WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the 2022 *CERN Courier* In Focus report on vacuum science, technology and innovation.

Design, construction, commissioning, operation and upgrade: the life-cycle of large-scale scientific vacuum systems informs the exclusive coverage in this *CERN Courier* In Focus report. Think technology innovation and implementation on an ambitious canvas like ITER's sprawling vacuum ecosystem, a core building block in the international research effort to transform nuclear fusion into an at-scale energy proposition (p20). Beyond the ITER campus, the "grand challenge" of fusion is supported by a network of top-tier research partners – among them the Karlsruhe Institute of Technology (KIT) Vacuum Lab and its holistic R&D model, knitting together fundamental vacuum science and integrated process development (p5). Elsewhere, the focus shifts to vacuum deployment in a very different big-science setting – Sweden's MAX IV synchrotron laboratory (p29) – while there are reports from CERN on the vacuum team's impressive upgrade and refit programme during Long Shutdown 2 (p25) as well as sustained advances in the use of plasma processing for surface modification of vacuum subsystems and components (p11). This In Focus report is vacuum writ large.

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IN FOCUS LARGE-SCALE VACUUM

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IN FOCUS LARGE-SCALE VACUUM


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From the Editor

Design, construction, commissioning, operation and upgrade: the life-cycle of large-scale scientific vacuum systems informs the exclusive coverage in this *CERN Courier In Focus* report. Think technology innovation and implementation on an ambitious canvas like ITER's sprawling vacuum ecosystem, a core building block in the international research effort to transform nuclear fusion into an at-scale energy proposition (p20). Beyond the ITER campus, the "grand challenge" of fusion is supported by a network of top-tier research partners – among them the Karlsruhe Institute of Technology (KIT) Vacuum Lab and its holistic R&D model, knitting together fundamental vacuum science and integrated process development (p5). Elsewhere, the focus shifts to vacuum deployment in a very different big-science setting – Sweden's MAX IV synchrotron laboratory (p29) – while there are reports from CERN on the vacuum team's impressive upgrade and refit programme during Long Shutdown 2 (p25) as well as sustained advances in the use of plasma processing for surface modification of vacuum subsystems and components (p11). This *In Focus* report is vacuum writ large.

Cover *Into the KIT Vacuum Lab, p5 (Pedro Lima)*

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OPINION
RESEARCH

Thinking big in vacuum R&D

The Vacuum Lab at Karlsruhe Institute of Technology is where fundamental vacuum science meets applied process and technology development. Joe McEntee talks to the lab's director Christian Day.

Vacuum versatility *Many of the core facilities in the KIT Vacuum Lab are non-standard and not found anywhere else. Even TIMO (shown above), the lab's large multipurpose vacuum vessel, is heavily customised, offering temperature cycling from 450 K down to 4 K.*

Christian Day is a vacuum scientist on a mission – almost evangelically so. As head of the Vacuum Lab at Karlsruhe Institute of Technology (KIT), part of Germany's renowned network of federally funded Helmholtz Research Centres, Day and his multidisciplinary R&D team are putting their vacuum know-how to work in tackling some of society's "grand challenges".

Thinking big goes with the territory. As such, the KIT Vacuum Lab addresses a broad-scope canvas, one that acknowledges the core enabling role of vacuum technology in all manner of big-science endeavours – from the ITER nuclear-fusion research programme to fundamental studies of the origins of the universe (Day is also technical lead for cryogenic vacuum on the design study for the Einstein Telescope, a proposed next-generation gravitational-wave observatory).

Here, Day tells *CERN Courier* about the Vacuum Lab's unique R&D capabilities and the importance of an integrated approach to vacuum system development in which modelling, simulation and experimental validation all work in tandem to foster process and technology innovation.

What are the long-term priorities of the KIT Vacuum Lab?

Our aim is to advance vacuum science and technology along three main pathways: an extensive R&D programme in collaboration with a range of university and scientific partners; design and consultancy services for industry; and vacuum education to support undergraduate and postgraduate science and engineering students at KIT. It's very much a multidisciplinary effort, with a staff team of 20 vacuum specialists working across physics, software development and the core engineering disciplines (chemical, mechanical, electrical). They're supported, at any given time, by a cohort of typically five PhD students.

Christian Day *"We take a holistic view that allows us to identify the main influences in the vacuum system and map them theoretically or experimentally."*

So what does that mean in terms of the team's core competencies?

At a headline level, we're focused around the two fundamental challenges in modern vacuum science: the realisation of a physically consistent description of outgassing behaviours for a range of materials and vacuum regimes; also the development of advanced vacuum gas dynamics methods and associated supercomputer algorithms. ▷

Next-generation pump designs: from ITER to the DEMO fusion project

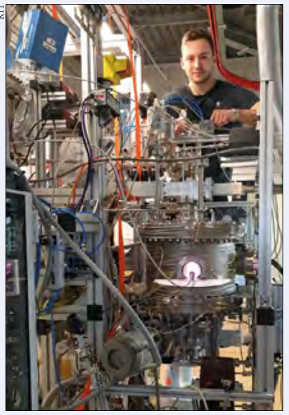
By Yannick Kathage

When the ITER experimental reactor enters operation later this decade, nuclear fusion will be realised in a tokamak device that uses superconducting magnets to contain a hot plasma in the shape of a torus. Herein the fusion reaction between deuterium and tritium (DT) nuclei will produce one helium nucleus, one neutron and, in the process, liberate huge amounts of energy (that will heat up the walls of the reactor to be exploited in a power cycle for electricity production).

In this way, fusion reactors like ITER must combine large-scale vacuum innovation with highly customised pumping systems. The ITER plasma chamber ($1400\,m^3$), for example, will be pumped at fine vacuum (several Pa) against large gas throughputs in the course of the plasma discharge – the so-called burn phase for energy generation. There follows a dwell phase, when the chamber will be pumped down (for approximately 23 minutes) to moderately high vacuum (5×10^{-4} Pa), before initiating the next plasma discharge. Meanwhile, surrounding the plasma chamber is an $8500\,m^3$ cryostat to provide a 10 mPa cryogenic insulation vacuum (required for the operation of the superconducting magnets).

A key design requirement for all of ITER's pumping systems is to ensure compatibility with tritium, a radioactive hydrogen isotope. Effectively, this rules out the use of elastomer seals (only metal joints are permitted) and the use of oil or lubricants (which are destroyed by tritium contamination). Specifically, the six torus exhaust systems are based on so-called discontinuous cryosorption pumps, cooled with supercritical helium gas at 5 K and coated with activated charcoal as sorbent material to capture helium (primarily), a mix of hydrogen isotopes and various impurities from the plasma chamber.

As with all accumulation pumps, these cryopumps must be regenerated by heating on a regular basis. To provide a constant pumping speed on the torus during the plasma pulse, it's therefore necessary to "build in" additional cryopumping capacity – such that four systems are always pumping, while the other two are in regeneration mode. What's more, these six primary cryopumps are backed by a series of secondary cryopumps and, finally, by dry mechanical rough pumps that compress to ambient pressure.



Next generation *Left: KIT chemical engineer Yannick Kathage adjusts the HERMES test stand for the evaluation of MFP pump designs based on a plasma-driven technique called superpermeation. Right: reconfiguration of the prototype mercury pumping systems in KIT's purpose-built mercury lab.*

Scaling up for DEMO

The operational principle of the cryosorption pump means that large quantities of tritium accumulate within the sorbent material over time – a safety concern that's very much on the radar of the ITER management team as well as Europe's nuclear regulatory agencies. Furthermore, this "tritium inventory" will only be amplified in the planned future DEMO power plant, providing real impetus for the development of new, and fully continuous, pumping technologies tailored for advanced fusion applications.

Among the most promising candidates in this regard is the so-called metal-foil pump (MFP), which uses a plasma source to permeate, and ultimately compress, a flux of pure hydrogen isotopes through a group V metal foil (e.g. niobium or vanadium) using an effect called superpermeation. The driving force here is an energy gradient in the gas species, up and downstream of the foil (due to plasma excitation, but largely independent of pressure). It's worth noting that the KIT Vacuum Pumping Task Force initiated development work on the MFP concept five years ago, with a phased development approach targeting "mature technical exploitation" of superpermeation pumping systems by 2027.

If ultimately deployed in a reactor context, the MFP will yield two downstream components: a permeated gas stream (comprising D and T, which will be cycled directly back into the fusion reactor) and an unprocessed stream (comprising D, T, He and impurities), which undergoes extensive post-processing to yield an additional D, T feedstock. It is envisaged that both gas streams, in turn, will be pumped by a train of continuously working rough pumps that use mercury as a working fluid (owing to the metal's compatibility with tritium). As the DEMO plant will feature a multibarrier concept for the confinement of tritium, mercury can also be circulated safely in a closed-loop system.

One of those alternative roughing pump technologies is also being developed by the KIT Vacuum Pumping Task Force – specifically, a full stainless-steel mercury ring pump that compresses to ambient pressure. Progress has been swift since the first pump-down curve with this set-up was measured (in 2013) and the task force now has a third-generation design working smoothly in the lab, albeit with all rotary equipment redesigned to take account of the fact that mercury has a specific weight 13 times greater than that of water (the usual operating fluid in a ring pump).

Hydrogen impacts

While mercury-based vacuum pumping is seen as a game-changer exclusively for fusion applications, it's evident that the MFP is attracting wider commercial attention. That's chiefly because superpermeation works only for the hydrogenic species in the gas mixture being pumped – thereby suggesting the basis of a scalable separation functionality. In the emerging hydrogen economy, for example, it's possible that MFP technology, if suitably dimensioned, could be implemented to continuously separate hydrogen from the synthesis gas of classical gasification reactions (steam reforming) and at purities that can otherwise only be achieved via electrolytic processes (which require huge energy consumption).

Put simply: MFP technology has the potential to significantly reduce the ecological footprint associated with the mass-production of pure hydrogen. As such, once the MFP R&D programme achieves sufficient technical readiness, the KIT Vacuum Lab will be seeking to partner with industry to commercialise the associated know-how and expertise.

