WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the 2023 *CERN Courier In Focus* report on *Enabling Technologies*.

Collaboration is the engine-room of scientific progress for Europe's large-scale research facilities. That truism also applies in equal measure to the enabling technologies that underpin day-to-day operations across those same big-science endeavours – as evidenced by the exclusive coverage in our latest In Focus report. Germany's Facility for Antiproton and Ion Research (FAIR) is a case study in this regard, working with R&D partners like CERN and INFN to support the implementation of its cryogenic systems and superconducting magnets (p6). Meanwhile, partnership is front-and-centre for CERN's vacuum and engineering specialists, who are working closely with their counterparts in the gravitational-wave community on design studies for the Einstein Telescope (p11), a proposed next-generation observatory.

Further reports highlight the importance of joined-up innovation in superconducting radio-frequency technologies (p18) and advanced materials R&D for fusion (p28), while Katy Foraz explains how she promotes a culture of cross-disciplinary collaboration and continuous improvement within CERN's engineering department (p3). Collaboration, it seems, is a win–win.

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

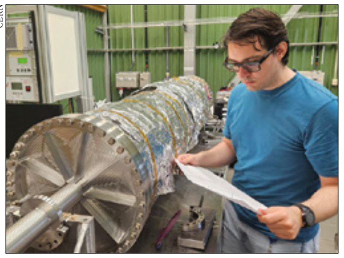
CERNCOURIER

IN FOCUS ENABLING TECHNOLOGIES

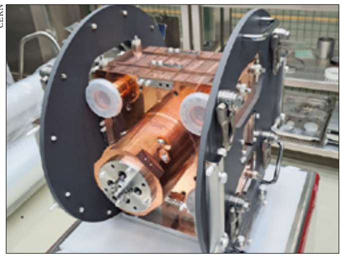
2023 cerncourier.com

IN THIS ISSUE

IN FOCUS ENABLING TECHNOLOGIES



Vacuum innovation *Shared insights on the Einstein Telescope beampipe studies.* 11



Going the distance *CERN's sustained commitment to SRF technologies.* 18

Special delivery *Transportation of the cold box into FAIR's cryogenic supply building.* 6

From the Editor

Collaboration is the engine-room of scientific progress for Europe's large-scale research facilities. That truism also applies in equal measure to the enabling technologies that underpin day-to-day operations across those same big-science endeavours – as evidenced by the exclusive coverage in our latest In Focus report. Germany's Facility for Antiproton and Ion Research (FAIR) is a case study in this regard, working with R&D partners like CERN and INFN to support the implementation of its cryogenic systems and superconducting magnets (p6). Meanwhile, partnership is front-and-centre for CERN's vacuum and engineering specialists, who are working closely with their counterparts in the gravitational-wave community on design studies for the Einstein Telescope (p11), a proposed next-generation observatory.

Further reports highlight the importance of joined-up innovation in superconducting radio-frequency technologies (p18) and advanced materials R&D for fusion (p28), while Katy Foraz explains how she promotes a culture of cross-disciplinary collaboration and continuous improvement within CERN's engineering department (p3). Collaboration, it seems, is a win-win.

Cover *Acceptance testing of FAIR superconducting magnets at CERN, p6. (Stephan Russenschuck, CERN)*

Editor Matthew Chalmers
Consultant editor Joe McEntee
E-mail cern.courier@cern.ch
Advisory board Peter Jenni, Christine Sutton, Claude Amsler, Philippe Bloch, Roger Forty, Mike Lamont, Joachim Kopp

Produced for CERN by IOP Publishing Ltd No.2 The Distillery, Glassfields, Avon Street Bristol BS2 0GR, UK
Tel +44 (0)117 929 7481
Head of media Jo Allen
Head of media business development Ed Jost
Content & production Kyla Rushman
Recruitment advertisement sales Chris Thomas
Display advertisement sales Curtis Zimmermann
Advertisement production Katie Graham
Marketing & circulation Alison Gardiner
Advertising Tel +44 (0)117 930 1026 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

IOP Publishing

OPINION ENGINEERING

Collaboration fuels innovation

Katy Foraz, head of CERN's engineering department, fosters a culture of cross-disciplinary collaboration and continuous improvement within a team of nearly 450 personnel. Joe McEntee hears how the prioritisation of individual and collective development is fundamental to long-term success.

Maximilien Brice/CERN

What does your working day look like?
There's no typical working day – though there are typical working periods that shape my schedule. These could be programmed stops of the accelerator complex versus regular operations; launching new projects or commissioning new systems; issuing calls for equipment tenders; or following up with our industry contractors. The common threads in each case include clear objective setting, cascaded communication, high-level problem-solving and effective decision-making – all aligned within a well-defined strategy to ensure the long-term success of the engineering department.

How do you measure success?
Operationally, the engineering management team is trying to maximise workflow and process efficiencies, ensure the successful execution of projects and drive continuous improvement across many different areas – infrastructure management, documentation, safety systems and programme coordination, among others. Innovation is another priority to maintain our position at the forefront of engineering practice, working with industry partners across Europe and further afield as well as our colleagues from other departments at CERN.

Win-win partnerships
Building a mutual value proposition is the key to establishing strong relationships with industry, says Katy Foraz.

What characteristics do you prioritise – individually and collectively – within the engineering department?
CERN is all about cross-disciplinary collaboration and relentless innovation – and especially so for the engineering department, which has a broad remit to support the accelerators, experimental programmes as well as tertiary infrastructure systems (such as cooling, ventilation, transport, handling, electricity, access and alarms). Put simply, the collision of ideas and perspectives from different disciplines leads to breakthrough thinking and innovative solutions.
A case in point: the integration

A mandate for engineering excellence

CERN's engineering department provides the competencies, infrastructure systems and technical coordination required for the design, installation, operation, maintenance and dismantling phases of the CERN accelerator complex and its experimental facilities. Core activities include:

- Operation, maintenance and consolidation of infrastructure systems for cooling, ventilation, transport, handling, electricity, access and alarms.
- Design and installation of infrastructure systems for new facilities.
- Mechanical engineering and materials expertise for the design, prototyping, manufacture and assembly of accelerator and detector components/subsystems.
- Coordination for the technical stops and shutdowns in the accelerators and experiments as well as support for day-to-day operations.

of mechanical design, mechanical engineering and materials science within the department promotes knowledge transfer and a more holistic approach to problem-solving. Our experts in materials science, for example, work closely with the team responsible for CERN's superconducting magnets – supporting consolidation activity and projects such as the HL-LHC and FCC. It's a win-win in every case. That same openness underpins ongoing R&D partnerships with laboratories like the ITER nuclear fusion facility in southern France and Italy's National Institute for Nuclear Physics (INFN), with whom we are performing design studies for medical applications and muon colliders.

Presumably the HL-LHC work programme is top of your agenda for the foreseeable future?
That's correct. Implementing the necessary infrastructure upgrades for the HL-LHC and the twin experimental programmes is a significant undertaking. This includes planning, designing and executing construction projects to support the future demands of the facility. Managing these projects effectively over the next two years will help to alleviate the workload during Long Shutdown 3 and ensure a seamless transition to research operations again in 2029.

Within the context of the HL-LHC – also more broadly – how does CERN optimise its engagement with industry suppliers?
Building a mutual value proposition is the key to establishing strong and long-term relationships with industry. The engineering department aims to lead by example in this regard and demonstrate how collaboration with our equipment suppliers underpins shared success – increased market exposure, access to cutting-edge R&D, and opportunities for joint technology and process innovation. Consider our ambitious partnership with ABB Motion, a technology leader in digitally enabled motor and drive solutions to support a low-carbon future.

Specifically, we are working together to optimise the laboratory's cooling and ventilation infrastructure, with the aim of reducing energy consumption across the campus. In this way, CERN's cooling and ventilation system is being equipped with smart sensors, which convert traditional motors, pumps, mounted bearings and gearing into an intelligent network of wirelessly connected devices. These devices will collect data to develop "digital twins" of selected cooling and ventilation units, allowing for the creation of energy-saving scenarios. Longer term, the plan is to disseminate the project outcomes publicly, so that industry and large-scale research facilities can apply the lessons we learn on energy-efficiency.

What are the main challenges facing the engineering department on an operational level?
The core systems for CERN's accelerator and experiment complex are our number-one priority on a day-to-day basis. In short, that means proactive monitoring, maintenance and troubleshooting to minimise downtime and ensure smooth operations. Equally, the engineering management team also needs to be proactive in addressing challenges related to ageing equipment – planning ahead for system upgrades or replacement to avoid disruption to CERN's research programme.

That forward-looking mindset comes with a sustained focus on technology and workflow innovation, integrating new tools, software and methodologies into our engineering processes to boost productivity, efficiency and safety. Underpinning it all, we work incredibly hard to scale the talent pipeline, attracting and retaining the brightest and best engineering talent – from junior technicians right through to senior management – and ensuring that all staff have opportunities for professional development.

On that last point: why should early-career scientists and engineers consider CERN as their preferred career pathway?
Big science endeavours like CERN have a lot to offer the early-career professional in terms of impactful and fulfilling work at the frontier of science and technology. Collaborating within multidisciplinary teams, for example, requires creative problem-solving, critical thinking and a willingness to embrace new ideas and learning – all of which are enhanced by working alongside experienced scientists, engineers and technicians from diverse disciplines. Ultimately, collaborations established at large-scale facilities like CERN can open doors to new opportunities in academia, industry and government agencies, providing adaptable and ambitious engineers with a solid platform for future career development.

With hindsight, what do you know today that you wish you had known when you started out in your career?
One of the biggest lessons I've learned along the way is to embrace new opportunities with confidence. I switched relatively early in my career from technical roles into engineering management – though for some time I was not at ease with the transition, wondering if it was the right choice. Nowadays, I can see that the move outside my comfort zone – far away from all those beautiful mathematical formulae – opened up new perspectives, new ways of working and helped me to build resilience. Over time, this all translated into greater versatility, so I became more confident and capable at navigating unfamiliar situations. The key take-away: trust in your abilities and remember that every role on the career journey offers valuable learning experiences and insights. ●

THE AUTHOR

Joe McEntee *is a consultant editor based in South Gloucestershire, UK.*

CRYOGENICS AT FAIR: ADAPTABILITY IS KEY

Cryogenics is a core enabling technology in the Facility for Antiproton and Ion Research (FAIR), which is under construction in Germany. Joe McEntee talks to Holger Kollmus and Marion Kauschke – who together head up the cryogenics programme at FAIR – about the secrets of success at ultralow temperatures.

