Commissioning of large vacuum systems

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Abstract
This paper will give an overview of the various steps of the commissioning of large vacuum systems for accelerators. Following some introductory remarks, the pump-down, leak check, bake-out as well as component, interlock, and safety checks will be covered in detail. Special emphasis will be given to beam vacuum systems in combination with cryogenic systems. Finally, the transition from the commissioning phase to beam operation will be treated. Practical examples will illustrate most of the topics.

1 Introduction

Once the manufacture and testing of all individual components of a complex system are successfully finished and the installation comes to completion, the last step before starting the routine operation is the system commissioning. During the commissioning phase it should be shown that the required performance is accessible with the installed equipment and that the system meets the needs and expectations of the user. The commissioning phase should also be used to prepare a system for standard operation with respect to functionality, safety, and remote operation. If necessary, additional equipment could be installed, and integrations, modifications, or extensions of control parameters, for example, could be performed.

Today's high-energy accelerators such as the 6.3 km long proton–electron collider HERA at DESY [1–3] or the 27 km long electron–positron collider LEP at CERN [4] (now dismantled) certainly contain large vacuum systems; the latter having about 1900 sputter ion pumps, 700 gauges, 2700 feedthroughs, 2200 pick-up connections, 130 sector and 520 roughing valves as well as 13 000 LEP-type flange pairs. However, systems are considered to be large not only due to their length or number of components, but also due to their complexity like the vacuum system of the 200 m long superconducting linear accelerator FLASH at DESY [5] containing various alternating sections operated at room temperature and 4 K, and an extremely large number of diagnostic elements.

For an accelerator vacuum system the required beam vacuum levels as well as beam pipe aperture, choice of material, RF shielding etc. are defined and strongly influenced by the beam parameters aimed for such as beam intensity, beam lifetime and beam stability. Thus during the commissioning phase the vacuum systems performance should be verified with respect to pressure, residual gas composition, outgassing rate, pump down and/or conditioning time, etc.

In order to carry out a 'smooth' commissioning the following premises should be fulfilled:

– a proper planning with respect to the overall system design, choice of materials, manufacturing techniques and vacuum equipment as well as specifications and vacuum controls;

– a thorough quality control during design and manufacture of components, handling procedures, cleaning, testing and installation;

– the availability of a continuous monitoring and data logging system.

2 Pump-down and leak check

Following the installation of the vacuum components into an accelerator, the next important step is the pump-down of the vacuum sections. In general, mobile pump stations are temporarily connected to a sector for this purpose. Before starting the pump-down, the proper attachment of the components should be carefully checked, especially for bellows. Vacuum forces can easily shift poorly fixed components and even damage them. Once the pressure is sufficiently reduced, the permanently attached high-vacuum pumps can be started.

Observing and recording the pressure during pump-down allows experienced staff a first analysis of the system’s behaviour. Any deviation from a usual pump-down curve is a hint of a possible leak as described in more detail in Ref. [6]. In case of such an indication, further checks using a residual gas analyser or the pressure rise method might be useful before starting a proper leak check.

As the initial pump-down of an accelerator vacuum section often takes a while, the leak check is usually done in several steps starting with a gross check at a pressure below 10^{-4} mbar followed by another check at a pressure value below 10^{-6} mbar. Systematic work is necessary so as not to forget any of the numerous flanged connections, ceramics, feedthroughs, windows etc. For leak detection either a residual gas analyser or a leak detector connected to a mobile pump station could be used. Although sputter ion pumps are normally switched on as soon as possible during pump-down to accelerate the decrease in pressure, they should be switched off during leak check so as not to reduce the helium flow to the leak detection cell and even more important to avoid spoiling the sputter ion pumps with helium in case of a leak.

The activation of further pumps like titanium sublimation or non-evaporable getter (NEG) pumps requires sufficiently long pumping times in the order of days or even weeks for NEG pumps. Practical examples are shown in Fig. 1 clearly indicating a significant pressure drop after the pump’s activation. A careful observation of the pressure behaviour should be continued and a leak check added if necessary. Finally the gas composition should be measured using a residual gas analyser.