Yannick Kathage *is a chemical engineering research student in the KIT Vacuum Lab.*

As such, one of the main strengths of the KIT Vacuum Lab is our prioritisation of predictive code development alongside experimental validation – twin capabilities that enable us to take on the design, delivery and project-management of the most complex vacuum systems. The resulting work programme is nothing if not diverse – from very-large-scale vacuum pumping systems for nuclear fusion to contamination-free vacuum applications in advanced manufacturing (e.g. extreme UV lithography and solar-cell fabrication).

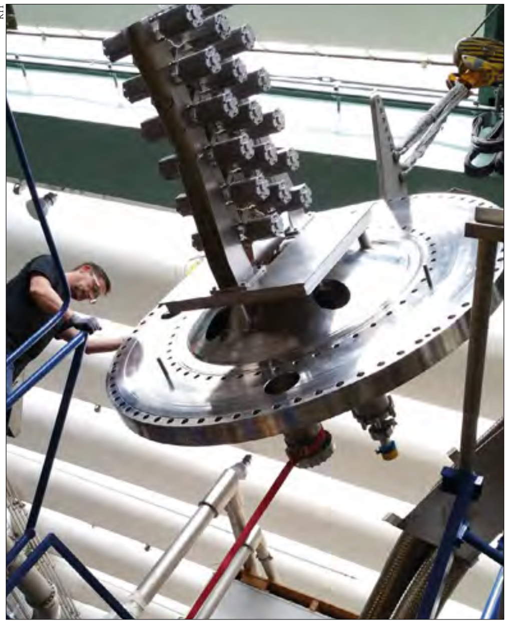
What sets the KIT Vacuum Lab apart from other vacuum R&D programmes?

Over the last 10 years or so, and very much driven by our contribution to the ITER nuclear fusion project in southern France, we have developed a unique and powerful software capability to model vacuum regimes at a granular level – from atmospheric pressure all the way down to extreme-high-vacuum (XHV) conditions (10^{-10} Pa and lower). This capability, and the massive computational resources that make it possible, are being put to use across all manner of advanced vacuum applications – quantum computing, HyperLoop transportation systems and gravitational-wave experiments, among others.

The Vacuum Lab's organising principles are built around "integrated process development". What does that look like operationally?

It means we take a holistic view regarding the development of vacuum processes, which allows us to identify the main influences in the vacuum system and to map them theoretically or experimentally. An iterative design evolution must not only be based on efficient models; it must also be validated and parameterised by using experimental data from different levels of the process hierarchy. Experimental data are indispensable to evaluate the pros and cons of competing models and to quantify the uncertainities of model predictions.

In turn, the department's research structure is set up to address elementary processes and unit functions within a vacuum system. When choosing a vacuum pump, for example, it's important to understand how the pump design, underlying technology and connectivity will influence other parts of the vacuum system. It's also necessary, though too often forgotten, for the end-user to understand the ultimate purpose of the vacuum system – the why – so that they can address any issues arising in terms of the vacuum science fundamentals and underlying physics.



Vacuum innovation *The KIT Vacuum Lab is developing high-capacity NEG materials for applications in nuclear fusion research. Above: installation of a NEG pumping module in TIMO, the lab's large vacuum vessel. Below: KIT scientist Katharina Battes uses the lab's custom Outgassing Measurement Apparatus (OMA) to determine specific outgassing rates related to the surface area of different metals, polymers and ceramics.*

What are your key areas of emphasis in fusion research right now?

Our vacuum R&D programme in nuclear fusion is carried out under the umbrella of EUROfusion, a consortium agreement signed by 30 research organisations and universities from 25 EU countries plus the UK, Switzerland and Ukraine. Collectively, the participating partners in EUROfusion are gearing up for the ITER experimental programme (due to come online in 2025; see p20), with a longer-term focus on the enabling technologies – including the vacuum systems – for a proof-of-principle fusion power plant called DEMO. The latter is still at the concept phase, though provisionally scheduled for completion by 2050.

As EUROfusion project leader for the tritium fuel cycle, I'm overseeing KIT's vacuum R&D inputs to the DEMO fusion reactor – a collective effort that we've labelled the Vacuum Pumping Task Force and involving multiple research/industry partners. The vacuum systems in today's nuclear fusion reactors – including the work-in-progress ITER facility – rely largely on customised cryosorption pumps for vacuum pumping of the main reaction vessel and the neutral beam injector (essentially by trapping gases and vapours on an ultracold surface). DEMO, though, will require a portfolio of advanced pumping concepts to be developed for ongoing operations, including metal-foil and mercury-based diffusion and ring pumps as well as high-capacity non-evaporable-getter (NEG) materials (see "Next-generation pump designs: from ITER to the DEMO fusion project", p6).

How does all that translate into the unique facilities and capabilities within the KIT Vacuum Lab?

Our work on fusion vacuum pumps requires specialist domain knowledge regarding, for example, the safe handling of mercury as well as how to manage, measure and mitigate the associated radioactivity hazard associated with tritium-compatible vacuum systems. We have set up a dedicated mercury lab, for example, to investigate the fluid dynamics of mercury diffusion pumps as well as a test station to optimise their performance at a system level. ▷

> **Mistakenly, early-career researchers often think that vacuum is a somehow old-fashioned service that they can buy off-the-shelf**

Many of the other laboratory facilities are non-standard and not found anywhere else. Our Outgassing Measurement Apparatus (OMA), for example, uses the so-called difference method for high-resolution measurements of very low levels of outgassing across a range of temperatures (from ambient to 570 K). The advantage of the difference method is that a second vacuum chamber, which is identical to the sample chamber, is used as a reference in order to directly subtract the background outgassing rate of the chamber.

Meanwhile, our TransFlow facility allows us to generate fluid flows at different levels of rarefaction, and across a range of channel geometries, to validate our in-house code development. Even TIMO, our large multipurpose vacuum vessel – a workhorse piece of kit in any vacuum R&D lab – is heavily customised, offering temperature cycling from 450 K down to 4 K.

What about future plans for the KIT Vacuum Lab?

A significant expansion of the lab is planned over the next four years, with construction of a new experimental hall to house a 1:1 scale version of the vacuum section of the DEMO fuel cycle. This facility – the catchily titled Direct Internal Recycling Integrated Development Platform Karlsruhe, or DIPAK – will support development and iteration of key DEMO vacuum systems and associated infrastructure, including a large vacuum vessel to replicate the torus – a non-trivial engineering challenge at 30 tonnes, 7 m long and 3.5 m in diameter.

How do you attract the brightest and best scientists and engineers to the KIT Vacuum Lab?

The specialist teaching and lecture programme that the vacuum team provides across the KIT campus feeds our talent pipeline and helps us attract talented postgraduates.

Early-career researchers often think – mistakenly – that vacuum is somehow old-fashioned and a "commoditised service" that they can buy off-the-shelf. Our educational outreach shows them otherwise, highlighting no shortage of exciting R&D challenges to be addressed in vacuum science and technology – whether that's an exotic new pumping system for nuclear fusion or a low-outgassing coating for an accelerator beamline.

The multidisciplinary nature of the vacuum R&D programme certainly helps to broaden our appeal, as does our list of high-profile research partners spanning fundamental science (e.g. the Weizmann Institute of Science in Tel Aviv), the particle accelerator community (e.g. TRIUMF in Canada) and industry (e.g. Leybold and Zeiss in Germany). Wherever they are, we're always keen to talk to talented candidates interested in working with us. ●

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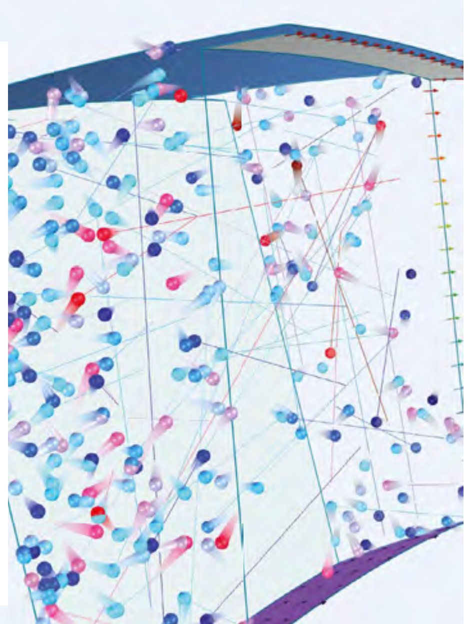
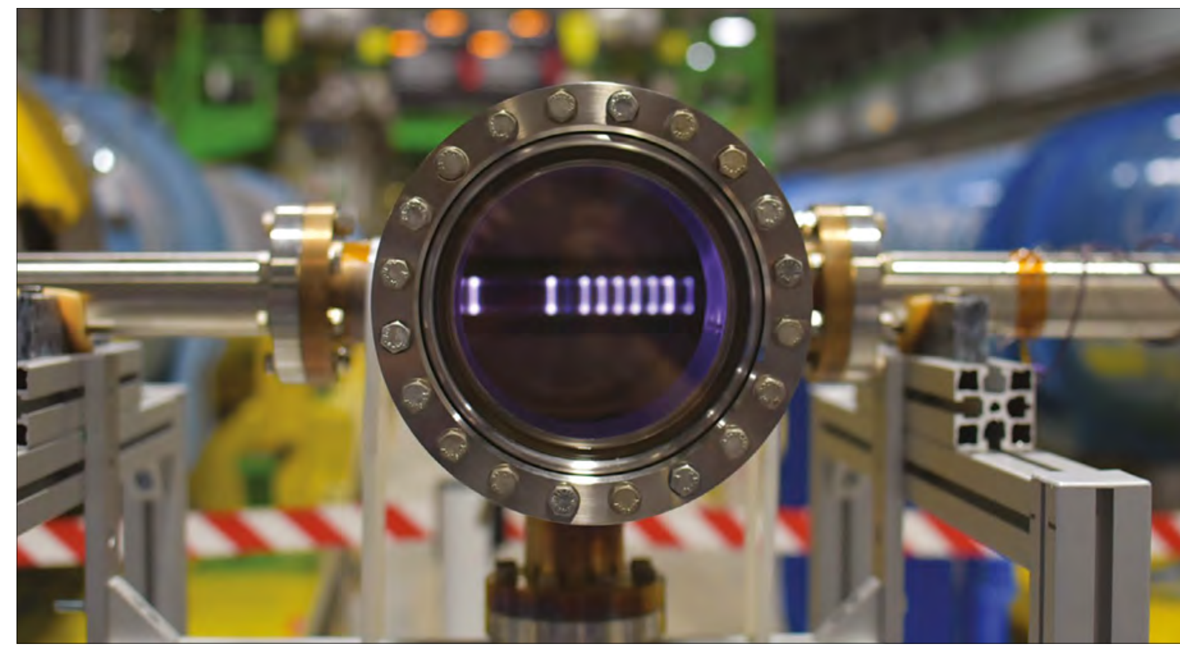
Joe McEntee *is a consultant editor based in South Gloucestershire, UK.*



PLASMAS ON TARGET IN VACUUM SCIENCE

Plasma-driven thin-film deposition is routinely deployed for re-engineering the surface properties of vacuum beam pipes, chambers and components in particle accelerators. CERN's Paolo Chiggiato, Pedro Costa Pinto and Guillaume Jonathan Rosaz explore the critical role that surface modification plays in large-scale vacuum systems.


