Contents

1. Scope

- The information presented in this document is intended as a basic reference to safety devices for FAIR cryogenics and not as a legally binding interpretation. This document contains minimum requirements for the layout of safety devices for protecting,

  (1) cryogenic process lines;

  (2) cryostat and vacuum jacket;

  (3) beam tubes,

  within FAIR accelerators.
- This document is not related to any purpose other than the aforementioned.
- This document is not related to safety devices of cryo-plants for FAIR.
- This document is not a complement to any requirements defined by [2] and [2].

2. Convention and Nomenclatures

- Without special notice it is understood that all pressures indicated in this document are absolute, static pressures.
- Operating Pressure: The pressure at which a piping or a vessel system is to be used on a steady-state basis. It may range from a vacuum to the design pressure. Special consideration should be given to the relief device choice to prevent pre-opening leakage if a pressure higher than 90 percent of design is used.
- Set Pressure: The pressure at which a protective device is set to discharge.
- Design Pressure: The pressure used in the design of a vessel for the purpose of determining the minimum required thickness of the components of the vessel. It is the value of pressure under which the vessel will normally operate and this value

must include any normal excess pressure that can occur during the vessel's operation.

- Maximum Allowable Working Pressure (MAWP): Some practical factors - such as available materials, fabrication techniques and other factors should be taken into consideration during the fabrication of a vessel. This will result in a vessel that not only meets the required design pressure, but often exceeds it. This is a conservative procedure because it ensures that the vessel will meet pressure safety expectations. Therefore the MAWP is the working pressure which is allowed for the ultimately fabricated vessel. It is the prime factor in setting the pressure at which the corresponding vessel safety relief devices will be activated. The MAWP is the most important pressure value attached to a vessel and it should be clearly understood and stamped on the vessel for all clearly to read [3]. The MAWP will change with time due to wear, corrosion, and vessel fatigue.

3. Definitions of Safety Devices

3.1. Safety Valve

- Safety Valve (Sicherheitsventil). An automatic protective device actuated by the static pressure upstream of the device and characterized by full opening pop action. Safety valve usually discharges gas, vapor or fluid into the atmosphere when the set pressure is reached.
- Relief Valve (Überströmventil). An automatic, reseatable protective device actuated by the static pressure upstream of the device and for which the opening is proportional to the increase in pressure over the opening pressure. Relief valve discharges gas, vapor or fluid in a volume which is over-pressurized into a closed volume with low pressure. Therefore there is no medium to be released into atmosphere and no harm to the surrounding. In principle safety valve could be used as relief valve. However, the back pressure at the discharge side must be compensated.
- Safety Relief Valve (Vollhub-sicherheitsventil). A protective device combining the functions of safety device and relief device, usually being proportional during the first part of its stroke and having pop action during the last part.

3.2. Rupture Disk

- Rupture Disks (Berstscheiben) are safety devices against excess pressure. They are specially dimensioned bursting elements, which is destroyed or permanently deformed on response. Rupture Disks are used if large mass flow must be discharged and / or the losses of sealing ring of safety valves must be avoided. In contrast to the safety valve, the opening can not be automatically closed again after pressure releases. Therefore rupture disks can be only used if no risk occurs at large mass flow discharge by bursting, e.g., discharge into one closed system, connection with a discharge line or in the application of non-toxic gas, e.g., helium.

