Failure Analysis of the Beam Vacuum in the Superconducting Cavities of the TESLA Main Linear Accelerator

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Abstract

For the long term successful operation of the superconducting TESLA accelerator it is essential to avoid any accidental contamination of the accelerating cavities. We discuss several failure scenarios of the beam vacuum system that could potentially result in such contaminations. The risk of individual failure situations is evaluated as well as preventive measures to avoid them.

1 Introduction

The beam vacuum system of the TESLA main linear accelerators contains about 20.000 superconducting cavities. In order to operate these cavities at high gradient and high quality factor Q perfect cleaning of the inner cavity surface is of utmost importance. To minimize the risk of particle contamination the inner surfaces of all other components of the beam vacuum system are carefully cleaned as well. In case of an accidental venting of the beam vacuum, the main concern is that dust particles get into cavities preventing further operation at high gradients. This might happen even at locations far away from the original gas entry.

Therefore a thorough analysis of possible sources of errors and adequate measures to avoid such incidents is of great importance. In the following a short description of the beam vacuum system of the TESLA linacs is given. Various scenarios which could lead to a vacuum accident are described in detail. This includes beam induced events, breaking of a ceramic window of the input coupler, failure of other equipment and the human factor. Measures to avoid such incidents including a beam interlock system as well as possible consequences to improve the present layout are described as well.

2 Beam vacuum system of the TESLA main linacs

The beam tube of the main linacs mainly consists of the superconducting cavities themselves. For beam operation, the beam vacuum system is operated at a temperatures of a 2 K. For the layout presented in the Technical Design Report (TDR) [1] gate valves are foreseen in the short warm sections in between two cryogenic units, resulting in 2.5 km long beam vacuum sections. There is considerable concern, that due to this coarse segmentation large sections of the accelerator modules may get spoiled with particles by accidental venting. Is should be noted, that the cold bore beam vacuum of HERA has a segmentation of 1.6 km, which did not cause any problem during the whole period of operation.

In addition there are manual valves at either end of each 17 m long module, however these valves can only be operated when the cavity string is at room temperature, the insulating vacuum is vented and the cryostat connections are opened. Fig. 1 shows the arrangement of the beam vacuum components for the 12.2 m long module of the TESLA Test Facility (TTF). In between two modules a short beam pipe with bellows and pump port connects the beam vacuum.

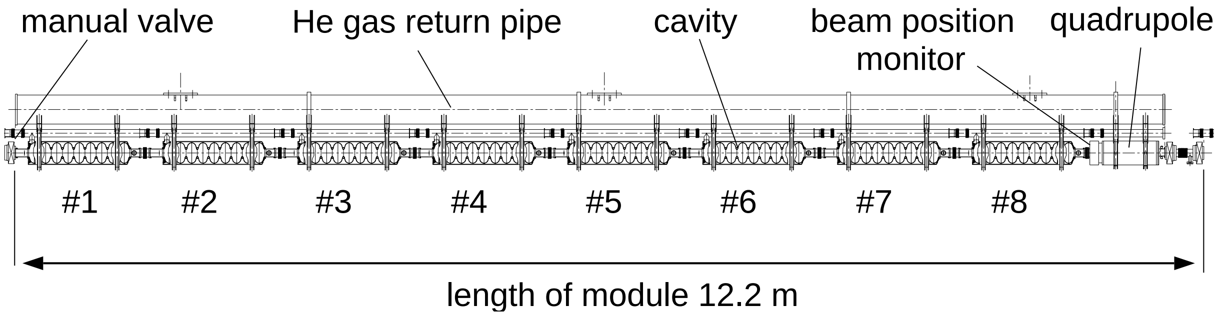

Figure 1: Beam vacuum components for the 12.2 m long module of the TESLA Test Facility (TTF).

To maintain the cleanliness of the cavity string during the assembly of the cryo module there are two ceramic windows in the input coupler. One which has vacuum on both sides - the beam vacuum and a separate input coupler vacuum; the other separates the input coupler vacuum from the wave guide, which is supposedly filled with nitrogen or dry air.

