

Thermohydraulic simulation of quenches and quench recovery for the HL-LHC IT String test bench at CERN

G Rolando, A Wanninger and A Perin

CERN, Technology Department, Cryogenics Group, 1211 Geneva 23, Switzerland

Email: gabriella.rolando@cern.ch

Abstract. In the framework of the High Luminosity LHC (HL-LHC) project, a new test system - the Inner Triplet (IT) magnets String - for the characterization and validation of the collective behaviour of a 60 m long string of magnets is being built in the SM18 cryogenic test facility at CERN. Among the main objectives of the IT String is the assessment of the magnet performance during the resistive transition from the superconducting to the normal state (quench) when energies up to 39.1 MJ are released into the magnet cold mass and into the helium. In this paper we present the thermohydraulic study performed to design the quench recovery system of the IT String, which limits the pressure rise in the magnets during a quench and ensures the recovery of the operating conditions within the required timeframe. As a new design method, a 1-D thermohydraulic model of the quench relief system has been created using the EcosimPro software with the CRYOLIB library developed at CERN.

1. Introduction

The Inner Triplet (IT) magnets provide the final focusing of the proton beams before collision at the interaction regions of the LHC. In the framework of the High Luminosity LHC (HL-LHC) project, the IT magnets at interaction points P1 and P5 will be replaced with new Nb₃Sn superconducting magnets [1]. The IT String test bench, under construction in the SM18 cryogenic test facility at CERN, aims at studying and validating the collective behaviour of the IT magnets before installation in the LHC [3].

The IT String includes four quadrupoles (Q1, Q2a, Q2b and Q3), a recombination/separation dipole (D1) and several corrector magnets (CP). A schematic layout is shown in Figure 1. The magnets are housed in three interconnected cryostats sharing a common He II volume at 1.9 K and 1.3 bar and a common insulation vacuum volume.

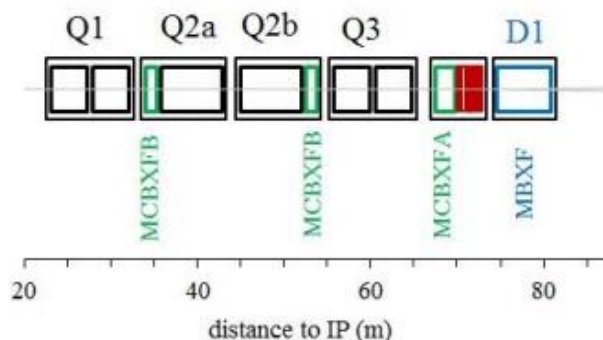


Figure 1. Schematic layout of the Inner Triplet (IT) magnets [1].



One of the objectives of the IT String test program is the assessment of the performance of the magnets during the resistive transition from the superconducting to the normal state (quench). Table 1 summarises the different quench energies of the quench test programme [2].

Table 1. IT String quench test program. I_{nom} designates the nominal current [2].

Name	Current	Quench Energy [MJ]
Nominal	$I_{nom} = 16.47$ kA	39.1
High	$0.75 \cdot I_{nom}$	22.0
Medium	$0.4 \cdot I_{nom}$	6.3
Low	$0.1 \cdot I_{nom}$	0.4

In this paper, we present the thermohydraulic study performed to design and size the IT String quench recovery system. The quench recovery system shall limit the pressure increase in the magnet cryostat below the design pressure (20 bar) and allow the recovery of the operating conditions in maximum 12 h. In the study, only quenches at nominal current, corresponding to a stored energy of 39.1 MJ, are considered as they represent the worst-case scenario for the quench recovery system.

2. The IT String quench recovery system

2.1. Components and layout

The layout of the IT String cryogenic system is presented in [4]. Figure 2 shows a simplified sketch of the components of the quench recovery system.

