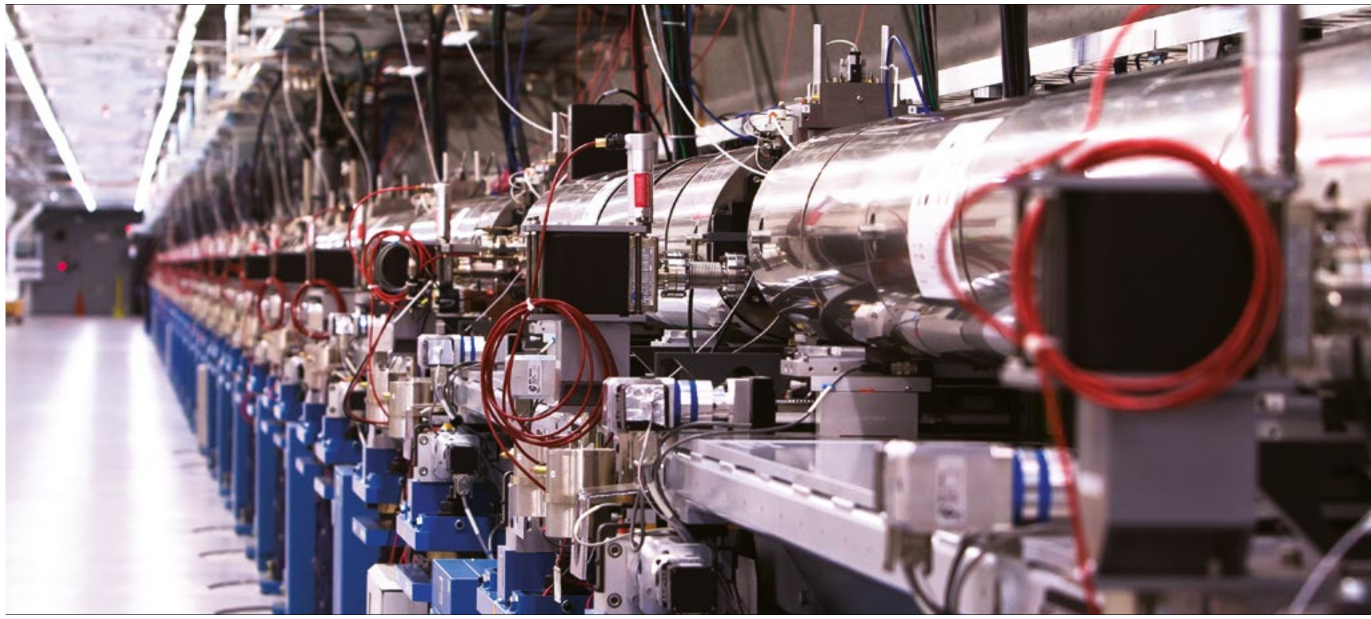
Many of the recent breakthroughs in understanding the ^{229}Th clock transition emerged from the European Union project "nuClock", which terminated in 2019. A subsequent project, ThoriumNuclearClock (ThNC), aims to demonstrate at least one nuclear clock by 2026. Laser-spectroscopy activities on the thorium isomer are also ongoing in the US, for example at JILA, NIST and UCLA.

In view of the large progress in recent years and ongoing worldwide efforts both experimentally and theoretically, the road is paved towards the first nuclear clock. It will complement highly precise optical atomic clocks, while in some areas, in the long run, nuclear clocks might even have the potential to replace them. Moreover, and beyond its superb timekeeping capabilities, a nuclear clock is a unique type of quantum sensor allowing for fundamental physics tests, from the variation of fundamental constants to searches for dark matter. ●

Further reading

A Ludlow *et al.* 2015 *Rev. Mod. Phys.* **87** 637.
T Masuda *et al.* 2019 *Nature* **573** 238.
E Peik *et al.* 2021 *Quantum Sci. Technol.* **6** 034002.
E Peik and C Tamm 2003 *Eur. Phys. Lett.* **61** 181.
B Seiferle *et al.* 2019 *Nature* **573** 243.
B Seiferle *et al.* 2017 *Phys. Rev. Lett.* **118** 042501.
T Sikorsky *et al.* 2020 *Phys. Rev. Lett.* **125** 142503.
J Thielking *et al.* 2018 *Nature* **556** 321.

CERNCOURIER
Volume 62 Number 5 September/October 2022
IOP Publishing



Intense *The LCLS undulator hall, where high-energy electrons run a gauntlet of 32 undulators each containing 224 magnets whose alternating poles force the electrons to zigzag violently and radiate X-rays. (Credit: SLAC)*

FIRST LIGHT BECKONS AT SLAC'S LCLS-II

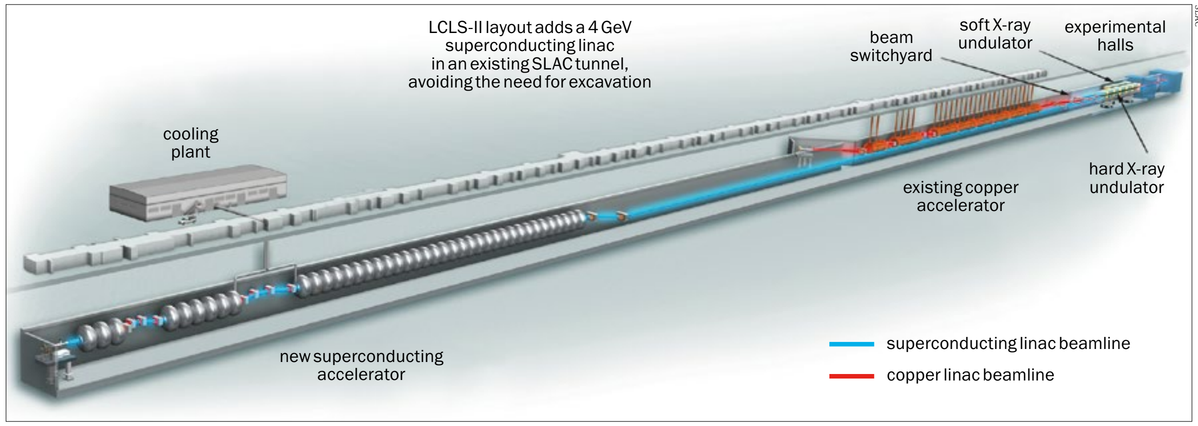
A major upgrade to SLAC's Linac Coherent Light Source (LCLS) will greatly increase its capacity for studies of the ultrafast and the ultrasmall. Richard Stanek, Joe Preble and Andrew Burrill share the secrets of successful collaboration from the sharp-end of LCLS-II project delivery.

An ambitious upgrade of the US's flagship X-ray free-electron-laser facility – the Linac Coherent Light Source (LCLS) at SLAC in California – is nearing completion. Set for "first light" early next year, LCLS-II will deliver X-ray laser beams that are 10,000 times brighter than LCLS at repetition rates of up to a million pulses per second – generating more X-ray pulses in just a few hours than the current laser has delivered through the course of its 12-year operational lifetime. The cutting-edge physics of the new facility – underpinned by a cryogenically cooled superconducting radio-frequency (SRF) linac – will enable the two beams from LCLS and LCLS-II to work in tandem. This, in turn, will help researchers observe rare events that happen during chemical reactions and study delicate biological molecules at the atomic scale in their natural environments, as well as potentially shed light on exotic quantum phenomena with applications in next-generation quantum computing and communications systems.

Successful delivery of the LCLS-II linac was possible thanks to a multi-centre collaborative effort involving US national and university laboratories, following the decision to pursue an SRF-based machine in 2014 through the design, assembly, test, transportation and installation of a string of 37 SRF cryomodules (most of them more than 12 m long) into the SLAC tunnel. All told, this major undertaking necessitated the construction of forty 1.3 GHz SRF cryomodules (five of them spares) and three 3.9 GHz cryomodules (one spare) – with delivery of approximately one cryomodule per month from February 2019 until December 2020 to allow completion of the LCLS-II linac installation

THE AUTHORS

Richard Stanek *is the Fermilab LCLS-II senior team leader;* **Joe Preble** *is the JLab LCLS-II senior team leader; and* **Andrew Burrill** *is the cryogenic systems lead for LCLS-II at SLAC.*



SLAC

Long view
LCLS-II will add a superconducting accelerator occupying one-third of SLAC's original 2 mile-long linear accelerator tunnel. At the beam switchyard, electron beams from each linac will be directed to one of two new undulators to produce hard or soft X-ray pulses that are subsequently routed to the experimental halls.

on schedule by November 2021.

This industrial-scale programme of works was shaped by a strategic commitment, early on in the LCLS-II design phase, to transfer, and ultimately iterate, the established SRF capabilities of the European XFEL in Hamburg into the core technology platform used for the LCLS-II SRF cryomodules. Put simply: it would not have been possible to complete the LCLS-II project, within cost and on schedule, without the sustained cooperation of the European XFEL consortium – in particular, colleagues at DESY, CEA Saclay and several other European laboratories as well as KEK – that generously shared their experiences and know-how.

Better together

These days, large-scale accelerator or detector projects are very much a collective endeavour. Not only is the sprawling scope of such projects beyond a single organisation, but the risks of overspend and slippage can greatly increase with a "do-it-on-your-own" strategy. When the LCLS-II project opted for an SRF technology pathway in 2014 to maximise laser performance, the logical next step was to build a broad-based coalition with other US Department of Energy (DOE) national laboratories and universities. In this case, SLAC, Fermilab, Jefferson Lab (JLab) and Cornell University contributed expertise for cryomodule production, while Argonne National Laboratory and Lawrence Berkeley National Laboratory managed delivery of the undulators and photoinjector for the project. For sure, the start-up time for LCLS-II would have increased significantly without this joint effort, extending the overall project by several years.

Each partner brought something unique to the LCLS-II collaboration. While SLAC was still a relative newcomer to SRF technologies, the lab had a management team that was familiar with building large-scale accelerators (following successful delivery of the LCLS). The priority for SLAC was therefore to scale up its small nucleus of SRF experts by recruiting experienced SRF technologists and engineers to the staff team. In contrast, the JLab team brought an established track-record in the production of SRF cryomodules, having built its own machine, the Continuous Electron Beam Accelerator Facility (CEBAF), as well as cryomodules for the Spallation Neutron Source (SNS) linac at Oak Ridge National Laboratory in Tennessee. Cornell, too, came with a rich history in SRF R&D – capabilities that, in turn, helped to solidify the SRF cavity preparation process for LCLS-II.

Finally, Fermilab had, at the time, recently built two cutting-edge cryomodules of the same style as that chosen for LCLS-II. To fabricate these modules, Fermilab worked closely with the team at DESY to set up the same type of production infrastructure used on the European XFEL. From that perspective, the required tooling and fixtures were all ready to go for the LCLS-II project. While Fermilab was the "designer of record" for the SRF cryomodule, with primary responsibility for delivering a working design to meet LCLS-II requirements, the realisation of an optimised technology platform was a team effort involving SRF experts from across the collaboration.

