WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the 2021 *CERN Courier* In Focus report on vacuum innovation.

Innovation in vacuum science, technology and engineering provides the unifying theme for this special *CERN Courier* In Focus report. Vacuum, of course, is an umbrella term for a suite of enabling technologies deployed in all manner of fundamental and applied research endeavours, many of which are explored in our exclusive feature coverage. CERN's mission in fundamental physics is a case in point, underpinned as it is by a diverse ecosystem of in-house vacuum expertise – not least the unique capabilities and know-how of Building 107's specialist surface-chemistry team (see p13 and p29).

Elsewhere, our correspondents profile vacuum system design, development and deployment in another big-science setting at the European Spallation Source (ESS) in Sweden (p5), a large-scale research facility that's likely to see significant upsides from ongoing progress in vacuum metrology and standardisation (p23).

Finally, commercial innovation continues at pace out in the marketplace as the nascent technology supply chain takes shape for hyperloop vacuum-based transportation systems (p35). For the vacuum industry, it seems, opportunity knocks.

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IN FOCUS VACUUM INNOVATION

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From the Editor

Innovation in vacuum science, technology and engineering provides the unifying theme for this special *CERN Courier In Focus* report. Vacuum, of course, is an umbrella term for a suite of enabling technologies deployed in all manner of fundamental and applied research endeavours, many of which are explored in our exclusive feature coverage. CERN's mission in fundamental physics is a case in point, underpinned as it is by a diverse ecosystem of in-house vacuum expertise – not least the unique capabilities and know-how of Building 107's specialist surface-chemistry team (see p13 and p29). Elsewhere, our correspondents profile vacuum system design, development and deployment in another big-science setting at the European Spallation Source (ESS) in Sweden (p5), a large-scale research facility that's likely to see significant upsides from ongoing progress in vacuum metrology and standardisation (p23). Finally, commercial innovation continues at pace out in the marketplace as the nascent technology supply chain takes shape for hyperloop vacuum-based transportation systems (p35). For the vacuum industry, it seems, opportunity knocks.

Cover: *CERN's ALICE beampipe, p13. (M Brice, J M Ordan/CERN)*

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OPINION FACILITIES

A joined-up vision for vacuum

Vacuum technologies are fundamental to the research mission of the European Spallation Source, a next-generation neutron-science facility under construction in Sweden. Joe McEntee talks to Marcelo Juni Ferreira, ESS vacuum group leader, about vacuum design, development and deployment in a 'green-field' big-science setting.

Roger Eriksson/ESS

Big science *An aerial view over the ESS construction site in Lund, Sweden, taken in September 2020.*

Neutron science 2.0 is evolving from concept to reality as construction progresses on the European Spallation Source (ESS), a €1.84 billion accelerator-driven neutron source in Lund, Sweden. ESS will deliver first science in 2023 and will, when in full operation, be the world's most powerful neutron research facility – between 20 and 100 times brighter than the Institut Laue-Langevin (ILL) in Grenoble, France, and up to five times more powerful than the Spallation Neutron Source (SNS) in Oak Ridge, Tennessee, US.

This industrial-scale endeavour represents an amalgam of the most powerful linear proton accelerator ever built; a two-tonne, rotating tungsten target wheel (which produces neutrons via the spallation process); a reference set of 22 state-of-the-art neutron instruments for user experiments (of which 15 are under construction); and a high-performance data management and software development centre (located in Copenhagen). Here, Marcelo Juni Ferreira, vacuum group leader at ESS, tells *CERN Courier* how vacuum technologies are equally fundamental to the ESS's scientific programme.

What does your role as ESS vacuum group leader involve?

I head up a 12-strong multidisciplinary team of engineers, scientists, designers and technicians who manage the international network of stakeholders developing the vacuum infrastructure for the ESS. Many of our partners, for example, make "in-kind" contributions of equipment and personnel rather than direct cash investments from the ESS member countries. As such, the ESS vacuum group is responsible for maintaining the facility's integrated vacuum design approach across all of these contributions and all of our vacuum systems – the proton accelerator, target section, neutron beamlines and the full suite of neutron instruments that will ultimately support user experiments (see "ESS science, funding and partnership", p6).

Monise Pavani Photo

Vacuum vision *Marcelo Juni Ferreira, ESS vacuum group leader, oversees an integrated approach to vacuum system design, with the use of standard industry components where possible to drive down training, maintenance and procurement costs.*

In terms of specifics, what is meant by integrated vacuum design?

The integrated approach to vacuum design works on several levels. Cost reduction is a fundamental driver for ESS. The use of standard industry components where possible reduces maintenance and training requirements, minimises the need for expensive product inventory and, through a single framework agreement covering our in-kind partners and industry suppliers, we can work at scale to lower our overall procurement costs.

Another motivation is to help the vacuum group support the diverse vacuum requirements across the neutron instruments. The goal in each case is to ensure sustainable,

Aitor Zugazaga Cortazar/ESS Bilbao

Ulrika Hammarlund/ESS

Heavy metal *The TMV (left) represents the core building block of the ESS target station and was assembled by in-kind partners at ESS Bilbao, Spain, working in collaboration with local manufacturers. Ahead of shipping and installation into the target station (underway on the right), ESS Bilbao successfully completed the leak and vacuum tests on the TMV with satisfactory measurements of dew-point temperature, pressure rise and leak detection.*

economical and long-term operation of each instrument's vacuum plant to minimise downtime and maximise research output. To make this possible, each of the neutron instruments (and associated beamlines) has its own "vacuum interface" document summarising key technical specifications and performance requirements – all ultimately aligned with the *ESS Vacuum Handbook*, the main reference source promoting the use of common vacuum equipment and standards across all aspects of the project.

So, standardisation is a big part of your vacuum strategy?
Absolutely. It's all about a unified approach to our vacuum equipment as well as the procurement policy for any major hardware/software purchases for the accelerator, the target and the neutron instruments. Another upside of standardisation is that it simplifies the interfaces between the ESS vacuum infrastructure and the ESS safety and control plant – for example, the personnel protection, machine protection and target safety systems.

ESS recently took delivery of the Target Monolith Vessel (TMV), one of the facility's main vacuum sections. What is the TMV and who built it?
The TMV represents the core building block of the ESS target station and was assembled by our in-kind partners at ESS Bilbao, Spain, working in collaboration with local manufacturers such as Cadinox and AVS. When ESS goes online in 2023, the TMV will enclose all of the target subsystems – the target wheel, moderator, reflector plugs and cryogenic cooling – in a vacuum atmosphere and, with the help of 6000 tonnes of stainless-steel shielding, also confine any activated materials and ionising radiation in case of a highly unlikely event, such as an earthquake or accident (see "ESS operational highlights", p9).

The monolith is an impressive and complex piece of precision engineering in its own right. The vessel requires exacting and repeatable alignment tolerances (±25 μm) for the target wheel, the moderator and reflector assemblies relative to the incident proton beam as well as the neutron-beam extraction system. Ahead of shipping, ESS Bilbao successfully completed the leak and vacuum tests on the TMV with satisfactory measurements of dew-point temperature, pressure rise and leak detection. The final pressure obtained was 1×10^{-6} mbar with a leakage $<1\times10^{-8}$ mbar.l/s.

ESS science, funding and partnership

- Large-scale neutron facilities are routinely used by academic and industrial researchers to understand material properties on the atomic scale, spurring advances across a spectrum of scientific discovery – from clean energy and environmental technology to pharma and healthcare, from structural biology and nanotech to food science and cultural heritage.
- ESS is a pan-European project with 13 European nations as members: the Czech Republic, Denmark, Estonia, France, Germany, Hungary, Italy, Norway, Poland, Spain, Sweden, Switzerland and the UK.
- Significant in-kind contributions of equipment and expertise – from more than 40 European partner laboratories – are expected to finance more than a third of the overall construction costs for ESS.
- ESS will deliver its first science in 2023, with up to 3000 visiting researchers expected every year once the lab is fully operational.

The reliability of all our components requires close collaboration as well as consistent communication on all levels

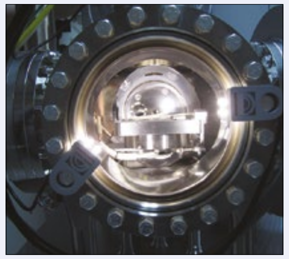
In terms of the TMV, how does your team design and build for maximum uptime?
The focus on project risk is a collective effort across all support functions and is framed by the ESS Strategic Installation and Test Strategy. With the TMV, for example, our design choices seek to minimise service interruptions to the scientific experiments at ESS. Put another way: each vacuum component in the TMV must offer the longest "time before failure" available on the market. In the case of the rough vacuum pumps, for example, this comes from Kashiyama Industries of Japan through ESS's supplier Low2High Vacuum in Sweden – offering a dry vacuum pump that's capable of 24/7, maintenance-free operation for up to three years. We've actually tested six of these units running at the laboratory for more than five years and none of them have required any intervention.

Smart choices like this add up and result in less maintenance, reduced manual handling of active materials (e.g. pump oil) and lower cost per unit life-cycle. Similar thinking informs our approach regarding the TMV's vacuum "plumbing". The use of aluminium gaskets and clamps, for example, streamlines installation (compared with CF flanges) and takes into account their low neutron ▷

ESS operational highlights

Fundamental principles

- At the heart of the ESS is a linear accelerator that produces up to a 5 MW beam of 2 GeV protons, with the bulk of the acceleration generated by more than 100 superconducting radio-frequency (RF) cavities.
- These accelerated protons strike a rotating tungsten target wheel (2.6 m diameter) to produce a beam of neutrons via nuclear spallation – i.e. the impact on the tungsten nuclei effectively "spalls" off free neutrons.
- The target wheel rotates at 23.3 rpm and is cooled by a flowing helium gas system interfaced with a secondary water system.
- The spalled neutrons pass through water premoderators, a supercritical hydrogen moderator (cooled to about 17 K) and a beryllium-lined reflector – all of which are housed in a replaceable plug – to slow the neutrons to useful energies before distribution to a suite of 15 neutron-science instruments.
- The TMV has an Active Cells Facility to perform remote handling, disassembly and storage of components that are taken out of the monolith after reaching the end of their lifetime; steel shielding blocks prevent the escape of neutron/gamma ionising radiation.



