The safety helium collectors for the ESS superconducting linac: functional specification and detailed design

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Abstract. The ESS proton linac includes 43 separate cryomodules which are cooled down by means of a saturated superfluid helium bath. For safety reasons, access to the machine is limited and strictly controlled. However, this does not exclude some oxygen deficiency hazards. In order to prevent exposure of personnel to helium releases during access to the tunnel (Beam OFF mode), it was decided to equip the machine with two safety helium collectors, which are intended to collect the helium released by the burst disks of the cryomodule 2 K helium vessels, in case of an accidental event and vent it outside the tunnel. However, in Beam ON mode, when more than one cryomodule can discharge cold helium at the same time, the collectors must not cause any significant back pressure to the burst disks or cavities. The paper presents the functional specification, feasibility study and design of the safety helium collectors.

1. Introduction

The European Spallation Source is an accelerator-driven neutron scattering facility, currently under construction in Lund, Sweden. The ESS proton linac includes 43 separate superconducting cavity cryomodules (CM), 13 Spoke CMs [1] and 30 Elliptical CMs [2]. The cavities are cooled down to 2 K by means of a saturated superfluid helium bath. The 2 K temperature is produced at each cryomodule by precooling and throttling 4.5 K helium, which is provided by a dedicated cryogenic plant and transferred via a cryogenic distribution system.

The ESS linac cryogenic distribution system (CDS) [3] and all the cryomodules are located in an underground tunnel. The cold section of the machine in the linac tunnel is 315 m long and at nominal conditions it may comprise 1400 kg of cold helium, including 1100 kg in a superfluid state at 2 K.

Due to safety reasons, access to the machine is limited and strictly controlled. However, this does not exclude some oxygen deficiency hazards. In 2016, ESS AD Safety Group investigated possible cold helium releases into the tunnel [4]. The study revealed that during personnel access to the tunnel the most critical risk regarding local oxygen concentration and temperature drops is the rapid loss of the 2K helium from 1 elliptical cryomodule. This event, which can be triggered by a rupture of the cryomodule power coupler ceramic window, may lead to a release of 28.4 kg of cold helium at 2.04 bara and around 5 K within 1.9 seconds. A detailed numerical analysis showed that if the CM helium vessel rupture disks were open to the tunnel the helium vapour propagation would cause some significant decreases of oxygen concentration and temperatures. Figure 1 shows that in the vicinity of a discharging cryomodule the oxygen concentration and temperature might drop to 6 % and -160°C, respectively.
Later, due to air ventilation, the cloud of cold helium-air mixture might be pushed by the air flow along the tunnel and cause severe oxygen deficiency hazards and cold burns in the vicinity of the neighbouring cryomodules. Therefore, it was decided to equip the machine with two safety helium collectors intended to collect the helium released by the burst disks of the cryomodule 2 K helium vessels, in case of an accidental event and vent it outside the tunnel.

2. Functional specification and requirements for the safety helium collectors

The function of the safety helium collectors is to prevent exposure of the ESS linac personnel to rapid and intense releases of cold helium from the rupture disks of the superconducting cavity cryomodule helium vessels. Consequently, it is difficult to predict when and which cryomodule will discharge cold helium. The outlets of all the CM rupture disks need to be tightly connected to the collectors to let the discharged helium freely flow into the collector and transferred outside the Cold Box Hall and tunnel. During access to the tunnel in Beam Off mode, all the CMs are separated by vacuum gate valves on the beam line. This means that, after a rupture of a ceramic window in one cryomodule, there will not be any propagation of the failure to the adjacent cryomodules.

However, in Beam On mode, the vacuum gate valves on the beam line are open and there is a risk that more than one cryomodule can discharge cold helium at the same time. Then, the collectors must not be constricted to let the helium easily flow into the tunnel to avoid any significant back pressure to the burst disks or cavities. In this mode the collectors shall be closed to the atmosphere in order to avoid air flowing into the tunnel where pressure is decreased to a sub-atmospheric value due to radiation safety.

The main design parameters for the safety helium collectors were specified based on the analyses of all potential helium releases from the ESS cryomodules \[5\]. The collectors need to be designed to take a maximum helium flow rate of 14.4 kg/s at a temperature and pressure of 5 K and 1.9 bara, respectively, from one cryomodule (7.2 kg/s for each rupture disk) with a maximum discharge duration of 1.9 seconds. The maximum allowable pressure in the entire piping of the collectors is equal to 1.9 bara for both Beam On and Beam Off modes.

3. Conceptual layout

Figure 1 shows the conceptual layout of the safety helium collectors. The collectors are composed of two headers, so-called Collector Right and Collector Left. They run along the cold section of the ESS linac in the underground tunnel and close to Elliptical CM30 they go into the CTL gallery, and further into the Cold Box Hall, where they vent outside the buildings. At Spoke CM01 the collectors are connected to the CDS Vent line.
Each cryomodule is connected to both collectors and each of those connections is extended with a shut-off valve. In total there are 86 shut-off valves. In Beam Off mode all these valves are closed, whilst in Beam On mode, when more than one cryomodule can discharge helium and personnel are not allowed in the tunnel, the valves are open.