Giovanni Marinaro/CERN

Surface science *The CERN vacuum, surfaces and coatings group has developed a dedicated set-up to evaluate new cathodes for sputter deposition of amorphous carbon thin films. Such films could, over time, be deployed to enhance the performance of vacuum chambers in the LHC's arcs.*

Within a particle accelerator, the surface of materials directly exposed to the beams interacts with the circulating particles and, in so doing, influences the local vacuum conditions through which those particles travel. Put simply: accelerator performance is linked inextricably to the surface characteristics of the vacuum beam pipes and chambers that make up the machine.

In this way, the vacuum vessel's material top surface and subsurface layer (just a few tens of nm thick) determine, among many other characteristics, the electrical resistance of the beam image current, synchrotron light reflectivity, degassing rates and secondary electron yield under particle bombardment. The challenge for equipment designers and engineers is that while the most common structural materials used to fabricate vacuum systems – stainless steel, aluminium alloys and copper – ensure mechanical resistance against atmospheric pressure, they do not deliver the full range of chemical and physical properties required to achieve the desired beam performance.

Aluminium alloys, though excellent in terms of electrical conductivity, suffer from high secondary electron emission. On the latter metric, copper represents a better choice, but can be inadequate regarding gas desorption and mechanical performance. Even though it is the work-

THE AUTHORS
Paolo Chiggiato *is leader of the vacuum, surfaces and coatings group at CERN;* **Pedro Costa Pinto** *and* **Guillaume Jonathan Rosaz** *are applied physicists in the vacuum, surfaces and coatings group.*

horse of vacuum technology, for its excellent mechanical and metallurgical behaviour, stainless steel lacks most of the required surface properties. The answer is clear: adapt the surface properties of these structural materials to the specific needs of the accelerator environment by coating them with more suitable materials, typically using electrochemical or plasma treatments. (For a review of electrochemical coating methods, see "Surface treatment: secrets of success in vacuum science", *CERN Courier In Focus 2021 – Vacuum Innovation*, p29.)

Variations on the plasma theme

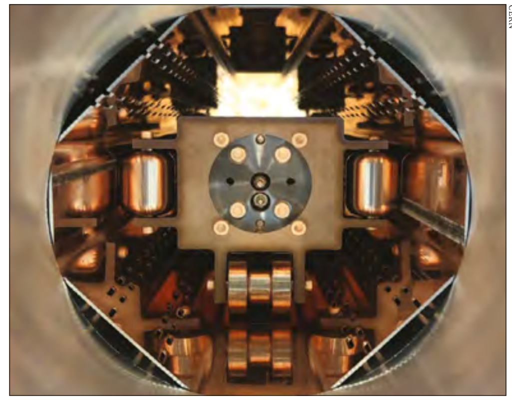
The emphasis herein is exclusively on plasma-based thin-film deposition, in which an electrically quasi-neutral state of matter (composed of positive and negative charged particles) is put to work to re-engineer the physical and chemical properties of vacuum component/subsystem surfaces. A plasma can be produced by ionising gas atoms so that the positive charges are ions, and the negative ones are electrons. The most useful properties of the resultant gas plasma derive from the large difference in inertial mass between the particles carrying negative and positive charges. Owing to their much lower inertial mass, electrons are a lot more responsive than ions to variations of the electromagnetic field, leading to separation of charges and electrical fields within the plasma. What's more, the particle trajectories for ions and electrons also differ markedly.

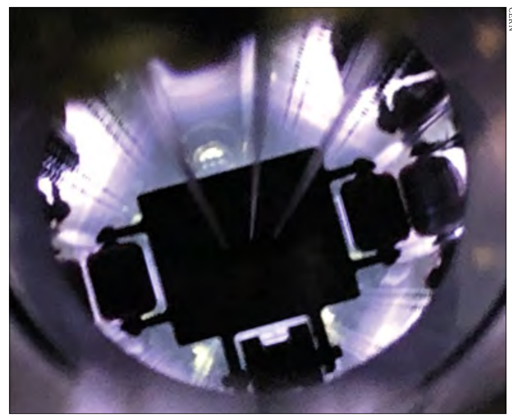
These characteristics can be exploited to deposit thin films and, more generally, to modify the properties of vacuum chamber and component surfaces. For such a purpose, noble-gas ions are extracted from a plasma and accelerated towards a negatively charged solid target. If the ions acquire enough kinetic energy (of the order of hundreds to thousands of eV), one of the effects of the bombardment is the extraction of neutral atoms from the target and their deposition on the surface of the substrate to be modified. This mechanism – called sputtering – is one of the methods used to produce thin films by physical vapour deposition (PVD), where film materials are extracted from a solid into a gas phase before condensing on a substrate.

In the plasma, the lost ions are reintroduced by electron ionisation of additional gas atoms. While the rate of ionisation is improved by increasing the gas density, an excessive gas density can have a detrimental effect on the sputtered atoms (as their trajectories are modified and their kinetic energy decreased by multiple collisions with gas atoms). The alternative is to increase the length of the electron trajectories by applying a magnetic field of several hundred gauss to the plasma.

Sputtering is one of the methods used to produce thin films by physical vapour deposition

Contrary to ions – which are affected minimally – electrons move around the lines of force of the magnetic field in longer helical-like curves, such that the probability of hitting an atom is higher. As electrons are sooner or later lost – either on the growing film or nearby surfaces – the plasma is refilled by secondary electrons extracted from the target (as a result of ion collisions). For a given set of parameters – among them target voltage, plasma power, gas pressure and magnetic flux density – the plasma





Innovation pipeline *A range of plasma sputtering sources is deployed at CERN for coating the interior walls of beam pipes up to 14 m long. Top: coating set-up inserted in an octagonal beam screen for LHC triplets. Bottom: coating set-up during operation, showing the visible glow discharge.*

ultimately attains stable conditions and a constant rate of deposition. Typical film thicknesses for accelerator applications range from a few tens of nm to 2–3 microns.

Unique requirements

The peculiarities of thin-film deposition for accelerator applications lie in the size of the objects to be coated and the purity of the coatings in question. Substrate areas, for example, range from a few cm^2 up to m^2, and in a great variety of 3D shapes and geometries. Large-aspect-ratio beam pipes that are several metres long or complicated multicell cavities for RF applications are typical substrates regularly coated at CERN. The coating process is implemented either in dedicated workshops or directly inside the accelerators during the retrofitting of installed equipment.

The simplest sputtering configuration can be deployed when coating a cylindrical beam pipe. The target, which is made of a wire or a rod of the material to be deposited, is aligned along the longitudinal axis of the beam pipe. Argon is the most commonly used noble gas, at a pressure that depends on the cross-section – i.e. the smaller

Efficiency gains *An in-vacuum cable spool for electrical powering of a movable sputtering target designed for* in situ *deposition of amorphous carbon thin films in the beam screen of the LHC's standalone magnets.*

HiPIMS target geometries and coating parameters must be optimised for each family of accelerator components

the diameter, the higher the pressure (a typical value for vacuum chambers that are a few centimetres in diameter is 0.1 mbar). The plasma is ignited by polarising the target negatively (at a few hundred volts) using a DC power supply while keeping the pipe grounded. It's possible to reduce the pressure by one or two orders of magnitude if a magnetic field is applied parallel to the target (owing to the longer electron paths). In this case, the deposition technique is known as DC magnetron sputtering.

When the substrate is not a simple cylinder, however, the target design becomes more complicated. That's because of the need to accommodate different target–substrate distances, while the angle of incidence of sputtered atoms on the substrate is also subject to change. As a result, the deposited film might have different thicknesses and uneven properties at different locations on the substrate (owing to dissimilar morphologies, densities and defects, including voids). These weaknesses have been addressed, in large part, over recent years with a new family of sputtering methods called high-power impulse magnetron sputtering (HiPIMS).

In HiPIMS, short plasma pulses (of the order of 10–100 µs) of high power density (kW/cm^2 regime) are applied to the target. The discharge is shut down between two consecutive pulses for a duration of about 100–1000 µs; in this way, the duty cycle is low (less than 10%) and the average power ensures there is no overheating and deformation of the target. The resulting plasma, though, is about 10 times denser (approximately 10^{13} ions/cm^3) versus standard DC magnetron sputtering – a figure of merit that, thanks to a bias voltage applied to the substrate, ensures a higher fraction of ionised sputtered atoms are transported to the surfaces to be coated.

The impingement of such energetic ions produces denser films and reduces the columnar structure resulting from the deposition of sputtered atoms moving along lines of sight. As the bias voltage is not always a safe and practical solution, the CERN vacuum team has successfully tested the application of a positive pulse to the target immediately after the main negative pulse. The effect is an increase in energy of the ionised sputtered atoms, with equivalent results as per the bias voltage (though with a simpler implementation for accelerator components).

Owing to the variety of materials and shapes encountered along a typical (or atypical) beamline, the HiPIMS target geometries and coating parameters must be optimised for each distinct family of accelerator components. This optimisation phase is traditionally experimental, based on testing and measurement of "coupon samples" and then prototypes. In the last five years, however, the CERN team has reinforced these experimental studies with 3D simulations based on a particle-in-cell Monte Carlo/direct simulation Monte Carlo (PICMS/DSMC) code – a capability originally developed at the Fraunhofer Institute for Surface Engineering and Thin Films (IST) in Braunschweig, Germany. ▷

Surface cleaning: putting plasmas to work

Notwithstanding their central role in thin-film deposition, plasmas are also used at CERN to clean surfaces for vacuum applications and to enhance the adherence of thin films. A case in point is the application of plasmas containing oxygen ions and free radicals (highly reactive chemical species) for the removal of hydrocarbons. In short: the ions and radicals are driven toward the contaminated surface, where they can decompose hydrocarbon molecules and form volatile species (e.g. CO and CO_2) for subsequent evacuation.

