Vacuum technology challenges: **Radiation-resistant pumps for spallation sources**

A new generation of neutron sources is making it possible to explore the structure and properties of materials; ranging from biomolecules to superconductors. The most recent spallation sources built in the United States, Japan, and China are currently the most powerful neutron sources in the world. However, the European Spallation Source (ESS) is under construction in Lund, Sweden, which will set even higher standards when the facility goes into operation in 2027.

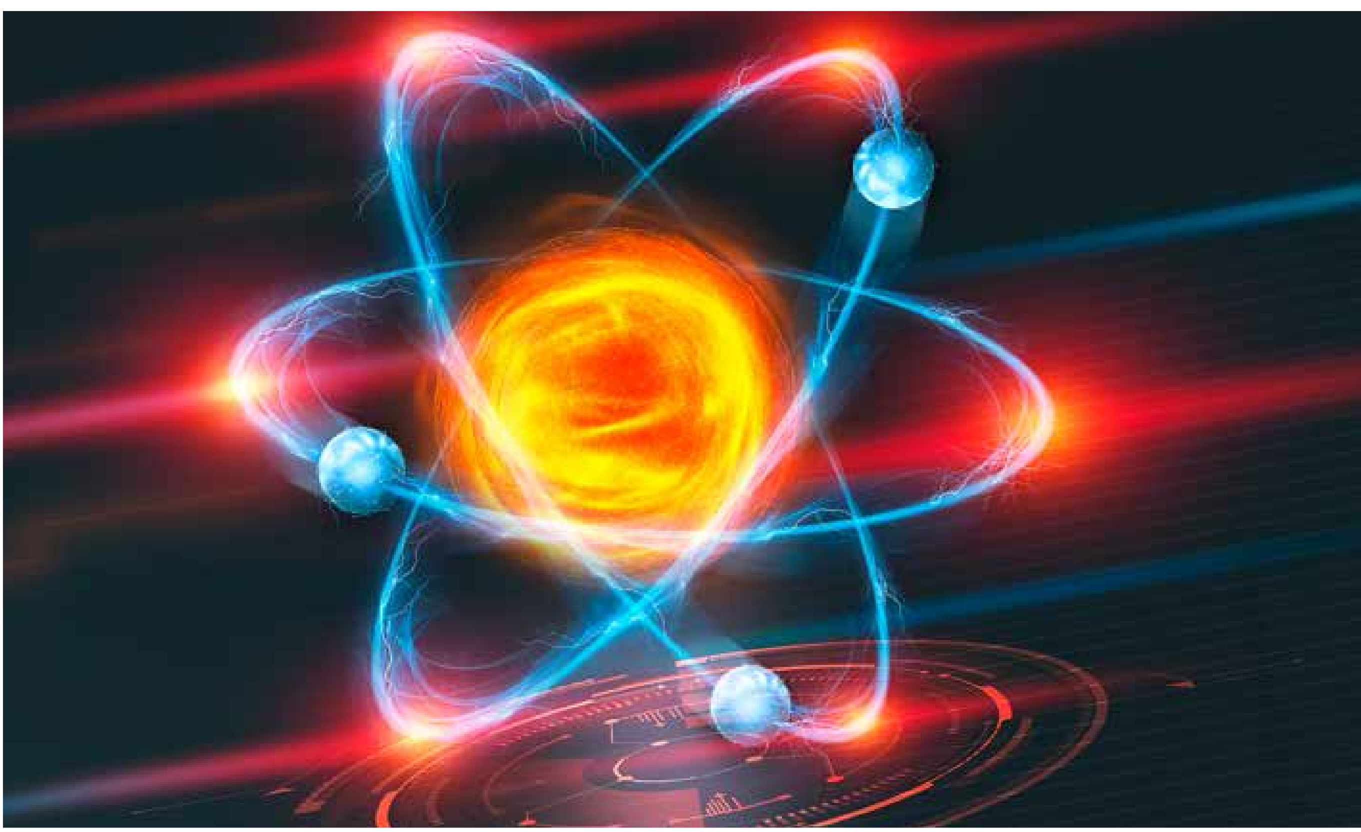

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Figure 1: Aerial view of the European Spallation Source (ESS) in Lund, Sweden. (Image: Perry Nordeng/ESS)