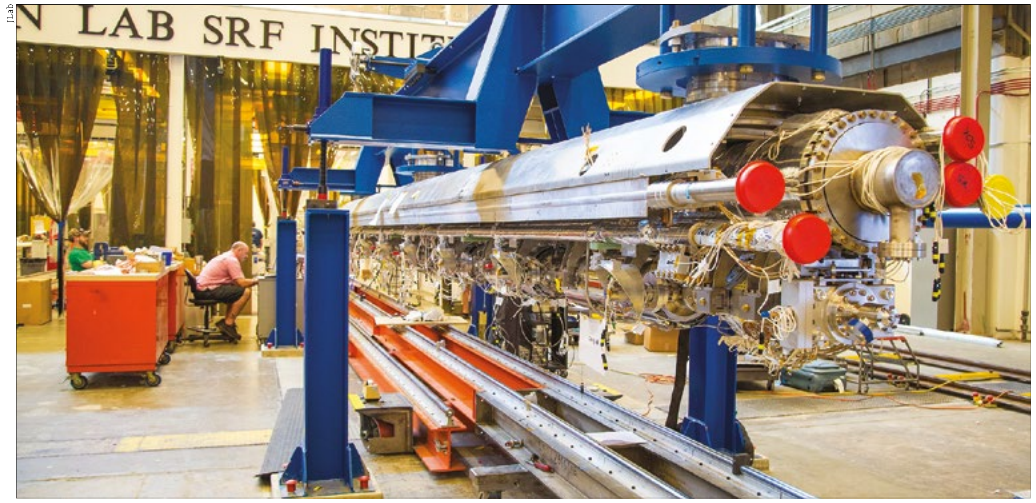
Collective problems, collective solutions

While the European XFEL provided the template for the LCLS-II SRF cryomodule design, several key elements of the LCLS-II approach subsequently evolved to align with the continuous-wavelength (CW) operation requirements and the specifics of the SLAC tunnel. Success in tackling these technical challenges – across design, assembly, testing and transportation of the cryomodules – is testament to the strength of the LCLS-II collaboration and the collective efforts of the participating teams in the US and Europe.

For one, the thermal performance specification of the SRF cavities exceeded the state-of-the-art and required development and industrialisation of the concept of nitrogen doping (a process in which SRF cavities are heat-treated in a nitrogen atmosphere to increase their cryogenic efficiency and, in turn, lower the overall operating costs of the linac). The nitrogen-doping technique was invented at Fermilab in 2012 but, prior to LCLS-II construction, had been used only in an R&D setting.

The priority was clear: to transfer the nitrogen-doping capability to LCLS-II's industry partners, so that the cavity manufacturers could perform the necessary materials-processing before final helium-vessel jacketing. During this knowledge transfer, it was found that nitrogen-doped cavities are particularly sensitive to the

JLab



Production line
The use of two facilities to produce the SRF cryomodules – Fermilab and JLab (left) – ensured a compressed delivery schedule and increased flexibility within the LCLS-II programme.

J Orrell/SLAC

Heavy lifting
The last cryomodule from Fermilab was unloaded at the LCLS-II site at SLAC on 19 May 2021.

base niobium sheet material – something the collaboration only realised once the cavity vendors were into full production. This resulted in a number of process changes for the heat treatment temperature, depending on which material supplier was used and the specific properties of the niobium sheet deployed in different production runs. JLab, for its part, held the contract for the cavities and pulled out all stops to ensure success.

At the same time, the conversion from pulsed to CW operation necessitated a faster cooldown cycle for the SRF cavities, requiring several changes to the internal piping, a larger exhaust chimney on the helium vessel, as well as the addition of two new cryogenic valves per cryomodule. Also significant is the 0.5% slope in the longitudinal floor of the existing SLAC tunnel, which dictated careful attention to liquid-helium management in the cryomodules (with a separate two-phase line and liquid-level probes at both ends of every module).

However, the biggest setback during LCLS-II construction involved the loss of beamline vacuum during cryomodule transport. Specifically, two cryomodules had their beamlines vented and required complete disassembly and rebuilding – resulting in a five-month moratorium on shipping of completed cryomodules in the second half of 2019. It turns out that a small (what was thought to be inconsequential) change in a coupler flange resulted in the cold coupler assembly being susceptible to resonances excited by transport. The result was a bellows tear that vented the beamline. Unfortunately, initial "road-tests" with a similar, though not exactly identical, prototype cryomodule had not revealed this behaviour.

Such challenges are inevitable when developing new facilities at the limits of known technology. In the end, the problem was successfully addressed using the diverse talents of the collaboration to brainstorm solutions, with the available access ports allowing an elastomer wedge to be inserted to secure the vulnerable section. A key take-away here is the need for future projects to perform thorough transport analysis, verify the transport loads using mock-ups or dummy devices, and install adequate instrumentation to ensure granular data analysis before long-distance transport of mission-critical components.

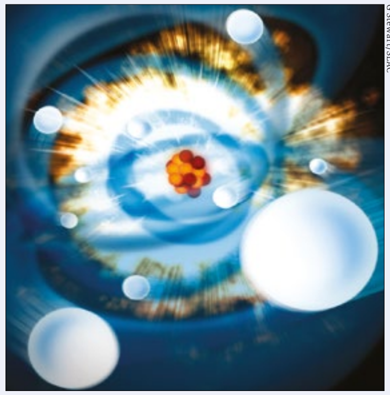
Challenges are inevitable when developing new facilities at the limits of known technology

Upon completion of the assembly phase, all LCLS-II cryomodules were subsequently tested at either Fermilab or JLab, with one module tested at both locations to ensure reproducibility and consistency of results. For high Q_0 performance in nitrogen-doped cavities, cooldown flow rates of at least 30 g/s of liquid helium were found to give

CERNCOURIER
VOLUME 62 NUMBER 5 SEPTEMBER/OCTOBER 2022
IOP Publishing

LCLS-II science: capturing atoms and molecules in motion like never before

The strobe-like pulses of the LCLS, which produced its first light in April 2009, are just a few millionths of a billionth of a second long, and a billion times brighter than previous X-ray sources. This enables users from a wide range of fields to take crisp pictures of atomic motions, watch chemical reactions unfold, probe the properties of materials and explore fundamental processes in living things. LCLS-II will provide a major jump in capability – moving from 120 pulses per second to 1 million, enabling experiments that were previously impossible. The scientific community has identified six areas where the unique capabilities of LCLS-II will be essential for further scientific progress:


G Stewart/SLAC

Nanoscale materials dynamics, heterogeneity and fluctuations
Programmable trains of soft X-ray pulses at high rep rate will characterise spontaneous fluctuations and heterogeneities at the nanoscale across many decades, while coherent hard X-ray scattering will provide unprecedented spatial resolution of material structure, its evolution and relationship to functionality under operating conditions.

Fundamental energy and charge dynamics
High-repetition-rate soft X-rays will enable new techniques that will directly map charge distributions and reaction dynamics at the scale of molecules, while new nonlinear X-ray spectroscopies offer the potential to map quantum coherences in an element-specific way for the first time.

Catalysis and photocatalysis
Time-resolved, high-sensitivity, element-specific spectroscopy will provide the first direct view of charge dynamics and chemical processes at interfaces, characterise subtle conformational changes associated with charge accumulation, and capture rare chemical events in operating catalytic systems across multiple time and length scales – all of which are essential for designing new, more efficient systems for chemical transformation and solar-energy conversion.

Emergent phenomena in quantum materials
Fully coherent X-rays will enable new high-resolution spectroscopy techniques to map the collective excitations that define these new materials in unprecedented detail. Ultrashort X-ray pulses and optical fields will facilitate new methods for manipulating charge, spin and phonon modes to both advance fundamental understanding and point the way to new approaches for materials control.

Revealing biological function in real time
The high repetition rate of LCLS-II will provide a unique capability to follow the dynamics of macromolecules and interacting complexes in real time and in native environments. Advanced solution-scattering and coherent imaging techniques will characterise the conformational dynamics of heterogeneous ensembles of macromolecules, while the ability to generate "two-colour" hard X-ray pulses will resolve atomic-scale structural dynamics of biochemical processes that are often the first step leading to larger-scale protein motions.

Matter in extreme environments
The capability of LCLS-II to generate soft and hard X-ray pulses simultaneously will enable the creation and observation of extreme conditions that are far beyond our present reach, with the latter allowing the characterisation of unknown structural phases. Unprecedented spatial and temporal resolution will enable direct comparison with theoretical models relevant for inertial-confinement fusion and planetary science.

the best results, helping to expel magnetic flux that could otherwise be trapped in the cavity. Overall, cryomodule performance on the test stands exceeded specifications, with a total accelerating voltage per cryomodule of 158 MV (versus specification of 128 MV) and average Q_0 of 3×10^{10} (versus specification of 2.7×10^{10}). Looking ahead, attention is already shifting to the real-world cryomodule performance in the SLAC tunnel – something that was measured for the first time in 2022.

Transferable lessons

For all members of the collaboration working on the LCLS-II cryomodules, this challenging project holds many lessons. Most important is to build a strong team and use that strength to address problems in real-time as they arise. The mantra "we are all in this together" should be front-and-centre for any multi-institutional scientific endeavour – as it was in this case. Solutions need to be thought of in a more global sense, as the best answer might mean another collaborator taking more onto their plate. Collaboration implies true partnership and a working model very different to a transactional customer–vendor relationship.

From a planning perspective, it's vital to ensure that the initial project cost and schedule are consistent with the technical challenges and preparedness of the infrastructure. Prototypes and pre-series production runs reduce risk and cost in the long term and should be part of the plan, but there must be sufficient time for data analysis and changes to be made after a prototype run in order for it to be useful. Time spent on detailed technical reviews is also time well spent. New designs of complex components need a comprehensive oversight and review, and should be controlled by a team, rather than a single individual, so that sign-off on any detailed design changes are made by an informed collective.

Work planning and control is another essential element for success and safety. This idea needs to be built into the "manufacturing system", including into the cost and schedule, and to be part of each individual's daily checklist. No one disagrees with this concept, but good intentions on their own will not suffice. As such, required safety documentation should be clear and unambiguous, and be reviewed by people with relevant expertise. Production data and documentation need to be collected, made easily available to the entire project team, and analysed regularly for trends, both positive and negative.

Supply chain, of course, is critical in any production environment – and LCLS-II is no exception. When possible, it is best to have parts procured, inspected, accepted and on-the-shelf before production begins, thereby eliminating possible workflow delays. Pre-stocking also allows adequate time to recycle and replace parts that do not meet project specifications. Also worth noting is that it's often the smaller components – such as bellows, feedthroughs and copper-plated elements – that drive workflow slowdowns. A key insight from LCLS-II is to place purchase orders early, stay on top of vendor deliveries, and perform parts inspections as soon as possible post-delivery. Projects also benefit from having clearly articulated pass/fail criteria and established procedures for handling non-conformance – all of which alleviates the need to make critical go/no-go acceptance decisions in the face of schedule pressures.

Finally, it's worth highlighting the broader impact – both personal and professional – on individual team members participating in a big-science collaboration like LCLS-II. At the end of the build, what remained after designs were completed, problems solved, production rates met, and cryomodules delivered and installed, were the friendships that had been nurtured over several years. The collaboration amongst partners, both formal and informal, who truly cared about the project's success, and had each other's backs when there were issues arising: these are the things that solidified the mutual respect, the camaraderie and, in the end, made LCLS-II such a rewarding project.

First light

In April 2022 the new LCLS-II linac was successfully cooled to its 2 K operating temperature. The next step was to pump the SRF cavities with more than a megawatt of microwave power to accelerate the electron beam from the new source. Following further commissioning of the machine, first X-rays are expected to be produced in early 2023.

As with many accelerator projects, LCLS-II is not an end-point in itself, more an evolutionary transition within a longer term roadmap. In fact, work is already under way on LCLS-II HE – a project that will increase the energy of the CW SRF linac from 4 to 8 GeV, enabling the photon energy range to be extended to at least 13 keV, and potentially up to 20 keV at 1 MHz repetition rates. To ensure continuity of production for LCLS-II HE, 25 next-generation cryomodules are in the works, with even higher performance specifications versus their LCLS-II counterparts, while upgrades to the source and beam transport are also being finalised.