GSI

GSI

Management science *Holger Kollmus (top) and Marion Kauschke head up the GSI/FAIR cryogenics programme.*

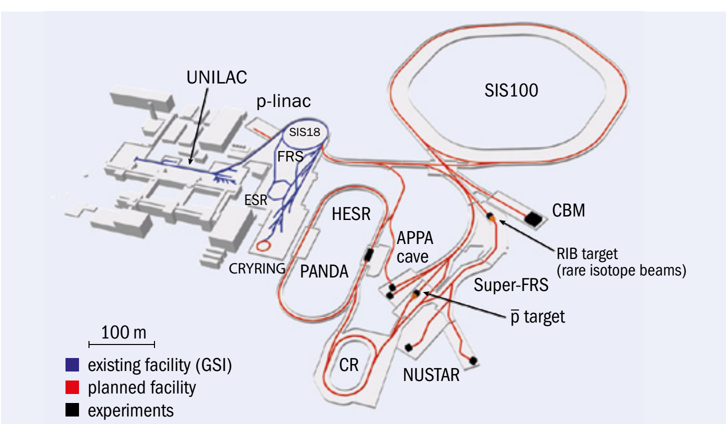
The Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany, represents an ambitious reimagining of the GSI Helmholtz Center for Heavy Ion Research, one of Europe's leading accelerator research laboratories. When it comes online for initial user experiments in 2027, FAIR will provide scientists from around the world with a multipurpose accelerator complex that's built to address a broad-scope research canvas – everything from hadron physics, nuclear structure and astrophysics to atomic physics, materials science and radiation biophysics (as well as downstream applications in cancer therapy and space science).

At the schematic level, FAIR will generate primary beams – from protons up to uranium ions – as well as secondary beams of antiprotons and rare isotopes. As such, the accelerator facility is optimised to deliver intense and energetic beams of particles to different production targets. The resulting beams will subsequently be steered to various fixed-target experiments or injected into specialist storage rings for in-ring experiments with high-quality beams of secondary antiprotons or radioactive ions.

Underpinning all this experimental firepower are FAIR's main building blocks: the fast-ramping SIS100 synchrotron, which provides intense primary beams; the Super Fragment Separator (Super-FRS), which filters out the exotic ion beams; and the storage rings (see "From here to FAIR", below). Meanwhile, the existing GSI accelerators (UNILAC and SIS18) will serve as injectors and pre-accelerators for SIS100, while a new proton linac will provide high-intensity injection into the synchrotron chain. Here Holger Kollmus and Marion Kauschke – head and deputy head, respectively, of the GSI/FAIR cryogenics programme – tell *CERN Courier* how the laboratory's cryogenic infrastructure and specialist expertise at ultralow temperatures are fundamental to FAIR's long-term scientific mission.

Let's start with the basics. How has the cryogenics programme at GSI evolved as FAIR moves from concept to reality?

HK: While cryogenics does not have an extensive back-story at GSI – only two large-scale experiments have deployed superconducting magnets to date – the strategic decision to build FAIR put ultralow-temperature technology at the heart of GSI's development roadmap. Consider the requirement for specialist infrastructure to provide at-scale testing of FAIR's superconducting magnets. A case in point is the Prototype Test Facility (PTF) which, between 2005 and 2012, was used to evaluate five candidate magnet designs. One of these prototypes, the so-called first-of-series (FOS) magnet, was subsequently specified for the SIS100 ring (110 dipole magnets in total, with two spares).



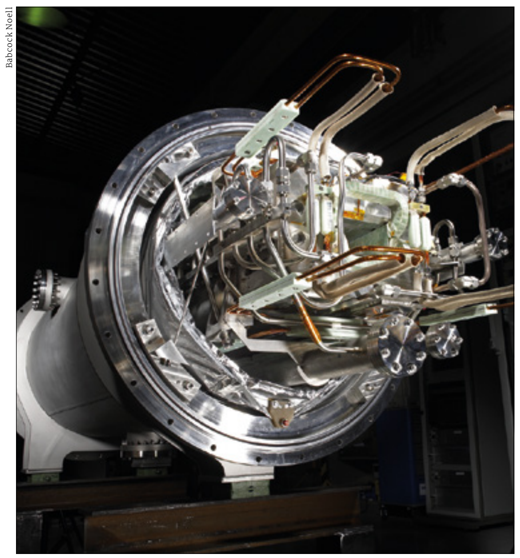
From here to FAIR *The existing GSI accelerators (blue) and the FAIR facilities (red). FAIR comprises the SIS100 synchrotron; the antiproton separator and the Super Fragment Separator (Super-FRS); the collector ring (CR); high-energy storage ring (HESR); and experimental stations for the APPA, CBM, NUSTAR and PANDA research programmes. The proton linac and the CRYRING (a low-energy storage ring for heavy ions) also belong to the FAIR instrumentation portfolio.*

Gabi Otto/GSI

Stephan Russenschuck/CERN

Test and measurement *The STF (top) handled the volume testing of FAIR's SIS100 dipole magnets (110 in total). Meanwhile, CERN's specialist test facility (right) is overseeing acceptance of Super-FRS superconducting magnets prior to delivery to Darmstadt.*

Babcock Noell



Supercool innovation *The SIS100 ring comprises an array of dipole and quadrupole magnets. The magnets have to be ramped during the acceleration of the heavy ions, with the ramp and repetition rate adapted to the ions and experimental set-up. Above: an SIS100 dipole magnet.*

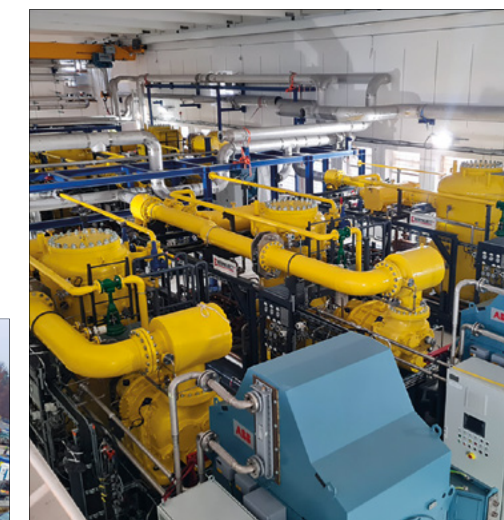
GSI

Cryo connections *Above: Cryogenic by-pass lines supplied to FAIR through an in-kind contribution by WUST in Poland.*

GSI

Heavy metal *Transportation of the cold box into the front hall of FAIR's cryogenic supply building. Provided by Linde Kryotechnik, the cold box is 18 m long, 5 m in diameter and weighs 85 tons.*

GSI



Pump it up *Installation of FAIR's warm compressor system is nearing completion. The hall contains two low-pressure and two high-pressure compressors (each specified at up to 1 kg/s) and a separate compressor for the CWU pre-cooler operation at medium pressure. The latter also serves as redundancy for the main compressors.*

FAIR's cold, cold heart

FAIR's central cryogenic plant, CRYO2, is already installed and will provide a cryogenic capacity of 14 kW at 4–5 K and 50 kW at 50–80 K. Those figures of merit will ultimately enable parallel and independent operation across FAIR's main cryogenic consumers – servicing, for example, the varying heat loads of SIS100 (for operation of different machine cycles) as well as accommodating the large cold mass of the Super-FRS (and its liquefaction requirements). Campus-wide, the cold helium is transported to the FAIR machines by a 1.5 km long distribution system, the installation of which is well under way.

Gabi Otto/GSI

It's cold inside *Installation of FAIR's cryogenic distribution system is proceeding at pace. Above: engineers oversee delivery of the central distribution box for provision of liquid helium to the SIS100 superconducting magnets.*

At the heart of CRYO2 is a helium refrigerator in tandem with oil-cooled screw compressors. To optimise long-term adaptation to load changes, the mass flow-rate of coolant will be regulated in near-stepless fashion using a variable-frequency driver for the compressors. The compressor station itself is set up from five compressor skids, each having its own oil system and including a rough separation of more than 99% of the oil from the process gas. The rest of the oil is separated on the high-pressure side before the gas enters the cold box. As the CWU operates independently from the CRYO2 plant, this compressor has its own oil removal system.

It soon became clear, however, that the PTF's single test stand was not fit-for-purpose to validate all of the magnets within a reasonable timeframe. Instead, that task was allocated to the Series Test Facility (STF), which came onstream in 2013 with cryogenic plant and equipment provided by Swiss manufacturer Linde Kryotechnik. Informed by lessons learned on the PTF, the STF maximised throughput and workflow efficiency for large-scale testing of the SIS100 dipole magnets.

How did you realise STF workflow efficiencies?

MK: Custom building design and layout are key, with a slide system for the superconducting magnets under test, a bellows-free mounting and accessible interfaces between the feed box, magnet and end box. The feed box and end box enclose the superconducting magnet on both sides for testing, with the former additionally supplying the magnet with liquid helium coolant and electrical current. The liquid helium keeps the magnet at a constant 4.5 K, while shielding (maintained between 50–80 K) reduces any heating of the cryogenically cooled magnet (the so-called "cold mass").

At the same time, the compressor and STF cold box for the liquid helium are physically separated in an adjacent building, thereby minimising noise and vibration levels in the test environment. The cryogenic distribution system is installed on a gallery to enhance staff access between the four test stands, while the cold box itself has a cooling power of 800 W at 4–5 K, 2000 W at 50–80 K and a liquefaction capacity of 6 g/s.

All of the SIS100 dipoles have now been tested in the STF, with the facility's four test stands allowing for "four-stroke" operation. Put simply: on one test stand, the magnet is assembled; the second is in cool-down; the third is cold and the magnet is under test; and the fourth is in warm-up mode. This resulted in each magnet being in the STF hall for about a month, with delivery of one new magnet each week. Worth noting as well that if any magnets had failed under test – though none did – they would have been taken to the PTF without interrupting the "assembly-line" work.

Does that mean the PTF and STF will now be decommissioned?