It's a method regularly used to clean beryllium surfaces (which cannot be treated by traditional chemical methods for safety reasons). If the impingement kinetic energy of the oxygen ions is about 100 eV, the chemical reaction rate on the surface is much larger than the beryllium sputtering rate, such that cleaning is possible without producing hazardous compounds of the carcinogenic metal.

Meanwhile, plasma treatments have recently been proposed for the cleaning of stainless-steel radioactive components when they are dismounted from accelerators, modified and then reinstalled. Using a remote plasma source, the energy of the plasma's oxygen ions is chosen (<50 eV) so as to avoid sputtering of the component materials, thereby preventing radioactive atoms from entering the gas phase. The main difficulty here is to adapt the plasma source to the wealth of different geometries that are typical of accelerator components.

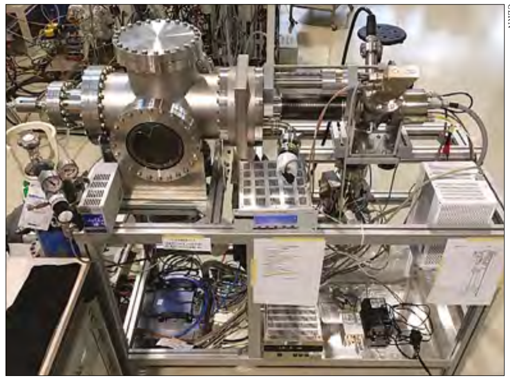
Plasma versatility

So much for the fundamentals of plasma processing, what of the applications? At CERN, the large-scale deployment of thin-film coatings began in the 1980s on the Large Electron–Positron (LEP) collider. To increase LEP's collision energy to 200 GeV and above, engineering teams studied, and subsequently implemented, superconducting niobium (Nb) thin films deposited on copper (Cu) for the RF cavities (in place of bulk niobium).

This technology was also adopted for the Large Hadron Collider (LHC), the High Intensity and Energy ISOLDE (HIE ISOLDE) project at CERN and other European accelerators operating at fields up to 15 MV/m. The advantages are clear: lower cost, better thermal stability (thanks to the higher thermal conductivity of the copper substrate), and reduced sensitivity to trapped magnetic fields. The main drawback of Nb/Cu superconducting RF cavities is an exponential growth of the power lost in an RF cycle with the accelerating electrical field (owing to resistivity and magnetic permeability of the Nb film). This weakness, although investigated extensively, has eluded explanation and proposed mitigation for the past 20 years.

It's only lately, in the frame of studies for the proposed electron–positron Future Circular Collider (FCC-ee), that researchers have shed light on this puzzling behaviour. Those insights are due, in large part, to a deeper theoretical analysis of Nb thin-film densification as a result of HiPIMS, though a parallel line of investigation involves the manufacturing of seamless copper cavities and their surface electropolishing. In both cases, the objective is the reduction of defects in the substrate to enhance film adherence and purity.

Related studies have shown that Nb films on Cu can perform as well as bulk Nb in terms of superconducting RF properties, though coating materials other than Nb are also under investigation. Today, for example, the CERN vacuum group is evaluating Nb_3Sn and V_3Si – both of which are part of the A15 crystallographic group and exhibit superconducting transition temperatures of about 18 K (i.e. 9 K higher than Nb). This higher critical temperature would allow the use of RF cavities operating at 4.3 K (instead of 1.9 K), yielding significant simplification of the cryogenic infrastructure and reductions in electrical energy consumption. Even so, intense development is still necessary before these coatings can really challenge pure Nb films – not least because A15 films are brittle, plus the coating of such materials is tricky (given the need to reproduce a precise stoichiometry and crystallographic structure).



CERN

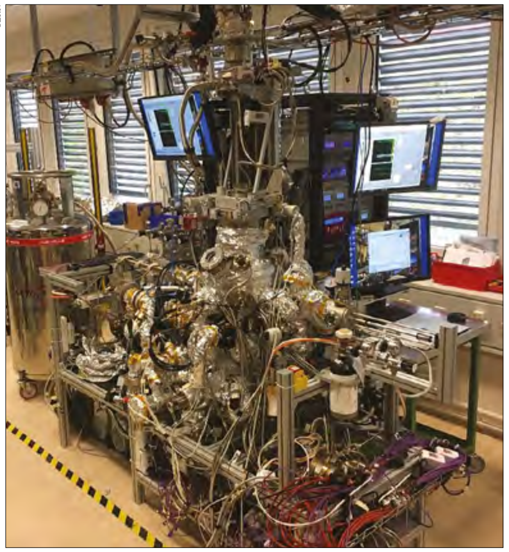
There's more *CERN vacuum scientists use this UHV system equipped with an energy-resolved mass spectrometer for the characterisation of HiPIMS plasma discharges.*

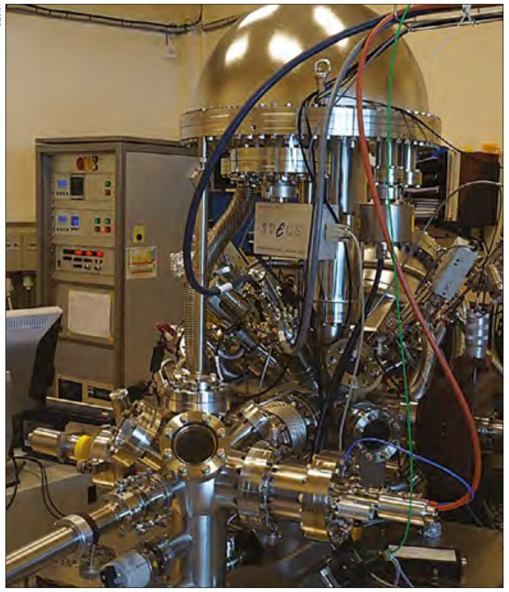
Game-changing innovations

Another wide-scale application of plasma processing at CERN is in the deposition of non-evaporable-getter (NEG) thin-film coatings, specialist materials originally developed to provide distributed vacuum pumping for the LHC. NEG coatings comprise a mixture of titanium, zirconium and vanadium with a typical composition around 30:30:40, respectively. For plasma deposition of NEG films, the target (comprising three interlacing elemental wires) is pulled along the main axis of the beam pipes. Once the coated vacuum chambers are installed within an accelerator and pumped out, the NEG films undergo heating for 24 hours at temperatures ranging from 180 to 250 °C – a process known as activation, in which the superficial oxide layer and any contaminants are dissolved into their bulk.

The clean surfaces obtained in this way chemically adsorb most of the gas species in the vacuum system at room temperature – except for noble gases (which are chemically inert) and methane (for which small auxiliary pumps are

NEG coatings comprise a mixture of titanium, zirconium and vanadium





Analytical insights *The HiPIMS coating parameters must be optimised for each distinct family of accelerator components and coated materials. This optimisation phase is traditionally experimental, involving a suite of powerful surface analysis tools including outgassing rate measurements (top) and X-ray photoelectron spectroscopy (bottom).*

necessary). The NEG-coated surfaces provide an impressively high pumping speed and, thanks to their cleanliness, a lower desorption yield when bombarded by electrons, photons and ions – and all this with minimal space occupancy. Moreover, owing to their maximum secondary electron yields (δ_{max}) below 1.3, NEG coatings avoid the development of electron multipacting, the main cause of electron clouds in beam pipes (and related unfavourable impacts on beam performance, equipment operation and cryogenic heat load).

More broadly, plasma processing of NEG coatings represents a transformative innovation in the implementation of large-scale vacuum systems. Hundreds of beam pipes were NEG-coated for the long straight section of the LHC, including the experimental vacuum chambers inserted in the four gigantic detectors. Beyond CERN, NEG coatings have also been employed widely in other large scientific instruments, including the latest generation of synchrotron light sources (see "MAX IV: thinking big in vacuum", p29).

Production of denser plasmas will be key for future applications in surface treatments for accelerators

In-situ capabilities

Of course, NEG coatings require thermal activation, so cannot be applied in vacuum systems that are unheatable (i.e. vacuum vessels that operate at cryogenic temperatures or legacy accelerators that may need retrofitting). For these specific cases, the CERN vacuum team has, over the past 15 years, been developing and iterating low-δ_{max} carbon coatings comprised mostly of amorphous carbon (a-C) with prevailing graphitic-like bonding among the carbon atoms.

Even though a-C thin films were originally studied for CERN's older Super Proton Synchrotron (SPS), they are now the baseline solution for the beam screen of the superconducting magnets in the long straight section of the High-Luminosity LHC. A 100 nm thin coating is deposited either in the laboratory for the new magnets (located on both sides of the ATLAS and CMS detectors) or *in situ* for the ones already installed in the tunnel (both sides of LHCb and ALICE).

The *in situ* processing has opened up another productive line of enquiry: the possibility of treating the surface of beam screens (15 m long, a few cm diameter) directly in the accelerators with the help of mobile targets. The expectation is that these innovative coating methods for a-C could, over time, also be applied to improve the performance of installed vacuum chambers in the LHC's arcs, without the need to dismount magnets and cryogenic connections.

Opportunity knocks

Looking ahead, the CERN vacuum team has plenty of ideas regarding further diversification of plasma surface treatments – though the direction of travel will ultimately depend on the needs of future studies, projects and collaborations. Near term, for example, there are possible synergies with the Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE), an accelerator R&D project based at CERN that's investigating the use of plasma wakefields driven by a proton bunch to accelerate charged particles over short distances. Certainly, the production of denser plasmas (and their manipulation) will be key for future applications in surface treatments for accelerators.