While the fascinating science opportunities for LCLS-II-HE continue to be refined and expanded, of one thing we can be certain: strong collaboration and the collective efforts of the participating teams are crucial. ●

● This is an updated version of an article published in 2021 in a *CERN Courier* "In Focus" issue about US accelerator projects.

As with many accelerator projects, LCLS-II is not an end-point in itself, more an evolutionary transition within a longer term roadmap

CERNCOURIER
Volume 62 Number 5 September/October 2022
IOP Publishing

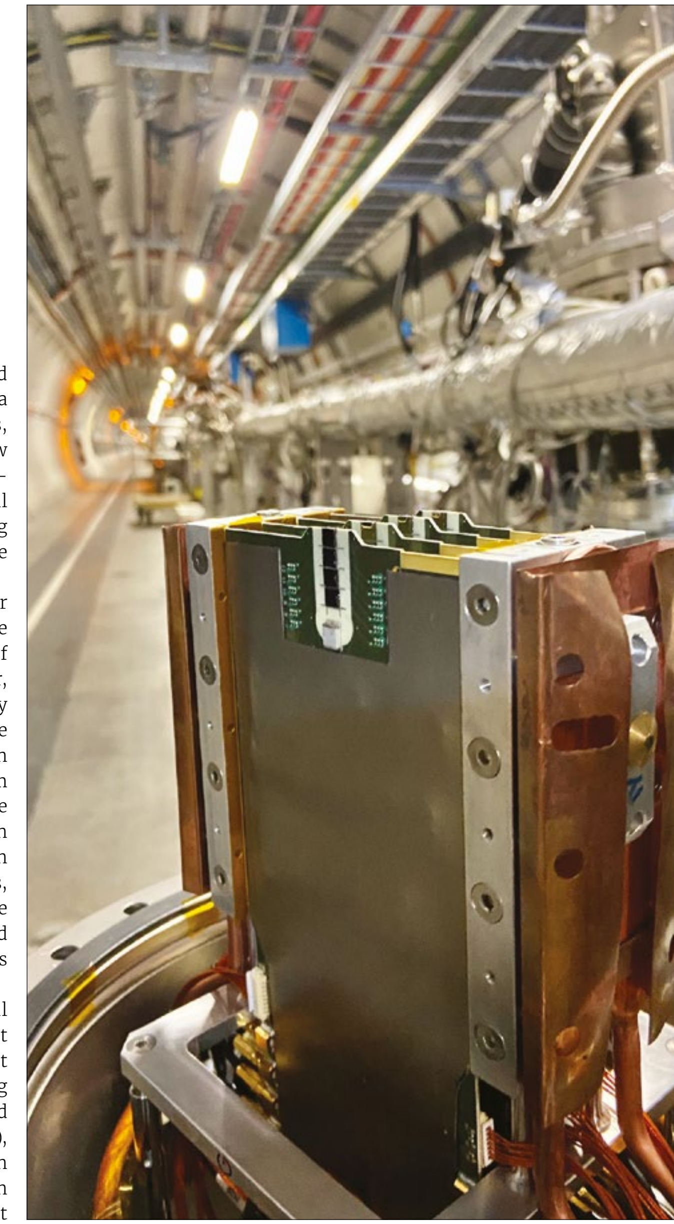
CMS LOOKS FORWARD TO NEW PHYSICS WITH PPS

A new CMS subdetector – the Precision Proton Spectrometer (PPS) – allows the electroweak sector of the Standard Model to be probed in regions so far unexplored, explain Michele Arneodo, Michael Pitt, Enrico Robutti and Ksenia Shchelina.

Colliding particles at high energies is a tried and tested route to uncover the secrets of the universe. In a collider, charged particles are packed in bunches, accelerated and smashed into each other to create new forms of matter. Whether accelerating elementary electrons or composite hadrons, past and existing colliders all deal with matter constituents. Colliding force-carrying particles such as photons is more ambitious, but can be done, even at the Large Hadron Collider (LHC).

The LHC, as its name implies, collides hadrons (protons or ions) into one another. In most cases of interest, projectile protons break up in the collision and a large number of energetic particles are produced. Occasionally, however, protons interact through a different mechanism, whereby they remain intact and exchange photons that fuse to create new particles (see "Photon fusion" figure). Photon–photon fusion has a unique signature: the particles originating from this kind of interaction are produced exclusively, i.e. they are the only ones in the final state along with the protons, which often do not disintegrate. Despite this clear imprint, when the LHC operates at nominal instantaneous luminosities, with a few dozen proton–proton interactions in a single bunch crossing, the exclusive fingerprint is contaminated by extra particles from different interactions. This makes the identification of photon–photon fusion challenging.

Protons that survive the collision, having lost a small fraction of their momentum, leave the interaction point still packed within the proton bunch, but gradually drift away as they travel further along the beamline. During LHC Run 2, the CMS collaboration installed a set of forward proton detectors, the Precision Proton Spectrometer (PPS), at a distance of about 200 m from the interaction point on both sides of the CMS apparatus. The PPS detectors can get as close to the beam as a few millimetres and detect protons that have lost between 2% and 15% of their initial kinetic energy (see "Precision Proton Spectrometer up close" panel). They are the CMS detectors located the


N Turini

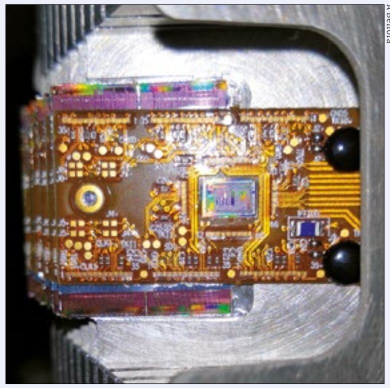
Timing detectors *The new PPS timing detector just before installation inside a Roman Pot. The sensitive elements are the dark crystals seen on the top part of the detector, made from synthetic diamond, with a total active surface of 4.5 × 18 mm² per plane.*

Precision Proton Spectrometer up close

PPS was born in 2014 as a joint project between the CMS and TOTEM collaborations (*CERN Courier* April 2017 p23), and in 2018 became a subsystem of CMS following an MoU between CERN, CMS and TOTEM. For the specialised PPS setup to work as designed, its detectors must be located within a few millimetres of the LHC proton beam. The Roman Pots technique – moveable steel "pockets" enclosing the detectors under moderate vacuum conditions with a thin wall facing the beam – is perfectly suited for this task. This technique has been successfully exploited by the TOTEM and ATLAS collaborations at the LHC and was used in the past by experiments at the ISR, the SPS, the Tevatron and HERA. The challenge for PPS is the requirement that the detectors operate continuously during standard LHC running conditions, as opposed to dedicated special runs with a very low interaction rate.

The PPS design for LHC Run 2 incorporated tracking and timing detectors on both sides of CMS. The tracking detector comprises two stations located 10 m apart, capable of reconstructing the position and angle of the incoming proton. Precise timing is needed to associate the production vertex of two protons to the primary interaction vertex reconstructed by the CMS tracker. The first tracking stations of the proton spectrometer were equipped with silicon-strip trackers from TOTEM – a precise and reliable system used since the start of the LHC. In parallel, a suitable detector technology for efficient operation during standard LHC runs was developed, and in 2017 half of the tracking stations (one per side) were replaced by new silicon pixel trackers designed to cope with the higher hit rate. The x, y coordinates provided by the pixels resolve multiple proton tracks in the same bunch crossing, while the "3D" technology used for sensor fabrication greatly enhances resistance against radiation damage. The transition from strips was completed in 2018, when the fully pixel-based tracker was employed.

In parallel, the timing system was set up. It is based on diamond pad sensors initially developed for a new TOTEM detector. The signal collection is segmented in relatively large pads, read out individually by custom, high-speed electronics. Each plane contributes to the time measurement of the proton hit with a resolution of about 100 ps. The design of the detector evolved during Run 2 with different geometries and set-ups, improving the performance in terms of efficiency and overall time resolution.



A Bellora

Tracking station *Each detector plane contains a silicon pixel sensor coupled to four readout chips.*

farthest from the interaction point and the closest to the beam pipe, opening the door to a new physics domain, represented by central-exclusive-production processes in standard LHC running conditions.

Testing the Standard Model

Central exclusive production (CEP) processes at the LHC allow novel tests of the Standard Model (SM) and searches for new phenomena by potentially granting access to some of the rarest SM reactions so far unexplored. The identification of such exclusive processes relies on the correlation between the proton momentum loss measured by PPS and the kinematics of the central system, allowing the mass and rapidity of the central system in the interaction to be inferred very accurately (see "Tagging exclusive events" and "Exclusive identification" figures). Furthermore, the rules for exclusive photon–photon interactions only allow states with certain quantum numbers (in particular, spin and parity) to be produced.

The most common and cleanest process in photon–photon collisions is the exclusive production of a pair of leptons. Theoretical calculations of such processes date back almost a century to the well-known Breit–Wheeler process. The first result obtained by PPS after commissioning in 2016 was the measurement of (semi-)exclusive production of e^+e^- and $\mu^+\mu^-$ pairs using about 10 fb^{-1} of CMS data: 20 candidate events were identified with a di-lepton mass greater than 110 GeV. This process is now used as a "standard candle" to calibrate PPS and validate its performance. The cross section of this process has been measured by the ATLAS collaboration with their forward proton spectrometer, AFP (*CERN Courier* September/October 2020 p15).

The sensitivity in many channels is expected to increase by a factor of four or five compared to that in Run 2

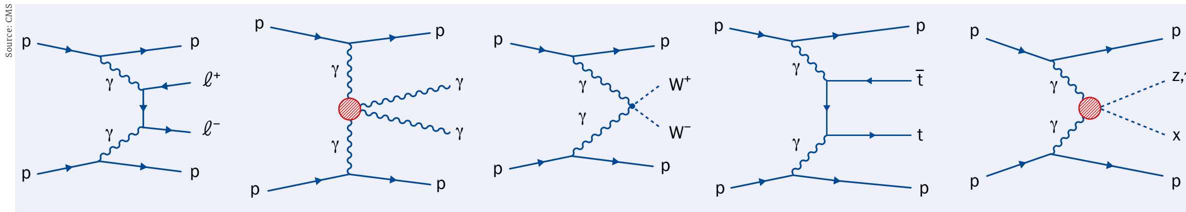
An interesting process to study is the exclusive production of W-boson pairs. In the SM, electroweak gauge bosons are allowed to interact with each other through point-like triple and quartic couplings. Most extensions of the SM modify the strength of these couplings. At the LHC, electroweak self-couplings are probed via gauge-boson scattering, and specifically photon–photon scattering. A notable advantage of exclusive processes is the excellent mass resolution obtained from PPS, allowing the study of self-couplings at different scales with very high precision.

During Run 2, PPS reconstructed intact protons that lost down to 2% of their kinetic energy, which for proton–proton collisions at 13 TeV translates to sensitivity for central mass values above 260 GeV. In the production of electroweak boson pairs, WW or ZZ, the quartic self-coupling mainly contributes to the high invariant-mass tail of the di-boson system. The analysis searched for anomalously large values of the quartic gauge coupling and the results provide the first constraint on γγZZ in an exclusive channel and a competitive constraint on γγWW compared to other vector-boson-scattering searches.