The collectors are also equipped with 3 additional shut-off valves, one in the interface to the CTL Vent Line and two others on the headers downstream Elliptical CM30. Those valves shall be closed in Beam On mode, in order to allow lowering the pressure in the tunnel. However, during Beam Off mode, they need to be open to let the discharged helium flow outside the buildings.

4. Detailed design and spatial integration in the ESS linac buildings
The detailed design of the safety helium collectors, including their connections to the Spoke and Elliptical cryomodules, is presented in Figure 3. The collectors are made of DN300 stainless-steel welded pipes which are mounted above the cryomodules along the tunnel in a length of 315 m.
hoses. These flexible components are for compensating axial displacements up to 35 mm, which may appear due to thermal contraction of the collectors. The collectors are supported with 78 sets of 1 fixed and 1 sliding supports, distributed uniformly along the tunnel. In the CTL gallery there are 1 fixed, 1 sliding and 6 vertical supports.

All shut-off valves are VAT Series 121 gate valves. They are equipped with a pneumatic double-acting actuator, with neither spring nor return mechanism, so when instrument air and/or power are lost the valves remain in the last position (fail in place). The 86 valves at CMs are DN ISO-250 in size, whilst the other 3 valves at the collectors’ extremities are DN ISO-320. Figure 4 shows a cross section of the ESS linac tunnel in its elliptical section. The collectors are placed at the tunnel ceiling on both sides of the cryomodules. They are installed 2.9 m above the tunnel floor to allow convenient access to the machine components.

5. Numerical verification of the final design

The final design of the safety helium collectors and their supports was numerically checked in order to validate their mechanical stability and flow capacity. A thorough thermo-hydraulic CFD study was performed to evaluate the evolution of pressure and temperature distributions in the helium collectors. The numerical analysis was performed in Ansys Academic R19.0, to simulate an unsteady compressible thermal flow of helium and air. Helium properties were taken from the NIST Chemistry WebBook, whilst air was treated as an ideal gas and its dynamic viscosity was derived from Sutherland’s law.

The CFD model geometry represents the inner volume of the collector headers and CDS Vent Line, and reflects the fluid domain. There are two cold helium inlets located close to the hydraulic centres of the headers, namely at the first elliptical cryomodule. The model geometry is discretized with 1.2E6 tetrahedron elements in the core flow region, and 2.4E6 prism cells in the boundary layer. A section of the CFD model geometry and mesh are shown in Figure 5.

In the initial conditions the headers are filled with air at the ambient temperature and pressure of 25°C and 1 bara, respectively. Then a helium inflow of 7.2 kg/s per header is released and the air is pushed by the cold helium towards the header outlets. The applied boundary conditions assume high speed heat transfer between the flowing gases, and the header walls remaining at ambient temperature. Figure 6 shows evolutions of pressure, temperature, velocity and helium fraction along the collectors, from the discharging cryomodule to the outlet of the CDS Vent Line. The highest pressure is in the interface to the discharging cryomodule, but inside the collectors its values reach 1.5 bara at 2.6 sec. In the inlets the helium flows at a speed of 63 m/s, whilst in the collectors its speed drops due to the larger diameter. The velocity, temperature and helium fraction distributions show that the discharged helium pushes the air out of the collectors and vent line and fills the entire lines at 3 sec. The temperature falls quickly to 8 K, whilst the pushed air compresses slightly and increases temperature to 318 K at 1.9 sec.

![Figure 4. Spatial integration of the safety helium collectors in the ESS linac tunnel](image1)

![Figure 5. CFD model and mesh of the collector headers and CDS Vent Line](image2)
Figure 6. Distributions of pressure (a), velocity (b), temperature (c) and helium fraction (d) along the collectors from the Elliptical CM01 to the CDS Vent Line outlet.

The cold front moves rapidly towards the outlet, where the temperature falls to 220 K already at 3 sec. Figure 7 shows the evolution of static pressure in the interface to the discharging cryomodule. In the first instant the pressure rapidly rises to 1.4 bara, and later it steadily increases to reach the maximum value of 1.89 bara. After 2.6 sec the pressure starts decreasing gradually to the ambient value.

6. Summary

Based on studies of potential accidental releases of helium in the ESS accelerator tunnel it was decided in 2016 to equip the cold section of the ESS proton linac with two helium safety collectors. They are intended to collect the helium which can be accidentally discharged by a CM (one at a time) and vent it outside the tunnel. The feasibility study showed that the collectors need to be made of DN300 pipes and placed at the tunnel ceiling above the cryomodules. They also need to consist of 89 large-size gate valves. The detailed design of the collectors and their supports has recently been completed. The mechanical stability, as well as flow capacity, were verified by numerical calculations.

The manufacturing and installation of the collectors are planned to be executed by a commercial company, selected in public procurement in Q4 2018. The installation and site acceptance tests are scheduled from May to August 2019.

References

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