Julia Öberg/ESS

Test and measurement *ESS vacuum components and subsystems (left) are put through their paces in a dedicated vacuum test facility, one of the project's first in-kind hardware shipments from STFC Daresbury Laboratory, UK, back in 2015. Right: members of the ESS and Daresbury vacuum teams.*

TMV vacuum considerations

- The TMV is designed to accommodate various leak-rate loads, including: outgassing of vacuum components; air leaks into the vacuum vessel; water leaks from internal piping plus humidity and condensation present during operations and pump down; and helium leaks from the target wheel.
- Total gas in-leakage is critical and, in conjunction with the capacity of the turbomolecular pumping system, will determine not only the TMV operating pressure but also the refrigeration capacity for the cryo-condensing coil for pumping of potential water leaks.
- In vacuum mode, TMV pressures < 10^{-4} mbar will be required for interfacing with the UHV environment of the proton accelerator (i.e. to keep gas flows into the accelerator section to an acceptable level).
- TMV vacuum components (including polymer seals) must be compatible with operation up to 35 °C in harsh gamma/neutron radiation environments.

activation in the case of maintenance removal and reassembly ahead of resumed operations (with hands-on manipulation being faster and simpler in each case).

What are the biggest operational challenges in terms of preparing the TMV for high-reliability vacuum performance?

The major effort on the vessel was – and still is – to qualify all in-vacuum parts and connections in terms of their leak rates, pressure-code requirements and surface finishing. This includes the water-cooled shielding blocks, hydrogen-cooled moderator/deflector, and the helium cooling unit for the rotating tungsten target wheel (which employs a ferrofluidic sealing system). It's a huge collective effort in vacuum: there are more than 1000 flanges, around 20,000 bolts and 6000 tonnes of load in the fully configured TMV (which measures 6 m internal diameter and 11 m high).

There will be two possible modes of TMV operation, with the target residing in either high vacuum or helium at slightly below atmospheric pressure. What's the rationale here?

One of the high-level design objectives for ESS states that the TMV should be built to last for 50 years of operation while satisfying all performance and safety criteria. Our initial simulations showed that "cleanliness" of the volume surrounding the collisions of the proton beam and the tungsten target wheel will be essential for slowing material degradation and therefore delivering against this objective. What's more, the specification of a 5 MW proton beam means that secondary gamma and neutron radiation will be produced as a side-effect of the spallation process, further emphasising the need for a controlled environment as well as appropriate cooling of the shielding blocks to counter radiation-induced heating effects.

Operationally, the optimal mode of operation will be high vacuum (< 10^{-4} mbar), which will negate the need for a proton beam window between the proton accelerator and the target. This, in turn, will lower the annual operating costs. Other advantages include up to 1% improved neutronic performance, reduced beam scattering on the TMV components (and therefore less heat load and radiation damage), as well as a cleaner image for the beam imaging diagnostics.

Nevertheless, we will design and build a proton beam window, so that it is ready to install for operation under helium should an unanticipated issue arise with the TMV vacuum. Worth noting that in this "helium mode" a pump-and-purge capability is provided to ensure high helium purity (> 99.9%).

What lessons can other big-science facilities learn from your experiences with the ESS vacuum project?

With ESS we are entering new territory and the reliability of all our components – vacuum and otherwise – requires close collaboration as well as consistent communication on all levels with our equipment vendors and in-kind partners. Operationally, there's no doubt that the TMV and the other ESS vacuum systems have benefited from our dedicated vacuum laboratory – one of the first in-kind hardware shipments back in 2015 – and our efforts to recruit and build a skilled team of specialists in those early days of the project. The laboratory includes test facilities for vacuum integration, gauge calibration and materials outgassing studies – capabilities that allow us to iterate and optimise field solutions in good time ahead of deployment. All of which ultimately helps us to minimise project risk, with technical decisions informed by real-world testing and not just prior experience. ●

THE AUTHOR

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

UHV Design advances bellows-free drive for critical beamline applications at CERN

Spring-loaded magnetically-coupled device provides a fail-safe solution that could reduce unscheduled downtime due to loss of ultra-high vacuum.

A customer enquiry for a linear power probe – a magnetically-coupled actuator that can operate remotely in vacuum – has led to a new fail-safe design that could improve the operability of beamlines around the world.

"CERN explained that they were looking for a product that would avoid using bellows", says Jonty Eyres, engineering director at UHV Design. The UK-based firm specializes in the design, manufacture and supply of motion and heating products specified for use in high- and ultra-high vacuum conditions.

"Bellows-sealed devices have been the go-to space for moving things in and out in a clean manner and with minimal outgassing", Eyres explains. Depending on the type of bellows used, and their application, their service life can reportedly range from 10 000 up to as many as 2 million actuations. But they won't last forever. And when they fail it can lead to an unexpected loss of vacuum and costly delays.

The challenge for Eyres and his colleagues was to come up with a solution that reproduced the clean operation of a bellows-sealed device, but in a fail-safe manner.

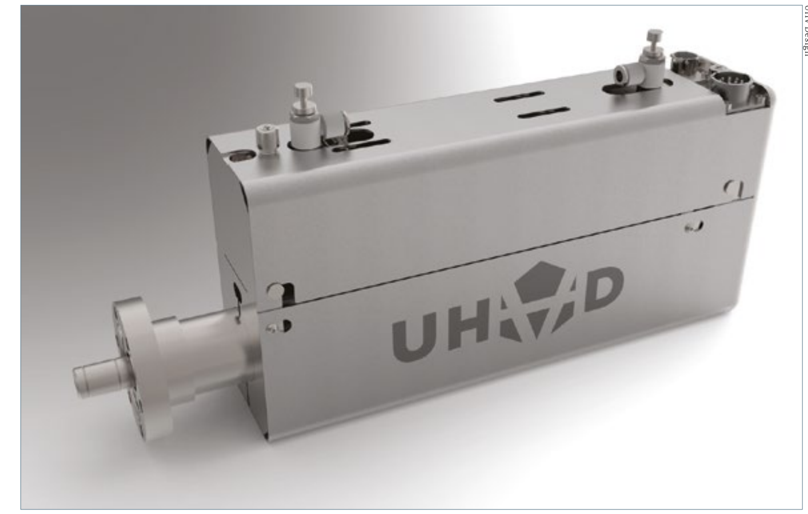
Magnets offer alternative

Over the past 20 years, the firm has developed considerable expertise in magnetically-coupled devices. Their bellows-free approach features an arrangement of magnets located inside and outside a rigid tubular vacuum envelope. Moving the magnetic housing on the outside advances and retracts an actuation shaft held centrally inside the device.

The team used specialized software to optimize both the magnetic coupling between the inside and the outside, and the screening of the device.

Online meetings allowed the client – in this case CERN – to voice the product criteria that were important to them. "We used the sessions to discover their feedback, the pros and cons and where we think the scope is in terms of performance", Eyres explains.

"Once we are confident in a prototype, the next stage is to put it on a vacuum rig and start running rigorous tests on performance and precision", says Eyres.



A magnetically-coupled actuator avoids the need for bellows in high- and ultrahigh-vacuums.

This includes carrying out residual gas analysis using a mass quadrupole device to examine how the mechanism affects the vacuum pressure. A major benefit of the firm's design is that there are no bellows to fail. But instead the team has to contend with moving parts in vacuum.

The engineers tackled this by keeping the contact areas to a minimum and using rolling parts, not sliding parts, to limit any pressure rise during operation. Preserving ultra-high vacuum conditions is critical.

Designed for cleanliness

But having rolling contacts isn't the end of the story. In addition, the materials combination must be inert to prevent the mechanism from bonding or sticking over time. And the requirement for absolute cleanliness means that all of the bearings have to be designed to operate without lubrication.

The company's solution was to use silicon nitride (a hard ceramic) ball races that pressed against two extremely tough shafts made out of tungsten carbide. This arrangement keeps the internal push-rod centrally supported, paving the way for precise movement into and out of the beamline. Furthermore, external constant force springs retract the in vacuum mechanism should any failure occur in the pneumatics driving the unit. In this fail-safe position, the linear actuator has no effect on the beam. A system of flexures ensures that no undue stresses are placed on any of the critical parts during bake out as they expand at different rates according to their composition.

The firm's bellows-free solution brings together creative design, smart materials selection and precision operation. Now that the linear drive is in its final prototype phase the team is working towards fulfilling multiple orders from CERN for what will be a bolt-on solution pre-wired with all of the necessary cables and switches.