Another area of interest is the use of plasma-assisted chemical vapour deposition to extend the family of materials that can be deposited. For the longer term, the coating of vacuum systems with inert materials that allow the attainment of very low pressures (in the ultrahigh vacuum regime) in a short timeframe (five years) without bakeout remains one of the most ambitious targets. ●

VACUUM SOLUTIONS FUEL FUSION DREAMS

When it becomes operational later this decade, the ITER fusion research project will be dependent on one of the most complex vacuum systems ever built. Joe McEntee checks out progress with ITER vacuum section leader Robert Pearce, while highlighting the downstream commercial opportunities already spinning out from the core construction programme.

Robert Pearce is all about the detail. That's probably as it should be for the section leader of the diverse, sprawling vacuum ecosystem now taking shape as part of the work-in-progress ITER experimental reactor in southern France. When it comes online in the mid-2020s, this collaborative megaproject – which is backed by China, the European Union, India, Japan, Korea, Russia and the US – will generate nuclear fusion in a tokamak device (the world's largest) that uses superconducting magnets to contain and control a hot plasma in the shape of a torus. In the process, ITER will also become the first experimental fusion machine to achieve "net energy" – when the total power produced during a fusion plasma pulse surpasses the power injected to heat the plasma – while providing researchers with a real-world platform to test the integrated technologies, materials and physics regimes necessary for future commercial production of fusion-based electricity (*CERN Courier* November/December 2021 p34).

ITER

Attention to detail *"We will need to achieve a lot of vacuum to ensure successful, sustained fusion operation," explains ITER vacuum section leader Robert Pearce (front left, during a lecture on the ITER campus in pre-COVID times).*

Vacuum reimagined

If ITER is big science writ large, then its myriad vacuum systems are an equally bold reimagining – at scale – of vacuum science, technology and innovation. "ITER requires one of the most complex vacuum systems ever built," explains Pearce. "We've overcome a lot of challenges so far in the construction of the vacuum infrastructure, though there are doubtless more along the way. One thing is certain: we will need to achieve a lot of vacuum – across a range of regimes and with enabling technologies that deliver bulletproof integrity – to ensure successful, sustained fusion operation."

The task of turning the vacuum vision into reality falls to Pearce and a core team of around 30 engineers and physicists based at the main ITER campus at Cadarache. It's a multidisciplinary effort, with domain knowledge and expertise spanning mechanical engineering, modelling and simulation, experimental validation, surface science, systems deployment and integration, as well as process control and instrumentation. At a headline level, the group is focused on delivery versus two guiding objectives. "We need to make sure all the vacuum systems are specified to our exacting standards in terms of leak tightness, cleanliness and optimal systems integration so that everything works together seamlessly," notes Pearce. "The other aspect of our remit involves working with multiple partner organisations to develop, validate and implement the main pumping systems, vacuum chambers and distribution network."

Sharing the load

Beyond the main project campus, the two primary partners on the ITER vacuum programme are the Fusion for Energy (F4E) team in Barcelona, Spain, and US ITER in Oak Ridge, Tennessee, both of which support the vacuum effort through "in-kind" contributions of equipment and personnel to complement direct cash investments from the member countries. While the *ITER Vacuum Handbook* – effectively the project bible for all things vacuum – provides a reference point to shape best practice across vacuum hardware, associated control systems, instrumentation and quality management, there's no one-size-fits-all ▷

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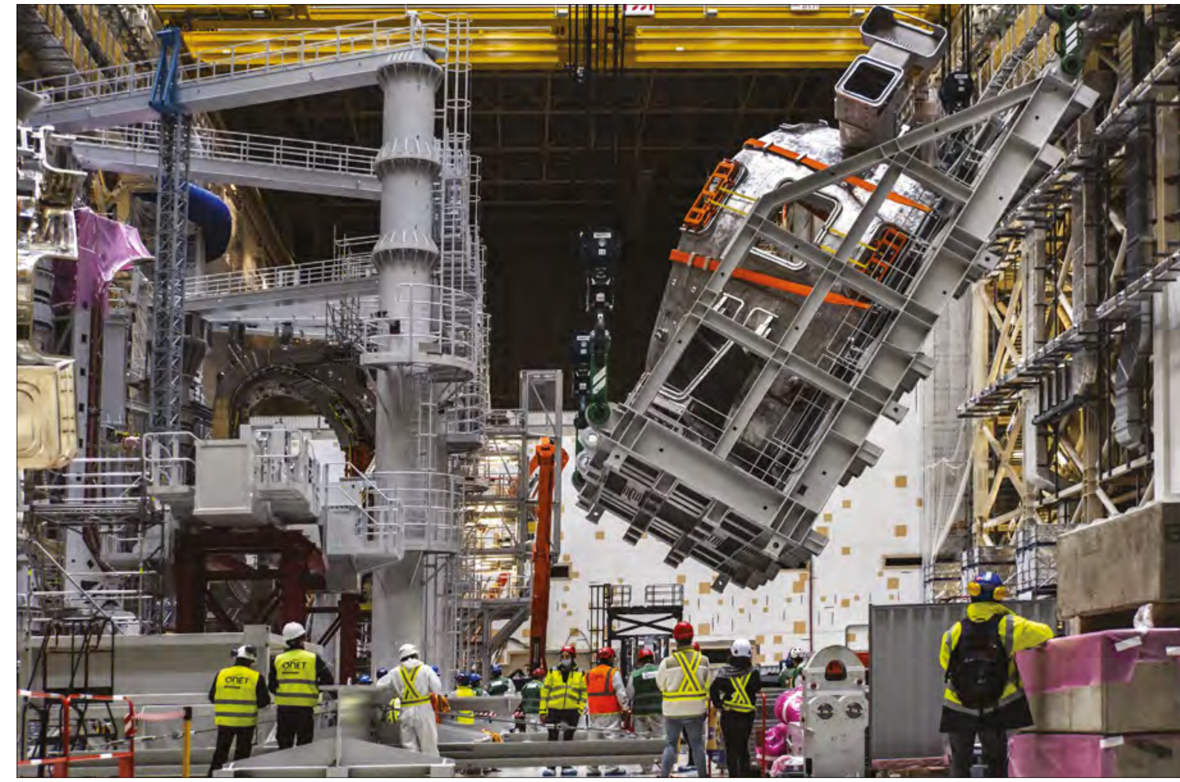


ITER

The big lift *The first sector of the main ITER vacuum vessel is manoeuvred into the tokamak pit in December. The tool and vessel assembly above weigh nearly 700 tonnes; the tool has been specifically designed to upend nine vacuum vessel sectors and 18 toroidal field coils.*

Vacuum innovation: ITER's impact dividend

While ITER's vacuum team pushes the boundaries of what's possible in applied vacuum science, industry partners are working alongside to deliver the enabling technology innovations, spanning one-of-a-kind pumping installations to advanced instrumentation and ancillary equipment.

The ITER neutral beam injector systems – accelerators that will drive high-energy neutral particles into the tokamak to heat the fusion plasma – are a case in point. The two main injectors (each roughly the size of a locomotive) will be pumped by a pair of open-structure, panel-style cryosorption pumps (with a single pump measuring 8 m long and 2.8 m high).

Working in tandem, the pumps will achieve a pumping speed of $4500\,m^3/s$ for hydrogen, with a robust stainless-steel boundary necessary for the cryogenic circuits to provide a confinement barrier between tritium (which is radioactive) and cryogenic helium.

Key to success is a co-development effort – involving ITER engineers and industry partner Ravanat (France) – to realise a new manufacturing method for the fabrication of cryopanels via expansion of stainless-steel tube (at around 2000 bar) into aluminium extrusions. It's a breakthrough, moreover, that delivers excellent thermal contact over the operating temperature range (4.5 K for pumping to 400 K for regeneration), while combining the robustness of stainless steel with the thermal conductivity of aluminium.

Industry innovation is also in evidence at a smaller scale. As the ITER project progresses to the active (nuclear) phase of operations, for example, human access to the cryostat will be very limited. With this in mind, the In-Pipe Inspection Tool (IPIT) is being developed for remote inspection and leak localisation within the tens of km of cryostat pipework.

An R&D collaboration between ITER vacuum engineers, F4E and Italian robotics firm Danieli Telerobot, the IPIT is capable of deployment in small-bore pipework up to 45 m from the insertion point. The unit combines a high-resolution camera for inspection of welds internal to the pipe, as well as a dedicated "bladder" for isolation of vacuum leaks prior to repair.

Other instrument innovations already well developed by industry to meet ITER's needs include a radiation-hardened (> 1 MGy) and magnetic-field-compatible (> 200 mT) residual gas analyser that permits remote operation via a controller up to 140 m away (supplied by Hidden Analytical, UK); and also an optical diaphragm gauge (> 1 MGy, > 200 mT) with a measurement capability in line with the best capacitive manometers (a co-development between Inficon, Germany, and OpSens Solutions, Canada).

When it comes to downstream commercial opportunities, it's notable that ITER member countries share the experimental results and any intellectual property generated by ITER during the development, construction and operation phases of the project.

ITER

ITER

Night shift *Left: the tokamak complex takes shape at the heart of the ITER construction site. Right: ITER's cryostat base was the first major component to be installed at the bottom of the 30 m-deep "machine well" in April 2020. Welding of the lower cylinder of the cryostat to the base (plus all testing) was completed in March 2021, with at least 1.5 tonnes of filler material used in the process.*

ITER

Stay cool *A two-year commissioning phase is now underway for the ITER cryoplant (above), comprising around 5000 tonnes of equipment – including tanks, compressors, piping, valves, electrical motors and associated vacuum systems.*

model for the relationship between the Cadarache vacuum team and its partner network.

"We supply 'build-to-print' designs to Barcelona – for example, in the case of the large torus cryopump systems – and they, in collaboration with us, then take care of the procurement with their chosen industry suppliers," explains Pearce. With Oak Ridge, which is responsible for provision of the vacuum auxiliary and roughing pumps systems (among other things), the collaboration is based on what Pearce calls "functional specification procurement… in which we articulate more of the functionality and they then work through a preliminary and final design with us".