The beam vacuum systems at both sides of the main linacs are operated at room temperature. These parts have a much shorter segmentation by gate valves. In addition fast shutters are installed next to the warm-cold transitions to protect the cold part of the system in case of a vacuum break in the room temperature sections as described in sec. 4.1.

Venting of the cavity vacuum is a delicate operation with the risk of particle contamination. Therefore the standard installation or removal of a module in the tunnel will be performed with the cavity string under vacuum with the manual valves closed. Only the short intermediate beam pipes in between will be pumped down or vented.

Pressure diagnostic in the isolation vacuum is done using Penning gauges at each second module.

3 Beam interlock system

The nominal TESLA beam carries a maximum power of 12 MW with a typical RMS cross section of $60 \times 3\ \mu m^2$, at the exit of the accelerating section. Under these circumstances only two bunches with $2 \cdot 10^{10}$ particles deposit enough energy in the niobium material to reach the melting point at 2500 ˚C.

Consequently vacuum accidents could be easily caused by the beam hitting the cavity wall or other beam pipe elements and by melting a hole into the material. However these accidents can be avoided by a proper interlock system as described in the following.

A proper beam interlock system needs to fulfill the following main features:

- There must exist a definition of the accelerator settings, which allows the save transportation of the beam.
- Unless a save setting is guaranteed no beam beyond a critical current value can be injected.
- If during operation the machine settings approach the limits for a save setting, further

injection must be stopped and an emergency dump must be initialized.

Save machine settings for injection of beam are defined by the following criteria:

- The settings of all magnets must match the energy of the beam along the linac within certain limits, which have to be defined.
- A certain type of operating modus must be specified (colliding beam operation; FEL operation; single linac test; damping ring test; low current test; others) either manually by the chief operator or automatically by an accelerator cycle machine.
- All valves along the linac beam lines must be open. This includes also the manual valves, which must be equipped with position readout.
- The beam loss monitor system must be functional.
- The beam position monitor system must be operative.
- The beam dump system must be operative.
- The RF system must be operative.
- The cryogenic system must be operative and the whole linac at operating temperature.
- All cooling water systems must give ok.
- For colliding beam operation the kicker magnets for the injection into and ejection out of the damping rings must be operative at the nominal values. For FEL operation the corresponding magnets must be at set values.
- The damping ring interlock must give ok for colliding beam operation.
- The vacuum pressure in all sections involved in the specific operation mode must be below a preset value.
- An allowance bit must be set by the chief operator (operation allowance). The other general operating interlocks like personnel interlock are necessary preconditions for this operation.
- If positron generation is set, the positron target and remainder must give ok.
- Proper settings of the pre- and post-linac collimation system are required to intercept beams with large offsets due to failures of the damping ring extraction system.

Some of these requirements are relatively easy to realize. The requirement of proper magnet settings with respect to the beam energy along the linac, however, can only be verified with beam. The proper phasing of all klystrons and the cavities belonging to the individual RF stations can also only be obtained with beam. These tests and adjustments must be done with a low current beam - a few bunches only and sufficiently low power which cannot cause any damage - and need to be done before full beam operation is allowed. Therefore there must be an allowed test beam operation, which requires most of the above requirements for a save machine setting except for the magnet settings with respect to the energy along the linac. Therefore we get an additional requirement for the save machine condition:

- A low current test beam is needed to establish the correct settings of the magnet elements according to the beam energy along the linac and in the beam delivery system. This test has to be performed after each RF failure or power supply failure. The operating modus jumps automatically into the low current test beam modus after a relevant failure. To define that the settings are ok with the test beam operation, the position of the beam along the linac measured with the beam position monitors must stay within a certain region around the ideal axis. If this condition is met, the first condition (proper magnet settings) is set true.

These procedures are straightforward for the electron linac. As the electron beam produces the positrons, the test procedure for the positron linac requires low power operation of the electron linac as well.

If during normal operation any of the above given conditions is not true any more, further injection must be stopped and an emergency dump is initialized. In addition if any of the following conditions is left, further injection is stopped and an emergency dump is initialized.