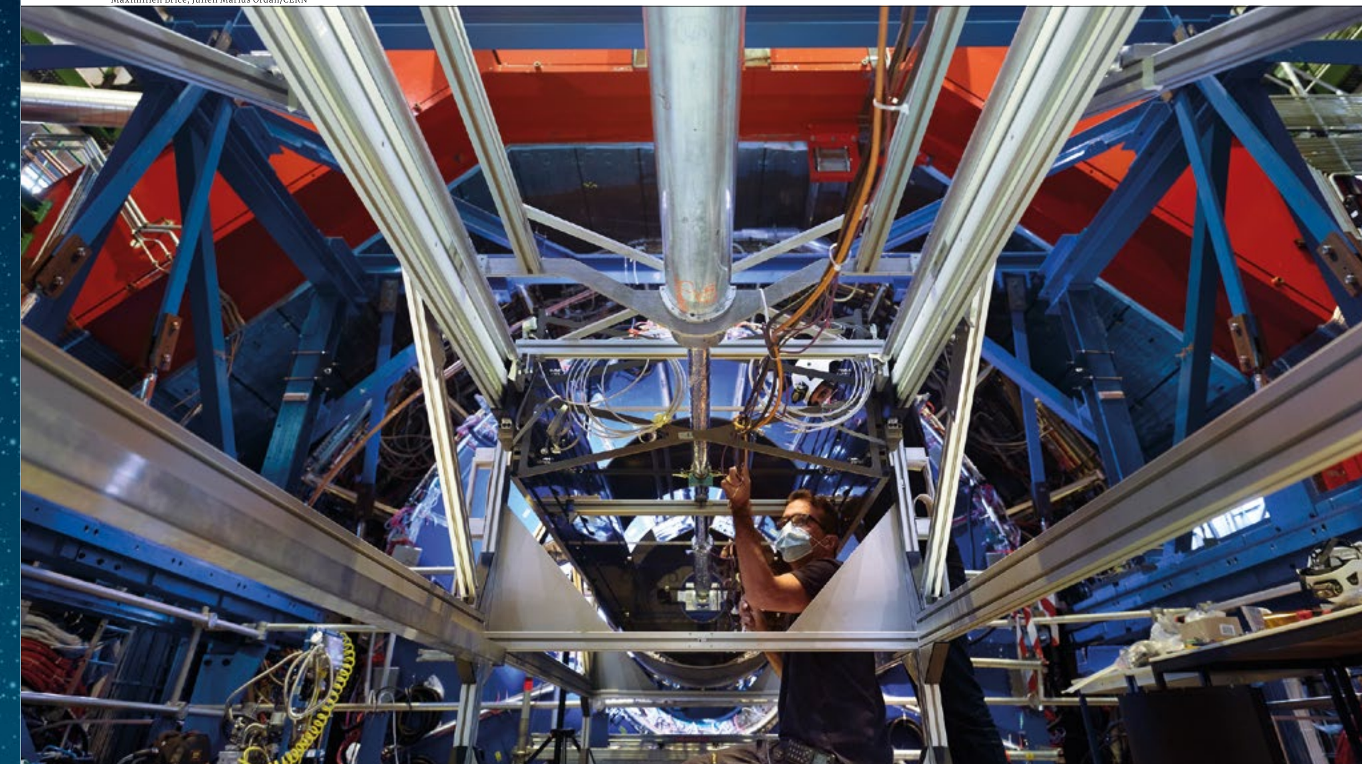
"Every beamline in the world needs beam diagnostics," Eyres comments. "And off the back of this project we're ready to work with more clients who are also looking to move away from bellows in critical areas."

For more information, visit **www.uhvdesign.com/products/push-pull-devices**.

UHVD

This article was written by *Physics World* on behalf of UHV Design. Read more on *physicsworld.com*.

Maximilien Brice, Julien Marius Ordan/CERN



Gearing up *2021 promises to be an intense period for the CERN vacuum team. An immediate concern is the restart of beam circulation in LHC vacuum systems that were open to the air for planned interventions and modification, including the ALICE beampipe (above).*

COLLABORATION YIELDS VACUUM INNOVATION

CERN is home to a unique innovation ecosystem pioneering advances in vacuum science, technology and engineering. Paolo Chiggiato and Paul Cruikshank provide an insider take.

Vacuum represents a core enabling technology in particle accelerators. Without the required degree of vacuum, the rate of interaction between circulating particles and residual gas molecules would generate several adverse conditions. Particle beams would increase in size and so decrease in luminosity at the interaction points. Beam instability and the rate of particle loss would grow, endangering instrumentation and increasing the background noise in physics experiments. Induced radioactivity and bremsstrahlung radiation would increase risks for personnel and cause damage to the accelerator hardware. What's more, vacuum is crucial for avoiding electrical breakdown in high-voltage equipment, as well as for thermal insulation of cryogenic fluids, reducing heat "inleaks" to acceptable levels.

THE AUTHORS

Paolo Chiggiato *is leader and* **Paul Cruikshank** *is deputy leader of the vacuum, surfaces and coatings group at CERN.*

Operationally, the level of vacuum required for particle accelerators spans a large range of residual gas densities – from high vacuum (HV, 10^{-3} to 10^{-9} mbar) through ultrahigh vacuum (UHV, 10^{-9} to 10^{-12} mbar) to extreme high vacuum (XHV, usually defined as 10^{-12} mbar and lower). Applications in thermal insulation, for example, require a gas-molecule density 10 million times lower than sea-level atmospheric pressure – i.e. less than 10^{-4} mbar. On the other hand, a modern synchrotron facility requires UHV residual gas densities of $\leq 10^{-9}$ mbar, while some antimatter experiments impose a rarefaction requirement in the region of 10^{-15} mbar. In the most challenging experiments, vacuum is an enclosed space where only several gas molecules per cm^3 persist in their random motion, bouncing from one wall of the vacuum vessel to another and able to travel thousands of millions of km before striking another peer (roughly equivalent to the distance from the Sun to Jupiter).

Writ large, it is no surprise that, 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. From HV to the UHV/XHV regimes, the complexity of vacuum systems for the particle accelerators at CERN, and other big-science laboratories like it, stems largely from the interaction between particle beams and the surfaces that surround them.

Beam interactions

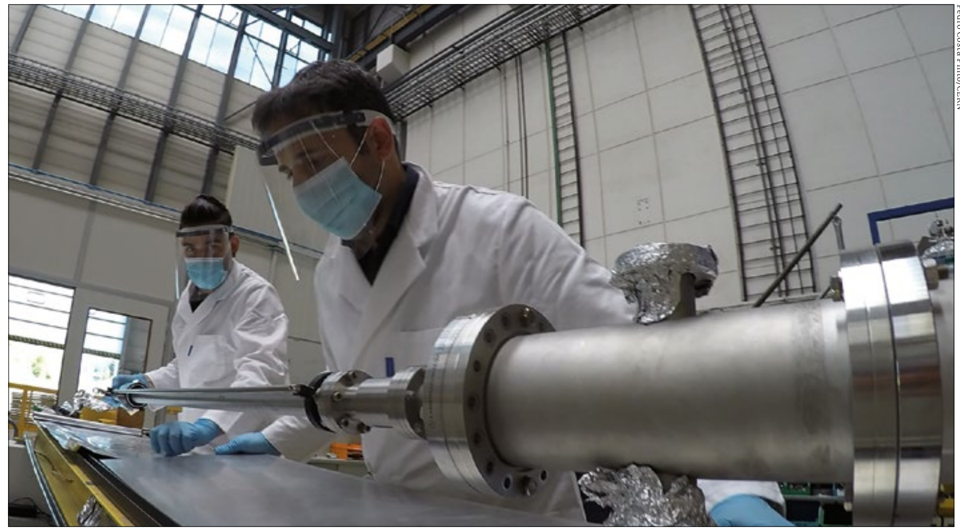
This "beam–surface dialogue" induces gas desorption from the vacuum system walls, an interaction that can be the dominant source of gas. Indeed, if atmospheric gas is evacuated rapidly from the vacuum system, with no in-leakage of air, it is possible to attain UHV conditions in just a few hours for chamber volumes of the order of a cubic metre. Although the vacuum-system walls release gases spontaneously – mainly water vapour and hydrogen – the choice of suitable materials and thermal treatments reduces the outgassing rates to an acceptable level before accelerator operation. As such, beam-induced gas desorption remains the biggest headache – and this effect, of course, arises only when the particle beams are in circulation.

Beam losses on the chamber walls can be a direct source of gas in the accelerator vacuum system. For the most part, however, beam-induced gas desorption occurs indirectly via the emission of synchrotron light and the beam-induced acceleration of electrons and ions created, for example, by residual gas ionisation. The synchrotron-light-induced desorption is mediated by surface-electron quantum transitions leading to the extraction of photoelectrons, which can desorb residual gas molecules in two ways – initially when leaving the chamber wall, also when striking the wall subsequently. This effect is by far the main source of gas in circular high-energy electron accelerators and plays a significant role in the Large Hadron Collider (LHC), where the critical energy of the emitted photons is around 40 eV (i.e. large enough to extract photoelectrons and induce desorption).

It's worth noting, though, that there's no "instant fix" for excessive gas desorption. Even with appropriate chemical surface treatments, accelerator vacuum systems (particularly those for electrons) cannot cope with full beam performance on day one of commissioning. Instead, it is necessary to ramp up the performance of the vacuum system while the beam current is increased in a stepwise fashion. In this way, the dose of particles hitting the surfaces of the vacuum vessel increases (though without excessive beam losses), while desorption yields are reduced via surface cleaning and chemical modification. In the jargon, this optimisation of surface conditioning is known as a "scrubbing run".

The complexity of vacuum systems for particle accelerators stems largely from the interaction between particle beams and the surfaces that surround them

The time taken for surface conditioning can be cut dramatically with the help of nonevaporable getter (NEG) coatings, a concept developed at CERN in the late 1990s. Put simply: the beampipe walls are coated with a micrometre-thick film of Ti–Zr–V alloy that, once heated for a few hours in the accelerator at about 200 °C, provides a clean metal surface that also acts as a pump (i.e. gas molecules are adsorbed by chemical reaction at the surface). During heating, the main reservoir of gas is eliminated as the oxide passivation layer dissolves into the film; after which the cycle repeats whenever adsorption of gas molecules saturates the surface or air venting is necessary.