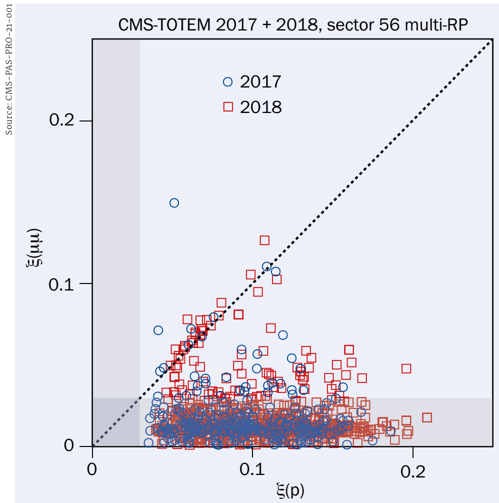
Many SM processes proceeding via photon fusion have a relatively low cross section. For example, the predicted cross section for CEP of top quark–antiquark pairs is of the order of 0.1 fb. A search for this process was performed early this year using about 30 fb^{-1} of CMS data recorded in 2017, with protons tagged by PPS. While the sensitivity of the analysis is not sufficient to test the SM prediction, it can probe possible enhancements due to additional contributions from new physics. Also, the analysis established tools with which to search for exclusive production processes in a multi-jet environment using machine-learning techniques.

CERNCOURIER.COM

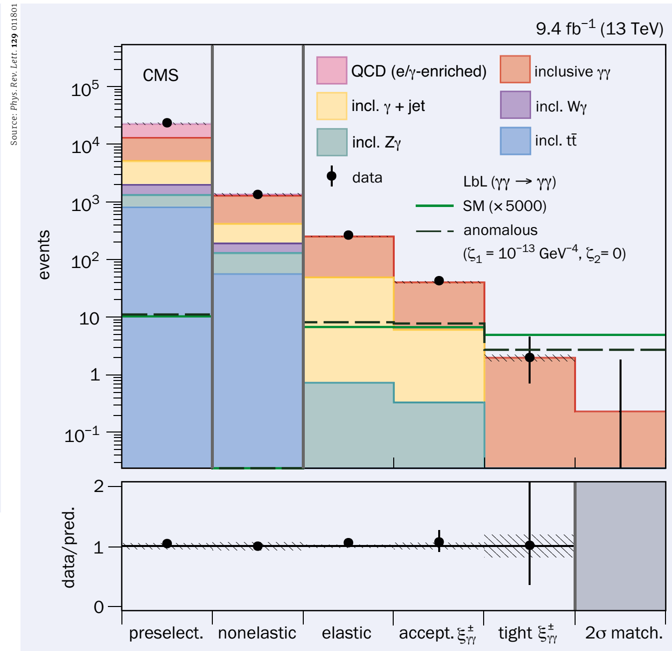
FEATURE DETECTORS



Photon fusion *Diagrams showing different final states produced via photon–photon fusion probed by CMS.*



Tagging exclusive events *When particles are produced exclusively, proton momentum loss ξ can be reconstructed from the central system or the intact proton. The dotted line illustrates the case of a perfect correlation, where exclusive events are expected.*



Exclusive identification *The number of background events expected in the di-photon exclusive production analysis, with each bin representing a different step in the selection procedure. The rightmost bin corresponds to the final selection, where kinematics matching between the proton–proton and di-photon systems is needed: this requirement almost completely rejects any residual background. Points with error bars indicate the number of events observed in data, showing no significant excess over the predicted background.*

Uncharted domains

The SM provides very accurate predictions for processes occurring at the LHC. Yet, it cannot explain the origin of several observations such as the existence of dark matter, the matter–antimatter asymmetry in the universe and neutrino masses. So far, the LHC experiments have been unable to provide answers to those questions, but the search is ongoing. Since physics with PPS mostly targets photon collisions, the only assumption is that the new physics is coupled to the electroweak sector, opening a plethora of opportunities for new searches.

Photon–photon scattering has already been observed in heavy-ion collisions by the LHC experiments, for example by ATLAS (*CERN Courier* December 2016 p9). But new physics would be expected to enter at higher di-photon masses, which is where PPS comes into play. Recently, a search for di-photon exclusive events was performed using about 100 fb^{-1} of CMS data at a di-photon mass greater than 350 GeV, where SM contributions are negligible. In the absence of an unexpected signal, a new best limit was set on anomalous four-photon coupling parameters. In addition, a limit on the coupling of axion-like particles to photon was set in the mass region 500–2000 GeV. These are the most restrictive limits to date.

A new, interesting possibility to look for unknown particles is represented by the "missing mass" technique. The exclusivity of CEP makes it possible, in two-particle final states, to infer the four-momentum of one particle if the other is measured. This is done by exploiting the fact that, if the protons are measured and the beam energy is known, the kinematics of the centrally produced final state can be determined: no direct measurements of the second particle are required, allowing us to "see the unseen". This technique was demonstrated for the first time at the

LHC this year, using around 40 and 2 fb^{-1} of Run 2 data in a search for $pp \rightarrow pZXp$ and $pp \rightarrow p\gamma Xp$, respectively, where X represents a neutral, integer-spin particle with an unspecified decay mode. In the absence of an observed signal, the analysis sets the first upper limits for the production of an unspecified particle in the mass range 600–1600 GeV.

Looking forward with PPS

For LHC Run 3, which began in earnest on 5 July, the PPS team has implemented several upgrades to maximise the physics output from the expected increase in integrated luminosity. The mechanics and readout electronics of the pixel tracker have been redesigned to allow remote shifting of the sensors in several small steps, which better distributes the radiation damage caused by the highly non-uniform irradiation. All timing stations are now equipped with "double diamond" sensors, and from 2023 an additional, second station will be added to each PPS arm. This will improve the resolution of the measured arrival time of protons, which is crucial for reconstructing the z coordinate of a possible common vertex, by at least a factor of two. Finally, a new software trigger has been developed that requires the presence of tagged protons in both PPS arms, thus allowing the use of lower energy thresholds for the selection of events with two particle jets in CMS.

The sensitivity in many channels is expected to increase by a factor of four or five compared to that in Run 2, despite only a doubling of the integrated luminosity. This significant increase is due to the upgrade of the detectors, especially of the timing stations, thus placing PPS in the spotlight of the Run 3 research programme. Timing detectors also play a crucial role in the planning for the high-luminosity LHC (HL-LHC) phase. The CMS collaboration has released an expression of interest to pursue studies of CEP at the HL-LHC with the ambitious plan of installing near-beam proton spectrometers at 196, 220, 234, and 420 m from the interaction point. This would extend the accessible mass range to the region between 50 GeV and 2.7 TeV. The main challenge here is to mitigate high "pileup" effects using the timing information, for which new detector technologies, including synergies with the future CMS timing detectors, are being considered.

PPS significantly extends the LHC physics programme, and is a tribute to the ingenuity of the CMS collaboration in the ongoing search for new physics. ●

THE AUTHORS

Michele Arneodo *Università del Piemonte Orientale and INFN Torino;* **Michael Pitt** *CERN;* **Enrico Robutti** *INFN Genova; and* **Ksenia Shchelina** *INFN Torino.*

Further reading

CMS and TOTEM Collab. 2022 CMS-PAS-EXO-19-009.
CMS and TOTEM Collab. 2022 CMS-PAS-EXO-21-007.
CMS and TOTEM Collab. 2022 CMS-PAS-SMP-21-014.
CMS and TOTEM Collab. 2022 CMS-PAS-TOP-21-007.
CMS Collab. 2021 CMS-NOTE-2020-008.

Science for peace? More than ever!

Somehow and sometime there will be a solution to the Russian invasion, says Herwig Schopper, and scientists have a special responsibility to build a new world out of the ruins.

CERN-PHOTO-201906-169-6

Herwig Schopper *was CERN Director-General from 1981 to 1988, and is a founder of SESAME and the future SEEIIST facility.*

What happened? A tragedy fell upon Ukraine and found many in despair or in a dilemma. After 70 mainly peaceful years for much of Europe, we were surprised by war, because we had forgotten that it takes an effort to maintain peace.

Having witnessed the horrors of war first hand, several years as a soldier and then as a displaced person, I could not imagine that humanity would unleash another war on the continent. As one of its last witnesses, I wonder what advice should be passed on, especially to younger colleagues, about what to do in the short term, and perhaps more importantly, what to do afterwards.

Scientists have a special responsibility. Fortunately, there is no doubt today that science is independent of political doctrines. There is no "German physics" any more. We have established human relationships with our colleagues based on our enthusiasm for our profession, which has led to mutual trust and tolerance.

This has been practised at CERN for 70 years and continued at SESAME, where delegates from Israel, Palestine, Iran, Cyprus, Turkey and other governments sit peacefully around a table. Another offshoot of CERN, the South East European International Institute for Sustainable Technologies (SEEIIST), is in the making in the Balkans. Apart from fostering science, the aim is to transfer ethical achievements from science to politics: science diplomacy, as it has come to be known. In practice, this is done, for example, in the CERN Council where each government sends a representative and an additional scientist who work effectively together on a daily basis.

The aim is to transfer ethical achievements from science to politics

In the case of imminent political conflicts, "Science for Peace" cannot of course help immediately, but occasionally opportunities arise even for this. In 1985, when disarmament negotiations between Gorbachev and Reagan in Geneva reached an impasse, one of the negotiators asked me to invite the key experts to CERN on neutral territory, and at a confidential dinner the knot was untied. This showed how trust built up in scientific cooperation can impact politics.

Hot crises put us in particularly difficult dilemmas. It is therefore understandable that the CERN Council has to follow, to a large extent, the guidelines of the individual governments and sometimes introduce harsh sanctions. This leads to considerable damage for many excellent projects, which should be mitigated as much as possible. But it seems equally important to prevent or at least alleviate human suffering among scientific colleagues and their families, and in doing so we should allow them tolerance and full freedom of expression. I am sure the CERN management will try to achieve this, as in the past.

Day after

But what I consider most important is to prepare for the situation after the war. Somehow and sometime there will be a solution to the Russian invasion. On that "day after", it will be necessary to talk to each other again and build a new world out of the ruins. This was facilitated after World War II because, despite the Nazi reign of terror, some far-sighted scientists maintained human relations as well as scientific ones. I remember with pleasure how I was invited to spend a sabbatical year in 1948 in Sweden with Lise Meitner. I was also one of the first German citizens to be invited to a scientific conference in Israel in 1957, where I was received without resentment.

CERN was the first scientific organisation whose mission was not only to conduct excellent science, but also to help improve relations between nations. CERN did this initially in Europe with great success. Later, during the most intense period of the Cold War, it was CERN that signed an agreement with the Russian laboratory in Serpukhov in the 1960s. Together with contacts with JINR in Dubna, this offered one of the few opportunities for scientific West–East cooperation. CERN followed these principles during the occupation of the Czechoslovak Socialist Republic in 1968 and during the Afghanistan crisis in 1979.

CERN has become a symbol of what can be achieved when working on a common project without discrimination, for the benefit of science and humanity. In recent decades, when peace has reigned in Europe, this second goal of CERN has somewhat receded into the background. The present crisis reminds us to make greater efforts in this direction again, even more so when many powers disregard ethical principles or formal treaties by pretending that their fundamental interests are violated. Science for Peace tries to help create a minimum of human trust between governments. Without this, we run the risk that future political treaties will be based only on deterrence. That would be a gloomy world.

A vision for the day after requires courage and more Science for Peace than ever before.

OPINION
INTERVIEW

Counting down to LISA

As the LISA gravitational-wave observatory moves into its final design phase, Stefano Vitale describes the immense achievements so far and the challenges ahead in preparing a 2.5 million km-long interferometer in space.

What is LISA?