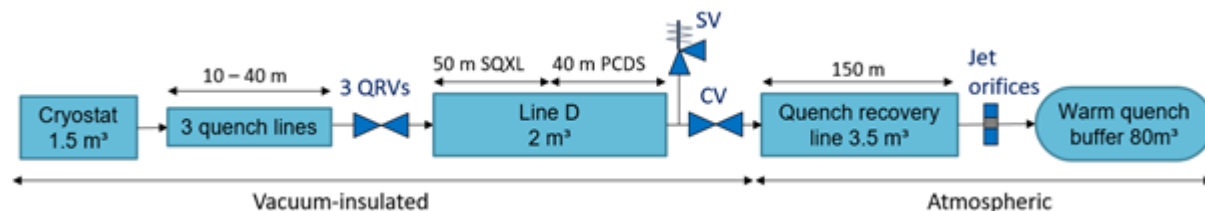


Figure 2. Layout of the IT String quench recovery system, including quench relief valves (QRVs), control valve (CV) and safety valve (SV).

Following a quench, the energy stored in the magnetic field is released in less than a second into the magnet coils and then into the surrounding cold mass and helium. The pressure increase in the magnet cryostats is limited by three quench relief valves (QRVs) that release the expanding helium to a cryogenic discharge line (line D) through quench lines LD, LD1 and LD2.

Line D is one of the headers of the cryogenic distribution line (SQXL) and has an overall volume of about 2 m^3 . During quenches, line D effectively acts as a cold (vacuum insulated) quench buffer with an initial temperature of 20 K.

The QRVs are pressure-balanced spring-loaded relief valves with a set pressure of 17 bar and reaching their full-open position at 20 bar. The pressure in line D is limited to 10 bar by releasing the helium through a control valve into a room temperature Warm Quench Buffer (WQB) with a volume of 80 m^3 .

The WQB is made of carbon steel, which limits its lowest operating temperature to -30°C . This requires for the cold helium expelled from line D to be heated before entering the WQB. For this purpose, a 150 m long non-vacuum insulated quench recovery line, acting as an atmospheric heat exchanger, is used to connect line D to the WQB.

Line D is also equipped with a safety valve (SV) for protection against accidental overpressure.

2.2. 1-D thermohydraulic model

The IT String quench recovery system has been simulated with the numerical tool EcosimPro [5]. The CRYOLIB library for cryogenic simulations developed at CERN [6] provides the user with pre-defined hydraulic components that can be interconnected to generate a 1-D thermohydraulic model of the system. Other components, like the safety valve, have been added to the existing library for the sake of this analysis. For all volume components, the balance equations for mass, momentum, and energy are solved. This allows the simulation of the analyzed system, including pressure losses and heat transfer. Figure 3 gives an overview of the quench recovery system as built in EcosimPro.