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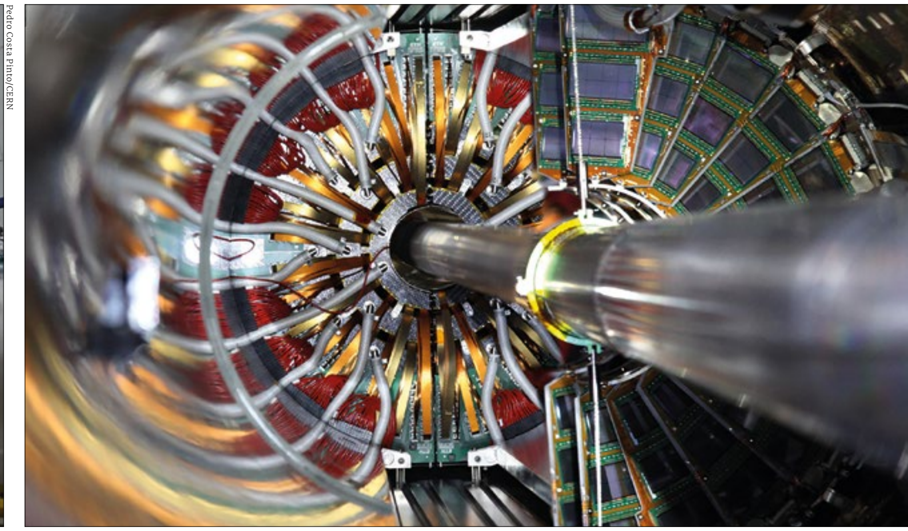

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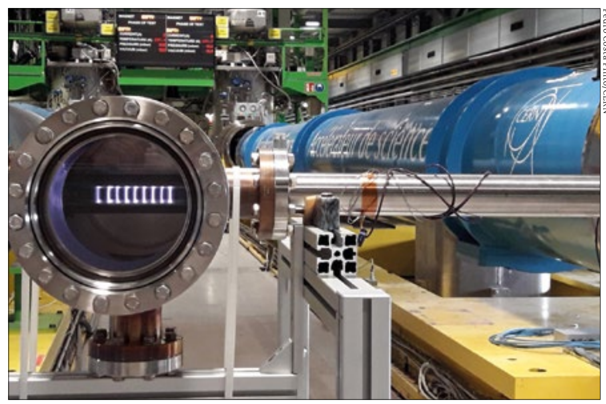

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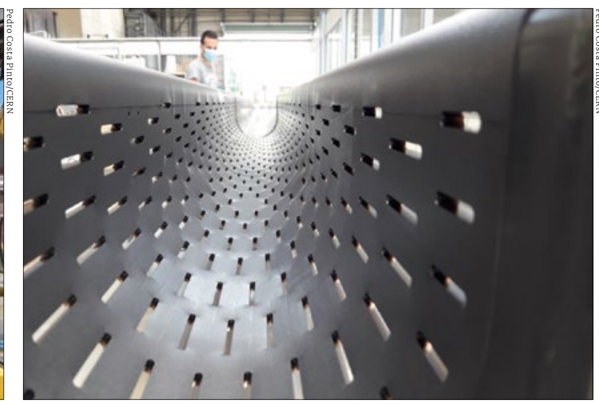


Pedro Costa Pinto/CERN

Pedro Costa Pinto/CERN

Vacuum diversity *CERN is home to world-leading R&D capabilities in vacuum science and technology. Top left: prototyping a new set-up for thin-film coating of the HL-LHC vacuum chambers. Top right: the CMS beampipe traversing the inner tracker detector. The central part is made of 0.8 mm- thick pure beryllium (a metal highly transparent to elementary particles), while the rest of the vacuum vessel is made largely of aluminium alloy. Bottom left: a system for the study of new cathodes for sputter deposition of amorphous carbon thin films. Centre: thin-film coating of the RF shield of the LHC's new target dump injection-segmented unit (a machine-protecting device). Right: an in-vacuum cable spool for electrical powering of a movable sputtering target designed for* in situ *amorphous carbon thin-film coating in the beam screen of the LHC's standalone magnets.*

This NEG capability is deployed at scale by CERN. The 6 km-long beam lines of the LHC's room-temperature straight sections, for example, are coated entirely with NEG materials, while uptake in several synchrotron research facilities is now envisaged after a pioneering implementation in MAX IV, the Swedish synchrotron. In summary: NEG coatings combine distributed, high-speed pumping with negligible space requirements – a win–win for small-diameter beampipes in the current generation of electron accelerators.

Another significant component of the beam–surface dialogue within particle accelerators is the heating of materials exposed to the circulating beams. One of two possible tracks for the transfer of thermal power is the interaction between the electromagnetic field generated by the beams with the surrounding materials, a process that induces electrical currents on the beam-facing surfaces.

These currents may in turn give rise to Joule heating, typically mitigated by using a good electrical conductor (like copper) as the material of choice for the beampipes or as a layer deposited on stainless steel, usually via electrolytic techniques. Geometrical discontinuities of the vacuum chambers may also result in resonant interaction with the beam, creating enhanced local power dissipation in trapped modes – a problem that can be solved through optimised design of the vacuum chambers and their transitions.

Taken together, these mitigation measures have another highly beneficial side-effect. Beam-induced surface currents generate electromagnetic fields which, in turn, interact back with the beam, potentially disrupting its characteristics or its long-term stability in the accelerator. As such, the overall drive to reduce the impedance of the vacuum system (and of all in-vacuum components) results in longer beam lifetimes and preserved beam emittance, ultimately leading to higher collision rates in physics experiments.

The heat is still on

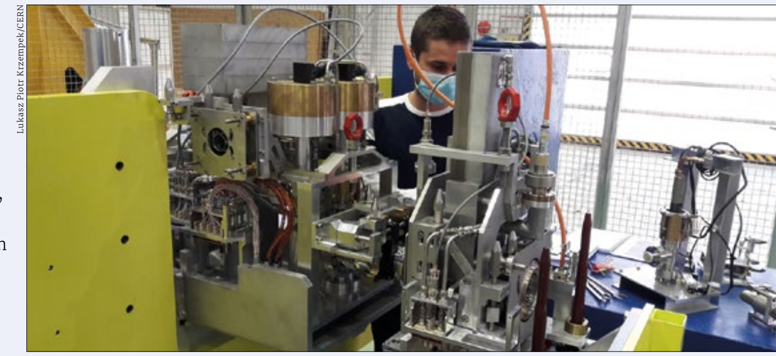
Ongoing innovation will be essential, however. In the next generation of high-energy proton accelerators operating with superfluid helium – the proposed Future Circular Collider (FCC-hh) is a case in point – the impedance of the beampipes could prove detrimental for the global heat-load balance of the cryogenic system. To counter this heat source, CERN has initiated an ambitious feasibility study in which the inner walls of vacuum chambers are coated with high-temperature superconductors (HTS). Owing to the much-reduced electrical losses of superconductors

Support for projects like the HL-LHC requires full cognisance of some pretty harsh operating environments

CERN's vacuum roadmap: collaboration is key

The evolution of vacuum technology and engineering at CERN is strictly aligned versus accelerator operation and priorities; the organisation's fundamental science programme; and, at a high level, the 2020 update of the European Strategy for Particle Physics. As the restart of the LHC physics programme approaches (slated for early 2022), the reliability of the CERN vacuum system is our primary focus – especially after a shutdown that will have run to more than two years.

For sure, 2021 will be an intense period for the CERN vacuum team. An immediate concern is the restart of beam circulation in vacuum systems that were open to the air for planned interventions and modification – sometimes for several days or weeks. The heat load generated by the beams in the LHC's arcs will be under the spotlight as well as the performance of the upgraded LHC's injector chain. There is no doubt that our nights will be filled with worries – worries that will hopefully dissipate as new science breakthroughs are announced for the LHC's beams and detectors.



Lukasz Piotr Krzempek/CERN

Robotic access *The VAX vacuum module is installed in an area of limited access and relatively high radioactivity within the HL-LHC. The set-up (shown above in the prototyping phase) is fully compatible with robot intervention, enabling leak detection, gasket change and complete removal of parts to be carried out remotely and safely.*

Maintaining momentum

In parallel, we will maintain the pace of the HL-LHC programme, implementing vacuum innovations elaborated in the past five years. Chief among them are the new beam screens for the triplet magnets of the two high-luminosity experiments – CMS and ATLAS. This advanced concept integrates a carbon coating (as electron multipacting suppressor) and tungsten blocks (to absorb collision debris before it interacts with the magnets). Design optimisation required several iterations and the running of multiphysics programs. The vacuum team subsequently evaluated the mechanical stability of the HL-LHC beam screen during the electromagnetic and thermal transient generated by magnet quench (i.e. a sudden loss of superconducting properties). Experimental investigations of the vacuum performance – via measurement of adsorption isotherms – allowed us to choose 60 K as the operational temperature for the new beam screen.

Another notable HL-LHC achievement is the vacuum module installed between the last focusing magnet of the accelerator and the high-luminosity experiments. Referred to as VAX, this arrangement comprises a compact set of vacuum components, pumps, valves and gauges installed in an area of limited access and relatively high radioactivity. As such, the VAX design is fully compatible with robot intervention, enabling leak detection, gasket change and complete removal of parts to be carried out remotely and safely. The direction of travel is clear: robotic technologies will have a pivotal role to play in the vacuum systems of next-generation, high-intensity particle accelerators.

Joined-up thinking

Operationally, it is already time to prepare CERN and a new generation of vacuum experts for the post-LHC era. Our reference point is the aforementioned European Strategy for Particle Physics, with its initial prioritisation of an electron–positron Higgs factory to be followed, in the long run, by a 100 km-circumference proton–proton collider at "the highest achievable energy".

These accelerators will push vacuum science and technology to the limit, amplifying the challenges that we have today with the LHC. Yet there's plenty of encouraging progress to report. An optimised design for the vacuum chambers is already in the works, thanks to advanced simulations of synchrotron radiation and gas molecule distribution performed using CERN-maintained software. Furthermore, the Karlsruhe Research Accelerator (KARA) in Germany reports excellent results in its evaluations of the proton–proton prototype vacuum chamber. The biggest challenge remains cost: engineering solutions adopted at the km scale cannot be implemented for systems 10 to 100 times longer – the vacuum system would be prohibitively expensive.

Herein lies an opportunity – and more specifically a call to arms for vacuum specialists to work collaboratively across their respective disciplines to imagine, and subsequently deliver, the technology innovations that will address the economic challenges of big science in the 21st century. The potential synergies are already evident as the next generation of particle accelerators takes shape alongside new concepts for advanced gravitational-wave telescopes. Diverse physics initiatives with a common interest in driving down the cost of their enabling vacuum systems.

versus normal metals, successful use of HTS promises to yield a considerable impedance reduction. It's early days, but initial results with HTS rare-earth barium copper oxide (ReBCO) test coatings are extremely encouraging.