LISA (Laser Interferometer Space Antenna) is a giant Michelson interferometer comprising three spacecraft that form an equilateral triangle with sides of about 2.5 million km. You can think of one satellite as the central building of a terrestrial observatory like Virgo or LIGO, and the other two as the end stations of the two interferometer arms. Mirrors at the two ends of each arm are replaced by a pair of free-falling test masses, the relative distance between which is measured by a laser interferometer. When a gravitational wave (GW) passes, it alternately stretches one arm and squeezes the other, causing these distances to oscillate by an almost imperceptible amount (just a few nm). The nature and position of the GW sources is encoded in the time evolution of this distortion. Unlike terrestrial observatories, which keep their arms locked in a fixed position, LISA must keep track of the satellite positions by counting the millions of wavelengths by which their separation changes each second. All interferometer signals are combined on the ground and a sophisticated analysis is used to determine the differential distance changes between the test masses.

S Vitale

Looking forward *Stefano Vitale of the University of Trento is co-lead of the LISA consortium and principal investigator for LISA Pathfinder.*

What will LISA tell us that ground-based observatories can't?

Most GW sources, such as the merger of two black holes detected for the first time by LIGO and Virgo in 2015, consist of binary systems; as the two compact companions spiral into each other, they generate GWs. In these extreme binary mergers, the frequency of the GWs decrease both with the increasing mass of the objects and with increasing distance from their final merger. GWs with frequencies down to about a few Hz, corresponding to objects with masses up to a few thousand solar masses, are detectable from the ground. Below that, however, Earth's gravity is too noisy. To access milli-Hertz and sub-milli-Hertz frequencies we need to go to space. This low-frequency regime is the realm of supermassive objects with millions of solar masses located in galactic centres, and also where tens of thousands of compact objects in our galaxy, including some of the Virgo/LIGO black holes, emit their signals for years and centuries as they peacefully rotate around each other before entering the final few seconds of their collapse. The LISA mission will therefore be highly complementary to existing and future ground-based observatories such as the Einstein Telescope. Theorists are excited about the physics that can be probed by multiband GW astronomy.

When and how did you get involved in LISA?

LISA was an idea by Pete Bender and colleagues in the 1980s. It was first proposed to the European Space Agency (ESA) in 1993 as a medium-sized mission, an envelope that it could not possibly fit. Nevertheless, ESA got excited by the idea and studies immediately began toward a larger mission. I became aware of the project around that time, immediately fell in love with it and, in 1995, joined the team of enthusiastic scientists, led by Karsten Danzmann. At the time it was not clear that a detection of GWs from ground was possible, whereas unless general relativity was deadly wrong, LISA would certainly detect binary systems in our galaxy. It soon became clear that such a daring project needed a technology precursor, to prove the feasibility of test-mass freefall. This built on my field of expertise, and I became principal investigator, with Karsten as a co-principal investigator, of LISA Pathfinder.

What were the key findings of LISA Pathfinder?

Pathfinder essentially squeezed one of LISA's arms from millions of kilometres to half a metre and placed it into a single spacecraft: two test masses in a near-perfect gravitational freefall with their relative distance tracked by a laser interferometer. It launched in December 2015 and exceeded all expectations. We were able to control and measure the relative motion of the test masses with unprecedented accuracy using innovative technologies comprising capacitive sensors, optical metrology and a micro-Newton thruster system, among others. By reducing and eliminating all sources of disturbance, Pathfinder observed the most perfect freefall ever created: the test masses were almost motionless with respect to each other, with a relative acceleration less than a millionth of a billionth of Earth's gravitational acceleration.

What is LISA's status today?

LISA is in its final study phase ("B1") and marching toward adoption, possibly late next year, after which ESA will release

CERNCOURIER
VOLUME 62 NUMBER 5 SEPTEMBER/OCTOBER 2022
IOP Publishing

the large industrial contracts to build the mission. Following Pathfinder, many necessary technologies are in a high state of maturity: the test masses will be the same, with only minor adjustments, and we also demonstrated a pm-resolution interferometer to detect the motion of the test masses inside the spacecraft – something we need in LISA, too. What we could not test in Pathfinder is the million-kilometre-long pm-resolution interferometer, which is very challenging. Whereas LIGO's 4 km-long arms allow you to send laser light back and forth between the mirrors and reach kW powers, LISA will have a 1 W laser: if you try to reflect it off a small test-mass 2.5 million km away, you get back just 20 photons per second! The instrument therefore needs a transponder scheme: one spacecraft sends light to another, which collects and measures the frequency to see if there is a shift due to a passing GW. You do this with all six test masses (two per spacecraft), combining the signals in one heck of an analysis to make a "synthetic" LIGO. Since this is mostly a case of optics, you don't need zero-g space tests, and based on laboratory evidence we are confident it will work. Although LISA is no longer a technology-research project, it will take a few more years to iron out some of the small problems and build the actual flight hardware, so there is no shortage of papers or PhD theses to be written.

How is the LISA consortium organised?
ESA's science missions are often a collaboration in which ESA builds, launches and operates the satellite and its member states – via their universities and industries – contribute all or part of the scientific instruments, such as a telescope or a camera. NASA is a major partner with responsibilities that include the lasers, the device to discharge the test masses as they get charged up by cosmic rays, and the telescope to exchange laser beams among the satellites. Germany, which holds the consortium's leadership role, also shares responsibility for a large part of the interferometry with the UK. Italy leads the development of the test-mass system; France the science data centre and the sophisticated ground testing of LISA optics; and Spain the science-diagnostics development. Critical hardware components are also contributed by Switzerland, the Netherlands, Belgium, the Czech Republic, Denmark and Poland, while scientists worldwide contribute to various aspects of the preparation of mission operation, data analysis and science utilisation. The LISA consortium has around 1500 members.


Lock and load *LISA Pathfinder being encapsulated within its Vega rocket fairing in 2015 at Europe's Spaceport in Kourou, French Guiana.*

ESA–CNES–Arianespace/Optique Vidéo du CSG

What is the estimated cost of the mission, and what is industry's role?
A very crude estimate of the sum of ESA, NASA and member-state contributions may add up to something below two billion dollars. One of the main drivers of ESA's scientific programme is to maintain the technological level of European aerospace, so the involvement of industry, in close cooperation with scientific institutes, is crucial. After having passed the adoption phase, ESA will grant contracts to prime industrial contractors who take responsibility for the mission. To foster industrial competition during the study phase, ESA has awarded contracts to two independent contractors, in our case Airbus and Thales Alenia. In addition, international partners and member-state contributions often, if not always, involve industry.

There is no other space mission with as many papers published about its science expectations before it even leaves the ground

What scientific and technological synergies exist with other fields?
LISA will look for deviations from general relativity, in particular the case where compact objects fall into a supermassive black hole. In terms of their importance, deviations in general relativity are a very close cousin of deviations from the Standard Model of particle physics. Which will come first we don't know, but LISA is certainly an outstanding laboratory for fundamental gravitational physics. Then there are expectations for cosmology, such as tracing the history of black-hole formation or maybe detecting stochastic backgrounds of GWs, such as "cusps" predicted in string theory. Wherever you push the frontiers to investigate the universe at large, you push the frontiers of fundamental interactions – so it's not surprising that one of our best cosmologists now works at CERN! Technologically speaking, we just started a collaboration with CERN's vacuum group. In LISA we have a tiny vacuum volume in the region where the test masses are located, and it is full of components and cables. It was a big challenge for Pathfinder, but for LISA we definitely need to understand more. The CERN vacuum group is really interested in understanding this, so we are very happy with this new collaboration. As with LIGO, Advanced Virgo and the Einstein Telescope, LISA is a CERN-recognised experiment.

What's the secret to maintaining the momentum in a complex, long-term global project in fundamental physics?
The LISA mission is so fascinating that it is "self-selling". Scientists liked it, engineers liked it, industry liked it, space agencies like it. Obviously Pathfinder helped a lot – it meant that even in the darkest moments we knew we were "real". But in the meantime, our theory colleagues did so much work. As far as I know, there is no other space mission with as many papers published about its science expectations before it even leaves the ground. It's not just that the science is inspiring, but the fact that you can calculate things. The instrumentation is also so fascinating that students want to do it. With Pathfinder, we faced many difficulties. We were naïve in thinking that we could take this thing that we built in the lab and turn it into an industrial project. Of course we needed to grow and learn, but because we loved the project so much, we never ever gave up. One needs this mind-set and resilience to make big scientific projects work.

When do you envision launch?
Currently it's planned for the mid-2030s. This is a bit in the future at my age, but I am grateful to have seen the launch of LISA Pathfinder and I am happy to think that many of my young colleagues will see it, and share the same emotions we did with Pathfinder, as a new era in GW astronomy opens up.

Interview by **Kristiane Bernhard-Novotny** *associate editor.*

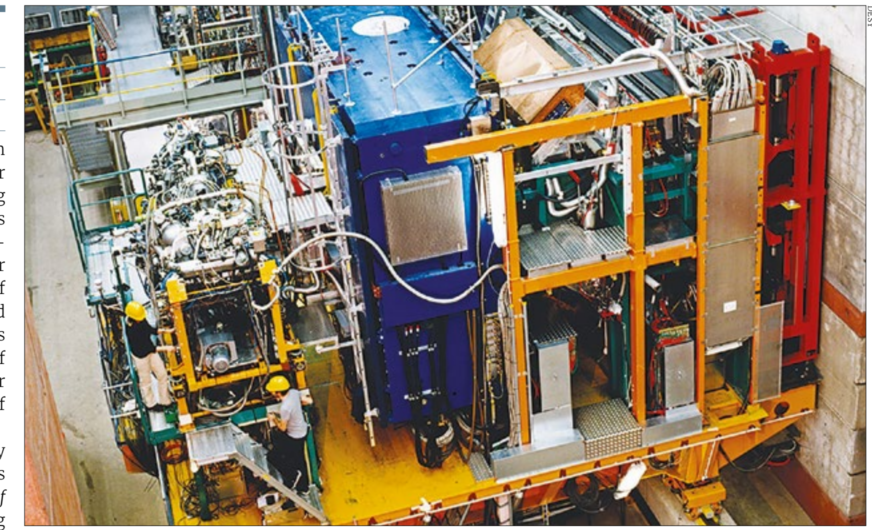
OPINION REVIEWS

Hymn to HERMES

The HERMES experiment – A Personal Story

By Richard Milner, Erhard Steffens

World Scientific


Spin messenger *The former HERMES detector at DESY's HERA collider collected data from the scattering of longitudinally polarised electrons on various polarised and unpolarised gas targets.*

DESY

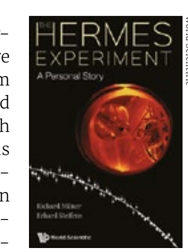
One hundred years ago, Otto Stern and Walther Gerlach performed their ground-breaking experiment shooting silver atoms through an inhomogeneous magnetic field, separating them according to their spatially quantised angular momentum. It was a clear victory of quantum theory over the still widely used classical picture of the atom. The results also paved the way to the introduction of the concept of spin, an intrinsic angular momentum, as an inherent property of subatomic particles.

The idea of spin was met with plenty of scepticism. Abraham Pais noted in his book *George Uhlenbeck and the Discovery of Electron Spin* that Ralph Kronig finishing his PhD at Columbia University in 1925 and travelling through Europe, introduced the idea to Heisenberg and Pauli, who drily commented that "it is indeed very clever but of course has nothing to do with reality". Feeling ridiculed, Kronig dropped the idea. A few months later, still against strong resistance by established experts but this time with sufficient backing by their mentor Paul Ehrenfest, Leiden graduate-students George Uhlenbeck and Samuel Goudsmit published their seminal *Nature* paper on the "spinning" electron. "In the future I shall trust my own judgement more and that of others less," wrote Kronig in a letter to Hendrik Kramers in March 1926.