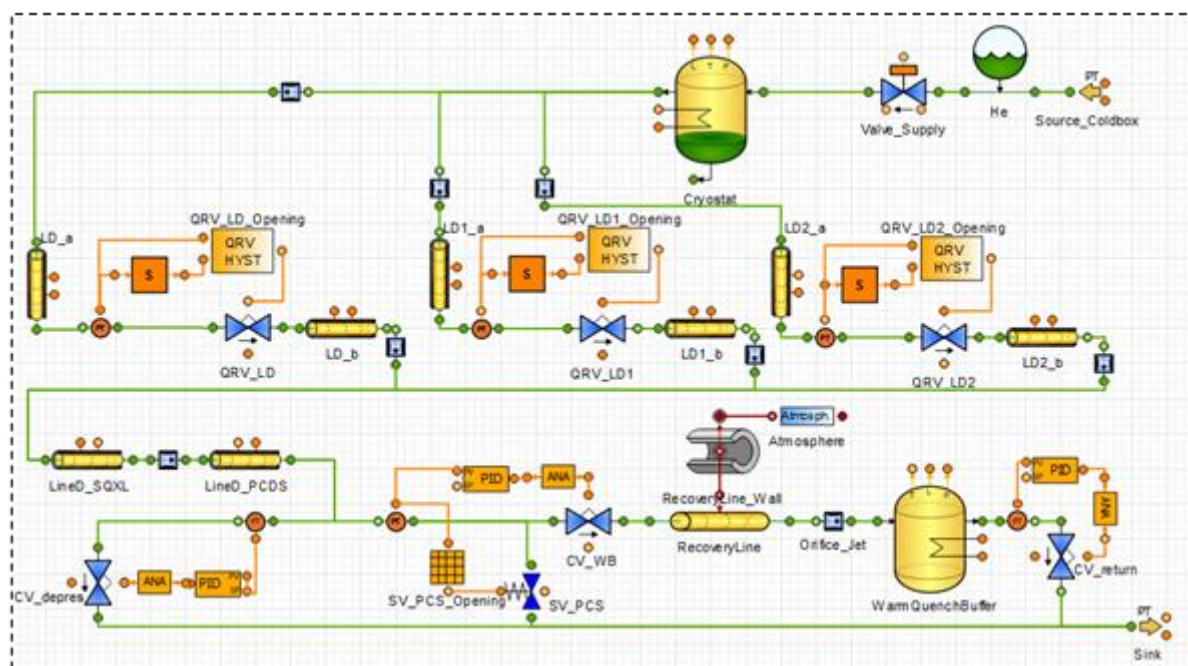


Figure 3. 1-D thermohydraulic model of the IT String quench recovery system in EcosimPro.

2.3. Modelling of the heat flow to the helium during a quench

Following a quench, the energy stored in the magnetic field is dissipated in the magnet coil within a few seconds. The coil may heat up to a temperature above 100 K, while part of the energy is transferred to the He bath. The heat flow from the coil to the helium depends on multiple factors including the geometry of the magnet, the insulation between coil layers and the coil impregnation. Due to the number of variables at play, accurate theoretical predictions of the heat transfer from the coil to the helium bath are difficult and experimental measurements provide more reliable information.

The empirical model used to reproduce the heat flow to the helium in the HL-LHC IT magnets is based on experimental data from the test of the LHC half-cell prototype during the String I program [7]. The model considers a single fluid volume for the He II bath and a single solid volume for the cold mass, mostly constituted of stainless steel and aluminium. Nearly perfect heat transfer is assumed between both volumes, meaning that the imposed heat flow is distributed between the metal cold mass and the helium depending on the ratio of their heat capacities. At the beginning of a quench, the heat capacity of the helium is dominant and most of the energy is transferred to the helium. As the temperature of the helium rises, the fraction of energy stored in the metal cold mass increases.

Figure 4 shows in dots the measured heat flow to helium after a quench of the LHC half-cell prototype with an initial energy of 15.3 MJ from [7]. The solid blue line represents the total heat flow from the coil to the cold mass and helium based on the heat capacity model described in the previous paragraph. The heat flow can be modelled with an exponential function over 120 seconds and an initial heat load of 375 kW. The dashed blue line represents the computed heat flow to the helium only. The model

estimates that 39 % of the energy initially stored in the magnetic field is transferred to the helium, which is above the measured value of 35 %. The model is therefore conservative regarding the heat load transferred to the cryogenic system. The orange solid line represents the total heat flow from the coil to the cold mass and helium for the HL-LHC IT String. The IT String heat flow model is based on the LHC experimental data and includes correction factors to account for the following differences:

- The peak coil temperature in the HL-LHC quadrupoles is expected to be about 30% higher than in the LHC String I dipoles because of the higher current density;
- The thermal resistance between the coil and the helium for Nb₃Sn coils is about one order of magnitude higher than for NbTi coils because Nb₃Sn magnets are fully impregnated with epoxy resin [1].

Assuming that the maximum heat load scales linearly with the peak coil temperature, the heat flow from the coil to the cold mass and helium in the IT String is modelled as an exponential function with an initial heat load of 500 kW. The quench energy is transferred to the cold mass and helium over 180 seconds due to the slower heat transfer resulting from the Nb₃Sn coil impregnation.