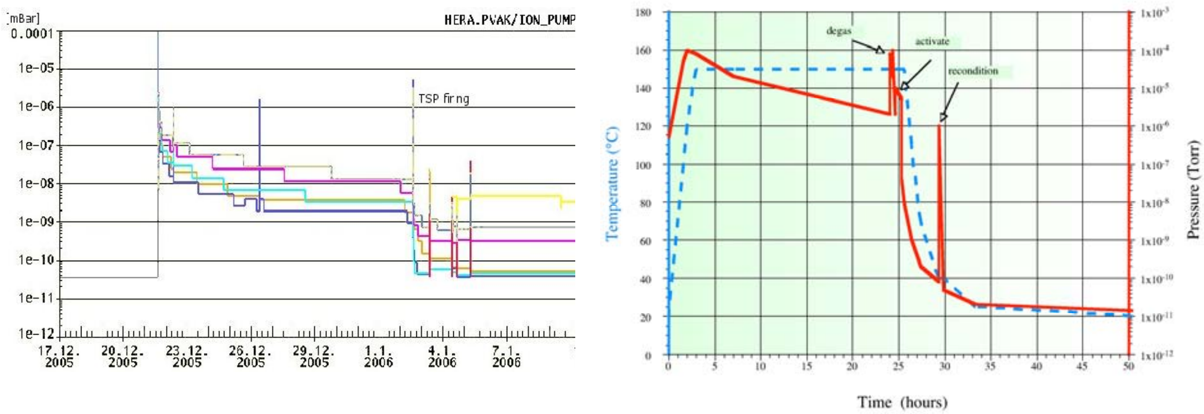

Fig. 1: Pressure drop due to activation of titanium sublimation pumps (left) and NEG pumps [7] (right)

3 Bake-out

The bake-out of a vacuum system to temperatures of typically 150–300°C is a delicate procedure requiring careful planning and execution. A lot of additional equipment such as heaters, thermocouples, insulating material, cabling etc. is necessary. The preparation should include thorough checks of the individual components and their functionality as well as of the heating process and interlocks in case of power failure, failure of the equipment, or unexpected pressure rise.

During bake-out large temperature gradients should be avoided and the movement of components due to the heating checked. Temperature-critical components such as magnets or monitors must be protected by sufficient insulation or active cooling. Figure 2 shows an example of the temperature versus time for a vacuum chamber inside a quadrupole magnet during a bake-out of the HERA proton ring [8].