At the same time, synchrotron radiation and electrons hitting the walls of the vacuum system also convey part of the beam power to the surrounding vessels. The multiplication of impinging electrons by the surface and their acceleration by the beam – a process known as electron multipacting – is of concern for cryogenic systems. In the LHC, for example, the heat load is intercepted by an intermediate wall that's maintained at a temperature of 10–20 K rather than 1.9 K (which is the temperature of the cold bore – i.e. the chamber in tight contact with the magnet). Underpinning this arrangement is the insertion into the cold bore of an additional pipe – the so-called beam screen – which is made of copper-colaminated stainless-steel and cooled by a dedicated helium circuit. The beam screen and cold bore in turn communicate through pumping slots so that gas molecules are cryoadsorbed on the coldest surface.

A granular understanding of the fundamental physics certainly helps here. While synchrotron radiation power depends only on the beam parameters, the contribution of electrons to the heat load depends on the surface parameters, above all the secondary electron yield – i.e. the ratio of emitted electrons versus incident electrons. This important characteristic of the surface walls decreases as the dose of impinging electrons accumulates – an additional outcome of beam conditioning. That said, such a decrease takes time and dedicated beam runs, while the mechanism of beam conditioning seems more complex than at first anticipated (as observed during Run 2 of the LHC from 2014–2018). In terms of specifics, the heat load transferred in the beam-screen cooling circuit was found to be higher than expected in four of the LHC's eight arcs. CERN's surface experts investigated several surface characteristics to understand this phenomenon and, finally, spotted anomalous behaviour in copper oxide that could lead to a less effective decrease of the secondary electron yield.

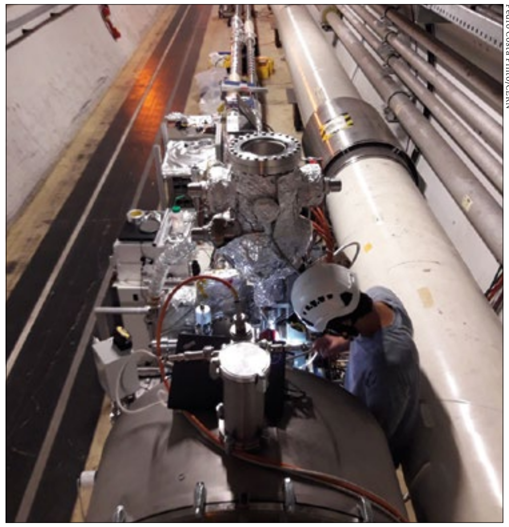
To circumvent the need for additional beam conditioning, CERN's vacuum group has developed amorphous carbon coatings with very low secondary-electron yields to effectively prevent electron multipacting. Such thin films are the baseline for the beampipes of the final focusing magnets for the High-Luminosity LHC (HL-LHC) upgrade, presently under way. The carbon coatings have also been implemented in selected areas of the Super Proton Synchrotron (which injects protons into the LHC) to reduce the direct effect of electron clouds on beam performance.

Another countermeasure to electron multipacting involves increasing the roughness of the walls of the vacuum vessel, such that secondary electrons are intercepted by the surfaces before they can be accelerated by the beam. In this instance, the CERN vacuum group is implementing laser treatments developed by two UK research centres – STFC Daresbury Laboratory and the University of Dundee. The laser, which is introduced into the beampipes using a dedicated robot from GE Inspection Robotics, engraves small grooves azimuthally, with a spacing of a few tens of micrometres. Furthermore, the redeposition of ablated material superposes nanometric particles that enhance the electron-capture effect.

Measurement and control

Zoom out from the esoteric complexity of beam–surface interactions and the sheer scale of CERN's vacuum infrastructure represents an engineering challenge in its own right – not least in terms of vacuum metrology, diagnostics and control. In all, more than 12,000 vacuum instruments – gauges, pumps, valves and associated controllers with almost a million configuration settings – are managed via a flexible database running in the Cloud. Work is well advanced to mine the vast amounts of data generated by this network of vacuum systems – ultimately creating a "data-streaming pipeline" that will integrate the latest analytics software with a new generation of open-source diagnostic and reporting tools.

Meanwhile, at the operational sharp-end, the measurement of extremely low pressures remains a core competency of the CERN vacuum team. This capability preserves, indeed builds on, the legacy of the Intersecting Storage Rings (ISR), the world's first hadron collider and a pioneering environment for vacuum technology during the late 1960s and 1970s. The vacuum gauges operating at CERN today in the 10^{-7}–10^{-12} mbar range are copies of the original models adopted for the ISR, while those in use in CERN's R&D laboratories and in antimatter experiments (for measurement down to 10^{-14} mbar) are the result of further developments in the late 1970s.



Pedro Costa Pinto/CERN

Tunnel vision *Preparation of amorphous carbon coatings in the LHC during Long Shutdown 2. These thin films have very low secondary electron yields to prevent electron multipacting.*

Studies of vacuum gauges to provide continuous measurement at even lower pressures are also under way at CERN, often in collaboration with Europe's metrological community. In the framework of the EURAMET-EMPIR programme, for example, CERN vacuum experts have participated in the development and characterisation of a vacuum gauge with an ultrastable sensitivity for the transfer of vacuum standards amongst European research institutes (see "Vacuum metrology: made to measure", p23).

More broadly, support for projects like the HL-LHC requires full cognisance of some pretty harsh operating environments. Fundamentally, increasing beam currents means that vacuum systems and their electronic control circuits are more and more susceptible to radiation damage. A key determinant of the global cost/performance of a large-scale vacuum system is the deployment of electronics in the accelerator tunnels – with weaknesses in the devices gradually revealed through increasing radiation exposure. With this in mind, and by using radiation sources available on site as well as at other European research institutes, the CERN vacuum team has been busy evaluating the "radiation hardness" of hundreds of critical components and electronic devices.

Looking to the future, it's evident that major accelerator initiatives such as the HL-LHC and the proposed FCC will maintain CERN's role as one of the world's leading R&D centres for vacuum science and technology – a specialist capability that will ultimately support fundamental scientific advances at CERN and beyond. ●

The sheer scale of CERN's vacuum infrastructure represents an engineering challenge in its own right

VACUUM METROLOGY: MADE TO MEASURE

A pan-European consortium is working towards an international standard for the commercial manufacture of ionisation vacuum gauges – an advance that promises significant upsides for research and industrial users of vacuum systems. Joe McEntee reports.

PTB

Measurement science *'Design for manufacturability' is a priority for the EMPIR 16NRM05 partners, such that any specialist manufacturer will be able to produce standardised, next-generation ionisation gauges at scale. Here, PTB scientists Karl Jousten (right) and Claus Illgen adjust the gauge assembly prior to bake-out and installation into a UHV system.*

Absence, it seems, can sometimes manifest as a ubiquitous presence. High and ultrahigh vacuum – broadly the "nothingness" defined by the pressure range spanning 0.1 Pa (0.001 mbar) through 10^{-9} Pa – is a case in point. HV/UHV environments are, after all, indispensable features of all manner of scientific endeavours – from particle accelerators and fusion research to electron microscopy and surface analysis – as well as a fixture of diverse multibillion-dollar industries, including semiconductors, computing, solar cells and optical coatings.

For context, the ionisation vacuum gauge is the only instrument able to make pressure measurements in the HV/UHV regime, exploiting the electron-induced ionisation of gas molecules within the gauge volume to generate a current that's proportional to pressure (see figure 1 in "Better traceability for big-science vacuum measurements" on p25). Integrated within a residual gas analyser (RGA), for example, these workhorse instruments effectively "police" HV/UHV systems at a granular level – ensuring safe and reliable operation of large-scale research facilities by monitoring vacuum quality (detecting impurities at the sub-ppm level), providing *in situ* leak detection and checking the integrity of vacuum seals and feed-throughs.

Setting the standard

Notwithstanding the ubiquity of HV/UHV systems, it's clear that many scientific and industrial users are sure to gain – and significantly so – from an enhanced approach to pressure measurement in this rarefied domain. For their part, HV/UHV end-users, metrology experts and the International Standards Organisation (ISO) all acknowledge the need for improved functionality and greater standardisation across commercial ionisation gauges – in short, enhanced accuracy and reproducibility plus more uniform sensitivity versus a broad spectrum of gas species.

That wish-list, it turns out, is the remit of an ambitious pan-European vacuum metrology initiative – the catchily titled 16NRM05 Ion Gauge – within the European Metrology Programme for Innovation Research (EMPIR), which in turn is overseen by the European Association of National Metrology Institutes (EURAMET). As completion of its three-year R&D effort approaches, it seems the EMPIR 16NRM05 consortium is well on its way to finalising the design parameters for a new ISO standard for ionisation vacuum gauges that will combine improved accuracy (total relative uncertainty of 1%), robustness and long-term stability with known relative gas sensitivity factors.