4. Codes and Standards

- The European Pressure Equipment Directive (PED) 97/23/EC [1] applies to the design, manufacture and conformity assessment of pressure equipment and assemblies with a maximum allowable pressure greater than 0.5 bar gauge including vessels, piping, safety accessories and pressure accessories. The Pressure Equipment Directive (97/23/EC) was adopted by the European Parliament and the European Council in May 1997. It has initially come into force on 29 November 1999. From that date until 28 May 2002 manufacturers had a choice between applying the pressure equipment directive or continuing with the application of the existing national legislation. From 29 May 2002 the pressure equipment directive is obligatory throughout the EU. The directive provides, together with the Directives related to Simple Pressure Vessels (2009/105/EC), Transportable Pressure Equipment (99/36/EC) and Aerosol Dispensers (75/324/EEC), for an adequate legislative framework on European level for equipment subject to a pressure hazard.
- The AD 2000 Code [2] meets the requirements of the European Pressure Equipment Directive (97/23/EC) and contains also the experience from decades of practice. Before implementation of the Pressure Equipment Directive (PED) 97/23/EC in 2002 safety valves and rupture disks have been designed according to the AD 2000 Merkblatt A2 and A1. After the introduction of the Pressure Equipment Directive (97/23/EC), the AD-2000-Merkblatt A2 and A1 are used as a basis for test.
- As alternative, the harmonized European standard series EN 4126 could be also applied. The series of standards EN 4126 has seven parts: Part 1: safety valves; Part 2: rupture disk; Part 3: safety valves and rupture disk in combination; Part 4: pilot operated safety valves; Part 5: controlled safety pressure relief systems (CSPRS); Part 6: rupture disk - selection, use and installation; Part 7: general data.

5. Risk Analysis for Large Superconducting Accelerator and its Cryogenic System

- In large superconducting accelerators, the superconducting magnets are contained in helium enclosures of cryostat and cooled by cold helium. Heat leak of the cryostat is kept low by using low heat leak supports, multi-layer super-insulation blankets and heat shield under high vacuum. Cryogenic transfer lines are used so that a helium refrigerator can provide cooling throughout a large accelerator. Depending on the system design, cryogenic lines can be integrated with the magnet cryostat (such as RHIC) or in a separate transfer line (such as HERA, LHC). Minor deterioration in insulating vacuum increases heat input to the magnets. As long as the refrigerator is able to provide the required cooling, the cryogenic system remains stable. There is no hazardous issue other than cold surface on cryostats.

- If there is a failure on the helium system, temperature and pressure in the cryogenic system will increase at rapid rates. Relief valves must be installed to protect the cryogenic hardware. The helium enclosure (helium vessel and piping), vacuum tank (Cryostat) and beam tubes are three major systems in a superconducting accelerator that require safety relief. Although the beam tube is normally not part of a conventional cryogenic system, major portion of the accelerator beam tube is installed inside cold magnets. Air could condense on the inner surface of the beam tubes. After a warm up, the pressure could rise and safety relief is required.
- Pressure rising in helium enclosure (vessel and piping) at 4 K can come in different ways, with break of the isolating vacuum, with a quench of the superconducting coils or with long lasting electricity-, control air or computer failures. In 40-80 K circuit it comes to an increase of pressure with collapse of the isolating vacuum or in the case of a longer persisting power failure. In the case of power failure over longer times (hours) rises the pressure in the entire helium system of a superconducting accelerator (i.e., HERA) up to the Maximum Allowed Working Pressure, where relief valves discharge into the atmosphere outside the tunnel through a so-called quench line. Therefore no oxygen deficiency issue in the tunnel exists. The increase of pressure in the case of power failure happens very slowly.
- The increase of pressure in the helium circuits due to the break of the isolating vacuum depends on the size of the leakage; however the pressure increases usually relatively slow, because the heat in leak per unit area is limited due to the many layers of super-insulation. Nevertheless the pressure could achieve very high values in the locked helium volume.
- With a Quench the energy essentially stored in the magnetic field is released. Before the circuit is disconnected, part of the energy is deposited as Joule heating in the coil in which resistive transition is finished and cause the pressure rising when it is finally transferred into the helium.
- A rapid increase in insulating pressure is a different phenomenon and is a safety issue. If any component connected to the cryostat in the warm region fails unexpectedly, ambient air will flow into the insulating space [4]. Also an outside damage of the vacuum vessel leads to an increase of insulating pressure [5], [6]. Heat input to the magnet will increase by several orders of magnitude. As a result, temperature and pressure of cooling helium will increase rapidly. To protect the helium enclosure from over pressure, helium must be vented out through relief valves. A sizable helium leak that develops inside the cryostat could lead to similar consequences. With a separate vacuum, abnormal heat input will occur only to

those magnets that share one vacuum space. Heat inputs remain normal to magnets in regions with good insulating vacuum.