MK: The R&D activity at the PTF and STF is far from over. One dipole magnet is undergoing endurance testing in the PTF, while the STF is being used to test SIS100 quadrupole modules as well as prototypes of other SIS100 and Super-FRS components (such as the transfer lines needed to distribute liquid helium from source and feed boxes for the SIS100 and Super-FRS). When testing at the STF is complete – most likely in 2028 – two of the four test benches will be dismantled and part of the hall will be repurposed for a superconducting CW linac (to be cryogenically supplied by the STF).

Presumably, the GSI cryogenics team engages with other large-scale facilities to enhance its R&D and test capabilities?

HK: That's correct. The testing of superconducting magnets requires technical personnel with specialist domain knowledge and expertise to measure and validate magnetic and electrical properties; provide the cryogenic supply within certain temperature/pressure limits; as well as to measure the magnet calorimetrically (for example, with regard to its heat load).

CERN, as a pioneer in superconducting magnets for high-energy physics, is one of our main technology partners. As such, the superconducting magnets for the Super-FRS – dipoles as well as multiplets – are undergoing acceptance testing at CERN on their way to Darmstadt from the manufacturers in Italy, France and Spain. Another joint effort is focused on FAIR's cryogenic machine control, transferring established solutions for the control of valves, temperature/pressure sensors and a range of other subsystems using the CERN software UNICOS.

So collaboration and knowledge exchange are fundamental to project delivery?

HK: Partnership with other cryogenics groups across Europe underpins our deployment model. The equipment needed for local cryogenic distribution to the magnets,

THE AUTHOR

Joe McEntee *is a consultant editor based in South Gloucestershire, UK.*

ion42/GSI

Blending in *Artistic rendering of FAIR's cryogenics building upon completion, showing helium storage tanks (centre) and the nitrogen supply (right).*

for example, is provided by an in-kind contribution from Wroclaw University of Science and Technology (WUST) – tapping into the Polish team's work on other large-scale cryogenics projects including the European Spallation Source (ESS) in Sweden and the European XFEL here in Germany. Another strategic R&D partner is the Test Facility for large Magnet and superconducting Line (TFML) in Salerno, Italy. Part of the Istituto Nazionale di Fisica Nucleare (INFN), the TFML's refrigeration capacity and testing facility are available for SIS100 quadrupole testing, thereby opening up test capacity at GSI for other cryogenic components/subsystems such as feed boxes and current lead boxes. The latter enable the warm-to-cold transition for the electrical current, on the way from the "warm" power converter to the "cold" magnets.

Where are the big crunch-points for cryogenic cooling within FAIR?

HK: The SIS100 and the Super-FRS are the principal consumers in terms of FAIR's cryogenic cooling capacity – each with a cold connection to a single large refrigeration plant called CRYO2. The SIS100 (with a circumference of 1100 m) is characterised by high dynamic-load changes with a duration of several hours. In terms of design, the ring comprises an array of dipole and quadrupole magnets in a configuration that exploits an internally cooled superconducting cable (with the superconducting strands cooled using two-phase helium).

Operationally, the SIS100 magnets have to be ramped during the acceleration of the heavy ions, with the ramp and repetition rate adapted to the ions and experimental set-up to yield different heat loads at the 4 K level. The change between these different cycles should be as short as possible (of the order of less than one hour), with control of the supply pressure inducing different helium flows for the magnet cooling.

Meanwhile, the Super-FRS (at 350 m long) will contain 1500 tons of cold mass that must be cooled in a realistic timeframe (typically one month). A dedicated cool-down and warm-up unit (CWU), using liquid nitrogen as coolant for a helium circuit, is pivotal in this regard and fulfils the Super-FRS requirements with respect to maximal cool-down rates and temperature differences.

What are the challenges of integrating FAIR's cryogenic infrastructure with the existing GSI facilities?

MK: FAIR's main cryogenic supply building comprises two independent halls, each having its own foundations. The front hall – which houses the cold box, distribution lines and cryogenic gas management – connects to the SIS100 tunnel via pillars and an arrangement that's designed to avoid any movement of the transfer line supplying supercritical helium to SIS100. Whereas the rear section – which houses the compressor station – sits on a "floating foundation", essentially decoupled from the cold-box hall to minimise the impact of any resulting ground-based vibration on the SIS100 ring.

A host of other design issues have also come into play, so adaptability is key. For starters, given that FAIR is situated in a wooded recreation area for neighbouring communities, the height of the helium storage tanks is limited to the height of the average tree in the vicinity. In the same way, FAIR's cryo buildings will integrate seamlessly with their surroundings – with the use of roof greening, for example, and a window-free design to cut out light pollution. Energy efficiency is also a priority, with the heat that's generated during the cryogenic compression process to be recovered and used for heating in other parts of the FAIR facility, while active noise mitigation of the air-conditioning systems will minimise disturbance to wild animals.

How is the roll-out of FAIR's cryogenic plant progressing?

HK: The installation of the cryogenic supply infrastructure in the cryogenic building will be finished this autumn, with the supporting infrastructure – including the electrical supply and cooling water – to be in place before spring 2025. Commissioning of the full cryogenic supply system is scheduled to complete by the end of 2025, with the first experiments at FAIR using superconducting technology to follow in 2027. ●

Partnership with other cryogenic groups across Europe underpins our deployment model

JOINED-UP THINKING IN VACUUM SCIENCE

CERN is home to a unique centre-of-excellence in vacuum science, technology and engineering. Paolo Chiggiato and Luigi Scibile explain how that collective expertise is being put to work as part of the international effort to develop the next generation of gravitational-wave telescopes.

Project planning *Two CERN groups are engaged as contributing partners on the beampipe studies for the Einstein Telescope – specifically, the vacuum, surfaces and coatings (TE-VSC) and mechanical and materials engineering (EN-MME) groups. Above: CERN members of the Einstein Telescope beampipe study teams install the first pre-prototype beampipe demonstrator.*

The first detection of gravitational waves in 2015 stands as a confirmation of Einstein's prediction in his general theory of relativity and represents one of the most significant milestones in contemporary physics. Not only that, direct observation of gravitational ripples in the fabric of space-time opened up a new window on the universe that enables astronomers to study cataclysmic events such as black-hole collisions, supernovae and the merging of neutron stars. The hope is that the emerging cosmological data sets will, over time, yield unique insights to address fundamental problems in physics and astrophysics – the distribution of matter in the early universe, for example, and the search for dark matter and dark energy.

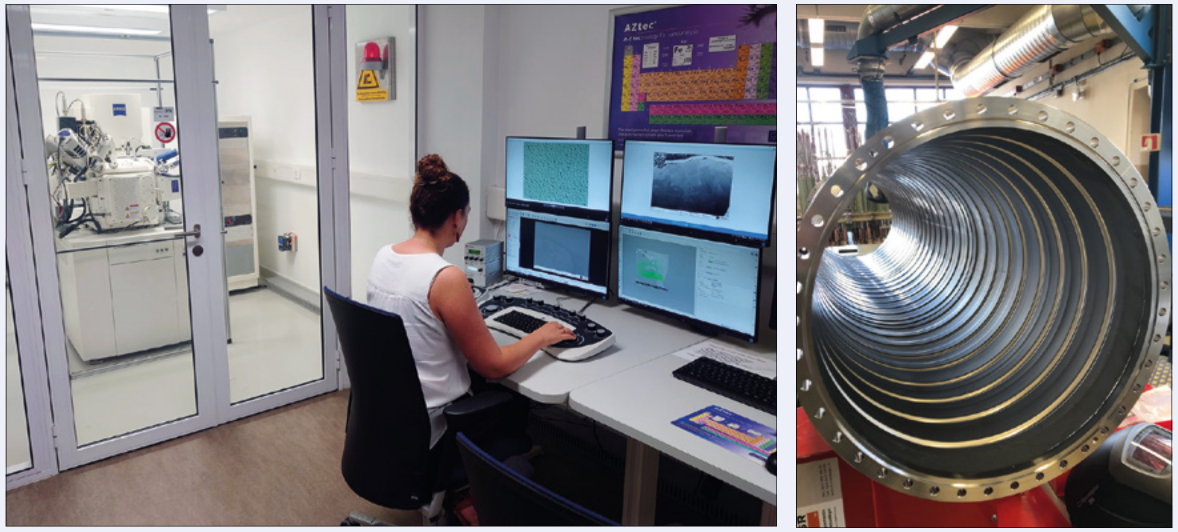
By contrast, an altogether more down-to-earth agenda – Beampipes for Gravitational Wave Telescopes 2023 – provided the backdrop for a three-day workshop held at CERN at the end of March. Focused on enabling technologies for current and future gravitational-wave observatories – specifically, their ultrahigh-vacuum (UHV) beampipe requirements – the workshop attracted a cross-disciplinary audience of 85 specialists drawn from the particle-accelerator and gravitational-wave communities alongside industry experts spanning steel production, pipe manufacturing and vacuum technologies (*CERN Courier* July/August 2023 p18).

If location is everything, Geneva ticks all the boxes in this regard. With more than 125 km of beampipes and liquid-helium transfer lines, CERN is home to one of the world's largest vacuum systems – and certainly the longest and most sophisticated in terms of particle accelerators. All of which ensured a series of workshop outcomes shaped by openness, encouragement and collaboration, with CERN's technology and engineering departments proactively sharing their expertise in vacuum science,

THE AUTHORS

Paolo Chiggiato *is leader of the vacuum, surfaces and coatings group at CERN.* **Luigi Scibile** *is technical coordinator of accelerator technologies at CERN. He oversees the logistics and installation work packages for the Einstein Telescope beampipe design study at CERN.*

Better by design: the Einstein Telescope beampipes



Tunnel vision *Left: CERN's microscopy lab in the EN-MME group is deploying a range of techniques – including focused ion-beam microscopy and scanning electron microscopy – for the analysis of candidate steels under consideration for the Einstein Telescope beampipe pilot sector. Right: a "mild-steel" pre-prototype vacuum chamber is shown after manufacturing as part of the beampipe studies at CERN.*

The baseline for the Einstein Telescope's beampipe design studies is the Virgo gravitational-wave experiment. The latter's beampipe – which is made of austenitic stainless steel (AISI 304L) – consists of a 4 mm thick wall reinforced with stiffener rings and equipped with an expansion bellows (to absorb shock and vibration).