Another priority for EMPIR 16NRM05 is "design for manufacturability", such that any specialist manufacturer will be able to produce standardised, next-generation ionisation gauges at scale. "We work closely with the gauge manufacturers – VACOM of Germany and INFICON of Liechtenstein

Better traceability for big-science vacuum measurements

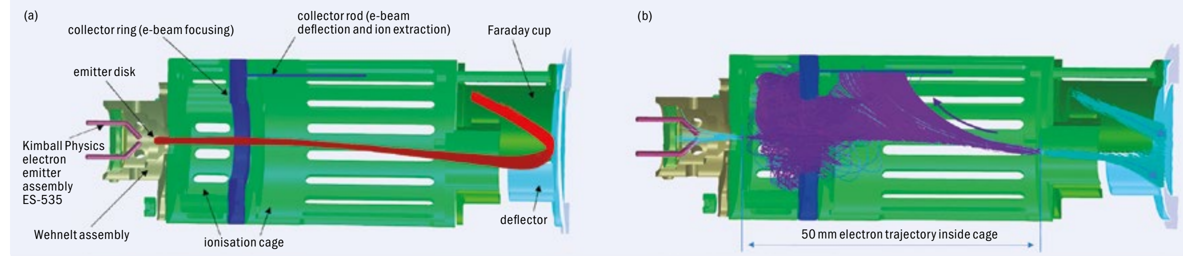


Fig. 1. *The EMPIR 16NRM05 ionisation vacuum gauge. (a) Electrons (red) leave the cathode (far left), are accelerated by the anode (green) to 200 eV, focused by the ion collector (blue) and collected by the Faraday cup (dark green) after passing a deflector (light blue). Some electrons will ionise gas molecules and those will be collected by the ion collector. The length of the electron path is well characterised and so the sensitivity of the gauge is predictable. (b) Ions (purple) generated by electrons within the anode grid are accelerated to the collector (dark blue) and measured as a current. Ions (light blue) generated outside the anode grid are caught by the deflector.*

The ionisation vacuum gauge is fundamental to the day-to-day work of the vacuum engineering teams at big-science laboratories like CERN. There's commissioning of HV/UHV systems in the laboratory's particle accelerators and detectors – monitoring of possible contamination or leaks between experimental runs of the LHC; pass/fail acceptance testing of vacuum components and subsystems prior to deployment; and a range of offline R&D activities, including low-temperature HV/UHV studies of advanced engineering materials.

"I see the primary use of the standardised gauge design in the testing of vacuum equipment and advanced materials prior to installation in the CERN accelerators," explains Berthold Jenninger, a CERN vacuum specialist and the laboratory's representative in the EMPIR 16NRM05 consortium. "The instrument will also provide an important reference to simplify the calibration of vacuum gauges and RGAs already deployed in our accelerator complex."

The underlying issue is that commercial ionisation vacuum gauges are subject to significant drifts in their sensitivity during regular operation and handling – changes that are difficult to detect without access to an in-house calibration facility. Such facilities are the exception rather than the norm, however, given their significant overheads and the need for specialist metrology personnel to run them.

Owing to its stability, the EMPIR 16NRM05 gauge design promises to address this shortcoming by serving as a transfer reference for commercial ionisation vacuum gauges. "It will be possible to calibrate commercial vacuum gauges simply by comparing their readings with respect to that reference," says Jenninger. "In this way, a research lab will get a clearer idea of the uncertainties of their gauges and, in turn, will be able to test and select the products best suited for their applications."

The measurement of outgassing rate, pumping speed and vapour pressure at cryogenic temperatures will all benefit from the enhanced precision and traceability of the new-look gauge. Similarly, measurements of ionisation cross-section induced by electrons, ions or photons also rely on gas density measurement, so uncertainties in these properties will be reduced.

"Another bonus," Jenninger notes, "will be enhanced traceability and comparability of vacuum measurements across different big-science facilities."

are consortium members – to make sure that any future standard will result in an instrument that is easy to use and economical to produce," explains Karl Jousten, project lead and head of section for vacuum metrology at Physikalisch-Technische Bundesanstalt (PTB), Germany's national measurement institute (NMI) in Berlin.

In fact, this engagement with industry underpins the project's efforts to unify something of a fragmented supply chain. Put simply: manufacturers currently use a range of electrode materials, operating potentials and, most importantly, geometries to define their respective portfolios of ionisation gauges. "It's no surprise," Jousten adds, "that gauges from different vendors vary significantly in terms of their relative sensitivity factors. What's more, all commercially available gauges lack long-term and transport stability – the instability being about 5% over one year."

The EMPIR 16NRM05 project partners – five national measurement institutes (including PTB), VACOM and INFICON, along with vacuum experts from CERN and the University of Lisbon – have sought to bring order to this disorder by designing an ionisation gauge that is at once compatible with standardisation while exceeding current performance levels. When the project kicked off in summer 2017, for example, the partners set themselves the goal of improving the relative standard uncertainty due to long-term and transport instability from about 5% to below 1% for nitrogen gas. Another priority involves tightening the spread of sensitivity factors for different gas species (from about 10% to 2–3%) which, in turn, will help to streamline the calibration of relative gas sensitivity factors for individual gauges and multiple gas species.

It's all about the detail

For starters, the consortium sought to identify and prioritise a set of high-level design parameters to underpin any future ISO-standardised gauge. A literature review of 260 relevant academic papers (from as far back as the 1950s) yielded some quick-wins and technical insights to inform subsequent simulations (using the commercial software packages OPERA and SIMION) of a v1.0 gauge design versus electrode positions, geometry and overall dimensions. Meanwhile, the partners carried out a statistical evaluation

It's a design that cannot be found on the market… The results have been very encouraging

of the manufacturing tolerances for the electrode positions as well as a study of candidate electrode materials before settling on a "model gauge design" for further development.

"It's a design that cannot be found on the market," explains Jousten. "While somewhat risky, given that we can't rely on prior experience with existing commercial products, the consortium took the view that the instabilities in current-generation gauges could not be overcome by modifying existing designs." With a clear steer to rewrite the rulebook, VACOM and INFICON developed the technical drawings and produced 10 prototype gauges to be tested by NMI consortium members – a process that informed a further round of iteration and optimisation.

"The results have been very encouraging," explains Jousten. Specifically, the measured sensitivity of the latest model gauge design agrees with simulations, while the electron transmission through the ionisation region is close to 100%. As such, the electron path length is well-defined, and it can be expected that the relative sensitivities will relate exactly to the ionisation probabilities for different gases. For this reason, the fundamentals of the model gauge design are now largely fixed, with the only technical improvements in the works relating to robustness (for transport stability) and better electrical insulation between the gauge electrodes.

"Robustness appears fine, but is still under test at CMI [in the Czech Republic]," says Jousten. "Right now, the exchange of the emitting cathode – particularly its positioning – seems to depend a little too much on the skill of the technician, though this variability should be addressed by future industrial designs."

Summarising progress as EMPIR 16NRM05 approaches the finishing line, Jousten points out that PTB and the consortium members originally set out to develop an ionisation vacuum gauge with good repeatability, reproducibility and transport robustness, so that relative sensitivity factors are consistent and can be accumulated over time for many gas species. "It seems that we have exceeded our target," he explains, "since the sensitivity seems to be predictable for any gas for which the ionisation probability by electrons is known." The variation of sensitivity for nitrogen between gauges appears to be < 5%, so that no calibration is necessary when the user is comfortable with that level of uncertainty. "At present," Jousten concludes, "it looks like there is no need to calibrate the relative sensitivity factors, which represents enormous progress from the end-user perspective."

Of course, much remains to be done. Jousten and his colleagues have already submitted a proposal to EURAMET for follow-on funding to develop the full ISO Technical Specification within the framework of ISO Technical Committee 112 (responsible for vacuum technology). In 2021, Covid permitting, the consortium members will then begin the hard graft of dissemination, presenting their new-look gauge design to manufacturers and end-users. ●

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SURFACE TREATMENT: SECRETS OF SUCCESS IN VACUUM SCIENCE

CERN's mission in fundamental physics benefits from the proximity and expertise of the laboratory's specialist surface-chemistry team. Paolo Chiggiato and Leonel Ferreira explain the critical role that surface modification plays in big-science vacuum systems.

Materials exposed to the high-energy beams in a particle accelerator must fulfil a demanding checklist of mechanical, electrical and vacuum requirements. While the structural function comes from the bulk materials, many other properties are ascribed to a thin surface layer, sometimes just a few tens of nanometres thick. This is typically the case for the desorption caused by electron, photon and ion collisions; Joule-effect heating induced by the electromagnetic field associated with the particle beams; and electron multipacting phenomena (see "Collaboration spurs vacuum innovation", p13). To deliver the required performance, dedicated chemical and electrochemical treatments are needed – and more often than not mandatory – to re-engineer the physical and chemical properties of vacuum component/subsystem surfaces.

The bigger drivers here are the construction and operation of the Large Hadron Collider (LHC) and the High-Luminosity LHC upgrade – projects that, in turn, have driven impressive developments in CERN's capabilities and infrastructure for surface chemistry and surface modification. The most visible example of this synergy is the new Building 107, a state-of-the-art facility that combines a diverse portfolio of chemical and electrochemical surface treatments with a bulletproof approach to risk management for personnel and the environment. Operationally, that ability to characterise, re-engineer and fine-tune surface properties has scaled dramatically over the last decade, spurred by the recruitment of a world-class team of scientists and engineers, the purchase of advanced chemical processing systems, and the consolidation of our R&D collaborations with specialist research institutes across Europe.

Surface chemistry *Building 107 is a state-of-the-art 5000 m^2 facility that provides a diverse portfolio of chemical and electrochemical surface treatments for vacuum components and subsystems. Safety-critical thinking is hard-wired into the facility's operations, underpinning the day-to-day storage, handling and large-scale use of chemical products.*

CERN

Chemistry in action

Within CERN's Building 107, an imposing structure located on the corner of Rue Salam and Rue Bloch, the simplest treatment to implement – as well as the most common – is chemical surface cleaning. After machining and handling, any accelerator component will be contaminated by a layer of dirt – mainly organic products, dust and salts. Successful cleaning requires the right choice of materials and production strategy. A typical error in the design of vacuum components, for example, is the presence of surfaces that are hidden (and so difficult to clean) or holes that cannot be rinsed or dried fully. Standard cleaning methods to tackle such issues are based on detergents that, in aqueous solution, will lower the surface tensions and so aid the rinsing of foreign materials like grease and dust.