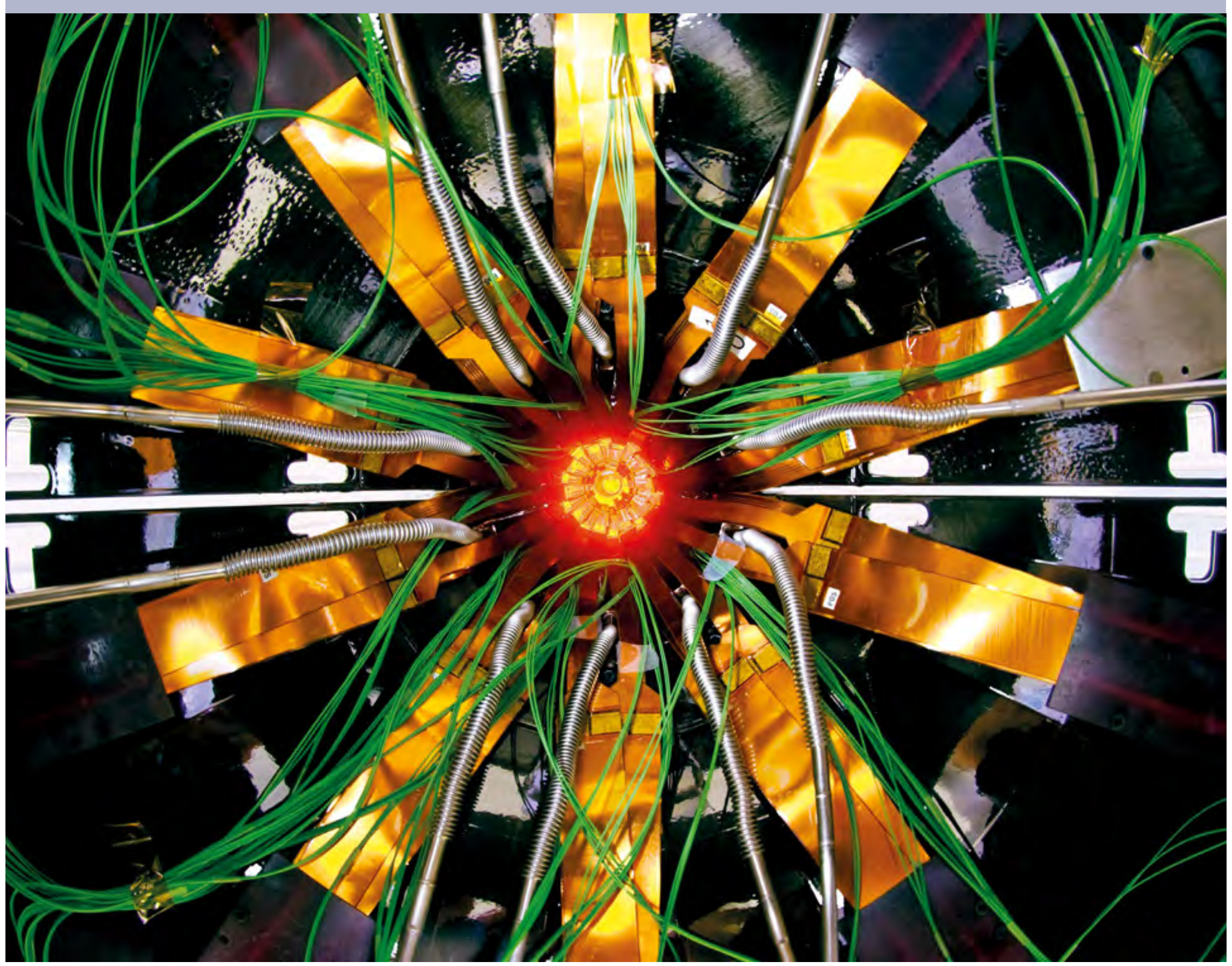
More broadly, because vacuum is central to so many of ITER's core systems – including the main tokamak vessel ($1400\ m^3$), the surrounding cryostat ($16{,}000\ m^3$) and the superconducting magnets – the vacuum team also has touch-points and dependencies with an extended network of research partners and equipment makers across ITER's member countries. Unsurprisingly, with more than 300 pumping systems and 10 different pumping technologies to be deployed across the ITER plant, complexity is one of the biggest engineering challenges confronting Pearce and his team.

"Once operational, ITER will have thousands of different volumes that need pumping across a range of vacuum regimes," notes Pearce. "Overall, there's high diversity in terms of vacuum function and need, though the *ITER Vacuum Handbook* does help to standardise our approach to issues like leak tightness, weld quality, testing protocols, cleanliness and the like."

Atypical vacuum

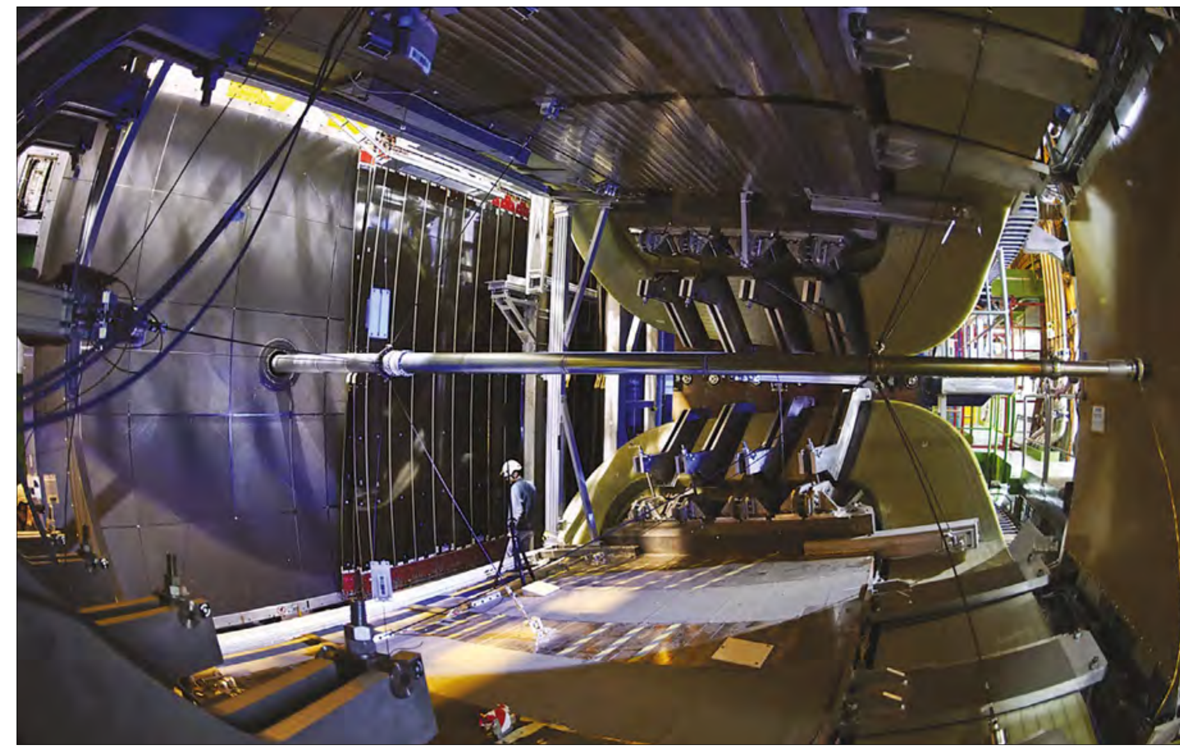
Notwithstanding the complexity of ITER's large-scale vacuum infrastructure, Pearce and his team must also contend with the atypical operational constraints in and around the fusion tokamak. For starters, many of the machine's vacuum components (and associated instrumentation) need to be qualified for operation in a nuclear environment (the ITER tokamak and supporting plant must enclose and securely contain radioactive species like tritium) and to cope with strong magnetic fields (up to 7 T in the plasma chamber and up to 300 mT for the vacuum valves and instruments). In terms of qualification, it's notable that ITER is being built in a region with a history of seismic activity – deliberately so, to demonstrate that a fusion reactor can be operated safely anywhere in the world.

"Ultimately," concludes Pearce, "any vacuum system – and especially one on the scale and complexity required for ITER – requires great attention to detail to be successful." ●



DETAIL AND DILIGENCE ENSURE LS2 PROGRESS

CERN's vacuum scientists and engineers have completed an intense period of activity during Long Shutdown 2 to prepare the accelerator complex for more luminous operation through LHC Run 3 and beyond. Joe McEntee reports.



CERN

Going the distance *In the LHC experimental area (shown is the LHCb detector), the disassembly of the vacuum chambers at the beginning of LS2 required 93 interventions and 550 person-hours of work in the equipment caverns. Reinstallation has progressed well in the four core LHC experiments.*

The reliability of the CERN vacuum systems is very much front-and-centre as the restart of the LHC physics programme approaches in mid-2022. The near-term priority is the recommencement of beam circulation in vacuum systems that were open to the air for planned interventions and modification – sometimes for several days or weeks – during Long Shutdown 2 (LS2), a wide-ranging overhaul of CERN's experimental infrastructure that's been underway since the beginning of 2019.

With LS2 now drawing to a close and pilot beam already circulated in October for a general check of the accelerator chain, it's worth revisiting the three operational objectives that CERN's engineering teams set out to achieve during shutdown: consolidation of the LHC dipole diodes (essential safety elements for the superconducting magnets); the anticipation of several interventions required for the High-Luminosity LHC (HL-LHC) project (the successor to the LHC, which will enter operation in 2028); and the LHC Injectors Upgrade project to enhance the injection chain so that beams compatible with HL-LHC expectations can be injected into CERN's largest machine.

"The CERN vacuum team has made fundamental con-

Thankfully, creative problem-solving is part of the vacuum team's DNA

Paolo Chiggiato
"Every single detail in a large-scale vacuum system can have important consequences."

CERN

tributions to the achievement of the LS2 core objectives and other parallel activities," notes Paolo Chiggiato, head of the CERN vacuum, surfaces and coatings group. "As such, we have just completed an intense period of work in the accelerator tunnels and our laboratories, as well as running and supporting numerous technical workshops."

As for vacuum specifics, all of the LHC's arcs were vented to the air after warm-up to room temperature; all welds were leak-checked after the diode consolidation (with only one leak found among the 1796 tests performed); while the vacuum team also replaced or consolidated around 150 turbomolecular pumps acting on the cryogenic insulation vacuum. In total, 2.4 km of non-evaporable-getter (NEG)-coated beampipes were also opened to the air at room temperature – an exhaustive programme of work spanning mechanical repair and upgrade (across 120 weeks), bakeout (spread across 90 weeks) and NEG activation (over 45 weeks). "The vacuum level in these beampipes is now in the required range, with most of the pressure readings below 10^{-10} mbar," explains Chiggiato.