While steel remains the material of choice for the Einstein Telescope beampipe, other grades beyond AISI 304L are under consideration. Ferritic steels, for example, can contribute to a significant cost reduction per unit mass compared to austenitic stainless steel, which contains nickel. Ferrite also has a body-centred-cubic crystallographic structure that results in lower residual hydrogen levels versus face-centred-cubic austenite – a feature that eliminates the need for expensive solid-state degassing treatments when pumping down to UHV.

Options currently on the table include the cheapest ferritic steels, known as "mild steels", which are used in gas pipelines after undergoing corrosion treatment, as well as ferritic stainless steels containing more than 12% chromium by weight. While initial results with the latter show real promise, plastic deformation of welded joints remains an open topic, while the magnetic properties of these materials must also be considered to prevent anomalous transmission of electromagnetic signals and induced mechanical vibrations.

Along a related coordinate, CERN is developing an alternative solution with respect to the "baseline design" that involves corrugated walls with a thickness of 1.3 mm, eliminating the need for bellows and reinforcements. Double-wall pipe designs are also in the mix – either with an insulation vacuum or thermal insulators between the two walls.

Beyond the beampipe material, studies are exploring the integration of optical baffles, which intermittently reduce the pipe aperture to block scattered photons. Various aspects such as positioning, material, surface treatment and installation are under review, while the transfer of vibrations from the tunnel structure to the baffle represents another line of enquiry.

With this in mind, the design of the beampipe support system aims to minimise the transmission of vibrations to the baffles and reduce the frequency of the first vibration eigen mode within a range where the Einstein Telescope is expected to be less sensitive. Defining the vibration transfer function from the tunnel's near-environment to the beampipe is another key objective, as are the vibration levels induced by airflow in the tunnel (around the beampipe) and stray electromagnetic fields from beampipe instrumentation.

Another thorny challenge is integration of the beampipes into the Einstein Telescope tunnel. Since the beampipes will be made up of approximately 15 m-long units, welding in the tunnel will be mandatory. CERN's experience in welding cryogenic transfer lines and magnet junctions in the LHC tunnel will be useful in this regard, with automatic welding and cutting machines being one possible option to streamline deployment.

Also under scrutiny is the logistics chain from raw material to final installation. Several options are being evaluated, including manufacturing and treating the beampipes on-site to reduce storage needs and align production with the pace of installation. While this solution would reduce the shipping costs of road and maritime transport, it would require specialised production personnel and dedicated infrastructure at the Einstein Telescope site.

Finally, the manufacturing and treatment processes of the beampipes will have a significant impact on cost and vacuum performance – most notably with respect to dust control, an essential consideration to prevent excessive light scattering due to falling particles and changes in baffle reflectivity. Dust issues are common in particle accelerators and the lessons learned at CERN and other facilities may well be transferable to the Einstein Telescope initiative.

materials processing, advanced manufacturing and surface treatment with counterparts in the gravitational-wave community.

Measurement science

To put all that knowledge-share into context, however, it's necessary to revisit the basics of gravitational-wave metrology. The principal way to detect gravitational waves is to use a laser interferometer comprising two perpendicular arms, each several kilometres long and arranged in an L shape. At the intersection of the L, the laser beams in the two branches interact, whereupon the resulting interference signal is captured by photodetectors. When a gravitational wave passes through Earth, it induces differential length changes in the interferometer arms – such that the laser beams traversing the two arms experience dissimilar path lengths, resulting in a phase shift and corresponding alterations in their interference pattern.

These are no ordinary interferometers, though. The instruments operate at the outer limits of measurement science and are capable of tracking changes in length down to a few tens of zeptometres (10^{-21} m), a length scale roughly 10,000 times smaller than the diameter of a proton. This achievement is the result of extraordinary progress in optical technologies over recent decades – advances in laser stability and mirror design, for example – as well as the ongoing quest to minimise sources of noise arising from seismic vibrations and quantum effects.

With the latter in mind, the interferometer laser beams must also propagate through vacuum chambers to avoid potential scattering of the light by gas molecules. The residual gas present within these chambers introduces spatial and temporal fluctuations in the refractive index of the medium through which the laser beam propagates – primarily caused by statistical variations in gas density.

As such, the coherence of the laser beam can be compromised as it traverses regions characterised by a non-uniform refractive index, resulting in phase distortions. To mitigate the detrimental effects of coherence degradation, it is therefore essential to maintain hydrogen levels at pressures lower than 10^{-9} mbar, while even stricter UHV requirements are in place for heavier molecules (depending on their polarisability and thermal speed).

Now and next

Right now, there are four gravitational-wave telescopes in operation: LIGO (across two sites in the US), Virgo in Italy, KAGRA in Japan, and GEO600 in Germany (while India has recently approved the construction of a new gravitational-wave observatory in the western state of Maharashtra). Coordination is a defining feature of this collective endeavour, with the exchange of data among the respective experiments crucial for eliminating local interference and accurately pinpointing the detection of cosmic events.

Meanwhile, the research community is already planning for the next generation of gravitational-wave telescopes. The primary objective: to expand the portion of the universe that can be comprehensively mapped and, ultimately, to detect the primordial gravitational waves generated by the Big Bang. In terms of implementation, this will demand experiments with longer interferometer arms accompanied by significant reductions in noise levels (necessitating, for example, the implementation of cryogenic cooling techniques for the mirrors).

Knowledge transfer *With more than 125 km of beampipes and liquid-helium transfer lines, CERN is home to one of the world's largest vacuum systems and an ideal technology partner to support next-generation gravitational-wave facilities. Above: the beampipe for the ALICE experiment.*

Two leading proposals are on the table: the Einstein Telescope in Europe and the Cosmic Explorer in the US. The latter proposes a 40 km long interferometer arm with a 1.2 m diameter beampipe, configured in the traditional L shape and across two different sites (as per LIGO). Conversely, the former proposes six 60° Ls in an underground tunnel laid out in an equilateral triangle configuration (10 km long sides, 1 m beampipe diameter and with a high- and low-frequency detector at each vertex).

For comparison, the current LIGO and Virgo installations feature arm lengths of 4 km and 3 km, respectively. As a result, the anticipated length of the vacuum vessel for the Einstein Telescope is projected to be 120 km, while for the Cosmic Explorer it is expected to be 160 km. In short: both programmes will require the most extensive and ambitious UHV systems ever constructed.

Extreme vacuum

At a granular level, the vacuum requirements for the Einstein Telescope and Cosmic Explorer assume that the noise induced by residual gas is significantly lower than the allowable noise budget of the gravitational interferometers themselves. This comparison is typically made in terms of amplitude spectral density. A similar approach is employed in particle accelerators, where an adequately low residual gas density is imperative to minimise any impacts on beam lifetimes (which are predominantly constrained by other unavoidable factors such as beam–beam interactions and collimation).

Two leading proposals are on the table: the Einstein Telescope in Europe and the Cosmic Explorer in the US

The specification for the Einstein Telescope states that the contribution of residual gas density to the overall noise budget must not exceed 10%, which necessitates that hydrogen partial pressure be maintained in the low 10^{-10} mbar range. Achieving such pressures is commonplace in leading-edge particle accelerator facilities and, as it turns out, not far beyond the limits of current

Materials processing *CERN's main workshop will support manufacture of the beampipe pilot sector for the Einstein Telescope. The workshop's core activities include welding services (right), sheet-metal work, machining and an independent metrology service.*

gravitational-wave experiments. The problem, though, comes when mapping current vacuum technologies to next-generation experiments like the Einstein Telescope.

In such a scenario, the vacuum system would represent one of the biggest capital equipment costs – on a par, in fact, with the civil engineering works (the main cost-sink). As a result, one of the principal tasks facing the project teams is the co-development – in collaboration with industry – of scalable vacuum solutions that will enable the cost-effective construction of these advanced experiments without compromising on UHV performance and reliability.

Follow the money

It's worth noting that the upward trajectory of capital/operational costs versus length of the experimental beampipe is a challenge that's common to both next-generation particle accelerators and gravitational-wave telescopes – and one that makes cost reduction mandatory when it comes to the core vacuum technologies that underpin these large-scale facilities. In the case of the proposed Future Circular Collider at CERN, for instance, a vacuum vessel exceeding 90 km in length would be necessary.

Of course, while operational and maintenance costs must be prioritised in the initial design phase, the emphasis on cost reduction touches all aspects of project planning and, thereafter, requires meticulous optimisation across all stages of production – encompassing materials selection, manufacturing processes, material treatments, transport, logistics, equipment installation and commissioning. Systems integration is also paramount, especially at the interfaces between the vacuum vessel's technical systems and adjacent infrastructure (for example, surface buildings, underground tunnels and caverns). Key to success in every case is a well-structured project that brings together experts with diverse competencies as part of an ongoing "collective conversation" with their counterparts in the physics community and industrial supply chain.

Within this framework, CERN's specialist expertise in managing large-scale infrastructure projects such as the HL-LHC can help to secure the success of future gravitational-wave initiatives. Notwithstanding CERN's capabilities in vacuum system design and optimisation, other areas of shared interest between the respective communities include civil engineering, underground safety and data management, to name a few.

Furthermore, such considerations align well with the latest update of the European strategy for particle physics – which explicitly prioritises the synergies between particle and astroparticle physics – and are reflected operationally through a collaboration agreement (signed in 2020) between CERN and the lead partners on the Einstein Telescope feasibility study – Nikhef in the Netherlands and INFN in Italy.

CERN teams are engaged directly on the beampipe studies for the Einstein Telescope

In this way, CERN is engaged directly as a contributing partner on the beampipe studies for the Einstein Telescope (see "Better by design: the Einstein Telescope beampipes", on page 12). The three-year project, which kicked off in September 2022, will deliver the main technical design report for the telescope's beampipes. CERN's contribution is structured in eight work packages, from design and materials choice to logistics and installation, including surface treatments and vacuum systems.

The beampipe pilot sector will also be installed at CERN, in a building previously used for testing cryogenic helium transfer lines for the LHC. Several measurements are planned for 2025, including tests relating to installation, alignment, *in-situ* welding, leak detection and achievable vacuum levels. Other lines of enquiry will assess the efficiency of the bakeout process, which involves the injection of electrical current directly into the beampipe walls (heating them in the 100–150 °C range) to minimise subsequent outgassing levels under vacuum.