- The beam positions must stay within a certain area around the ideal beam axis.
- All magnet settings must stay within a certain range around their nominal file settings.
- The readings of all beam loss monitors must stay below predefined limits.
- The background conditions in the detector are below predefined limits.

The described interlock philosophy should avoid the beam to hit any vacuum wall and still leave the operator or an automated system sufficient freedom to optimize the accelerator setting.

4 Various damage scenarios

4.1 Beam punches hole in room temperature vacuum beam pipe

In the long room temperature sections upstream and downstream of the main linacs the probability that the beam hits the vacuum vessel is higher due to smaller acceptances. Therefore fast shutters will be installed just in front of the warm-cold transitions. These shutters will be activated if the pressure readings of a certain number of pumps or gauges (≥ 2) exceed a preset limit. The shock wave caused by sudden venting propagates with ~1000 m/s leading to a sudden pressure increase up to 10^{-3} mbar. The fast shutters close within a few ms and the pressure reading to trigger the shutters takes about another 10 ms. Therefore shock waves from accidental venting about 20 m or more away from the cold part of the system can be intercepted with the fast shutters. As a shutter usually does not close off the beam pipe completely (typical leak rate 1 mbar l/s), it is used in combination with a gate valve close by which than stops the further gas flow and pressure increase completely after closing within a few seconds.

4.2 Beam punches hole in cold vacuum beam pipe

If the beam would perforate part of the beam pipe between beam vacuum and insulating vacuum, there will be no detectable vacuum incident. Due to the quite low pressure in the isolation vacuum (typically 10^{-6} mbar) the leak rate will be small and it would take extremely long till the pressure in the cold beam vacuum would raise significantly such that the vacuum readings would notice. But presumably large amounts of power will be deposited in the cavity walls and the liquid helium if the beam would be so far off the nominal orbit to perforate the beam pipe. The RF system will certainly react first as this will cause a quench. As substantial amounts of energy will be deposited in the cold mass the cryogenics will notice next. Both reactions will cause the beam to be inhibited by the beam interlock system. The post mortem beam orbit and other history data must tell us that the beam went far off the axis, although these measurements should have prevented the event to happen in the first place. The same information one would get if a large fraction of the beam got lost without causing any damage.

The damage of the vacuum wall will only be clearly noticed once the system is warmed up and the isolation vacuum will be vented. Therefore this will require special precaution and well defined procedures as described in sec. 5.

4.3 Beam punches hole in cold cavity wall

If the beam damages the wall of a cavity, this will look the same for the RF and the cryogenics as described in sec. 4.2. The helium entering the beam vacuum will be liquid or liquefy soon in nearby cold sections. The liquid will accumulate at the bottom of the cells and will overflow from one cell to the next as long as there is sufficient supply. The immediate supply is the liquid in one cryo-sector, which is ~150 m long containing about 100 cavities, so a lot of liquid. However, only the liquid from the damaged cavity can flow through the hole, as the super-fluid film in the helium pipe connecting cavities is pumped away by the pumping station of the cryo-plant. Therefore the immediate supply is only the content of the damaged cavity (which may have evaporated, but we neglect this). Thus the helium will only overflow to a rather small number of cavities. The vapor pressure is ~30 mbar. The helium gas will condensate on the cold walls of the neighboring cavities and a helium film will expand along the cavity structure. When the film reaches the position of a pumping port with an ion getter pump, which are about 150 m apart, we will observe a sudden pressure increase and will suspect what happened.

The propagation of a helium pressure front in a cryogenically cooled stainless steel tube has been measured and can be described by a simple model [2], [3]. In case of a large leak (e.g. 1 mbar l/s at room temperature) the pressure front will propagate quite fast and reach the nearest pump within a few seconds. By the time difference between the pressure increase in neighboring pumps we can determine rather precisely (within several meters) the position of the hole.