The nature of the accelerator materials means there are also secondary effects of cleaning that must be considered at the design phase – e.g. removal of the oxide layer (pickling) for copper and etching for aluminium alloys. To improve the cleaning process, we apply mechanical agitation via circulation of cleaning fluids, oscillation of

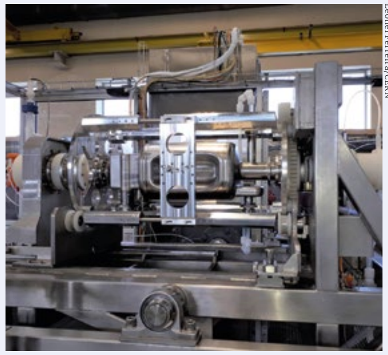
THE AUTHORS

Paolo Chiggiato *is leader of the vacuum, surfaces and coatings group at CERN.*
Leonel Ferreira *is a senior chemical engineer in the vacuum, surfaces and coatings group.*

Safety always comes first in Building 107

Safety-critical thinking is hard-wired into the operational DNA of CERN’s Building 107, underpinning the day-to-day storage, handling and large-scale use of chemical products for surface treatments. That safety-first mantra means the 5000 m² facility is able to confine all hazards inside its walls, such that risks for the surrounding neighbourhood and environment are negligible. Among the key features of Building 107:

- There are retention basins that allow containment of the liquid from all surface-treatment tanks (plus, even in the unlikely case of a fire, there is enough retention capacity for the water pumped by the firefighting teams).
- The retention basins have leak detection sensors, pumping systems, buffer tanks and a special coating that’s able to withstand more than 100 types of chemical for several days in the event of a leak.
- Toxic and corrosive vapours are extracted continuously from the tanks and washed in dedicated scrubbers, while any escaped solvents are adsorbed on active carbon filters.
- A continuous spray of alkaline solution transfers toxic products (liquid phase) for decontamination at CERN’s wastewater treatment plant.
- In terms of fire prevention, all plastics used for the treatment tanks and extraction ducts are made of self-extinguishing polypropylene – removing the source of energy to sustain the flames.
- The safety of technicians is ensured by strict operating procedures (including regulated building access), enhanced air extraction and the storage of incompatible products in separate retention zones.
- State-of-the-art sensors provide permanent monitoring of critical airborne products and link to local and fire-brigade alarms.


Leonel Ferreira/CERN

Absolutely flawless *CERN’s new polishing facility during the treatment of the HL-LHC niobium RFD crab cavity (centre). The dedicated machine can provide rotation while chemically polishing with a mixture of nitric, hydrofluoric and phosphoric acids.*

components and ultrasonic vibration. The last of these creates waves at a frequency higher than 25 kHz. In the expansion phase of the liquid waves, microbubbles of vapour are generated (cavitation), while in the compression phase the bubbles implode to generate pressures of around 1000 bar at the equipment surface – a pressure so high that the material can be eroded (though the higher the frequency, the smaller the gas bubbles and the less aggressive the surface interaction).

Chemical fine-tuning

An alternative cleaning method is based on non-aqueous solvents that act on contamination by dilution. Right now, modified alcohols are the most commonly used solvents at CERN – a result of their low selectivity and minimal toxicity – with the cleaning operation performed in a sealed machine to minimise the environmental impacts of the volatile chemicals. While the range of organic products on which solvents are effective is usually wider than that of detergents, they cannot efficiently remove polar contaminants like salt stains. Another drawback is the risk of contaminants recollecting on the component surface when the liquid does not flow adequately.

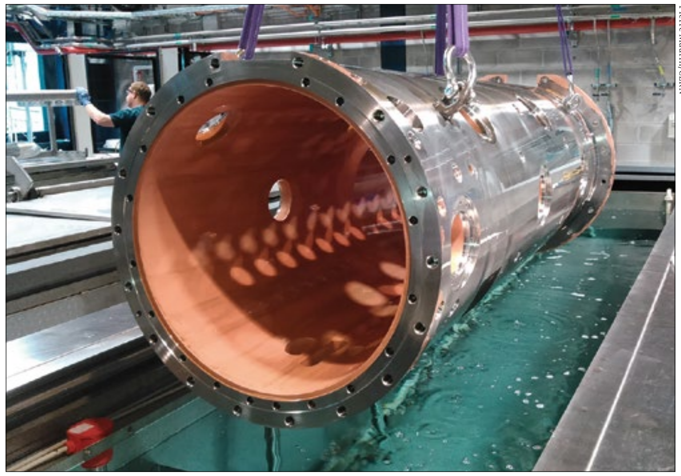
Ultimately, the choice of detergent versus solvent relies on the experience of the operator and on guidelines linked to the type of vacuum component and the nature of the contamination. In general, the coating of components destined for ultrahigh-vacuum (UHV) applications will require a preliminary cleaning phase with detergents. Meanwhile, solvents are the optimum choice when there are no stringent cleanliness requirements – e.g. degreasing of filters for cryoplants or during the component assembly phase – and for surfaces that are prone to react with or retain water – e.g. steel laminations for magnets, ceramics and welded bellows. (It is worth noting that trapped water is released in vacuum, compromising the achievement of the required pressure, while wet surfaces are seeds for corrosion in air.)

After rinsing and drying, the components are then ready for installation in the accelerator or for ongoing surface modification. In the case of the latter, the chemical treatments aim to generate a thinner, more compact oxide layer and/or a smoother surface – essential for subsequent plating processes. As such, the components can undergo etching, pickling and passivation (to reduce the chemical reactivity of the surface). Consider the copper components for the LHC’s current-lead support: before brazing (a joining process using a melted filler metal), these components are pickled in hydrochloric acid and passivated in chromic acid. Similarly, the aluminium contacts of busbars (for local high-current power distribution) must be pickled by caustic soda and/or a mixture of nitric and hydrofluoric acid before silver coating. Another instructive example is found in the LHCb’s Vertex Locator (VELO) detector, in which the aluminium RF-box window is thinned down to 150 microns by caustic soda.

Frequently, chemical or electrochemical polishing are required in addition to cleaning. Polishing removes the damaged subsurface layer generated by lamination and machining – essentially a tangle of voids, excess dislocations and impurities. In this context, it is worth highlighting the surface treatments for RF acceleration cavities. Best practice dictates that materials for such applications – essentially niobium and copper – must undergo chemical and/or electrochemical polishing to remove a surface layer of 150 micron thickness. As such, the final state of the material’s topmost layer is flawless and without residual stress. (Note that while mechanical polishing can achieve lower roughness, it leaves behind underlayer defects and abrasive contaminations that are incompatible with the high-voltage operation of RF cavities.) A related example is the niobium RFD crab cavity for the HL-LHC project. This complex-shaped object is treated by a dedicated machine that can provide rotation while chemically polishing with a mixture of nitric, hydrofluoric and phosphoric acids. In

Successful cleaning requires the right choice of materials and production strategy

Pierre Mautin/CERN



Pierre Mautin/CERN

Bath time *The Building 107 team has extensive experience in the electroplating of large vacuum components and can plate with copper, silver, nickel, gold and rhodium. The laboratory also provides custom surface-treatment services for other big-science facilities, including the electroplating of the above component for the Drift Tube Linac tanks of the European Spallation Source (ESS).*

this chemical triple-whammy, the first acid oxidises niobium; the second fluorinates and "solubilises" the oxide; and the last acts as a buffer controlling the reaction rate.

The final set of treatments involves plating the component with a functional material. In outline, this process works by immersing the accelerator component (negatively biased) into an electrolytic solution containing the functional metal ions. The electrolytic solution is strongly acid or basic to ensure high electrical conductivity, with deposition occurring via reduction of the metallic ions on the component surface – all of which occurs in dedicated tanks where the solution is heated, agitated and monitored throughout.

At CERN, we have extensive experience in the electroplating of large components and can plate with copper, silver, nickel, gold and rhodium. Copper is by far the most common option and its thickness is frequently of the order of hundreds of microns (while gold and rhodium are rarely thicker than a few microns). Current capacity varies from 7 m-long pipes (around 10 cm diameter) to 3.5 m-long tanks (up to 0.8 m diameter). It is worth noting that these capabilities are also used to support other big-science facilities – including a recent implementation for the Drift Tube Linac tanks of the European Spallation Source (ESS) in Lund, Sweden.

Chemical innovation

Notwithstanding the day-to-day provision of a range of surface treatments, the Building 107 chemistry team is also tasked with driving process innovation. As safety is our priority, the main focus is on the replacement of toxic products with eco- and personnel-friendly chemicals. A key challenge in this regard is to substitute chromic acid and cyanate baths, and ideally limit the current extensive use of hydrofluoric acid – a development track inextricably linked to the commercialisation of new products and close cooperation with our partners in industry.

Elsewhere, the chemistry team has registered impressive progress on several fronts. There's the electroforming of tiny vacuum chambers for electron accelerators and RF cavities with seamless enclosure of flanges at the extremities. This R&D project is supported by CERN's knowledge transfer funds and has already been proposed for the prototyping of the vacuum chamber of the Swiss Light Source II. A parallel line of enquiry includes production of self-supported graphite films for electron strippers that increase the positive charge of ions in beams – with the films fabricated either by etching the metallic support or by electrochemical delamination (a technique already proposed for the production of graphene foils).

Another intriguing opportunity is the switch from wet to dry chemistry for certain niche applications

Another intriguing opportunity is the switch from wet to dry chemistry for certain niche applications. A case in point is the use of oxygen plasmas for surface cleaning – a technique hitherto largely confined to industry but with one notable exception in accelerator science. The beryllium central beam pipes of the four main LHC experiments, for example, were cleaned by oxygen plasma before non-evaporable-getter coating, removing carbon contamination without dislodging atoms of the hazardous metal. Following on from this successful use case, we are presently studying oxygen plasmas for *in situ* decontamination and cleaning of radioactive components, a priority task for the chemistry team as the HL-LHC era approaches.

The future of surface chemistry at CERN looks bright – and noticeably greener. The Building 107 team, for its part, remains focused on developing chemical surface treatments that are, first and foremost, safer and, in some cases, drier. ●

Further reading

C Pralavorio 2018 Building 107: a safe space for chemicals *CERN Bulletin* 13 February.

A Rao 2018 Honey, I shrunk the vacuum chambers! *CERN Bulletin* 2 May.

OPINION
INDUSTRY

Hyperloop: think big, win big

Leybold's Tom Kammermeier talks to Joe McEntee about the German manufacturer's long-range bet on hyperloop vacuum-based transportation systems.