Given that installation of the beampipe pilot sector is time-limited, while details around the manufacturing and treatment of the vacuum chambers are still to be clarified, the engagement of industry partners in this early design stage is a given – an approach, moreover, that seeks to replicate the collaborative working models pursued as standard within the particle-accelerator community. While there's a lot of ground to cover in the next two years, the optimism and can-do mindset of all participants at Beampipes for Gravitational Wave Telescopes 2023 bodes well. ●

NEW HORIZONS IN SRF: BEYOND THE HL-LHC

Innovation in superconducting radio-frequency (SRF) technology and applications is fundamental for the success of the High-Luminosity LHC (HL-LHC) project and the next-generation particle colliders that will follow. Frank Gerigk, leader of CERN's RF group, assesses progress on the SRF R&D roadmap and the exacting fabrication and performance requirements already coming into view.

CERN

CERN

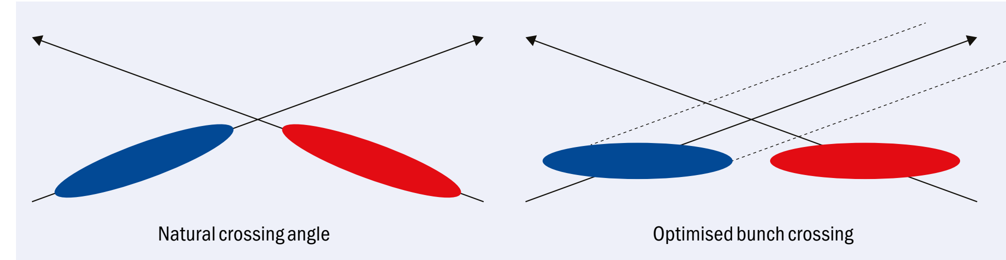
Precision engineering *The HL-LHC will use superconducting bulk-niobium crab cavities to optimise the bunch crossing at particle interaction points. Left: clean-room assembly of a prototype DQW crab cavity ahead of testing in the SPS beam pipe. Right: a completed DQW cryomodule installed in the SPS. The SPS test stand has a movable platform for the cryomodule to enhance workflow efficiency.*

THE AUTHOR
Frank Gerigk *is leader of the RF group in CERN's systems department.*

CERN's commitment to superconducting radio-frequency (SRF) technologies goes back a long way – spanning more than four decades of sustained investment in infrastructure, applied R&D, device- and systems-level innovation, as well as international collaboration with academic and industry partners. If that's the headline, though, what's next for CERN's SRF programme?

A recap of CERN's SRF achievements is instructive at this point before unpacking the longer-term R&D and innovation roadmap. For starters, SRF cavities – a workhorse technology for frontier accelerators in particle physics, nuclear physics and materials science – were instrumental in pushing CERN's Large Electron–Positron (LEP) collider to new energy regimes. Through the late 1990s, a total of 288 SRF cavities – each comprising a thin film of superconducting niobium sputtered onto a copper cavity – were installed in LEP-II, providing up to 7 MV/m of accelerating gradient and allowing the machine to eventually reach a centre-of-mass energy of 209 GeV (versus 91 GeV for the original LEP machine). At the start of the millennium, LEP-II was the most powerful SRF installation worldwide.

Fast forward to 2010 and the advent of the HIE-ISOLDE project, the "high-intensity and energy" upgrade to CERN's radioactive beam facility, which unlocked further investment in the SRF programme. Operationally, HIE-ISOLDE was all about increasing the energy of ISOLDE's radionuclide beams from 3 MeV/u up to 10 MeV/u through the construction of a superconducting post-accelerator –



CERN

Crafted collisions *SRF crab cavities will increase and "level" the luminosity of the proton–proton collisions in the HL-LHC. Left: particle bunches collide with their natural crossing angle. Right: bunches colliding in a "crab crossing".*

necessitating, in turn, the design, processing and testing of bulk-niobium SRF cavities along with improved coating performance for thin-film niobium-copper SRF cavities.

CERN engineers duly developed a full prototype of the 100 MHz coated quarter-wave cavities for HIE-ISOLDE before spinning out the technology to industry. Subsequently, however, several of the outsourced cavities exhibited performance limitations, linked to a welding seam in a cavity region with high surface currents. To address this problem, CERN's RF team came up with an innovative work-around that proved to be crucial in pushing the performance envelope of thin-film SRF cavities.

Put simply, the HIE-ISOLDE cavity was redesigned in such a way that it could be machined out of a single piece of copper with no welds. After coating with niobium and subsequent testing in 2017, the new-look cavity yielded unprecedented surface peak fields of over 60 MV/m and a Q value of 10^9 at 2.3 K. These figures of merit – well above the qualification target of approximately 30 MV/m ($Q = 5\times10^8$) – gave a clear direction for further R&D on thin-film cavities on seamless copper substrates, with four cryomodules (each containing five SRF cavities) later installed as part of the HIE-ISOLDE upgrade. Significantly, this was also the first time that a "production" cavity using thin-film niobium on copper gave comparable results to bulk-niobium cavities, the performance of which had seen rapid advances over the previous decade as a result of the collective R&D effort geared towards the International Linear Collider (ILC).

Crab cavities in the HL-LHC

Right now, front-and-centre on the SRF technology roadmap is the HL-LHC project, an ambitious undertaking to increase the integrated luminosity by a factor of 10 beyond the LHC's design value and, in so doing, open up new opportunities for fundamental physics from 2030 onwards. Once operational, the HL-LHC will use superconducting bulk-niobium "crab cavities" to optimise the bunch crossing at the particle interaction points – thereby increasing and "levelling" the luminosity of the proton–proton collisions. This is achieved by turning the particle bunches slightly before collision and then returning them to their original orientation after the interaction (see "Crafted collisions", above).

At ATLAS and CMS, there will be two 400 MHz crab cavities deployed for each beam on each side of the experiments – i.e. a total of 16 cavities (eight cryomodules) will be installed during Long Shutdown 3 (LS3), starting in 2026. As the beampipes for the colliding beams are only 194 mm apart, an ultracompact cavity design is necessary to produce the required kick voltage of 3.4 MV per cavity. An intensive R&D effort – involving a network of international partners and funding sources – resulted in two final designs, one for horizontal crabbing (RF dipole, RFD) and one for vertical crabbing (double quarter-wave, DQW). These advanced cavity shapes are roughly four times more compact versus the elliptical LHC accelerating cavities and, as such, present significant challenges in terms of their fabrication.

To test the envisaged technical concepts – and, by extension, demonstrate the crabbing of a proton beam – CERN's RF development team carried out a beam test of two DQW cavities in the Super Proton Synchrotron (SPS) back in 2018 (*CERN Courier* May 2018 p18). After construction and processing at CERN, the cavities were subsequently assembled into a cryomodule at the SM18 test facility (a dedicated CERN site for evaluation of superconducting magnets and SRF cavities).

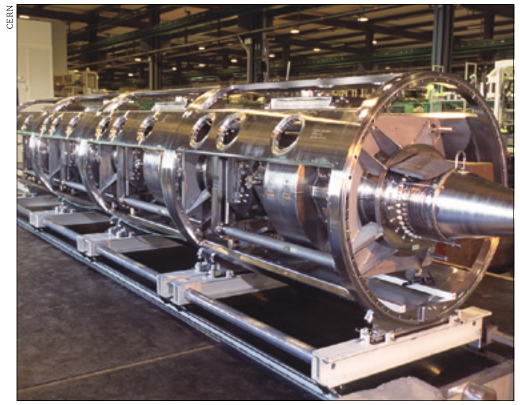
To maximise workflow efficiency, the SPS test stand has a movable platform for the cryomodule, which is connected with flexible elements to the SPS beampipe. This arrangement makes it possible to move the cavities in and out of the beam and thereby reduce the impact on regular SPS operation. The beam tests validated not only the crabbing effect on the circulating proton beam, but also the design and engineering choices for these new cryomodules.

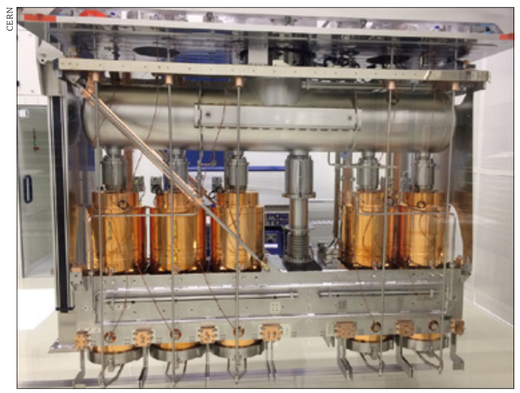
It's worth noting that the streamlined prototyping of the SPS DQW cryomodule was only possible thanks to CERN's ongoing investment in SRF R&D and expertise. At a more granular level, that translates into a portfolio of core skill-sets spanning niobium-sheet forming and welding; niobium surface chemistry with buffered chemical processing and electropolishing; surface cleaning with high-pressure ultrapure water; assembly of cavities in ISO4 clean rooms; preparation and conducting of cold tests at 2K; as well as the clean assembly of cavity strings and their integration into full cryomodules with cutting-edge alignment precision.

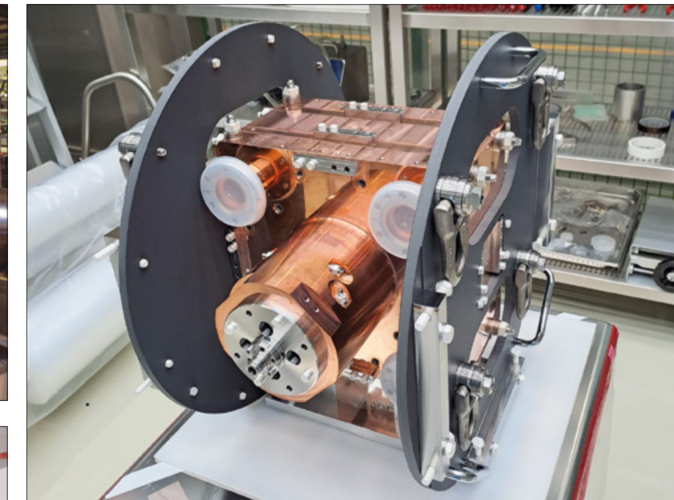
The next milestone in the HL-LHC crab-cavity programme is the testing of the first RFD module in the SPS

Collaborate, innovate, accelerate

Following the verification of the underlying technical concepts, CERN established a network of international collaborations for an initial consignment of 10







Generational technologies *The 16 SRF cavities for the LHC were built using established LEP technology with an emphasis on robustness rather than pushing the boundaries. Top left: a four-cavity LHC cryomodule during assembly. Bottom left: clean-room assembly of a cryomodule for HIE-ISOLDE, the "high-intensity and energy" upgrade to CERN's radioactive beam facility. Above: the latest R&D cavity from CERN's RF group is the SWELL (Slotted Waveguide ELLiptical) cavity, which is a hybrid of normal-conducting accelerating cells and an elliptical superconducting cavity. Shown here is a scaled prototype for a 600 MHz design that is being evaluated as an alternative to the baseline FCC-ee cavities. The cavity features strong HOM damping through the four slots and helium cooling channels instead of helium tanks (to drastically reduce the helium inventory of future colliders). Coating will follow soon, with first cold tests expected before the end of 2023.*

cryomodules for the HL-LHC plus a spare DQW module and spare RFD module. Division of labour is key here, with German manufacturer RI Research Instruments handling the fabrication and chemical processing of the DQW cavities. After cold-testing the bare cavities at CERN, they are sent back to RI to be equipped with a helium tank and cold magnetic shields, which are provided by Daresbury Laboratory in the UK as part of a joint effort between CERN and the UK's Science and Technology Facilities Council (STFC).