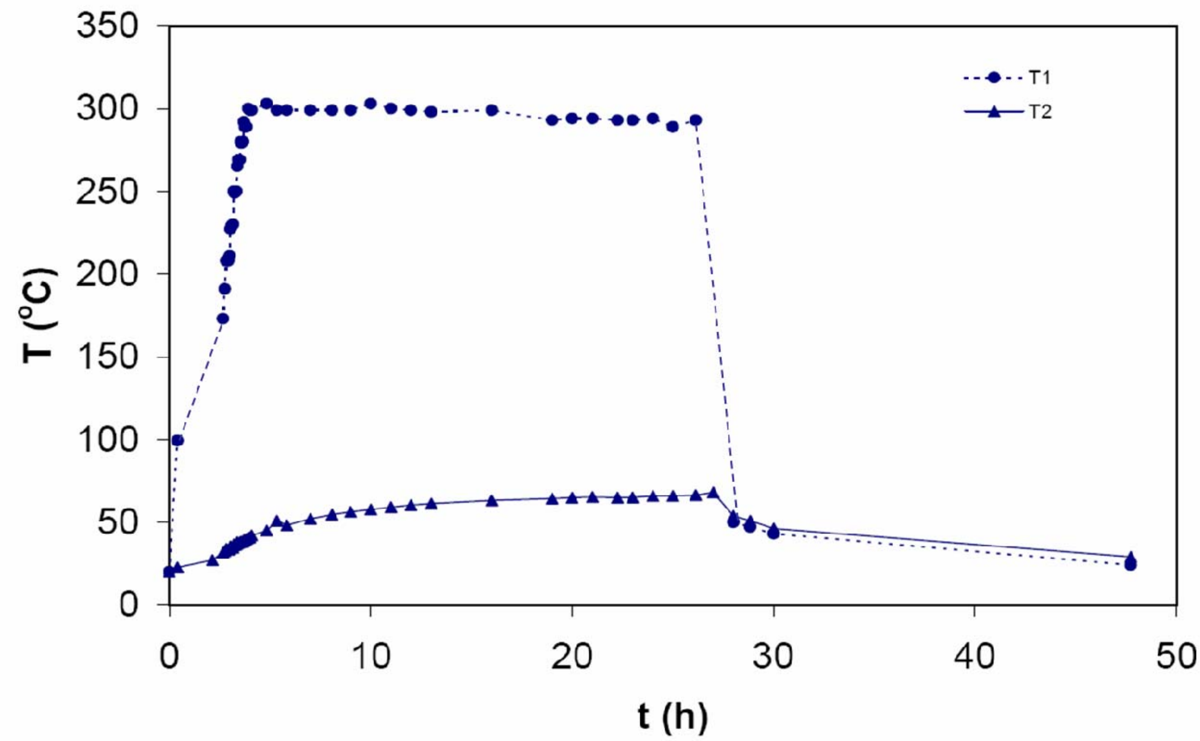

Fig. 2: Temperature versus time of a vacuum chamber (●) and a magnet coil of a quadrupole magnet (▲) during a bake-out cycle of the HERA proton ring [8]

4 Components check

An important task of a systems commissioning is the check-out of the components. This includes checking the correct allocation of the vacuum equipment, cables and corresponding electronics as well as testing the functionality of pumps, gauges, valves, etc.

Following the more hardware-oriented work the vacuum controls need to be checked as well. This should include verifying the correct display of the vacuum components within the various vacuum and accelerator control programs, checking the remote operation of components, and testing the functionality of the control programs. Wherever necessary, handling options should be improved or added and additional parameters be integrated.

The check-out of the vacuum system should also include components of other subsystems and special equipment of experiments such as gas inlet systems, which are installed in the vacuum system. For example, the correct path length and proper functioning of end switches of movable elements like collimators and diagnostic units as well as their remote operation should be tested. Pressure increases during initial movements of such elements are not exceptional and should be observed carefully.

5 Interlock and safety checks

In order to protect the vacuum system against severe damage in case of failure of vacuum components or other subsystems, a proper interlock system is an essential part of the vacuum system and thus requires a thorough testing of the various interlock conditions. In general the operation of the vacuum system should be designed in a self-safe way such that failing of equipment like pumps or pressure gauges will not require manual operations to avoid damage of the system. Failing of single components like gauges or pumps should not affect the proper functioning of the overall system and thus the beam operation of an accelerator.

Testing the foreseen vacuum interlock conditions and reactions of the system is an essential step towards a safe system operation. Adequate tools for the check-out like complete accessibility to the status and timing information will ease this important step. Examples are checking the proper closing of gate valves or fast shutters in case of significant pressure increases or failure of certain pieces of equipment like pumps or gauges being part of the interlock signal chain, as well as switching off equipment under certain circumstances. In addition interlock conditions allowing or stopping beam operation as well as allowing different modes of beam operation need to be carefully tested. Last but not least there are usually interlocks connected to other subsystems like diagnostic units or experiments.

The final tests of interlock systems require the completeness and correct conditions of the systems to be tested. On the other hand, the time available before the start of beam operation is often substantially reduced due to major shifts within the installation schedule. Nevertheless, taking the required testing time for the vacuum system will finally pay off with respect to proper functionality and reliability during beam commissioning and routine operation.

6 Vacuum systems in cryogenic environments

In this section special emphasis will be given to the commissioning of vacuum systems in combination with cryogenic applications. Such systems are generally complex arrangements requiring substantially more effort and time for the commissioning phase. In addition to the beam vacuum system a second vacuum system is required as insulation of the cold components against the ambient air. Although the required pressure level within an insulating vacuum system is moderate—typical pressure values are around 10^{-3} mbar before cool down—such systems comprise rather large volumes containing huge numbers of components. In the following some examples of cryogenic applications at accelerators will be given and the typical commissioning procedures for the beam and insulating vacuum system described in detail.