Virgin Hyperloop

Going the distance *Leybold aims to establish itself as a key technology partner for the hyperloop development community and has supplied a large-scale vacuum pumping unit for Virgin Hyperloop's DevLoop test facility (above) in the Nevada desert.*

Tom Kammermeier is an industrial physicist in a hurry. Hardly surprising given that the commercial roadmap he's following points to a multibillion-dollar opportunity for vacuum equipment makers – an opportunity that, in turn, promises to transform ground-based mass-transportation of people and goods over the coming decades using energy-efficient hyperloop technologies.

Put simply: if technology hype translates into commercial reality, today's proof-of-principle hyperloop test facilities will, ultimately, scale up to enable the transit of passenger and freight capsules from A to B through steel tubes (roughly 4 m in diameter) maintained at partial vacuum (typically less than 1 mbar).

The end-game: journeys of several hundred kilometres at speeds in excess of 1000 km/h – Los Angeles to San Francisco, Mumbai to Chennai, Montreal to Toronto are just some of the high-demand routes on the drawing board – with maglev technologies teed up to provide the required propulsion, acceleration and deceleration along the way.

While the journey to commercial hyperloop deployment is only just beginning, a thriving and diverse innovation ecosystem is already hard at work, with heavily financed technology start-ups and dozens of academic groups and established manufacturers coalescing into a nascent hyperloop supply chain. As Leybold's global application development manager (industrial vacuum), Kammermeier is front-and-centre in the German manufacturer's efforts to establish itself as the "go-to" vacuum technology partner for the hyperloop development community. Here he talks to *CERN Courier* about the trade-offs, challenges and near-term benefits of playing the long game on technology strategy.

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How does your application development team support technical and commercial outcomes within Leybold?

I coordinate a team of 20 application specialists worldwide who handle what we call third-level product support – essentially any unique or non-standard technical requests that get referred to us by our regional sales and field engineering colleagues. In each case, we'll work closely with Leybold's product engineering and R&D teams to come up with solutions, ensuring that any new learning and insights are shared across the organisation through a structured programme of knowledge dissemination – online webinars, tutorial videos and the like. Our remit also includes the investigation and development of new vacuum applications. This work is informed by emerging customer needs in markets where Leybold already has an established presence – for example, surface coatings, semiconductors, solar technology and food and drink – as well as evaluation of longer-range commercial applications like hyperloop transportation.

What's the back-story to Leybold's engagement with the hyperloop community?

The hyperloop opportunity was initially championed at Leybold back in 2015 by my colleague Carl Brockmeyer, who at the time was head of new business development (and is now president of Leybold's scientific vacuum division). While Carl articulated the long-term commercial vision, my team focused on initial simulations and high-level requirements-gathering for the enabling vacuum technologies. At the outset, we worked closely with pioneering development companies such as Hyperloop Transportation Technologies (HTT) in the US and Virgin Hyperloop (US), while subsequent collaborations include TransPod (Canada) and the EuroTube Foundation (Switzerland).

I'm a physicist by training and, from the off, it was evident to me that there are no insurmountable technical barriers to hyperloop transportation. As such, it seems clear that the large-scale deployment of hyperloop systems will ultimately be driven by policy-makers and by commercial factors such as capital/operational costs versus return on investment.

Hyperloop represents a long-term commercial opportunity for Leybold. Are there any near-term upsides?

The calculus is simple: in the absence of volume orders, we invest time and resources in early-stage R&D collaborations with leading hyperloop companies in return for the publicity, benefits of association and the acquisition of technical and commercial domain knowledge. The work is bursty and comes in waves – essentially an R&D programme and reciprocal learning exercise at this stage. More widely, we're seeing some payback in our established market sectors, where the hyperloop activity has opened doors with new customers who might not know Leybold so well. What we see is that hyperloop is a great topic for our sales teams to talk about – it's very relatable.

Leybold GmbH

Tom Kammermeier *"If hyperloop transportation really takes off, it will represent a massive growth market for the vacuum industry."*

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What do these hyperloop collaborations typically involve?

Our approach is project-led, bringing together ad hoc teams of engineering, simulation and application specialists to address a range of customer requirements. Most of our collaborations to date have kicked off with simulation studies – a relatively cheap way to test the water and build a fundamental understanding of hyperloop vacuum systems and their core technologies.

It wasn't long, however, before our systems group began supplying one-off hardware orders, including a large-scale vacuum pumping unit for Virgin Hyperloop's DevLoop test facility in the Nevada desert. While this is a custom installation, it's based on existing commercial pumping units that we sell into steel degassing applications, though with several modifications to the programmable controller.

There's been lots of hype about hyperloop over the last five years. How do you see the market trajectory right now?

My take is that hyperloop R&D and commercialisation activities are gathering pace, as evidenced by the first successful demonstration of human travel in a hyperloop pod at Virgin Hyperloop's DevLoop test site back in October. This represents a significant breakthrough after more than 400 previously unoccupied test-runs at DevLoop. Elsewhere, we recently sold another big pumping system into HTT for its work-in-progress test-track near Toulouse, France. We're frequently in contact with them regarding simulation or engineering considerations, with safety-critical aspects very much to the fore as HTT also plans to transport human passengers in the near future.

What sort of technical challenges is Leybold being asked to address by hyperloop developers?

Pumping down a hyperloop vacuum tube over hundreds of kilometres is a non-trivial engineering challenge. From a vacuum perspective, you need to think carefully about the spacing of your pumping stations along the tube; optimisation of each pumping system; what happens in case of tube failures or accidents; and how the distributed pumping network can provide back-up pumping capacity and compensation (see "Hyperloop: rewriting the rules of large-scale vacuum", p38).

What lessons have you learned from Leybold's engagement with the hyperloop community?

A lot of the learning here has been around the simulation of large-scale distributed vacuum systems – because no-one has ever built a vacuum system on the scale necessary to support commercial hyperloop transportation. We've had plenty of discussions to date regarding our models and whether they're still valid over distances of several hundred kilometres, while our ▷

Hyperloop: rewriting the rules of large-scale vacuum

Leybold GmbH/Virgin Hyperloop

Big vacuum *Leybold is working to optimise its custom pumping systems (shown above) for the very long pump-downs (between 12–24 hours) that will be required in large-scale hyperloop tubes.*

"Pumping down a hyperloop vacuum tube over hundreds of kilometres is a non-trivial engineering challenge," notes Leybold's Tom Kammermeier in our accompanying interview. Here he outlines some of the key design and engineering considerations for hyperloop vacuum systems.

Location, location, location

The aspect ratio (diameter/length) of a hyperloop system is enormous – 1/1000,000 is easily within reach – and imposes inescapable design constraints in terms of vacuum pumping capability. A single-site pumping station, while minimising capital outlay, would result in some odd pressure distributions and gradients along the hyperloop track. During pump-down, for example, the operator might register the target base pressure at one end of the pipe while the other end is still at atmospheric pressure. What's needed instead is an intelligent distribution of pumping capacity along the track – crucial for compensation of any leaks and pump failures, and doubly so in terms of reducing capital/operational expenditure (as every additional pumping site means more outlay in terms of enclosures, power supply, water supply and associated infrastructure).

Smart strategies for leak management

A vacuum system can be defined along a number of coordinates, not least in terms of its pump-down requirements and target operating pressure (where the total pumping speed equals the inleak flow rate). The higher the permissible operating pressure, the lower the pumping speed, and the greater the aggregate energy savings over time. A large-scale hyperloop system will therefore require a smart pumping network to optimise the distribution of pumping speed dynamically versus local inleak flow conditions – a capability that, in turn, will yield significant (and recurring) operational savings. It's also worth noting that an understanding of the pumping-speed distribution (essentially a granular map of pressure along the tube) will enable efficient leak detection without recourse to a conventional and time-consuming leak search.

Gearing up, pumping down

Peak energy consumption for any hyperloop vacuum system will occur during end-to-end pump-down along the track. With this in mind, Leybold is working to optimise its multistage Roots pumping systems for the very long pump-downs (of the order of 12–24 hours) that will be required in large-scale hyperloop tubes. Roots pumps are an excellent option for high-volume flows at low pressures – i.e. the usual operating regime of hyperloop systems – but their efficient use for an extended pump-down from atmospheric pressure is problematic. Issues can include overheating due to gas compression; overload of the motor; or exceeding temperature limits due to low heat dissipation at low gas pressures. The answer is to employ variable-speed drives, which basically "know" the thermodynamics of each individual pump and enable optimised use. In this way, the programmable logic controller of the pumping system is able to orchestrate the individual pumps to yield the highest possible pumping speed during a pump-down – equating to some millions of m^3/h for a 1000 km track.

technology roadmap focuses on what an optimised pumping system will look like for future "live" hyperloop deployments. To date, because the market is still not mature enough, we've created smart hyperloop pumping systems by adapting our existing product lines – specifically, units that we've developed for steel-industry applications.

Is cost a big driver of your hyperloop R&D priorities?

Always. Cost-of-ownership calculations feature prominently in discussions with all our hyperloop customers. We've given a lot of input, for example, on required pumping speed versus leak flow rate versus operating pressure. Fundamental studies like this help our partners to evaluate whether it's worth focusing more of their investments on a leak-tight pipe or on the vacuum pumping systems. Another priority for developers is energy consumption, so our system-level simulations provide vital insights for the accurate calculation of pump-down time and vacuum performance versus energy budget. In this context, it's worth noting that Leybold's DRYVAC Energy Saver – which reduces the energy consumption of our dry compressing screw pumps and systems by as much as 50% – is emerging as a potential game-changer for the large-scale pumping systems that will underpin hyperloop installations.

Are vacuum equipment makers ready if hyperloop's technology push translates into market pull?

If hyperloop transportation really takes off, it will represent a massive growth market for the vacuum industry. Even a mid-size hyperloop project will require significant focus and scale-up from suppliers like Leybold. The biggest challenge will be developing, then bringing to market, a new generation of application-specific pumping systems – at the required scale and the right price-points. ●

THE AUTHOR

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