- If a major failure occurs in a cryogenic line, cold helium will be released to the vacuum space. A rapid increase of pressure in the vacuum vessel takes place, for example with larger leakages from the helium circuits. If the pumps for the isolating vacuum fail, the pressure can rise up to the design pressure of the vacuum vessel. To prevent over pressure of the cryostat, cold helium in the vacuum space must be vented through tank relief valves. When bursting a helium line the increase of pressure in the vacuum vessel could be so abrupt and powerful that large scale damage of magnet cryostat may occur. Cryogenic line failure can occur also in test phase at warm state. As an individual component, an improperly designed cryogenic process pipe can fail during a pressure test at less than its static normal operating limit. Under the pressure test for a magnet string with the application of Maximum Allowed Working Pressure, the asymmetric longitudinal movement of individual magnets and subsequent breakage of internal support structures and cryogenic connections may occur. Such a failure could be avoided if the dynamic application of pressure is fully considered in the design of the support structure in the cryostat [7].
- The situation would be catastrophic when the helium enclosure is punctured by an electric arc [8], [9] due to the un-controllable quench of Bus bar connection between magnets or failure of individual components, e.g., soft solder joint on safety leads. The helium pipes and also copper connections could be vaporized by the energy from the magnets through the electric arc. It leads to large amounts of helium release into the insulating vacuum of the cryostat, severe degradation of the beam tube vacuum and pressure in the insulation vacuum may rise rapidly above its design pressure. Insufficient relief capacity on the vacuum tank may lead to over pressure of cryostat. Major damage on accelerator magnets due to severe mechanical failure of the cryostat may occur. Helium could release into the accelerator tunnel. Cold helium may cause equipment damage or personal injury due to a safety hazard on oxygen deficiency. Large amounts (tons) of helium discharge into the tunnel can cause a severe Oxygen Deficiency Hazard and the ODH monitors should be implemented in the accelerator tunnel.
- The layout of the cryogenic system has to consider fault conditions like the sudden loss of insulation vacuum in the cryostat or venting of the beam vacuum. These fault conditions should be investigated by experiments, to validate simulations as in [4], [10]. All the safety relief devices should be certified periodically by the Notified Bodies, i.e., TUEV and the safety aspects related with applicable design conditions should be estimated routinely as in [11].

6. Technical Requirements

- Safety systems must be applied for all systems having a pressure source (for example, liquid helium evaporation) that can exceed the maximum allowable pressure of the system or for which the malfunction or failure of any component can cause the maximum allowable pressure to be exceeded.

- Safety and pressure-relief devices should be sized and tested in accordance with the capacities of the pressure source and provide initial relief at the maximum allowable working pressure, or lower, in accordance with Pressure Equipment Directive 97/23/EC and AD 2000 code.
- Liquid helium vessels and each section of liquid helium piping capable of being isolated must be considered to be a pressure vessel with a source of external energy. This energy, for which the source is the heat leak into the line, can cause the pressure to increase many orders of magnitude when the fluid in the line heats to atmospheric temperature. Insulation vacuum failures in liquid helium systems can cause air condensation and an increased heat flux into the system. Each such section must be equipped with a protective device for overpressure control.
- Insulation vacuum spaces shall have overpressure protection sized with sufficiently discharge rate.
- The pipelines and safety valves should be secured, taking into account local working conditions, so the static dynamic stresses (reaction forces) occurring with the quickest opening and closing can be taken up safely. All cross sections of pipelines should be designed to ensure the necessary discharge and undisturbed functioning of the safety valve. The material of all parts pressured by helium during operations and testing should be suitable for the temperature and pressure arising conditions.
- Pressure-relief systems should protect against a pressure regulator sticking or failing in the fully open position.
- Pressure-relief devices are required downstream of all regulating valves and orifices unless the downstream system is designed to accept full source pressure
- The maximum internal pressure and temperature allowed shall include considerations for occasional loads and transients of pressure and temperature. Variations in pressure and temperature may occur; therefore the piping system, except as limited by component standards or by manufacturers of components, shall be considered safe for occasional, short operating periods at higher than design pressure.
- The safety device of each point may consist of one or more safety valves in parallel. However, not more than two valves in parallel at each point will be accepted.
- In contrast to safety valves, blow off orifices remain open after the rupture disk bursts. A similarly tested bursting element needs to be mounted or an exchange device inserted for further operation of the vessel. The rupture disk needs to be directly connected with the pressure space to be protected and may not be shut off.