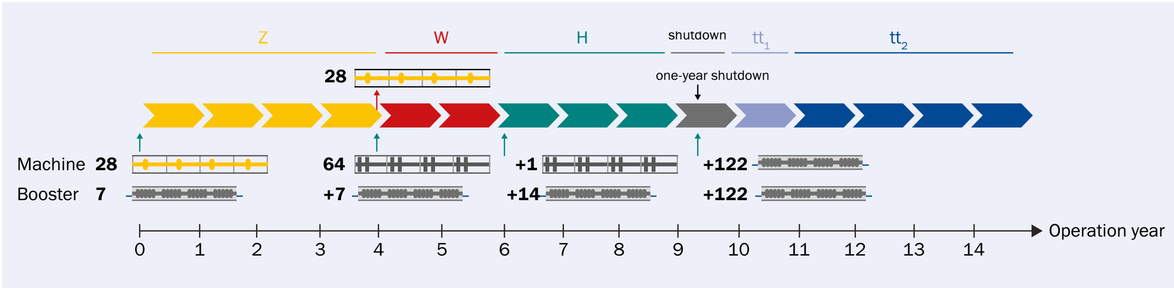
These so-called "jacketed" cavities return to CERN for another round of cold-testing before being fitted with higher-order-mode (HOM) RF couplers, manufactured in the CERN workshops. Once the performance of the now "dressed" cavities is validated, they are assembled into cryomodules at Daresbury before coming back to CERN for cold-test validation and installation.

Meanwhile, the production of RFD modules takes place in North America as part of the US HL-LHC Accelerator Upgrade Project (AUP) collaboration. In terms of specifics: Fermilab has contracted the Italian manufacturer Zanon for production of bare cavities, with the laboratory retaining responsibility for the chemical treatments, cold magnetic shields, helium vessel and HOM couplers. Fermilab scientists also conduct the cold-tests for the bare, jacketed and dressed cavities. Once the cavities reach the desired performance level, they are shipped to TRIUMF in Canada for re-testing and assembly into cryomodules.

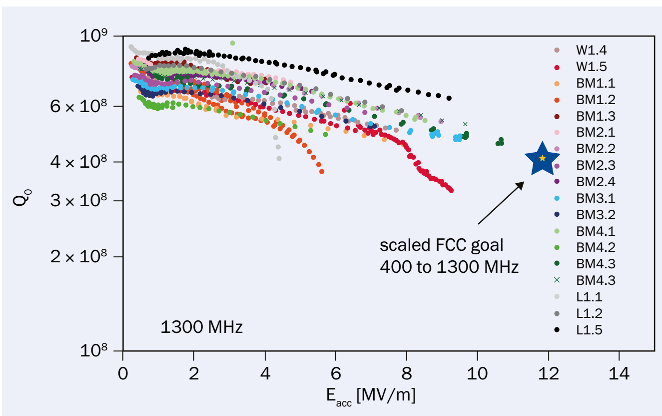
Ensuring this complex collective endeavour remains on track is no small challenge, requiring implementation of well-defined technical interfaces and rigorous performance monitoring while also keeping tabs on day-to-day project scheduling, transportation and thorny logistics issues (including Brexit-related paperwork). More broadly, it's worth noting that the experience gained from prototyping the crab cavities and cryomodules at CERN has enabled the RF team to establish a stringent quality-assurance system, subsequently shared with all our collaborators to ensure standardised production processes, workflows and system integration.

Looking ahead, the next milestone for the HL-LHC crab cavity programme is the testing of the first RFD module in the SPS. Currently, this module is being assembled at Daresbury Laboratory and will be delivered to CERN in September 2023, after which it will be cold-tested in SM18 prior to installation in the SPS during the 2023/24 year-end technical stop.

While the crab-cavity programme will keep CERN's RF team occupied until the conclusion of LS3 in 2028, preparations are already under way for the 2030s and beyond. Right now, there is a consensus that the next major collider after the LHC will be a lepton machine focused on precision measurements of the Higgs boson. In the case of a circular collider, this will necessitate a powerful RF system to attain collision energies surpassing those achieved by



A longer view *The number of cryomodules that need to be installed for each FCC-ee physics scenario. A "+" means installation of additional modules, while the change from the Z to W thresholds involves the removal of 28 single-cell modules and installation of 64 two-cell modules.*



Numbers game *Test results at 4.2 K for HIPIMS-coated 1.3 GHz cavities, which were welded (W), bulk machined (BM) or electroformed (L).*

LEP. Two potential candidates are the electron–positron Future Circular Collider (FCC-ee), which would require over 1000 SRF cavities, and a muon collider with more than 3000 SRF cavities (for a 10 TeV centre-of-mass scenario). Meanwhile, a linear collider such as the proposed 500 GeV ILC would necessitate over 7000 SRF cavities.

Progressions of power

Regardless of the eventual scenario, it is evident that the RF system poses a significant technological challenge, with most options involving deployment of SRF cavities at levels an order of magnitude greater than those used in LEP. With rising electricity prices, and growing calls for operational sustainability within high-energy physics, CERN has an obligation to pursue all means of reducing the power consumption of the next big collider. In this context, the CERN RF group is prioritising two strategic R&D objectives: to reduce the surface losses of superconducting cavities while engaging in higher-efficiency RF power generation.

It's instructive to consider CERN's SRF strategy in the context of the FCC-ee – and specifically, the potential impact of reduced cavity losses on FCC-ee power consumption and how that is shaping SRF R&D priorities. The present FCC-ee scenario foresees four main stages of operation at increasing centre-of-mass energies, enabling precision measurements of the Z boson (91 GeV), W boson (161 GeV), Higgs boson (250 GeV) and the top quark (365 GeV). The high beam currents needed to support Z and W physics enforce the use of low-frequency cavities (400 MHz) to control the beam-excited HOM power. This means single-cell 400 MHz cavities were chosen for the Z, which will be exchanged for two-cell 400 MHz cavities for the W. At the same time, the booster accelerator will be equipped with 800 MHz five-cell cavities. The number of cryomodules will then increase progressively when moving to the H and ttbar scenarios.

According to projections, the total power consumption of the FCC-ee ttbar scenario is estimated at 384 MW. Within this budget, 148 MW will be needed for the RF power system and 47.5 MW for the associated cryogenics systems. The RF component is dominated by the synchrotron losses (100 MW), which need to be compensated, and the efficiency of the RF power system to generate this power and transfer it to the beam. The cryogenic budget, on the other hand, is related to the surface resistance of the SRF cavities. The maths is simple enough: decrease the SRF surface resistance by a factor of two – and the power consumption of the cryogenic system falls by a factor of two (which, in turn, would cut the size of the cryogenic plant by half).

Is such an outcome realistic, though? The current stated R&D goal for 400 MHz FCC-ee cavities is an approximately 30% reduction of surface losses (versus the LHC cavities) together with a doubling of the accelerating gradient. It's an ambitious goal and, as such, CERN RF engineers are applying the lessons learned from the HIE-ISOLDE project, where the use of seamless cavity substrates made it possible to increase the peak fields in the cavity while lowering surface losses.

Testing, iteration, continuous improvement

Proof-of-principle tests to date required seamless elliptical cavities, with the CERN workshop able to machine such cavities out of bulk copper pieces, while the technology department's vacuum group pioneered a method using electroforming. (In the latter, copper is deposited onto an aluminium mandrel, with the aluminium subsequently dissolved to leave behind only the deposited copper layer.) Both approaches were used to make small (scaled) 1.3 GHz cavities, which were then chemically

RF power sources for future accelerators

Alongside the broad-scope R&D efforts around SRF cavity surface losses, parallel work programmes are under way at CERN to increase the efficiency of the RF power sources. As discussed in the main text, the FCC-ee beam needs to receive 100 MW from the RF power system just to compensate for synchrotron radiation losses. The actual required RF power budget therefore increases to 148 MW (including 2 MW for the booster RF) given the anticipated FCC-ee RF power estimation efficiencies of 80%, 90% and 95% for klystrons, klystron modulators and RF distribution, respectively.

Today, however, klystron efficiency is in the region of 55% (which would mean 215 MW for the FCC-ee RF system). Pushing on to that 80% target specification falls within the remit of CERN's RF group and its focused R&D effort to increase the RF efficiency of high-power klystrons. By applying modern electron-beam dynamics techniques and in-house developed 3D simulation codes (KLYC), the team has already demonstrated tangible results. Last year, for example, the first CERN-designed, high-efficiency klystron was built by Canon and reached exactly the predicted efficiency (53.3%) for a pulsed X-band system (*CERN Courier* September/October 2022 p39).

For FCC-ee, an advanced, two-stage multibeam klystron for the 400 MHz system is also under development in collaboration with industry partners. The goal is 80% efficiency with much reduced high-voltage requirements (60 kV instead of 110 kV) and a much smaller footprint (2.5 m total length instead of approximately 5.5 m).