The most prominent accelerator application of cryogenic systems is the use of superconducting magnets as in several of today’s high-energy proton or heavy-ion storage rings like the TeVatron (Fermilab), HERA (DESY), RHIC (Brookhaven) and the LHC (CERN). The iron yoke of the magnets is directly assembled onto the beam tube. When filling the housing of the magnets with liquid helium for cooling, part of the beam pipe is also directly surrounded by liquid helium and thus cooled to temperatures around 4 K. In this way the beam pipe itself will act as a huge cryo pump. Long chains of magnets and interconnecting elements are inserted into large vacuum vessels which are connected and evacuated for insulation.

Another application requiring cryogenic systems is the operation of superconducting accelerating structures, so-called cavities. Here the superconducting cavity itself, surrounded by liquid helium, forms the beam pipe. During recent years the interest in this technology has greatly increased on account of the huge progress in performance reached with the TESLA technology [9]. Figure 3 shows schematically the layout of the TESLA vacuum vessel containing the superconducting cavities and all necessary cryogenic supply lines. Superconducting cavities are currently in use on a larger scale, for example, at the accelerators TRISTAN at KEK, CEBAF at Jefferson Lab and FLASH at DESY and were applied at the now dismantled LEP ring at CERN.

Other cryogenic applications include superconducting wigglers as insertion devices at synchrotron radiation sources and special superconducting magnets within experimental set-ups.

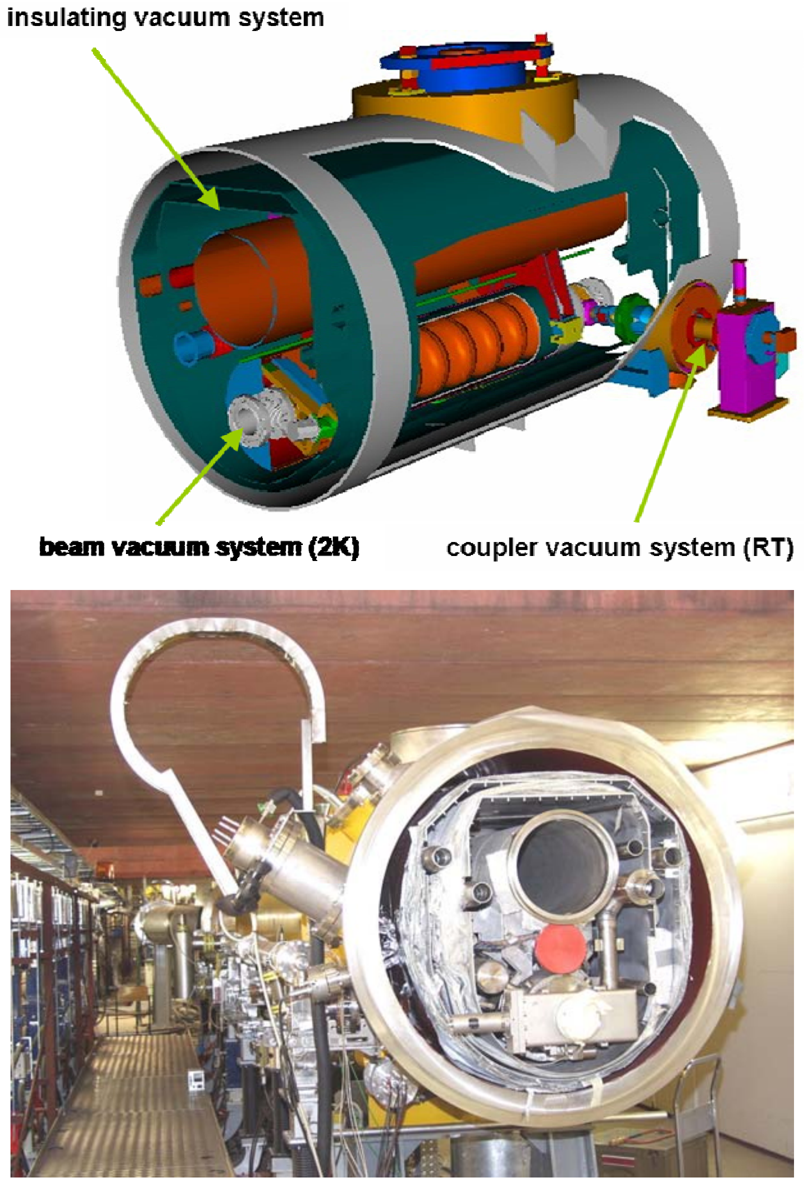

Fig. 3: TESLA vacuum vessel containing the superconducting cavities and all necessary cryogenic supply lines as used at the FLASH linear accelerator at DESY [9]