Spin crisis

Spin quickly became a cornerstone of 20th-century physics. Related works of paramount importance were Pauli's exclusion principle and Dirac's description of relativistic spin-1/2 particles, as well as the spin-statistics theorems (namely the Fermi–Dirac and Bose–Einstein distributions for identical half-integer-spin and integer-spin particles, respectively). But more than half a century after its introduction, spin re-emerged as a puzzle. By then, a rather robust theoretical framework, the Standard Model, had been established within which many precision calculations became a comfortable standard. It could have been all that simple: since the proton consists of two valence-up and one valence-down quarks, with spin up and down (i.e. parallel and antiparallel to the proton's spin, respectively), the origin of its spin is easily explained. The problem dubbed "spin crisis" arose in the late 1980s, when the European Muon Collaboration at CERN found that the contribution of quarks to the proton spin was consistent with zero, within the then still-large uncertainties, and that the so-called Ellis–Jaffe sum rule – ultimately not fundamental but model-dependent – was badly violated. What had been missed?

Today, after decades of intense experimental and theoretical work, our picture of the proton and its spin emerging from high-energy interactions has changed substantially. The role of gluons both in unpolarised and polarised protons is non-trivial. More importantly, transverse degrees of freedom, both in position and momentum space, and the corresponding role of orbital angular momentum, have become essential ingredients in the modern description of the proton structure. This description goes beyond the picture of collinearly moving partons encapsulated by the fraction of the parent proton's momentum and the scale at which they are probed; numerous effects, unexplainable in the simple picture, have now become theoretically accessible.



World Scientific

Understanding the mysteries

The HERMES experiment at DESY, which operated between 1995 and 2007, has been a pioneer in unravelling the mysteries of the proton spin, and the experiment is the protagonist in a new book by Richard Milner and Erhard Steffens, two veterans in this field as well as the driving forces behind HERMES. The subtitle and preface clarify that this is a personal account and recollection of the history of HERMES, from an emergent idea on both sides of the Atlantic to a nascent collaboration and experiment, and finally as an extremely successful addition to the physics programme of HERA (the world's only lepton–proton collider, which started running at DESY 30 years ago for one and a half decades).

CERNCOURIER
VOLUME 62 NUMBER 5 SEPTEMBER/OCTOBER 2022

IOP Publishing

Milner and Steffens are both experts on polarised gas targets, with complementary backgrounds leading to rather different perspectives. Indeed, HERMES was independently developed within a North American initiative, in which Milner was the driving force, and a European initiative around the Heidelberg MPI-K led by Klaus Rith, with Erhard Steffens as a long-time senior group member. In 1988 two independent letters of intent submitted to DESY triggered sufficient interest in the idea of a fixed-target experiment with a polarised gas target internal to the HERA lepton ring; the proponents were subsequently urged to collaborate in submitting a common proposal. In the meantime, HERMES' feasibility needed to be demonstrated. A sufficiently high lepton-polarisation had to be established, as well as smooth running of a polarised gas target in the harsh HERA environment without disturbing the machine and the main HERA experiments H1 and Zeus.

By summer 1993, HERMES was fully approved, and in 1995 the data taking started with polarised ^{3}He. The subsequently used target of polarised hydrogen or deuterium employed the same concepts that Stern and Gerlach had already used in their famous experiment. The next decade saw several upgrades and additions to the physics programme, and data taking continued until summer 2007. In all those years, the backbone of HERMES was an intense and polarised lepton beam that traversed a target of pure gas in a storage cell, highly polarised or unpolarised, avoiding extensive and in parts model-dependent corrections. This constellation was combined with a detector that, from the very beginning, was designed to not only detect the scattered leptons but also the "spray" produced in coincidence. These features allowed a diverse set of processes to be studied, leading to numerous pioneering measurements and insights that motivated, and continue to motivate, new experimental programmes around the world, including some at CERN.

The HERMES experiment has been a pioneer in unravelling the mysteries of the proton spin

Richard Milner and Erhard Steffens provide extensive insights, in particular into the historic aspects of HERMES, which are difficult to obtain elsewhere. The book gives an insightful discussion of the installation of the experiment and of the outstanding efforts of a group of highly motivated and dedicated individuals who worked too often in complete ignorance of (or in defiance of) standard working hours. Their account enthrals the reader with vivid anecdotes, surprising twists and personal stories, all told in a colloquial style. While clearly not meant as a textbook – indeed, one might notice small mistakes and inconsistencies in a few places – this book makes for worthwhile and enjoyable reading, not only for people familiar with the subject but equally for outsiders. In particular, younger generations of physicists working in large-scale collaborations might be surprised to learn that it needs only a small group and little time to start an experiment that goes on to have a tremendous impact on our understanding of nature's basic constituents.

Gunar Schnell *University of the Basque Country and Ikerbasque.*

Parallels

Directed by Benjamin Rocher and Jean-Baptiste Saurel and screened on Disney+

Disney

Released in March 2022 on Disney+, *Parallels* merges two of the most popular concepts in science fiction: time travel and the multiverse. The series, in French, created by Quoc Dan Trang and directed by Benjamin Rocher and Jean-Baptiste Saurel, is set in a village in the mountains of the French–Swiss border where a particle-physics laboratory called "ERN" and a collider strongly resembling the LHC have a major role.

The story begins with a group of four friends who recently graduated from middle school celebrating one of their birthdays near an area where, 10 years earlier, a kid called Hugo disappeared. At the same time, ERN is performing an experiment with its particle accelerator. However, something goes wrong. The lights go out in the village, while a strange space–time phenomenon unfolds, transporting the teenagers to different timelines once the lights are restored. Does this have anything to do with the particle accelerator? Where, or rather "when" are they? Each of the teenagers tries to unravel their temporal confusion in an attempt to return to their original timeline.

Although the age of the main characters targets younger audiences, *Parallels* addresses topics such as depression, regret and family issues, which, combined with some humour, make it relevant to other age groups. The visual effects and music create a suspenseful atmosphere and the compact nature of the series (six episodes of around 35 minutes each) draws the viewer into watching it in a single session.

CERN's experiments and locations are referenced several times throughout, ranging from visual details in the ERN buildings to mentions of ATLAS, CMS and the Antiproton Decelerator – going so far as to reference an "FCC scheduled for operations in October 2025". The Globe of Science and Innovation and the CMS silicon tracker are also represented.

Many of the concepts introduced, especially those related to the LHC experiments, are not scientifically accurate. The clear depiction of CERN in all but name may also make some physicists feel uncomfortable, given that the plot plays on YouTube-based conspiracy theories about what CERN's experiments are capable of. For young science-fiction lovers, however, and especially for those who love to unravel temporal paradoxes, as in the popular Netflix series *Stranger Things*, *Parallels* is worth a look. For the more inquisitive and open-minded viewer, it also offers a chance to go beyond fiction and explore the often even more incredible ideas explored for real in particle physics.

***Parallels* offers a chance to go beyond fiction and explore the often even more incredible ideas explored for real in particle physics**

Bryan Pérez Tapia *editorial assistant.*

Your guide to becoming a CERN guide

If a technical student based at CERN for just one year can become a fully-fledged CERN guide, says Bryan Pérez Tapia, then so can you!

Do you remember the first time you heard about CERN? The first time someone told you about that magical place where bright minds from all over the world work together towards a common goal? Perhaps you saw a picture in a book, or had the chance to visit in person as a student? It is experiences like these that motivate many people to pursue a career in science, whether in particle physics or beyond.

In 2016 I had the pleasure of visiting CERN on a school trip. We toured the Synchrocyclotron and the SM18 magnet test facility. I was hooked. The tour guides talked with passion about the laboratory, the film presenting CERN's first particle accelerator and the laboratory's mission, and all those big magnets being tested in SM18. It was this experience that motivated me to study physics at university and to try to come back as soon as I could.

Accreditation

That chance arrived in September 2021 when I started a one-year technical studentship as editorial assistant on the *Courier*. From the first day I was eager to see as much as I could. During the final months of Long Shutdown 2, my supervisor and I visited the ATLAS cavern. The experience motivated me to ask one of my newly made friends, also a technical student who had recently become a tour guide, how to apply. The process was positive and efficient. After completing all the required courses from the learning hub and shadowing experienced guides, I became a certified ATLAS underground guide in November 2021 and gave my first tour soon after. I was nervous and struggled with the iris scanner when accessing the cavern, but all ended well, and further tours were scheduled. Then, in mid-December, all in-person tours were cancelled due to COVID-19 restrictions. I needn't have worried, as CERN was fully geared up to provide virtual visits. Among my first virtual audience members were students from the high school that brought me to CERN five years earlier and from my university, Nottingham Trent in the UK.

B Pérez Tapia

Going underground *Bryan Pérez Tapia in the ATLAS cavern in December 2021.*

The most satisfying thing is people's enthusiasm and their desire to learn more about CERN and its mission

The virtual visits were quite challenging at first. It was harder to connect with the audience than during an in-person visit. But managing these difficulties helped me to improve my communication skills and to develop self-confidence. During this period, I conducted more than 10 virtual visits for different institutes, universities, family and friends, in both English and Spanish.

At the beginning of March 2022, CERN moved into "level yellow" and in-person visits were resumed. Although only possible for a short period, I had the chance to guide visitors underground and had the honour of guiding the last in-person visit into the ATLAS cavern on 23 March before preparations for LHC Run 3 got under way. With the ATLAS cavern then off-limits, I signed up to present at as many CERN visit points as possible. At the time of writing, I am a guide for the Synchrocyclotron, the ATLAS Visitor Centre, Antimatter Factory, Data Centre, Low Energy Ion Ring and CERN Control Centre.

Get involved

The CERN visits service always welcomes new guides and is working towards opening new visit points. Anyone working at CERN or registered as a user can take part by signing up for visit-point training on the tour-guide website: guides.web.cern.ch. General training for new guides is also available. All you need to show CERN to the public is passion and enthusiasm, and you can sign up for as many or as few as your day job allows. Diversity is encouraged and those who are multilingual are also highly valued.

Today, visits are handled by a dedicated section in the Education, Communications and Outreach group. The number of visitors has gradually increased over recent years, with 152,000 annual visitors before the pandemic started, excluding special events such as the CERN Open Days. The profile of visitors ranges from school pupils and university students to common-interest groups such as engineers and scientists, politicians and VIPs, and people with a wide range of interests and educational levels.

The benefits of becoming a CERN guide are immense. It gives you access to areas that would otherwise not be possible, the chance to experience important events in-person and to see your work at CERN, whatever it involves, from a fresh perspective. My personal highlight was watching test collisions at 13.6 TeV before the official start of Run 3 while showing Portuguese high-school students the ATLAS control room. The most satisfying thing is people's enthusiasm and their desire to learn more about CERN and its mission. I particularly remember how a small child asked me a question about the matter–antimatter asymmetry of the universe, and how another young visitor ran from Entrance B at the end of a tour just to tell me how much she loved the visit.

The visits service makes it as easy as possible to get involved, and exciting times for guides lie ahead with the opening of the CERN Science Gateway next year, which will enable CERN to welcome even more visitors. If a technical student based at CERN for just one year can get involved, so can you!

Bryan Pérez Tapia *editorial assistant.*

CERNCOURIER
VOLUME 62 NUMBER 5 SEPTEMBER/OCTOBER 2022
IOP Publishing

Appointments and awards

SNOLAB

Jodi Cooley leads SNOLAB
Jodi Cooley (Southern Methodist University and deputy operations manager for the SuperCDMS collaboration) has been appointed executive director of SNOLAB for a period of five years. The position is effective from 1 August, succeeding interim executive director Clarence Virtue. Following her PhD in 2003 based on measurements of neutrinos from diffuse astronomical sources with the AMANDA-II detector, Cooley held postdoc positions in MIT and Stanford. She arrives at SNOLAB at a critical moment as the underground laboratory moves into a new five-year strategic planning period. "SNOLAB plays a unique and vital role in both the international astroparticle physics community and in Canada's research ecosystem, and I look forward to continuing this legacy of excellence," she said.