A changeover valve or similarly controlled fitting (interlocking device) is permissible in front of the rupture disk if two rupture disks are present and one serves as a reserve, provided one of the two rupture disks is always positively connected to the pressure space. The reliability of the interlocking device should be confirmed.

- A rupture disk can be connected in series with a safety valve if it is operationally appropriate and it is not necessary to reckon with a rapid pressure rise (response inertia of safety valves). It should be ensured by suitable measure that fragments from bursting elements do not make the safety valve ineffective and cannot restrict the outflow cross section. It is also necessary to avoid the possibility of counter pressure (leaky disk) building up in the space between the rupture disk and safety valve because this affects the response pressure level of the disk.
- The strength properties of the material used for the bursting elements should exhibit the least possible dependence on the type of stress (static or ballooning), temperature, and duration of the stress (curve of creep dependent on time).
- The safety devices will be placed indoors at atmospheric pressure and ambient temperature. No special environmental conditions have to be foreseen. It is essential to limit as much as possible the heat flow into the helium temperature environment. With the relief valve closed in normal working conditions, it has to isolate the helium in the FAIR magnets from the discharge line with the required leak tightness over the seat.

7. Test

7.1. Test by Notified Bodies (Benannte Stellen)

- The safety valves have to be tested. The tests are carried out by Notified Bodies, e.g., TÜV or similar institutions. Method and extent of the component testing are listed in the VdTÜV "safety valve 100" (VdTÜV-Merkblatt Sicherheitsventil 100).

7.2. Acceptance Tests at GSI

- A pressure and leak test will be done by GSI after delivery. The pressure test will be done to verify the set pressure, full opening pressure and reseat pressure, and will be done at ambient temperature and with atmospheric back pressure.
- The helium leakage will be measured using an upstream pressure of 1 bar abs, and the outlet connected to a vacuum pump and a mass-spectrometer. The test will be done at ambient temperature.
- Acceptance will be given by GSI only after applicable material certificates and documentation have been delivered, all tests specified have been successfully completed and all test or other certificates have been supplied to GSI.

8. References

[1] The European Pressure Equipment Directive (PED) 97/23/EC, European parliament and the council of the European Union
[2] Arbeitsgemeinschaft Druckbehälter AD 2000-Regelwerk (AD 2000 Codes, Verband der TÜV e. V., Beuth Verlag GmbH, Berlin, Germany, 2009)
[3] Technical Guideline No. 10.7e: Cryostat Label Plates
[4] Boeckmann T., Hoppe D., Jensch K., Lange R., Maschmann W., Petersen B., Schnautz T. , Experimental tests of fault conditions during the cryogenic operation of a XFEL prototype cryomodule, Proceedings of ICEC 22-ICMC 2008, pp. 723~728
[5] Cancelli, C., Demichela, M., Piccinini, N., Accidental release of hydrogen from a cryogenic tank, Cryogenics 45 (2005) 481–488.
[6] Safety Standard for Hydrogen and Hydrogen Systems, National Aeronautics and Space Administration, USA
[7] LHC Root Cause Analysis Report, Fermilab Research Alliance, September 14, 2007
[8] Report of the task force on the incident of 19 September 2008 at the LHC, LHC Project Report 1168, 31-March-2009
[9] Failure of TSDR169 at F47 on July 8, 2001 (Autopsy Report for TSDR169), Fermilab Technical Note TD-01-063
[10] Chorowski, M., Lebrun, Ph., and Riddone, G., Preliminary risk analysis of the LHC cryogenic system, LHC Project Report 324, Proceeding of the Cryogenic Engineering and International Cryogenic Materials Conference (CEC-ICMC'99), 12-16 July 1999, Montreal, Canada
[11] Wu, K. C., Evaluation of RHIC Safety Relief System in Response to the LHC Incident, Magnet Note 660-8 (AM-MD-360), Superconducting Magnet Division, BNL, January 26, 2009