6.1 Cold beam vacuum systems

Following the installation of the beam line vacuum components a leak check of the final connections like flanges and *in situ* welds is mandatory. One has to keep in mind that a local leak check once the insulating vacuum vessel is closed and thus under cold conditions will not be possible. Therefore the final checks need to be taken with extreme care by applying integral leak tests, for example. In addition a careful and systematic pre-checking of the components is necessary.

Before starting to cool down the beam pipe, sufficiently stable pressure conditions should be reached. The pressure level depends on the specific system. For example at HERA [1] one requires a pressure of 10^{-6} mbar using sputter ion pumps, while at RHIC there is no active pumping of the beam pipe after pump-down by mobile pump stations to a value of 10^{-4} mbar [10]. During cool-down to final temperatures below 4.5 K, the pressure will drop significantly once the beam pipe starts to act as a huge cryo pump as shown in Fig. 4.

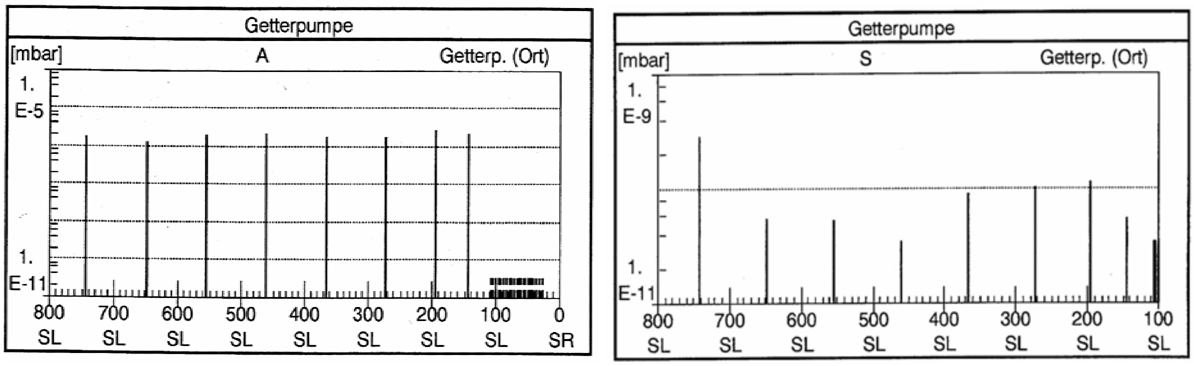

Fig. 4: Pressure distribution within the beam pipe section SL of the HERA proton ring before (left) and after (right) cool down to 4.5 K. The pressure scale in the right plot is enlarged [11].

Once the system has been exposed to very low temperatures and partially to liquid helium for some time, the integral leak rate as well as the wall coverage could be measured. Therefore the system needs to be warmed up to sufficiently high temperature such that the accumulated gas will be released and could be measured using a residual gas analyser as described in more detail in Ref. [6].

6.2 Insulating vacuum systems

The application of large numbers of superconducting magnets or cavities in accelerators results in rather large insulating vacuum systems up to several kilometres in length. A proper segmentation of such systems is necessary for commissioning as well as for reliable operation in case of failure of equipment and leaks. Technically the segmentation is realized by massive barriers and bypass lines with sufficient conductance for pumping, which can be closed off by valves. The distance of such barriers within the insulating vacuum system has increased with time. While at HERA a very conservative distance of 20 m was chosen, this number was increased to 500 m at RHIC and 200 m at the LHC. Major benefits of the enlarged distances are financial and reduced heat load, however, one has to face an increased complexity for the commissioning phase, especially for leak checking.