Next ALICE spokesperson
Marco van Leeuwen (Nikhef) has been elected ALICE spokesperson, effective from January 2023 for a period of three years. Previously ALICE physics coordinator and

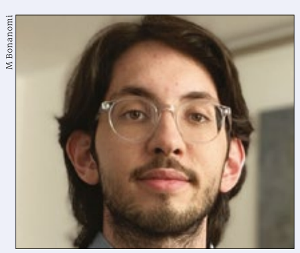
M van Leeuwen

currently upgrade coordinator, he will take over from current spokesperson Luciano Musa. Van Leeuwen obtained his PhD at Utrecht University in 2003 working on the NA49 experiment. Later he joined Lawrence Berkeley Laboratory working on the STAR experiment at RHIC, before joining ALICE in 2005. He highlights three key challenges for the collaboration during his term as spokesperson: the efficient operation of the detector during LHC Run 3, data analysis and the production of new scientific results, and the preparation of detector upgrades for Run 4 and Run 5.

CMS recognises young researchers
The CMS collaboration has announced the recipients of its 2021 thesis awards, selecting three outstanding PhD students from a total of 25 nominations. Michael Andrews (below; Carnegie Mellon University)

M Andrews

developed a novel algorithm for particle reconstruction based on deep-learning models trained on "raw" detector data to measure the invariant mass of merged pairs of photons, a measurement not previously possible at CMS. Matteo Bonanomi (below; LLR – Institut Polytechnique de Paris) analysed Higgs-boson decays via the so-called golden channel, where a Higgs boson decays into two Z bosons, which consequently decay into two pairs of opposite-sign leptons. Finally, working on detector upgrades for the high-luminosity LHC era, Viktoria Hinger (above; HEPHY) developed a compact set of test structures



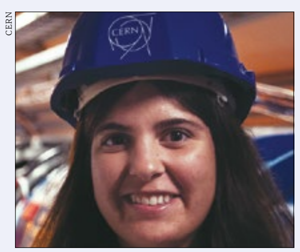
M Bonanomi

that allows the quality assurance of thousands of position-sensitive silicon sensors. The CMS collaboration also announced the winners of its 2022 Young

ÖAW/Klaus Pichler

Researchers Prize, recognising the outstanding achievements of its younger members: Davide Ceresa (CERN), Rajdeep Mohan Chatterjee (University of Minnesota), Jan Keseler (CERN) and Yuta Takahashi (University of Zurich).

LHCb thesis and early-career awards
On 14 June the LHCb collaboration – which comprises more than 1000 authors and 400 PhD students – announced the winners of its 2022 PhD Thesis and Early-Career Scientist Awards. The thesis prize went to Giulia Tulci (below; Pisa), Guillaume Pietrzyk (above right; EPFL) and Mengzhen Wang (Tsinghua).



CERN

"The thesis prize is awarded to students who have performed exceptional research in their PhD and contributed fully to the collaboration," explains Ulrik Egede, chair of the award committee. "This year's winners worked in charm CP violation and mixing and complex amplitude analyses for spectroscopy, and also contributed to the trigger, novel FPGA-based tracking, outreach and the construction of the Upgrade I tracker." The prizes for outstanding contributions by early-career scientists were awarded to: Maarten van Veghel (Groningen), Saverio Mariani (Florence), Sevda Esen (Zurich), Valeriia Zhovkovska (Orsay), Maarten Van Dijk (Lausanne), Fabio Ferrari (Bologna) and Vladyslav Orlov (CERN), recognising improvements

Gaëlle Khreich IJCLab

to electron identification and reconstruction, real-time reconstruction of beam-gas collisions, the persistence of the data produced by the trigger and the development of LHCb's new luminometer system.

And the BL4S winners are…
Three teams of high-school students – from the Elsewedy Technical Academy (Cairo, Egypt), the École du Sacré-Coeur (Reims, France) and the Club de Física Enrico Fermi (Vigo, Spain) – have won the 2022 edition of the CERN Beamline for Schools (BL4S) competition. The prize is a trip to CERN for the Spanish and Egyptian teams, and to DESY for the French team, in autumn 2022, to perform their proposed experiments. The Egyptian team (the first Middle Eastern school to win the competition) will analyse the detection efficiency of multi-gap resistive plate chambers (MRPCs) based on environmentally friendly gases. The Spanish team will also work on MRPCs, investigating the charge induced by the passage of ultra-relativistic charged particles, while the French team will investigate the detection efficiency of water in the super-cooled state. The BL4S competition was launched in 2014 to commemorate the 60th anniversary of CERN, and the fruitful collaboration between CERN and DESY started in 2019.

RECRUITMENT

For advertising enquiries, contact *CERN Courier* recruitment/classified, IOP Publishing, 2 The Distillery, Glassfields, Avon Street, Bristol BS2 0GR, UK. Tel +44 (0)117 930 1264 E-mail sales@cerncourier.com.
Please contact us for information about rates, colour options, publication dates and deadlines.

CERNCOURIER
Volume 62 Number 5 September/October 2022
IOP Publishing

CERNCOURIER.COM

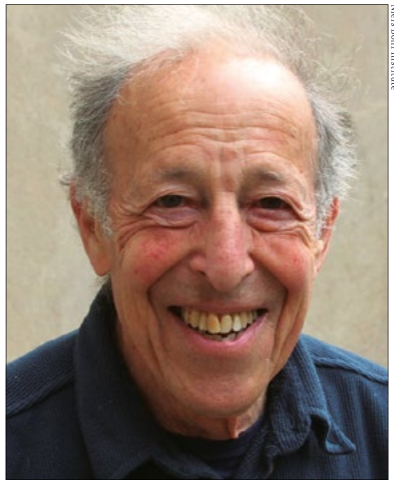
PEOPLE OBITUARIES

Ben Roy Mottelson 1926–2022

A decisive role in understanding the nucleus

Ben R Mottelson passed away on 13 May aged 95. He will be remembered as an outstanding physicist who played a decisive role in the understanding of atomic nuclei and as an inspiring and warm human being with an engaging and outgoing personality.

Ben Mottelson was born in Chicago in 1926 into a family where his father held a university engineering degree. He finished high school in 1944 and was drafted into the navy, which rapidly recognised the young man's potential and sent him to Purdue University to train as a naval officer. He completed his bachelor degree there in 1947 and subsequently obtained his PhD from Harvard University in 1950 with Julian Schwinger as his supervisor. He won a Sheldon travel fellowship and chose in 1950 to go to the Niels Bohr Institute in Copenhagen, where he was to remain the rest of his life, becoming a Danish citizen in 1971.



Niels Bohr Institute

Ben Mottelson shared the 1975 Nobel Prize in Physics.

After a number of temporary positions, Ben became a permanent member of CERN's theoretical study group, which was temporarily established in Copenhagen in 1953–1957 while the Geneva site was being completed. He became a tenured professor at Nordita, then the Nordic Institute for Theoretical (Atomic) Physics, at the Niels Bohr Institute in 1957 and headed Nordita from 1981 to 1983.

Ben had a close scientific collaboration and friendship with Aage Bohr, the son of Niels Bohr

In Copenhagen, he established a close scientific collaboration and friendship with Aage Bohr (1922–2009), the son of Niels Bohr. The pair worked on understanding the structure of atomic nuclei based on an interplay between collective and single-particle degrees of freedom which, as first pointed out by James Rainwater, might not all be spherical. A consequence of deformation would be the existence of rotational bands, as for molecules, which were discovered experimentally early in the 1950s using Coulomb excitation with the cyclotron at the Niels Bohr Institute. A central question was why the effective moment of inertia of a deformed atomic nucleus is smaller than for a rigid rotor. This was understood by Aage, Ben and David Pines in 1958 as a consequence of the pairing of nucleons leading to an energy gap, in analogy with the pair correlations between electrons in a superconductor.

In subsequent decades Aage and Ben refined the theoretical description of nuclei with a unified nuclear model that accounted for the variety of nuclear excitations in a coherent fashion, establishing a lively collaboration with experimentalists from all over the world. In 1975 Aage, Ben and David Pines were awarded the Nobel Prize in Physics for their work. Ben also received the Atoms for Peace award in 1969.

The partnership between Aage and Ben was fruitful in spite of their different personalities, Aage being the more reserved and Ben the more outgoing personality. The author of this obituary fondly remembers the pair attending the weekly experimental group meetings and attentively questioning all the speakers, sharing insights and always providing kind inspiration to both young and old. Later, Ben turned his attention to other manifestations of shell structure in mesoscopic systems of atomic clusters and to the properties of cold atomic Bose–Einstein gases. From 1993–1997 he was director of the ECT* theory centre, which he helped establish in Trento, Italy.

Ben Mottelson was an unpretentious, open and engaging family man. Until close to the end he continued to come regularly to the Niels Bohr Institute, attending seminars and scientific events, often to be seen on his bicycle. He will be sorely missed.

Jens Jørgen Gaardhøje *Niels Bohr Institute.*

Bernard Bigot 1950–2022

An inspirational leader across multiple fields

Director-general of the ITER Organization, Bernard Bigot, passed away on 14 May, aged 72. An inspirational leader for more than four decades across multiple fields of science and energy, his personal dedication and commitment to ITER over the past seven years shaped every aspect of the project. While his untimely passing will be felt as a tragic blow to the global fusion community, Bigot's careful design and preparation of the ITER senior management team in recent years gives reassurance for the project's continued success.

Bigot took the helm at ITER in March 2015 at a critical point in the project's history, when it was experiencing significant difficulties reflecting the managerial challenges inherent in both its complex engineering and its multinational approach to design, manufacturing and construction. He accepted these challenges with humility and unwavering resolve, proposing a multifaceted plan that transformed the project's culture. Today, ITER is more than 75% complete and stands as a monumental example of scientific and engineering prowess, and a testimony to the merits of international collaboration.

Trained as a physical chemist at the École ▷

normale supérieure, with a PhD in chemistry, Bigot had a deep understanding of the challenges that went with mastering hydrogen fusion. He was a high-ranking university professor at the École normale supérieure de Lyon, which he helped to establish and then directed for several years. The author of more than 70 publications in theoretical chemistry, Bigot was also in charge of research at the École normale supérieure, director of the Institut de recherche sur la catalyse (a CNRS laboratory specialising in catalysis research) and president of the Maison de la Chimie foundation.

The experience he acquired at the highest levels of the scientific and research establishment – as private secretary to ministers, high commissioner for atomic energy, chairman and CEO of the CEA, and as such the principal interface between France and ITER between 2008 and 2015 – had prepared him for the daunting task of leading a 35-nation, long-term endeavour, as unique in its goals as it is in its organisation and governance. However, the uniqueness of ITER required more than experience in science, the management of large institutions and the oversight of complex construction projects. ITER – particularly at the time Bigot took over – also demanded political finesse and diplomatic subtlety, qualities that he had in abundance. Always ready to exchange with media representatives, politicians, economists, VIPs or general visitors, he knew how to make complex subjects understandable and meaningful.


ITER Organization

Bernard Bigot successfully steered the ITER project through treacherous waters.

He received numerous awards, including his status as a Commander in the French Order of the Legion of Honour, a Commander in the Royal Swedish Order of the Polar Star, an Officer of the French Order of the National Merit, the holder of the Gold and Silver Star in the Japanese Order of the Rising Sun, and the recipient of the China Friendship Award. Beyond these achievements and accolades, he will be remembered as a visionary leader, intensely focused on the enhancement of global society and the desire to leave the world a better place. The greatest honour we can pay is to continue delivering the ITER project with the same unwavering commitment and dedication that he demonstrated to all of us.