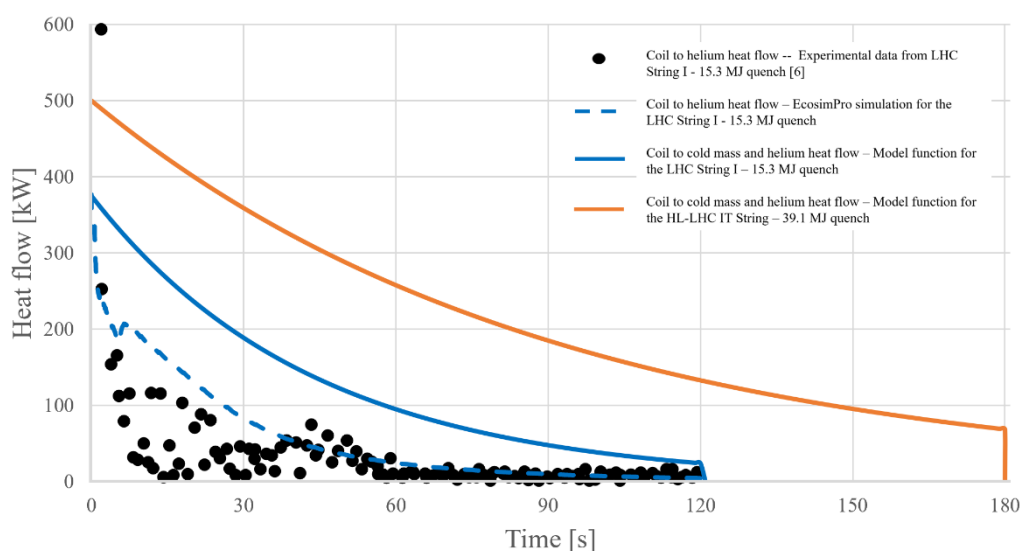


Figure 4. Measurement, simulated data and model functions for the heat flow from the coil to the cold mass and helium in the LHC String I and HL-LHC IT String.

3. Results and discussion

3.1. Sizing of the quench recovery system

The sizing case for IT String quench recovery system is a quench at nominal current, which releases 39.1 MJ of energy into the cold mass and helium. The design of the quench recovery system and the sizing of the hydraulic components (i.e. valves, orifices and piping) is an iterative process limited by the following constraints:

- Space availability in the magnet cryostats and the cryogenic distribution system for the routing of the quench lines (LD, LD1 and LD2) and line D;
- Requirement to re-use, where possible, existing equipment (i.e. the QRVs from the LHC, the quench recovery line and the WQB from LHC String I);
- Design pressure of the magnets (20 bar);
- Maximum time to recover nominal operating conditions following a quench (12 hours);
- Minimum operating temperature of the WQB (-30 °C).

The simulated pressure and mass flow evolution in the quench recovery system during a 39.1 MJ quench are shown in Figure 5 and Figure 6, respectively.

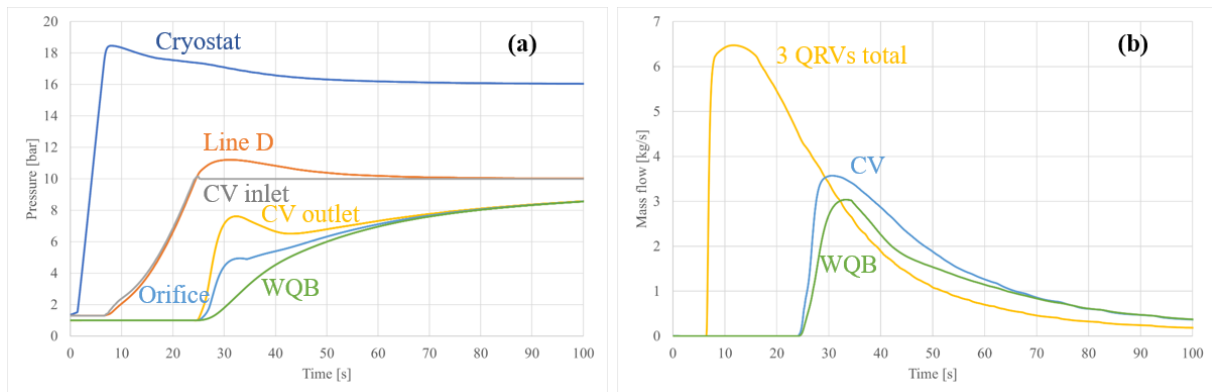


Figure 5. Simulated evolution of pressure (a) and mass flow (b) at different locations of the IT String quench recovery system in the first 100 s after a 39.1 MJ quench.