The length of structure, which may be polluted by molten metal and dust particles out of the isolation vacuum or helium vessel, is still rather limited for the cases discussed so far for the cold beam vacuum. Only the section where liquid has been flowing would contain contaminations. Thus up to now the possibility of a further segmentation of the beam vacuum would not have made any difference. But to take out the module with the damaged cavity and maybe neighboring modules, the whole cryogenic section has to be warmed up. During this process streaming gas could spread the contamination further. Now the possibility to divide the vacuum section into smaller parts while the system is still cold would be very beneficial. It would ensure that a possible contamination stays contained within the separated part of the vacuum system. This will be discussed in more detail in sec. 6.

4.4 Non beam induced leaks in cold vacuum system

Non beam induced leaks in the cold vacuum vessels and from the helium system into the beam vacuum will behave similar to the scenarios described in sec. 4.2 and 4.3. If a leak from the helium system is small, the time between the occurrence of the leak and the pressure increase can be rather long (e.g. up to 40 h at a leak rate of 10^{-6} mbar l/s at 2 K). Therefore one would probably not detect the leak due to a pressure increase but rather due to deterioration of the performance of cavities close to the leak (see also sec. 7).

It is obvious, that great care has to be applied during all installations and a careful leak check of all components and connections is absolutely mandatory to minimize the risk of leaks.

4.5 Broken ceramic window in input coupler

This event seems to be much more likely than a beam-induced vacuum accident. There is no interlock to prevent such an event.

If the outer window develops a leak it is immediately noticed by the pressure increase in the coupler vacuum. However, a break of the inner window will happen unnoticed. It will only show up, when one of the vacuum systems gets vented, then clearly identifying the module which has to be taken out. As by the cracking window ceramic particles might have entered the beam vacuum, special measures must be taken to prevent a further distribution of these particles in the cavity string. Venting of the beam vacuum is presently not foreseen as a standard operation, however it might be necessary in case of a leak in the beam vacuum system as described in sec. 5. In this scenario a further segmentation of the beam vacuum is not necessary.

Venting the coupler vacuum while a module is cold is an absolutely forbidden action. Once the system is warm, venting of the coupler vacuum needs a careful monitoring of the beam vacuum.

4.6 Failure of equipment

In case of failures in the electronics controlling valves, pump-stations, pressurized air supply and so on, the systems must be designed such that the whole vacuum system and the accelerator remains in a safe situation. There is substantial experience in the layout of components meeting these goals from HERA and TTF.

In HERA we experienced the case that some of the remotely controllable all metal gate valves in front of the cold vacuum section of the superconducting magnets would not be leak tight when closed for the venting of the adjacent room temperature vacuum section. These defects have caused nitrogen leaking into the cold section. As there is no pressure diagnostics at HERA on the cold side of the valves, this sometimes was even not realized immediately. For TESLA the situation will be improved by installing always double valves with intermediate pumping in front of the cold sections as well as pressure diagnostics on the cold sides of the valves as presently done at TTF.

4.7 The human factor

From the experience at the DESY accelerators one must conclude that the highest potential for fatal incidents lies in inattentive or accidental actions of personnel during installation, maintenance or repair work. This danger is hard to prevent. However, there are several measures that can and must be taken to limit the damages from erroneous actions.

The logic of the operating systems for pump-stations and valves must prevent dangerous actions. This falls into the category of interlocks. As most actions on the vacuum system will be done via computer control, delicate actions will be password protected. Education of staff and contractors will be necessary but not sufficient.

Special care must be also given to sufficient mechanical protection of fragile components like input couplers, feedthroughs, pump ports, etc. Also the transport of heavy equipment in the tunnel must follow quite strict rules.

For any access the double valves, mentioned in the preceding paragraph, must be closed automatically. For this scenario a finer segmentation of the cold vacuum sections as discussed in the following section would be certainly beneficial.

5 Venting procedures

Although venting of the cavity vacuum is not foreseen as standard operation in the tunnel (see sec. 2), it might still be necessary in case of problems, especially in case of a leak in the beam vacuum.