Close control

Another LS2 priority for Chiggiato and colleagues involved upgrades to CERN's vacuum control infrastructure, with the emphasis on reducing single points of failure and the removal of confusing architectures (i.e. systems with no clear separation of function amongst the different programmable logic controllers). "For the first time," adds Chiggiato, "mobile vacuum equipment was controlled and monitored by wireless technologies – a promising communication choice for distributed systems and areas of the accelerator complex requiring limited stay."

Elsewhere, in view of the higher LHC luminosity (and consequent increased radioactivity) following LS2 works, the vacuum group developed and installed advanced radiation-tolerant electronics to control 100 vacuum gauges and valves in the LHC dispersion suppressors. This roll-out represents the first step of a longer-term campaign that will be scaled during the next Long Shutdown (LS3 is scheduled for 2025–2027), including the production of 1000 similar electronic cards for vacuum monitoring. "In parallel," says Chiggiato, "we have renewed the vacuum control software – introducing resilient, easily scalable and self-healing web services technologies and frameworks used by some of the biggest names in industry."

Success breeds success

In the LHC experimental area, meanwhile, the disassembly of the vacuum chambers at the beginning of LS2 required 93 interventions and 550 person-hours of work in the equipment caverns. Reinstallation has progressed well in the four core LHC experiments, with the most impressive refit of vacuum hardware in the CMS and LHCb detectors.

For the former, the vacuum team installed a new central beryllium chamber (internal diameter 43.4 mm, 7.3 m long), while 12 new aluminium chambers were manufactured, surface-finished and NEG-coated at CERN. Their production comprised eight separate quality checks, from surface treatment to performance assessment of the NEG coating. "The mechanical installation – including alignments, pump-down and leak detection – lasted two months," explains Chiggiato, "while the bake-out equipment installation, bake-out process, post-bake-out tests and venting with ultrapure neon required another month."

In LHCb, the team contributed to the new version of the Vertex Locator (VELO) sub-detector. The VELO's job is to pick out B mesons from the multitude of other particles produced – a tricky task as their short lives will be spent close to the beam. To find them, the VELO's RF box – a delicate piece of equipment filled with silicon detectors, electronics and cooling circuits – must be positioned perilously close to the point where protons collide. In this way, the sub-detector faces the beam at a distance of just 5 mm, with an aluminium window thinned down to 150 µm by chemical etching prior to the deposition of a NEG coating.

As the VELO encloses the RF box, and both volumes are under separate vacuum, the pumpdown is a critical operation because pressure differences across the thin window must be lower than 10 mbar to ensure mechanical integrity. "This work is now complete," says Chiggiato, "and vacuum control of the VELO is in the hands of the CERN vacuum team after a successful handover from specialists at Nikhef [the Dutch National Institute for Subatomic Physics]."

Wrapping up a three-year effort, the vacuum team's last planned activity in LS2 involves the bake-out of the ATLAS and CMS beampipe in early 2022. "There was no shortage of technical blockers and potential show-stoppers during our LS2 work programme," Chiggiato concludes. "Thankfully, creative problem-solving is part of the vacuum team's DNA, as is the rigorous application of vacuum best practice and domain knowledge accumulated over decades of activity. Ours is a collective mindset, moreover, driven by a humble approach to such complex technological installations, where every single detail can have important consequences." •

A detailed report on the CERN vacuum team's LS2 work programme – including the operational and technical challenges along the way – will follow in the March/April 2022 issue of CERN Courier magazine.

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OPINION FACILITIES

MAX IV: partnership is the key

Openness to new ideas and enabling technologies – as well as calculated risk-taking – were fundamental to the successful realisation of the 3 GeV storage-ring vacuum system at the MAX IV synchrotron laboratory in Sweden. Joe McEntee talks specifics with Marek Grabski, vacuum section leader at MAX IV.

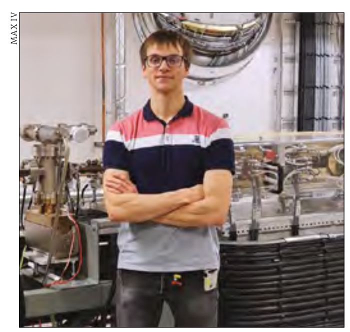
Leif Jansson/MAX IV

Better together *Construction of the MAX IV advanced light source relied on key collaborations between the lab's multidisciplinary staff teams and other research institutes. CERN and the ESRF, for example, provided operational support on the intricate NEG-coated vacuum system, while Russia's Budker Institute of Nuclear Physics supported on installation of the linac and the vacuum systems for the 1.5 and 3 GeV storage rings.*

Sweden's MAX IV synchrotron radiation facility is among an elite cadre of advanced X-ray sources, shedding light on the structure and behaviour of matter at the atomic and molecular level across a range of fundamental and applied disciplines – from clean-energy technologies to pharma and healthcare, from structural biology and nanotech to food science and cultural heritage (*CERN Courier* September 2016 p36).

In terms of core building blocks, this fourth-generation light source – which was inaugurated in 2016 – consists of a linear electron accelerator plus 1.5 and 3 GeV electron storage rings (with the two rings optimised for the production of soft and hard X rays, respectively). As well as delivering beam to a short-pulse facility, the linac serves as a full-energy injector to the two storage rings which, in turn, provide photons that are extracted for user experiments across 14 specialist beamlines.

MAX IV



System-level thinking *"There are many dependencies between the chosen enabling technologies in a project as complex as the MAX IV 3 GeV storage ring," says Marek Grabski, MAX IV's vacuum section leader.*

Underpinning all of this is a ground-breaking implementation of ultrahigh-vacuum (UHV) technologies within MAX IV's 3 GeV electron storage ring – the first synchrotron storage ring in which the inner surface of almost all the vacuum chambers along its circumference are coated with non-evaporable-getter (NEG) thin film for distributed pumping and low dynamic outgassing. Here, Marek Grabski, MAX IV vacuum section leader, gives *CERN Courier* the insider take on a unique vacuum installation and its subsequent operational validation.

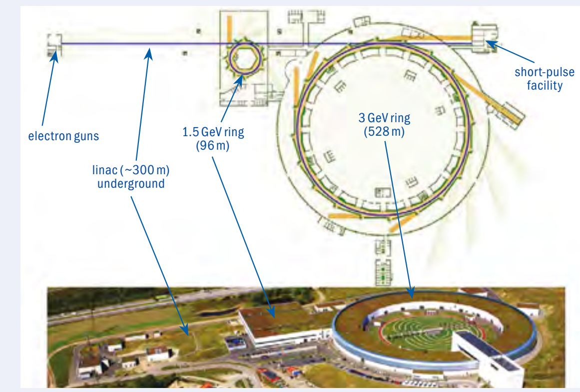
What are the main design challenges associated with the 3 GeV storage-ring vacuum system?

We were up against a number of technical constraints that necessitated an innovative approach to vacuum design. The vacuum chambers, for example, are encapsulated within the storage ring's compact magnet blocks with bore apertures of 25 mm diameter (see "The MAX IV 3 GeV storage ring: unique technologies, unprecedented performance", p31). What's more, there are requirements for long beam lifetime, space limitations imposed by the magnet design, the need for heat

The MAX IV 3 GeV storage ring: unique technologies, unprecedented performance

Among the must-have user requirements for the 3 GeV storage ring was the specified design goal of reaching ultralow electron-beam emittance (and ultrahigh brightness) within a relatively small circumference (528 m). As such, the bare lattice natural emittance for the 3 GeV ring is 328 pm rad – more than an order of magnitude lower than typically achieved by previous third-generation storage rings in the same energy range.

Even though the fundamental concepts for realising ultralow emittance had been laid out in the early 1990s, many in the synchrotron community remained sceptical that the innovative technical solutions proposed for MAX IV would work. Despite the naysayers, on 25 August 2015 the first electron beam circulated in the 3 GeV storage ring and, over time, all design parameters were realised: the fourth generation of storage-ring-based light sources was born.



Big picture *The layout of the MAX IV lab and aerial view of the main facilities.*

MAX IV

Stringent beam parameters

The MAX IV 3 GeV storage ring represents the first deployment of a so-called multibend achromat magnet lattice in an accelerator of this type, with the large number of bending magnets central to ensuring ultralow horizontal beam emittance. In all, there are seven bending magnets per achromat (and 20 achromats making up the complete storage ring).

Not surprisingly, miniaturisation is a priority in order to accommodate the 140 magnet blocks – each consisting of a dipole magnet and other magnet types (quadrupoles, sextupoles, octupoles and correctors) – into the ring circumference. This was achieved by CNC machining the bending magnets from a single piece of solid steel (with high tolerances) and combining them with other magnet types into a single integrated block. All magnets within one block are mechanically referenced, with only the block as a whole aligned on a concrete girder.

Vacuum innovation

Meanwhile, the vacuum system design for the 3 GeV storage ring also required plenty of innovative thinking, key to which was the close collaboration between MAX IV and the vacuum team at the ALBA Synchrotron in Barcelona. For starters, the storage-ring vacuum vessels are made from extruded, oxygen-free, silver-bearing copper tubes (22 mm inner diameter, 1 mm wall thickness).

Copper's superior electrical and thermal conductivities are crucial when it comes to heat dissipation and electron beam impedance. The majority of the chamber walls act as heat absorbers, directly intercepting synchrotron radiation coming from the bending magnets. The resulting heat is dissipated by cooling water flowing in channels welded on the outer side of the vacuum chambers. Copper also absorbs unwanted radiation better than aluminium, offering enhanced protection for key hardware and instrumentation in the tunnel.

The use of crotch absorbers for extraction of the photon beam is limited to one unit per achromat, while the section where synchrotron radiation is extracted to the beamlines is the only place where the vacuum vessels incorporate an antechamber. Herein the system design is particularly challenging, with the need for additional cooling blocks to be introduced on the vacuum chambers with the highest heat loads.