Bernard Bigot was a man of duty and service, who placed loyalty above all virtues, a deeply human leader, as demanding of others as he was of himself. He will be deeply missed.

Based on materials provided by the ITER Organization.

Boris Lazarevich Ioffe 1926–2022

A life in theory

Leading Soviet particle physicist Boris Ioffe passed away in Moscow on 18 July at the age of 96.

Boris Ioffe was born in Moscow in 1926 into a Jewish family. In the late 1940s he passed Landau's famous "theoretical minimum" entry exam and in 1949 he graduated from Moscow State University with a diploma in theoretical physics. He started his research work under the supervision of Isaak Pomeranchuk. Between 1950 and 1955 Ioffe participated in the original Soviet nuclear-bomb project, at its later stage devoted to the hydrogen bomb. Until 18 July he was the only participant of this project still alive.

In 1960–1980 Ioffe was one of the leading Soviet particle physicists. He was a pioneer of parity (non-)conservation (with Okun and Rudik, 1957). His work with E Shabalin (1967) provided an impetus for the creation of the Glashow–Iliopoulos–Maiani mechanism. Ioffe's work on deep inelastic scattering (1969) helped establish the Bjorken scaling and the parton model of Feynman–Bjorken.

Ioffe was the last surviving member of the original Soviet nuclear-bomb project.

During the later stages of his career, Ioffe focused on quantum chromodynamics and its consequences for the theory of hadrons. His contributions to the theory of baryons are well-known and appreciated worldwide.

Ioffe never abandoned his early research in nuclear physics. In fact, he was an expert nuclear physicist and in the early 1970s was in charge of the physics design of the first commercial nuclear power plant in former Czechoslovakia. Since 1977 he was the head of the ITEP Laboratory for Theoretical physics, where he had a number of PhD students.

All his life Ioffe was a devoted mountaineer. It is hard to name a mountain peak that he had not conquered. His life journey was long, adventurous and misadventurous simultaneously. Ioffe's memoirs are available both in Russian and English.

Mikhail Shifman *University of Minnesota.*

Arthur M Poskanzer 1931–2021

A pioneer in high-energy nuclear collisions

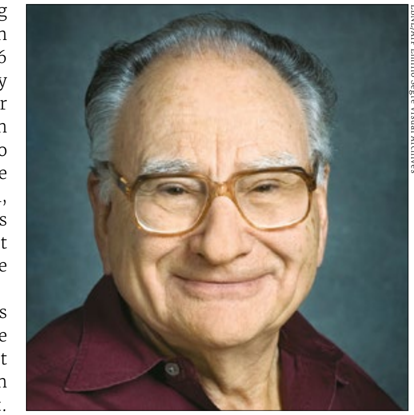
Arthur M (Art) Poskanzer, distinguished senior scientist emeritus at Lawrence Berkeley National Laboratory (LBNL), passed away peacefully on 30 June 2021, two days after his 90th birthday. Art had a distinguished career in nuclear physics and chemistry. He made important discoveries of the properties of unstable nuclei and was a pioneer in the study of nuclear collisions at very high energies.

Art worked on a ground-breaking experiment at the Proton Synchrotron measuring the masses of sodium isotopes

Born in New York City, Art received his degree in physics and chemistry from Harvard in 1953, an MA from Columbia in 1954, and a PhD in Chemistry from MIT in 1957 under Charles D Coryell. He spent the first part of his career studying the properties of nuclei far from stability produced in high-energy proton collisions. After graduating from MIT, he joined Gerhard Friedlander's group at Brookhaven ▷

National Laboratory (BNL), which was using the Cosmotron to produce beta-delayed proton emitters and neutron-rich light nuclei. In 1966 he moved to the Lawrence Radiation Laboratory (now LBNL) and continued to study nuclei far from stability at the Bevatron in collaboration with Earl Hyde, Joe Cerny and others. He also began his long connection to research in Europe as a Guggenheim fellow at Orsay in 1970–1971, during which he worked with Robert Klapisch's group on a ground-breaking experiment at the CERN Proton Synchrotron measuring the masses of sodium isotopes.

Soon after Art's return to Berkeley, beams from the SuperHILAC were injected into the Bevatron, creating the Bevalac, the world's first high-energy nuclear accelerator. Together with Hans Gutbrod he led the Plastic Ball Project. Analysis of its data in 1984 by Art and Hans Georg Ritter identified directed flow, the first definitive demonstration of the collective behaviour of nuclear matter in nuclear collisions. In 1986 the experiment was moved to CERN and the collaboration with GSI continued with a series of experiments at the Super Proton Synchrotron. During these years, Art made two more extended visits to CERN as a Senior Alexander von Humbold Fellow: first in 1986–1987 working on the WA80 experiment, and then in 1995–1996 on NA49.


LBNL/AIP Emilio Segrè Visual Archives

Art was a well-loved member of the heavy-ion community.

From 1990 to 1995 Art was the founding head of LBNL's relativistic nuclear collisions programme, bringing together local groups to plan an experiment at the Relativistic Heavy Ion Collider (RHIC) under construction at BNL. This resulted in the proposal for STAR, one of the two large multi-purpose RHIC detectors. Art stepped down as programme head in 1995 and returned to research, authoring a seminal paper with Sergey Voloshin on methods for flow analysis and leading the measurement of elliptic flow by STAR. After his retirement in 2002, he remained active for a further decade, leading the successful search for higher order flow components at STAR, and enthusiastically mentoring many postdocs and young scientists.

Art was a well-known and well-loved member of the heavy-ion community. For his work on nuclei far from stability, he was awarded the Nuclear Chemistry Prize of the American Chemical Society in 1980. For the discovery of collective flow, he was awarded the Tom Bonner Prize of the American Physical Society in 2008. This rare "double" is a lasting tribute to his half-century career at the frontiers of nuclear science.

James Symons *Lawrence Berkeley National Laboratory.*

CERNCOURIER
Volume 62 Number 5 September/October 2022
IOP Publishing

BACKGROUND

Notes and observations from the high-energy physics community

Tiny creatures

Y Amhis

Tiny creatures have arrived at CERN to brighten everyone's day. These curious and light-hearted figures, which were created by LHCb's Yasmine Amhis after participating in the 2021 "Inktober" drawing challenge, discuss science, ask questions and, like all good physicists, agree to be interviewed by the *Courier* (above). Amhis places the tiny creatures on typical CERN scenes, allowing herself a maximum of five minutes per sketch, and as well as hanging out on Twitter, they can be found at home on yasmineamhis.com.

Giant leap for lambkind

ESA

Ovine encounters *Training on a parabolic flight in 2019.*

Inspired by the 2019 film *Farmageddon*, Shaun the Sheep has been granted a place on NASA's uncrewed Artemis I mission, which is soon to make a lunar flyby. The full Artemis mission aims to revitalise lunar exploration, including the first crewed landing since Apollo 17 in 1972, with Shaun charting the adventure in a series of blog posts. "Although it might be a small step for a human, it's a giant leap for lambkind," said David Parker, director for human and robotic exploration at ESA, which will provide the service module for NASA's Orion spacecraft.

Media corner

"Personally, I am optimistic that the cracks in the Standard Model will add up to an earthquake. However, the exact position of the cracks may still be a moving target."

Theorist **Aida El-Khadra** speaking to *The New York Times* (13 June) about LHC Run 3.

"When I'm the only woman in a room, if I give the right answers or have the right insights, they're going to stop thinking of me as a woman and focus on what I contribute."

Fermilab director **Lia Merminga** tells *Physics World* (19 July) how gender has not been an obstacle in her career.

"We have a bit of a hangover from the Higgs discovery. But we're getting over it."

Jon Butterworth quoted in *New Scientist* magazine (27 June).

"To those who worry that particle physics could be approaching its last gasp, we urge you to allow science to take its course, to be prepared for surprises and to recall that it took more than four decades for one aspect of a theory to be confirmed by experiment."

A *Nature* editorial (5 July) dedicated to the 10th anniversary of the discovery of the Higgs boson.

From the archive: September/October 1982

Some of the little we know …

CERN 216.8.82

During the visit of Pope John Paul II to CERN on 15 June 1982, Director General Herwig Schopper presented him with a representation of a high energy proton–antiproton interaction, now seen in the SPS collider and believed to have been prevalent during the origin of the Universe, a period of vital interest to both science and religion.

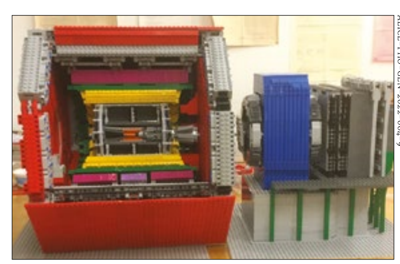
At the International Conference on High Energy Physics in Paris, July 1982, the emphasis was on improving the considerable level of agreement between experimental results and theoretical predictions. A conference novelty was a parallel session on the comparison of laboratory and cosmic ray data. The conventional picture of the unified electroweak force is beginning to look almost unassailable and the description of strong interactions in terms of the promising new theory of quantum chromodynamics QCD is gaining ground. However, lurking uncomfortably in the background are Higgs mesons, an essential part of the electroweak theory. With the underlying theories in such good shape, the intermediate bosons of weak interactions could soon be found, the sixth quark uncovered, and the reluctant Higgs bosons located.

● Based on text from *CERN Courier* September 1982 pp 261–362 and October 1982 pp311–316.

Compiler's note

All three of ICHEP's 1982 wishes have been granted. Within a few months, in May 1983, the W and Z electroweak bosons were found by UA1 and UA2 at CERN's SPS proton–antiproton collider. In February 1995, CDF and DØ announced the discovery of the top quark at the Fermilab Tevatron. And with yet another advance in accelerator technology, Higgs bosons showed up at CERN's LHC, to be detected by ATLAS and CMS in July 2012. Now the physics world is agog with spectacular data sourced from the furthest reaches of the cosmos, complementing Earth-bound research into the elusive 95% of the universe that remains dark and unknown.

ALICE in Legoland



ALICE-PHO-GEN-2022-004-9

ALICE has become the latest LHC experiment to be rebuilt in miniature from LEGO. The 18,000-brick "ALICE 2.0" (upgraded from a 16,000-brick version last year) was completed in July by high-school students from Italy together with ALICE summer students. Full instructions for this and other LHC-experiment models can be downloaded at build-your-own-particle-detector.org.


POWER SUPPLY
CAEN Electronic Instrumentation
PLUG THE CAEN VME HIGH VOLTAGE MULTICHANNEL POWER SUPPLY SYSTEM IN YOUR EXISTING DAQ CRATE
Perfect Balance • Perfect Balance • Perfect Balance
DAQ System
HV System
ONE STOP SHOP FOR ALL YOUR NEEDS!
VME Programmable HV Family
Thanks to the GECO2020 and CoMPASS software and the Multimaster capability of CAEN VME Bridges, your VME High Voltage Boards become a System. You can house your power supplies within the same standard crate of your DAQ. All data and parameters are easily organized and accessible on your computer!
VME High Voltage Family
V65xx Common Features
CHECK THIS OUT!
• Up to 6 kV and 3 mA
• Very Low Ripple
• Optional Imon-Zoom available
• 6 independent channels
• Available with positive, negative or mixed polarity
V/VX4718 - VME Bridge
USB-3.0/Ethernet/Optical Link Interfaces
V/VX3718 - VME Bridge
USB-2.0/Optical Link Interfaces
CHECK THIS OUT!
• DAQ Master/System Controller (arbiter or requester)
• Front Panel DataWay Display for quick VMEbus monitoring
VME solutions... longstanding quality, outstanding reliability
www.caen.it
Small details... Great differences