Alongside the technology innovation on klystrons, CERN's RF group is engaged on several other fronts – whether pushing the efficiencies of solid-state based amplifiers or making simple, cost-efficient inductive output tube (IOT)-based amplifiers. The in-house RF team also allocates considerable time and resource – spanning R&D, testing and implementation – to realise power couplers with unprecedented power delivery to the cavities; new tuning mechanisms for the SRF cavities; RF feedback systems and controllers; as well as simulation codes to model longitudinal beam dynamics.

CERN

Shaping up *Frank Gerigk (left) and CERN colleague Said Atieh show off the first hydroformed copper prototypes from KEK. The SRF cavity substrates will be coated and tested at CERN later this year.*

polished and coated using high-power impulse magnetron sputtering (HIPIMS), a specialised method for physical vapour deposition of thin films.

The figure on page 22 ("Numbers game") shows the results of the first cold tests as well as the target value for the FCC-ee 400 MHz cavities (the latter scaled, in Q value, to be comparable to the 1.3 GHz cavity results). What's evident from the data is that the seamless coated cavities have clear potential to reach the FCC-ee performance goal – though it's worth emphasising that these are simplified test cavities without power couplers and without HOM couplers (plus these cavities are around three times smaller in diameter versus the 400 MHz cavities foreseen for FCC-ee).

Qualifiers notwithstanding, these results constitute the first significant step forward in thin-film SRF cavity performance since LEP – underpinned by the enhanced HIPIMS coatings, the use of seamless cavity substrates, and the precision control of cavity surface states during chemistry, coating and cold testing. In terms of next steps, CERN's R&D effort will focus on further improvements in quality factor (inversely proportional to the surface resistance); extending the field reach (so far limited by the experimental set-up, and not by the properties of the test cavities); and the scale-up to much larger cavities.

The challenges posed by cavity size are twofold: on the one hand, to ensure equal film quality over several square metres of inner surface; on the other, to find a fabrication method that avoids a welding seam at the equator of the cavities. All elliptical cavities built today – whether coated cavities or bulk niobium – are assembled from pre-shaped half-cells. While small 1.3 GHz cavities are straightforward to machine out of a bulk piece of copper, this method quickly becomes uneconomical when considering 400 MHz FCC-type cavities.

For this reason, CERN has initiated a collaboration with KEK in Japan to explore the potential for seamless cavity fabrication via hydroforming (an advanced die-molding process that relies on highly pressurised fluids to shape metals). While the initial results are encouraging, a lot of prototyping and subsequent coating tests will be needed to develop this technology into a process that can be scaled and industrialised. If successful, the hope is that SRF cavity substrates could ultimately be produced like bodywork pieces for cars – and at a fraction of today's fabrication costs.

Another active area of SRF R&D – and the focus of an ongoing CERN collaboration with Fermilab – involves the 800 MHz multicell bulk-niobium cavities foreseen in the FCC-ee baseline scenario. Over the past decade, Fermilab has pioneered advanced surface treatment methods (such as nitrogen doping or infusion) along with various temperature treatments to tailor the surface resistance of 1.3 GHz bulk-niobium cavities for specific applications.

There's been significant progress in lowering the surface resistance and the technology has found initial application in the SRF cavities of the Linac Coherent Light Source (LCLS-II) at SLAC in California (with the cavities first being treated and then assembled into cryomodules at Fermilab). In line with the requirements for its Proton Improvement Plan (PIP-II), an ambitious upgrade of the Fermilab accelerator complex, the US laboratory has also started to apply its surface tailoring methods to larger cavities (650 MHz) and, as part of this effort, is keen to include FCC-ee prototypes.

If the cavities can operate at 4.2 K instead of 2 K with the same surface resistance, the aggregate cryogenic power consumption will be cut by two-thirds

The outer limits

To push beyond the performance limits of today's coated or bulk-niobium cavities, CERN, Fermilab and other partner laboratories are evaluating new superconducting materials that operate at higher cryogenic temperatures. CERN, for its part, is making sample tests with thin Nb_3Sn or Vn_3Si layers on copper, while Fermilab scientists are creating a thin layer of Nb_3Sn on pure niobium surfaces. The physics is compelling: if the 800 MHz cavities can operate at 4.2 K instead of 2 K with the same surface resistance, the aggregate cryogenic power consumption will be cut by two-thirds.

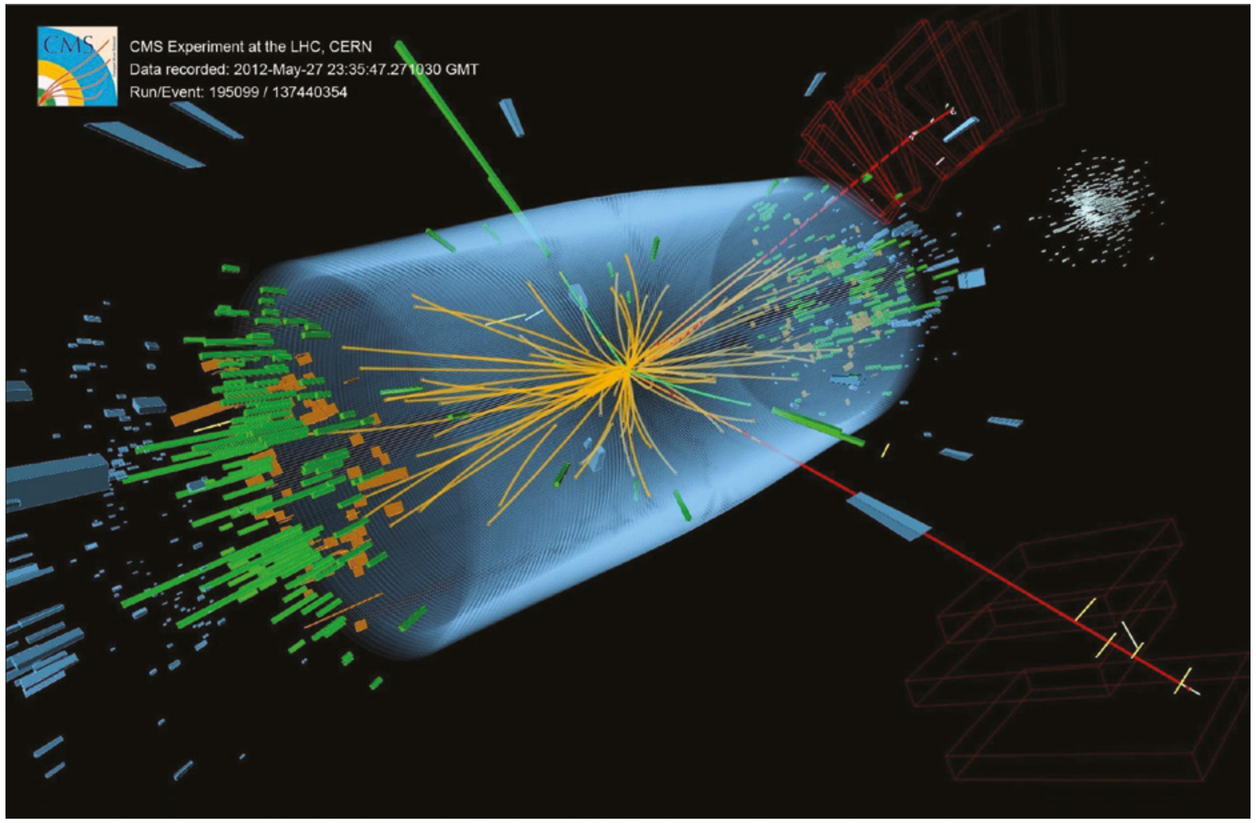
Along another coordinate, unprecedented accelerating gradients can theoretically be achieved by having multi-layered films on top of niobium or copper cavities, with researchers at CEA in France reporting significant progress with the deposition of single atomic layers onto substrates. In short, with the help of targeted R&D, this looks like a promising path to reducing the SRF surface resistance by 50% on average, though success will ultimately depend on the availability of skilled manpower, state-of-the-art materials processing infrastructure as well as precise diagnostics to evaluate SRF performance.

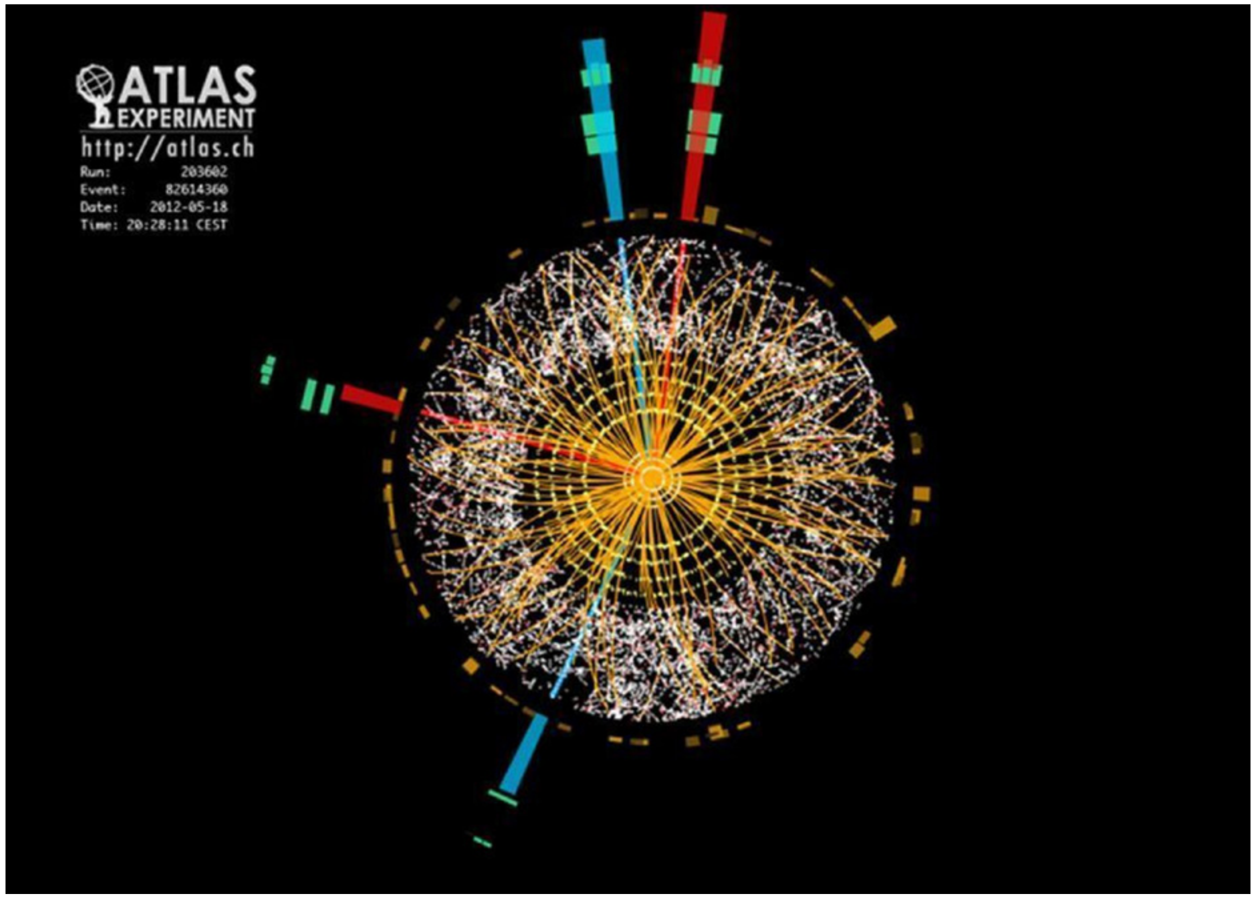
With this in mind, CERN's RF group has proposed the construction of a dedicated SRF infrastructure next to the SM18 facility. The new building will provide almost 5000 m^2 of space for advanced cavity chemistry as well as clean rooms, cryomodule assembly area and materials cleaning facilities. A full integration study and cost estimate is now complete and the project is under consideration for inclusion in CERN's next Medium-Term Plan (2023–26).