Other important components of the vacuum system are the beam position monitors (BPMs), which are needed to keep the synchrotron beam on an optimised orbit. There are 10 BPMs in each of the 20 achromats, all of them decoupled thermally and mechanically from the vacuum chambers through RF-shielded bellows that also allow longitudinal expansion and small transversal movement of the chambers.

Ultimately, the space constraints imposed by the closed magnet block design – as well as the aggregate number of blocks along the ring circumference – was a big factor in the decision to implement a NEG-based pumping solution for MAX IV's 3 GeV storage ring. It's simply not possible to incorporate sufficient lumped ion pumps to keep the pressure inside the accelerator at the required level (below 1×10^{-9} mbar) to achieve the desired beam lifetime while minimising residual gas–beam interactions.

Operationally, it's worth noting that a purified neon venting scheme (originally developed at CERN) has emerged as the best-practice solution for vacuum interventions and replacement or upgrade of vacuum chambers and components. As evidenced on two occasions so far (in 2018 and 2020), the benefits include significantly reduced downtime and risk management when splitting magnets and reactivating the NEG coating.

dissipation from incoming synchrotron radiation, as well as minimal beam-coupling impedance.

The answer, it turned out, is a baseline design concept that exploits NEG thin-film coatings, a technology originally pioneered by CERN that combines distributed pumping of active residual gas species with low photon-stimulated desorption. The NEG coating was applied by magnetron sputtering to almost all the inner surfaces (98% lengthwise) of the vacuum chambers along the electron beam path. As a consequence, there are only three lumped ion pumps fitted on each standard "achromat" (20 achromats in all, with a single acromat measuring 26.4 m end-to-end). That's far fewer than typically seen in other advanced synchrotron light sources.

How important was collaboration with CERN's vacuum group on the NEG coatings?

Put simply, the large-scale deployment of NEG coatings as the core vacuum technology for the 3 GeV storage ring would not have been possible without the collaboration and support of CERN's vacuum, surfaces and coatings (VSC) group. Working together, our main objective was to ensure that all the substrates used for chamber manufacturing, as well as the compact geometry of the 3 GeV storage-ring vacuum vessels, were compatible with the NEG coating process (in terms of coating adhesion, thickness, composition and activation behaviour). Key to success was the deep domain knowledge and proactive technical support of the VSC group, as well as access to CERN's specialist facilities, including the mechanical workshop, vacuum laboratory and surface treatment plant (see p11).

What did the manufacturing model look like for this vacuum system?

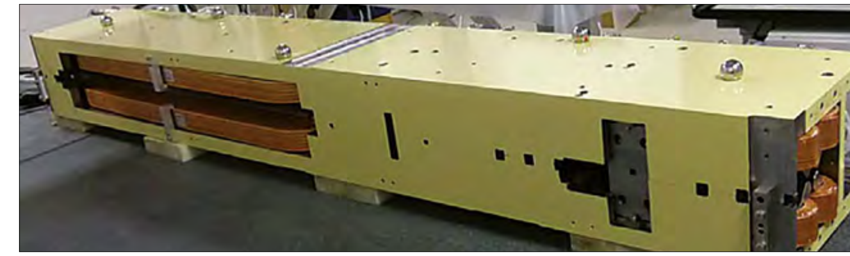
Because of the technology and knowledge transfer from CERN to industry, it was possible for the majority of the vacuum chambers to be manufactured, cleaned, NEG-coated and tested by a single commercial supplier – in this case, FMB Feinwerk- und Messtechnik in Berlin, Germany. Lengthwise, 70% of the chambers were NEG-coated by the same vendor. Naturally, the manufacturing of all chambers had to be compatible with the NEG coating, which meant careful selection and verification of materials, joining methods (brazing) and handling. Equally important, the raw materials needed to undergo surface treatment compatible with the coating, with the final surface cleaning certified by CERN to ensure good film adhesion under all operating conditions – a potential bottleneck that was navigated thanks to excellent collaboration between the three parties involved.

To spread the load, and to relieve the pressure on our commercial supplier ahead of system installation (which commenced in late 2014), it's worth noting that most geometrically complicated chambers (including vacuum vessels with a 5 mm vertical aperture antechamber) were NEG-coated at CERN. Further NEG coating support was provided through a parallel collaboration with the European Synchrotron Radiation Facility (ESRF) in Grenoble.

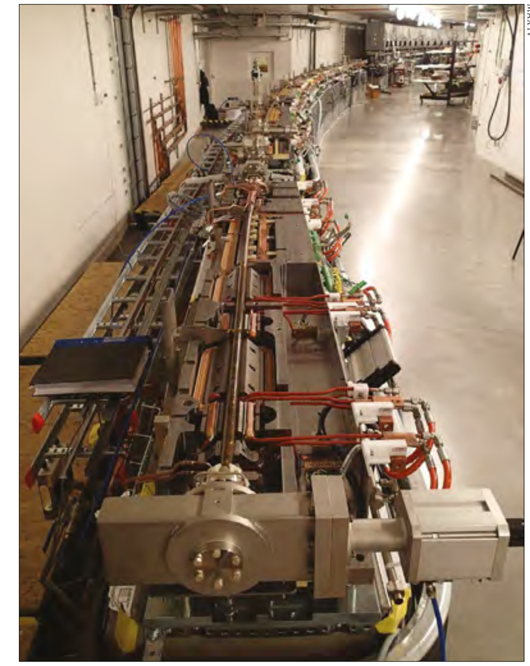
How did you handle the installation phase?

This was a busy – and at times stressful – phase of the project, not least because all the vacuum chambers were being delivered "just-in-time" for final assembly *in situ*. This approach was possible thanks to exhaustive testing and qualification of all vacuum components prior to shipping from the commercial vendor, while extensive dialogue with the MAX IV team helped to resolve any issues arising before the vacuum components left the factory.

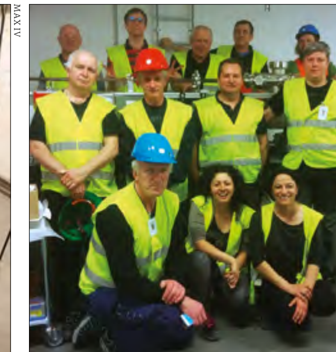
Owing to the tight schedule for installation – just eight months – we initiated a collaboration with the Budker Institute of Nuclear Physics (BINP) in Russia to provide additional support. For the duration of the installation phase, we had two teams of specialists from BINP working alongside (and coordinated by) the MAX IV vacuum team. All vacuum-related processes – including assembly, testing, baking and NEG activation of each achromat (at 180 °C) – took place inside the accelerator tunnel directly above the opened lower magnet blocks of MAX IV's multibend achromat (MBA) lattice. Our installation approach, though unconventional, yielded many advantages – not least, a reduction in the risks related to transportation of assembled vacuum sectors as well as reduced alignment issues.



Scanditronix Magnet



MAX IV



MAX IV

Magnetic *Top: one magnet block (2.4 m-long) with visible coils of dipole magnet to the left. Seven of these blocks make up one achromat in the 3 GeV storage ring, with 20 achromats along the accelerator circumference. Left: the magnet blocks of one complete achromat of the 3 GeV storage ring during installation. The top magnet halves are removed so that the installed vacuum chambers and magnet families are visible. Above: the vacuum installation team inside the 3 GeV storage ring tunnel, with staff from MAX IV and BINP.*

Presumably not everything went to plan through installation and acceptance?

One of the issues we encountered during the initial installation phase was a localised peeling of the NEG coating on the RF-shielded bellows assembly of several vacuum vessels. This was addressed as a matter of priority – NEG film fragments falling into the beam path is a show-stopper – and all the effected modules were replaced by the vendor in double-quick time. More broadly, the experience of the BINP staff meant difficulties with the geometry of a few chambers could also be resolved on the spot, while the just-in-time delivery of all the main vacuum components worked well, such that the installation was completed successfully and on time. After completion of several achromats, we installed straight sections in between while the RF cavities were integrated and conditioned *in situ*.

How has the vacuum system performed from the commissioning phase and into regular operation?

Bear in mind that MAX IV was the first synchrotron light source to apply NEG technology on such a scale. We were breaking new ground at the time, so there were credible concerns regarding the conditioning and long-term reliability of the NEG vacuum system – and, of course, possible effects on machine operation and performance. From commissioning into regular operations, however, it's clear that the NEG pumping system is reliable, robust and efficient in delivering low dynamic pressure in the UHV regime.

Initial concerns around potential saturation of the NEG coating in the early stages of commissioning (when pressures are high) proved to be unfounded, while the same is true for the risk associated with peeling of the coating (and potential impacts on beam lifetime). We did address a few issues with hot-spots on the vacuum chambers during system conditioning, though again the overall impacts on machine performance were minimal.

To sum up: the design current of 500 mA was successfully injected and stored in November 2018, proving that the vacuum system can handle the intense synchrotron radiation. After more than six years of operation, and 5000 Ah of accumulated beam dose, it is clear the vacuum system is reliable and provides sustained UHV conditions for the circulating beam – a performance, moreover, that matches or even exceeds that of conventional vacuum systems used in other storage rings.

What are the main lessons your team learned along the way through design, installation, commissioning and operation of the 3 GeV storage-ring vacuum system?

The unique parameters of the 3 GeV storage ring were delivered according to specification and per our anticipated timeline at the end of 2015. Successful project delivery was only possible by building on the collective experience and know-how of staff at MAX-lab (MAX IV's predecessor) constructing and operating accelerators since the 1970s – and especially the lab's "explorer mindset" for the early-adoption of new ideas and enabling technologies. Equally important, the commitment and team spirit of our technical staff, reinforced by our collaborations with colleagues at ALBA, CERN, ESRF and BINP, were fundamental to the realisation of a relatively simple, efficient and compact vacuum solution.

Operationally, it's worth adding that there are many dependencies between the chosen enabling technologies in a project as complex as the MAX IV 3 GeV storage ring. As such, it was essential for us to take a holistic view of the vacuum system from the start, with the choice of a NEG pumping solution enforcing constraints across many aspects of the design – for example, chamber geometry, substrate type, surface treatment and the need for bellows. The earlier such knowledge is gathered within the laboratory, the more it pays off during construction and operation. Suffice to say, the design and technology solutions employed by MAX IV have opened the door for other advanced light sources to navigate and build on our experience. ●

THE AUTHOR

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