The models estimates that the pressure in the magnet cold masses reaches the QRV opening pressure of 17 bar six seconds after the quench is triggered and reaches a maximum value of 18.5 bar one second later. The maximum mass flow expelled from the magnet cryostat to line D is 6.5 kg/s. The mass flow is distributed over the three QRVs as a function of the hydraulic resistance of the quench lines. The maximum mass flow is observed in quench line LD with nearly 2.5 kg/s and a maximum opening of 30%. After 24 seconds from the start of the quench, the pressure in line D reaches 10 bar and the control valve to the WQB opens. The maximum mass flow through the control valve is 3.6 kg/s. At the end of the quench, the pressure in the magnet cryostat decreases to 16 bar, the reseating pressure of the QRVs. The final pressure in line D reaches 10 bar, the set point pressure of the control valve, while the pressure in the WQB increases to 9.5 bar. Due to the heat transfer from the environment, the final pressure in the WQB pressure varies with ambient temperature and the duration of the quench relief.

Figure 6(a) shows the temperature evolution in the cryostats and line D during a 39.1 MJ quench. The temperature in the cold masses increases continuously during the quench and reaches a final value of 28 K. The average temperature in line D initially drops from 20 K to 7 K as cold helium is expelled from the cryostats. It then increases to about 14 K at the end of the quench. Figure 6(b) shows the distribution of the quench energy among the cold mass and the different components of the quench recovery system. Most of the quench energy is initially transferred to the helium in the magnet cryostats. As the temperature rises, the heat capacity of the metal cold mass increases and the share of energy taken by the cold mass grows. The total energy fraction dumped into the helium is distributed between the helium in the magnet cryostats, line D, and the WQB at the end of the quench. According to the simulation results it amounts to 38% of the quench energy, which is in good agreement with the value of 35% observed during the quench experiments performed with the String I [7].

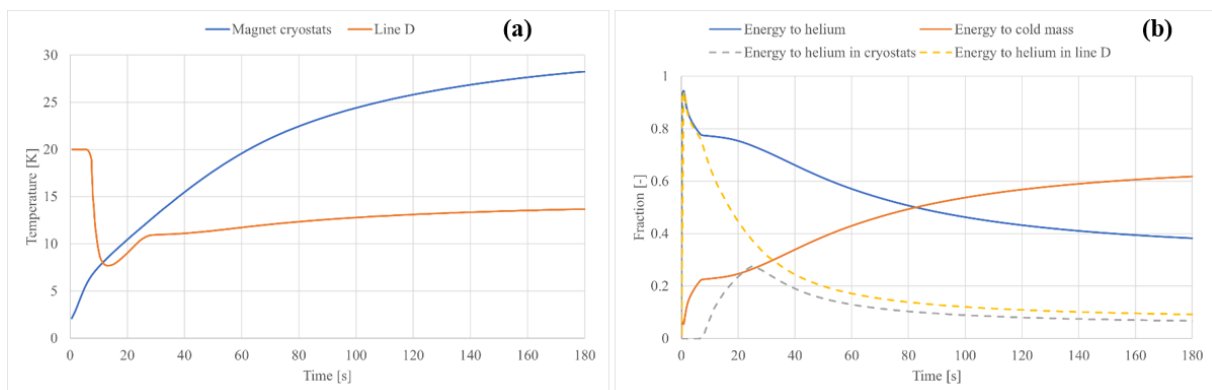


Figure 6. Simulated evolution of temperature (a) and energy distribution (b) during a 39.1 MJ quench of the IT String.

Table 2 summarises the value of the main variables describing the quench recovery system at the end of a 39.1 MJ quench. Only about 40 kg of the initial 220 kg of helium remain in the magnet cryostats. Line D stores about 60 kg of helium, while the remaining 120 kg are transferred to the WQB and the quench recovery line.