The future's bright, it seems, for CERN's SRF technology programme. ●

Advertisement

Element Six Synthetic Diamond Protects CERN Particle Detectors in Higgs boson Experiment Results





Back in 2012, CERN (European Organization for Nuclear Research) particle detection systems used Element Six synthetic diamond in their first line of defence against beam-induced radiation damage in their Higgs boson experiment results.

Element Six, a world leader in synthetic diamond supermaterials, supplied its highest purity synthetic diamond as an integral part of the CERN LHC (Large Hadron Collider) CMS (Compact Muon Solenoid) and ATLAS Beam Condition Monitoring Systems, used in the milestone experiments which revealed the discovery of the Higgs boson.

"The diamond synthesised by Element Six measures LHC beam conditions in key areas of the main experiments that have been used in the search for the Higgs boson," said Heinz Pernegger, CERN scientist at the ATLAS experiment.

"The CMS experiment relies on the stability of the synthetic diamond sensors produced by Element Six to monitor the LHC beam arriving to the CMS experiment and the particles created in the collision. The robustness of this synthetic diamond-based system is crucial in protecting the most sensitive components of the 66 million channel pixel-tracking detector," said Anna Dabrowski, CERN scientist at the CMS experiment.

"The use of synthetic diamond sensors was essential for a smooth operation of the LHC and the collection of high quality data by the LHC experiments, making the observation of the new particle possible," concluded Professor Wolfgang Lohmann from the Brandenburg University of Technology.

Element Six electronic grade synthetic diamond was selected as the optimum detector material by CERN scientists over the decade-long development of CERN's CMS and ATLAS Beam Condition Monitoring Systems. Synthetic diamond was shown to be the most robust sensor material available which could withstand the harsh, high radiation environment and react almost instantaneously to be able to protect the advanced measurement systems.

Element Six manufactures the synthetic diamond used in the detectors using a process called chemical vapour deposition (CVD). This process takes a mixture of gases and forms plasma with the extreme high temperature of a sun spot to allow carbon to precipitate onto a substrate layer as synthetic diamond.

The purpose of the CERN CMS and ATLAS experiments was to count, track and characterise the different particles produced from the particle collisions inside the LHC. The synthetic diamond detectors in the monitoring system protected the experiments from adverse beam conditions and contributed to the luminosity measurement, which was crucial for obtaining the five sigma result.

Leveraging Element Six's over 70 years of innovation leadership and patented technology, the grades of synthetic diamond used in these monitoring systems are grown to ultra high levels of purity, incorporating less than one part per billion of boron, and less than 50 parts per billion of nitrogen. When diamond is synthesised with these levels of purity, it becomes an ideal radiation detector material. It can exhibit properties such as very low leakage current with negligible temperature dependence, a fast signal response and a vastly improved radiation hardness and reduction of leakage-current compared to silicon, the material traditionally used for detectors.

Dr Daniel Twitchen, Chief Technologist at Element Six, said:

"We are incredibly proud of the small, but important, contribution our synthetic diamond has made in helping the CMS and ATLAS experiments that enabled the team at CERN realise their milestone discoveries."

"This is yet another demonstration of why synthetic diamond is an ideal advanced engineering material capable of delivering extreme performance in the toughest environments. At Element Six, we are committed to engineering and manufacturing the highest purity synthetic diamond to help our partners meet their scientific and technology application challenges."

Professor Dr. Erich Griesmayer, CEO at CIVIDEC, with more than 20 years' experience of working at CERN, added:

"Beam condition monitoring is critical to the safe operation of the LHC at CERN. The diamond synthesised by Element Six was able to provide that protection in key areas of the main experiments that have been used in the search for the Higgs boson. Now that the synthetic diamond has been proven in this application, there is scope for its further use in medicine such as radiation therapy and diagnostic imaging."

To find out more about Element Six's collaboration with CIVIDEC, read the related case study.

elementsix™
DE BEERS GROUP

www.e6.com
www.e6CVD.com
E-mail gabriella.sciarrone@e6.com

OPINION
SERVICES

Navigating the fusion roadmap

The UKAEA Materials Research Facility does the heavy-lifting on materials engineering assurance for emerging fusion technologies. Joe McEntee reports.

The UK Atomic Energy Authority (UKAEA) is busy shaping a quiet revolution in advanced materials research as part of its fusion R&D roadmap. The goal: to fast-track development of next-generation reactor materials that can withstand the "triple-whammy" of tritium fuel permeation (into "first-wall" components), transmutation (induced radioactivity) and atomic displacement effects (mechanical damage) – all of which represent potential show-stoppers when it comes to the UK's strategic objective of delivering fusion power into the electricity grid by the middle of the century.

In a signal of intent, the UKAEA completed a £10 million extension of its Materials Research Facility (MRF) at Culham Science Centre, Oxfordshire, at the end of last year. The investment doubled the size of MRF, providing an additional 12 shielded research rooms (used to house high-end analytical instrumentation) and more than 250 m² of radioactive-capable laboratory space (to investigate enhanced neutron-tolerant materials).

Operationally, a key driver for MRF is the realisation of radiation-hardened materials and platform technologies for the so-called Spherical Tokamak for Energy Production (STEP), a UK prototype fusion energy plant targeting operation in 2040 and, thereafter, a sustainable pathway to commercially viable nuclear fusion (see "Back to basics on STEP"). That's an ambitious timeline – and one currently preoccupying the project team sweating the details for STEP's four-year, £220 million design phase (due for completion by mid-2024).

With this in mind, the MRF offers a focal point for R&D collaboration, bringing together academic and industrial researchers, as well as experimentalists and modellers, to address materials gaps in the STEP programme and to foster innovative approaches to materials qualification for fusion. By extension, the MRF also provides workers with specialist experience to support users with their sample preparation and analysis, plus logistics advice for the transport of radioactive materials.

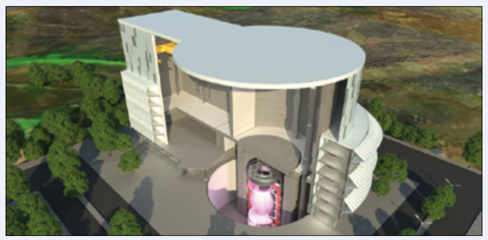
A case study in this regard is the £2 million MRF FaSCiNATe initiative (or, to give it its full name – Facility for the Structural Characterisation of materials for Nuclear Applications operating at high Temperatures). Headed up by UKAEA in partnership with the University of Oxford and the University of Birmingham, FaSCiNATe provides what UKAEA claims is "a unique and complementary suite of scientific instruments" to characterise the thermal stability of microstructural damage in neutron-irradiated materials and the associated effects on mechanical properties.

Specifically, FaSCiNATe focuses on the materials defects resulting from irradiation damage: what strain they create (as measured by high-temperature X-ray diffraction), what energy they store (using high-vacuum differential scanning calorimetry), and what influence they have on mechanical behaviour at the micron scale (using an *in situ* mechanical test stage mounted inside an electron microscope).

"The FaSCiNATe instruments are integrated in shielded environments and equipped with robotic sample mounting systems to remotely insert and retrieve radioactive samples," explains Andy London, scientific lead for active testing at MRF. "Being able to predict materials degradation under neutron irradiation will help us to extend the lifetime of existing nuclear reactors as well as inform the materials requirements of future fission and fusion reactors."

The *in situ* load frame, for example, enables researchers to observe how materials deform at fusion-relevant operational temperatures (–160 to 1000 °C), yielding insights for designer materials that prevent the accumulation of more serious damage. Meanwhile, the heating of defective materials can actually cause atoms to rearrange and therefore "heal" some of the irradiation damage, releasing energy in the process. High-vacuum differential scanning calorimetry is able to quantify these energy changes as a function of temperature, while X-ray diffraction tracks the evolution of defect strain at the atomic scale as it recovers with increasing temperatures. ●

Back to basics on STEP


UKAEA

● In the prototype STEP power plant (artist rendering, shown above), nuclear fusion will be realised in a spherical tokamak device that uses superconducting magnets to confine and control a hot plasma of fusion fuels in a torus configuration.

● At the heart of it all is the fusion reaction between deuterium and tritium nuclei, yielding one helium nucleus, one neutron and, in the process, liberating huge amounts of thermal energy for electricity production. STEP is aiming to generate 100 MW of net electricity as the demonstration of a commercially relevant plant.

● While most of today's experimental fusion devices – including JET at Culham and the work-in-progress ITER project in southern France – are built in the shape of a ring doughnut, STEP's spherical plant will be shaped more like a cored apple. This spherical tokamak design is expected to minimise STEP's physical footprint, improve operating efficiency, as well as potentially reduce capital and running costs.

THE AUTHOR
Joe McEntee *is a consultant editor based in South Gloucestershire, UK.*