Before pumping down the insulating vacuum, the connections of the process lines, usually *in situ* welded joints should be leak checked. Therefore the lines could be pumped out and sprayed with helium gas. Alternatively they are pressurized and the leak check is done using a sniffer or a vacuum-jacketed fixture. While the last method results in a much better sensitivity, one has to invest a significant effort for assembly and pump-out of the fixtures at the numerous joints. At RHIC, for example, there are about 25 000 *in situ* helium line welds [10].

The initial pump-down of such large insulating vacuum systems is usually very slow. The gas load is dominated by huge amounts of water from the superinsulating foils. Sufficient mobile equipment must be added to the permanently installed pump stations starting initially with large, if necessary, roughing pumps. Operating the roughing pumps under air ballast and, if necessary, flushing the system with nitrogen will assist the process. In addition one should be prepared for frequent maintenance of the roughing pumps.

The leak check for air leaks should start as early as possible. A full leak check of a section is often an iterative process. Initially, large leaks are not exceptional and often prevent the detection of smaller leaks at high pressure levels. Thus one needs to repair large leaks first and repeat the complete leak check of the section thereafter. Owing to the size of the systems and the number of connections, sufficient granularity of the leak detection equipment is of utmost important. Vacuum gauges could complement mobile leak detectors and/or leak detection cells attached to the mobile pump stations. The base pressure is usually not sufficient for the use of residual gas analysers directly attached to the insulating vacuum vessels. An example of a pump-down curve of a section of the RHIC insulating vacuum system including venting to repair air and helium leaks is shown in Fig. 5 (left) [10]. Without major air leaks a pressure of 10^{-2} mbar is reached within a few days.

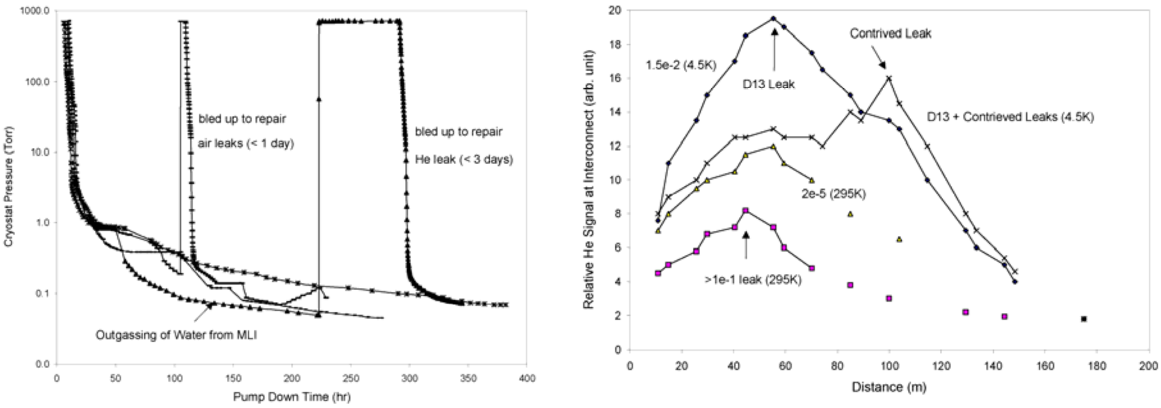

Fig. 5: Pump-down curve of the RHIC 494 m arc cryostats (left) and distribution of the helium signal at the various detectors in case of a leak in a process line interconnection (right) [10]

One should be aware that both the dead time of the leak detection system and the helium background within the tunnel may be significant, the latter due to leaks of the cryogenic helium supply lines within the tunnel. This could reduce the sensitivity of the leak detectors by helium penetrating through the exhaust of the roughing pumps or giving false signals when permanently entering through leaks. In extreme cases different tracer gases should be used. Owing to the moderate pressure requirements for the insulating vacuum, O-rings are often used as gaskets. In contrast to metal seals the permeation of especially light gases from the outside, e.g., helium sprayed during the leak check, is not negligible and finally determines the detection limit for leaks. As the permeation takes some time, sufficient experience is required to distinguish leaks from helium signals due to permeation.