These powerful new instruments also pose a challenge to the engineering systems needed to support them. The spallation process add if you need an explainer: where neutrons are released from the tungsten nuclei by being impacted by pulses of neutrons generate radiation, which is challenging for critical infrastructure such as the vacuum systems. The latter are used to maintain the ultra-high vacuum in the accelerator and experimental facilities. Pfeiffer Vacuum works closely with users to develop customized vacuum solutions for the novel spallation sources. However, problems can arise with both the electronic systems used to control vacuum pumps, measurement instruments, and the materials used in their manufacture.

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Understanding materials using neutrons

Neutrons are widely used to study material properties because they can penetrate deep into the sample. In doing so, they bring information on atomic level, generating data to determine the exact structure within the material. In addition, neutrons have the appropriate wavelength to transfer their momentum and energy to particles in the sample. This provides valuable information about lattice vibrations in the solid. Moreover, neutrons are characterized by a nuclear spin that makes them extremely sensitive to the position and orientation of magnetic moments in materials.

While neutron sources have now been around for many years, the new generation of spallation sources can produce neutron beams that are much stronger than previous beams produced using nuclear reactors. This allows experiments to be accelerated, enabling scientists to study materials and their interactions in greater detail than ever before.

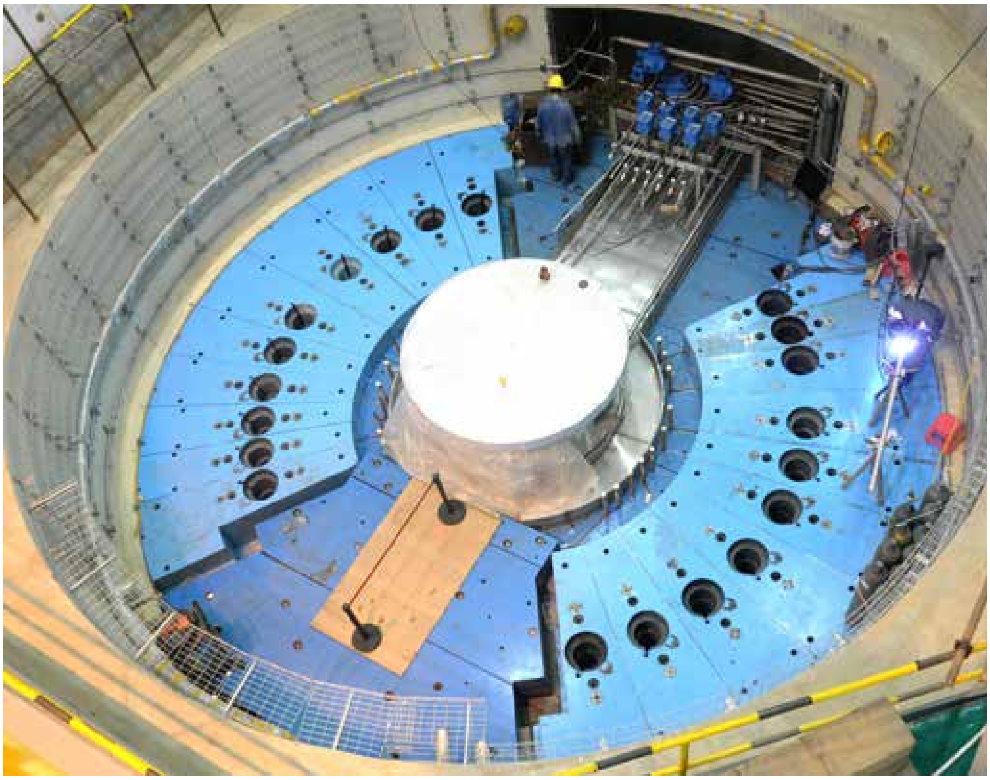

Figure 2: The tungsten target of the China Spallation Neutron Source (CSNS) at the Institute of High Energy Physics (IHEP) in Beijing is installed as a monolith. (Image: IHEP)