Whenever the isolation vacuum will be vented, careful monitoring of the beam vacuum is mandatory. If a pressure increase in the beam vacuum will be noticed during venting of the isolation vacuum, this clearly indicates a leak between beam and isolation vacuum. Further venting of the isolation vacuum should be stopped and it should be pumped down again. Instead the beam vacuum should be carefully and slowly vented first to avoid that contaminations by dirty gas form the isolation vacuum or even particles would enter the cavities through the leak pore. Eventually the beam vacuum should be even set to slight overpressure before venting of the isolation vacuum is continued. Also in this case a further segmentation of the beam vacuum will be useful to minimize the risk to spoil a section during the venting process by an accident.

If one knows that there is a leak in the beam vacuum in advance one would rather start venting the beam vacuum before the isolation vacuum.

Once it is known that there is a leak in the beam vacuum, the faulty module must be identified. A rough indication will be given by the pressure profile of the ion getter pumps, which are separated by 150 m, during the first pressure rise in the beam vacuum when venting the isolation vacuum. The pressure profile of the Penning gauges in the isolation vacuum located at each second module will give more detailed information during venting of the beam vacuum.

6 Further segmentation of the cold vacuum sections

As discussed above, a further segmentation of the cold vacuum sections would be advantageous for various damage scenarios like venting of the beam vacuum in case of a leak in the beam pipe to limit the spread out of contaminations as well as during installation of components in the tunnel or even tunnel access to reduce the damage in case of errors by the technical crew.

From what has been said up to now, it is clear that the valves would have to be operated when the cavity system is cold. They should also operate at room temperature to be able to segment the system during installation and repair work. As far as we can see, there is no need to operate them at intermediate temperatures. However, when closed at cryogenic temperatures, they must stay tight during warm-up to room temperature.

One possibility for segmentation valves would be to equip several of the manual valves with motor drives that work at low temperatures. The smallest distance between these valves could be 150 m, the distance between two ion getter pumps. This has to be discussed with the valve manufacturers and tests on the reliability and leak tightness have to be performed.

7 Experiences from other accelerators

At the low energy linear accelerator ELBE in Rossendorf the electron beam burned a hole into a vacuum pipe recently. This was presumably due to improper handling of the beam inhibit interlock [4]. This event shows, that a carefully designed and tested interlock system constitutes an essential part of the protection against vacuum accidents.

At TTF one of the two modules has a leak between isolation and beam vacuum in the order of 10^{-3}–10^{-4} mbar l/s. This was realized after the first warm up during venting of the isolation vacuum. Beam operation with this module however did not cause any problems due to this leak up to now since installation into the TTF linac in summer 98.

At the superconducting machine CEBAF a cold leak from the Helium system was detected some time ago [3]. This problem was indicated by a deterioration of the cavity performance, however there was no change of pressure visible. The leak was later verified during warm up using an RGA. So far the module has not been repaired and this is not foreseen in the next future as beam operation is not affected if the module is slightly warmed up to 30 K regularly.

8 Conclusions

A long term successful operation of the TESLA accelerator requires to maintain the high quality conditions of the inner cavity surface. We identified three potentially dangerous damage scenarios: Destruction of the cavity wall or other components of the vacuum system due to interaction with the high power TESLA beam, secondly failure of critical equipment as for example coupler windows, and finally failure due to faulty human operation. While the probability for the occurrence of the first two scenarios can be kept at a minimum by a carefully set up interlock system, test operation with pilot beams and proper design of critical components, the third possibility is hardly excluded.

However, it is certainly possible to reduce also the chance of a human failure, for example with interlock systems that avoid faulty operation of valves. Other measures are mechanical protection to avoid accidental destruction of the coupler windows and proper training of the operation crew and technicians.

In addition to such preventive measures we will investigate cost effective options for a finer segmentation of the beam vacuum with motor driven valves. If a catastrophic failure occurs this can help to restrict the length of the contaminated section to a few modules that could be replaced within a relatively short period by spare modules.

In summary we have to state that the danger of seriously disturbing the accelerator operation by accidental venting of the vacuum system should not be underestimated. However, with carefully designed interlock systems and other precautions it will be possible to allow a safe and stable operation, comparable to the operation of normal conducting accelerators which require a high degree of cleanliness as well.

References

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