Following the search for air leaks, the process lines need to be checked. Usually the same equipment is used as before, however, one should make sure that the pump system disposes of sufficient helium compression such that in case of leaks from the supply lines into the insulating vacuum the helium is efficiently removed. With the insulating vacuum well evacuated all process lines are pumped out. After checking the background level of the detectors, one process line after the other is pressurized with several bars of preferably helium gas. In this way an integral leak rate of each line within the insulating vacuum will be measured.

Once a leak in a process line has been detected, finding its location will be the more difficult task. With sufficient diagnostics available, the profile of the helium signal within the various detectors should clearly indicate the area of the leak as shown in the example of Fig. 5 (right) [10]. After venting the insulating vacuum, the corresponding sliding sleeve of the vacuum vessel needs to be opened and the leak check of the joints of the pressurized process line continued. Diagnostics could be done by a sniffer or a vacuum-jacketed fixture as described above. In any case, locating and repairing leaks in the process lines is a difficult and time-consuming task requiring lots of experience and sometimes innovative approaches.

The last step of the insulating vacuum systems commissioning is the cool-down. The pressure of the insulating vacuum will significantly drop once substantial surfaces are well below 0°C and thus act as very efficient pumps for water. Typical pressure values are 10^{-3} mbar before and 10^{-6} mbar or below after cool-down for routine operation. Once the pressure has stabilized, part of the mobile pump stations from the pump-down can be removed.

During the cool-down one should check for spots with condensation and/or freezing of water due to thermal bridges. The helium signal should be continuously monitored as additional leaks in the process lines might open up during this phase. Usually one has to live with such leaks at least till the next warm-up of the system, when the leak will eventually be localized and repaired. However, not all leaks can be localized or repaired, some cold leaks even disappear once the system gets warmed-up. Depending on the size of the leak, additional pumping equipment might be added in order to keep the pressure within an acceptable level. An example from HERA is shown in Fig. 6 [12]. Permanent air leaks at the flanges of the insulating tank might be sealed off by using glue or rubber mastic.

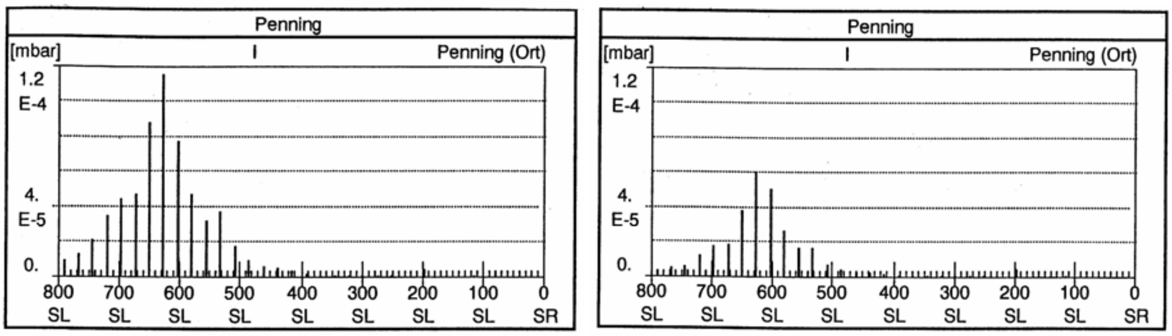

Fig. 6: HERA SL section having a large leak from the helium supply lines into the insulating vacuum: pressure distribution with normal distribution of pumping stations (left) and an additional pumping station (right) [12]

The beam vacuum should be observed frequently during commissioning of the insulating vacuum, e.g., during leak check of the process lines and during cool-down. Direct leaks from the (liquid) helium at the superconducting magnets or cavities or even combined leaks from the process lines through the insulating vacuum into the beam vacuum could be observed. Therefore it is advantageous to supply sufficient pumping speed for helium at the beam vacuum by sputter ion pumps with enhanced helium pumping speed or charcoal, for example. One should be aware that in the case of a cold beam tube, helium leaks might not been seen immediately as the helium will be partially pumped by the cold surfaces and thus a helium front will propagate through the beam tube.