The most powerful reactor-based neutron source available today is located at the Institut Laue-Langevin in Grenoble, France. It achieves a flux of $1.5 \cdot 10^{15}$ neutrons per second and square centimeter at a thermal power of 58 megawatts. For comparison, the most powerful reactor units used for energy provide thermal power around 4 megawatts. The European Spallation Source, when completed in 2027, will have 10^{18} neutrons per second and square centimeter by firing a high-energy proton beam at a fixed target of tungsten. This proton bombardment releases neutrons, which are then slowed down and bundled into a neutron beam. This is available in pulsed form for experiments using neutron scattering. Other spallation sources operate on a similar principle, but may use different methods of acceleration and different target types. In this case, heavy hielding is are capable of absorbing radioactive nuclear species produced during the spallation process.

However, radiation poses an even greater problem for the high-power neutron sources. At the Japan Proton Accelerator Research Complex (J-PARC) – the world's most powerful neutron source currently in operation – radiation levels in the immediate vicinity of the neutron beam can reach millions of grays.

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Two major problems arise from such high levels of ionizing radiation for the vacuum pumps and measurement instruments located near the neutron source. First, electronic systems cannot be connected directly to vacuum pumps or measuring instruments because they would fail and stop operating due to the radiation. Also, it must be considered whether certain materials, such as Teflon, should be avoided in the pump design because they are affected by high radiation.

The importance of radiation resistance

For electronics, the solution is to place them at a great distance from the pumps. For example, at the China Neutron Spallation Source – which began operating in February 2020 with a 100 W beam – some of the vacuum gauges are connected to their controls by cables up to 220 meters long. Vacuum generation is just as important, so turbopumps as well as fore-vacuum pumps must be designed to be radiation resistant.

Operating the pumps over long cables is a major challenge because the line resistance is significant. Long cable solutions (up to 1000 m) for turbopumps have been available for some time, but these have had to be newly developed for dry backing pumps. Due to their higher electrical power compared to turbopumps, the cable lengths and line diameters between backing pumps and power electronics have to be adapted accordingly.

Meanwhile, the effects of ionizing radiation on certain materials may also require a completely new approach to pump design.

In the case of J-PARC, the project team was concerned that the Teflon used in the dry-running backing pumps would become more brittle under the influence of the radiation.

The solution was to select an oil-free backing pump design in the form of the multistage Roots pump. Multistage Roots pumps do not require any sealing material and therefore no Teflon. They are up to a six-stage combination of Roots blowers that can compress the gas from fine vacuum pressure to atmospheric pressure. The frictionless operation of the pump also avoids wear and reduces the need for maintenance, which is particularly practical with Teflon-free pumps.

J-PARC was the first neutron research facility to use a multistage Roots pump in the initial pump-down phase. Subsequently, Pfeiffer Vacuum has developed a new model in which other spallation sources such as the ESS, can withstand high levels of radiation.

Solution approach of the European Spallation Source

For the equipment at ESS, the powerful accelerator and the higher neutron flux mean that radiation is even more problematic. The project team had concerns not only about the backing pump, but also about the small amounts of Teflon in the turbopumps. For example, one turbopump contains an electric motor that is insulated with Teflon. Damage to the insulation could lead to an electrical short circuit, which would interrupt the operation of the pump and thus also the course of the experiment.

Figure 3: The HiPace turbomolecular pump series has been adapted for use on the ESS.

On a turbopump, it is virtually impossible to do without all Teflon, but could be feasible in some places. For this reason, constant and very intensive communication with the people responsible for the project at the plant is a top priority for Pfeiffer Vacuum.

Only through close contact and ongoing discussions between Pfeiffer Vacuum and the project manager is it possible to analyze the various materials in the pump and tailor them to the customer's needs. In some cases, a lack of alternatives complicates the process. In such cases, a holistic approach is necessary, and it means finding an alternative way for the customer's application with a combination of dry backing pumps and turbopumps. This way, the best result can be achieved with coordination in the overall system.

Based on experience with similar applications, Pfeiffer Vacuum began discussions with the project managers at ESS at a very early stage of the project. That way any necessary adjustments can still be made to the product before it is deployed.

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https://j-parc.jp/c/en/facilities/index.html
http://english.ihep.cas.cn/csns

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