7 First beam operation

Having successfully finished the previous steps the vacuum system should be well prepared for the first passage of beam particles. There are many possible reasons why the operators are not able to fill particles into the accelerator. Prominent ones are of course closed vacuum valves or obstacles in the path of the beam, e.g., RF fingers. But there are many more reasons like malfunctioning magnets, etc.

Once a significant amount of beam is filled, the behaviour of the vacuum pressure should be carefully monitored. Noticeable changes in the pressure should be well understood. In the presence of substantial synchrotron radiation a significant pressure increase might be expected initially due to the photon-induced desorption of gas molecules from the surfaces. The rise of the dynamic pressure depends on the accumulated photon dose. Thus operating the accelerator with beam will condition the vacuum pressure by cleaning the surfaces by photon bombardment. An example for the decrease of the normalized dynamic pressure with beam dose is shown in Fig. 7 for the conditioning of the LEP vacuum system [13]. However, a pressure rise could also be due to other reasons like heating of components due to insufficient cooling or RF shielding, or beam–gas effects.

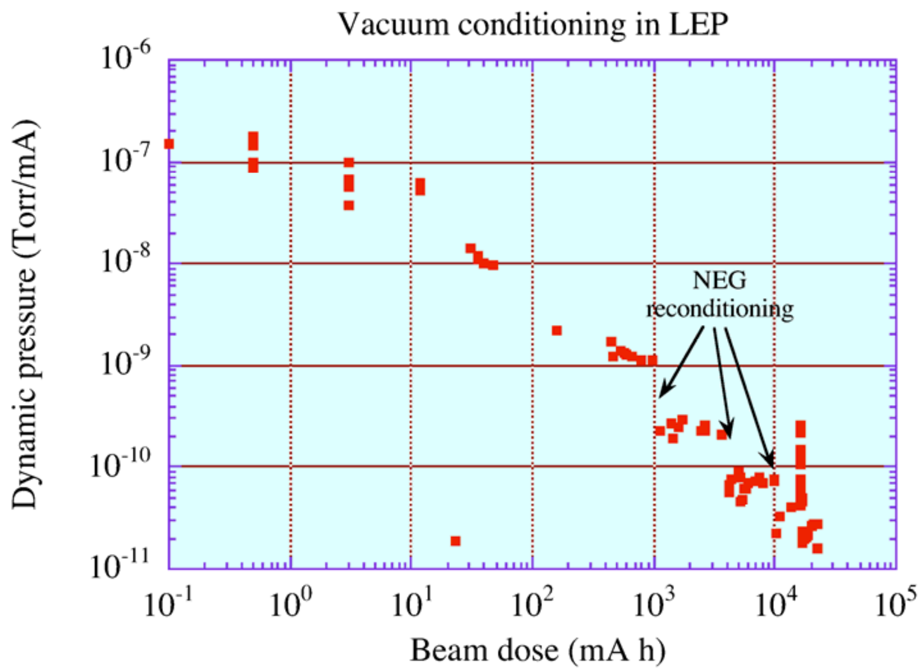

Fig. 7: Conditioning of the LEP vacuum system resulting in a decrease of the normalized dynamic pressure with accumulated beam dose [13]

8 Concluding remarks

The commissioning of accelerator vacuum systems should be the (final) proof of the correct layout, design, manufacture, and installation of the system. Owing to the complexity of the systems and the care required it should be clear that, in addition to well-trained and experienced personnel, sufficient time for the various tests of the systems is also necessary. As the installation of the vacuum system is one of the final steps of an accelerator installation, the available time slot is often reduced owing to delays in preceding steps. Since one is under time pressure, one should keep in mind that the commissioning phase is an essential part of the overall work package of delivering a subsystem of an accelerator. The foreseen checks and tests are an important basis for a reliable performance of the vacuum system during beam operation.

A proper planning of the commissioning phase is thus an integral part of the vacuum system planning. In the case of cryogenic applications, in particular one should be aware that locating and repairing helium leaks in the insulating vacuum systems will be a difficult and time-consuming task. Commissioning parts of the systems as early as possible will be advantageous in order to apply modifications to the remaining parts of the system when necessary.

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