Table 2. State variables and energy distribution in the quench recovery system at the end of a 39.1 MJ quench. The masses in parenthesis correspond to initial values.

Item	Pressure [bar]	Temperature [K]	Helium mass [kg]	Quench energy [%]
Helium in cryostats	16	28	39 (221)	9
Cold mass	-			62
Helium in line D	10	14	61 (5)	7
Warm Quench Buffer	9.5	297	124 (13)	22
Quench recovery line		86	16 (<1)	

3.2. Mechanical integrity of the Warm Quench Buffer and design of the jet injection

Being made of carbon steel, the minimum operating temperature of the WQB shall be limited to -30°C . To prevent brittle fracture, the vessel wall temperature shall be above the minimum allowed value during the entire quench process under the most unfavorable operating conditions. These correspond to a 39.1 MJ quench occurring with an outside ambient air temperature of -10°C and with control valve CV accidentally fully open from the beginning of the quench. Figure 7(a) shows the evolution of the helium temperature at different positions of the quench recovery line and in the quench buffer during this scenario. Due to the compression of the helium entering the buffer, the temperature of the mixed helium in the WQB does not decrease below the initial value of -10°C . The helium temperature at the orifice placed at the WQB inlet reaches a minimum of about 140 K after 130 seconds from the start of the quench. This corresponds to a minimum temperature of 104 K of the choked flow in the orifice throat.

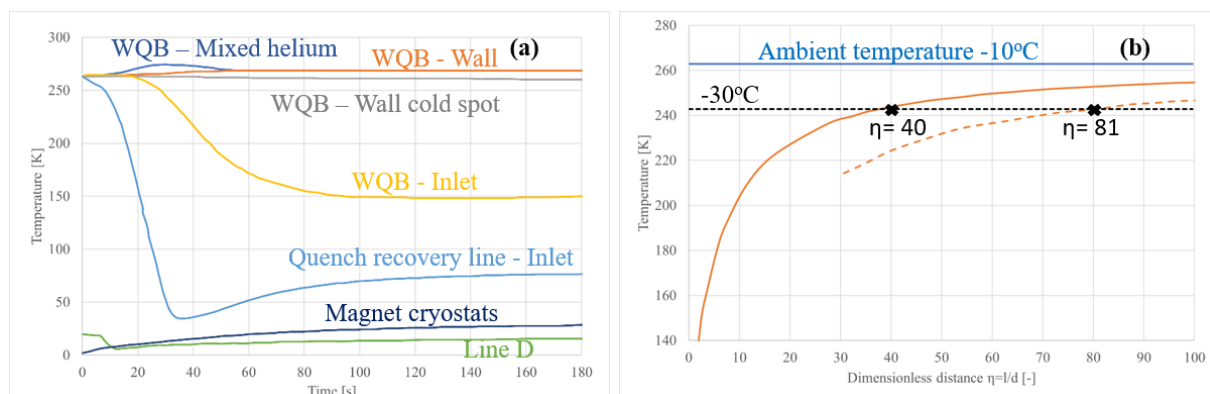


Figure 7. Simulated evolution of the temperature in the quench recovery system (a) and calculated jet temperature as a function of the distance from the orifice (b) during a 39.1 MJ quench and worst-case conditions.

To ensure mixing and avoid stratification of warm and cold helium inside the buffer, the helium shall be injected into the WQB as a turbulent jet. This is achieved by placing an orifice of diameter d_o at the WQB inlet. This strategy is derived from the LHC warm buffers [8]. The coldest spot in the vessel structure is located where the jet impinges on the vessel wall at a distance $x = l$ from the orifice, as

shown in the schematic of a turbulent jet in Figure 8(a). To determine the mean jet temperature $T(l)$ at the wall for a given inlet temperature $T(0)$, a 1-D model has been developed based on turbulent jet theory [9]. The model solves the steady-state area-averaged mass, momentum, and energy balance equations at discretised nodes along the dimensionless jet length $\eta = x/d_o$. The simulation model has been validated with experimental measurements of gaseous nitrogen cryogenic jets [9]. The solid orange curve in Figure 7(b) shows the jet mean temperature $T(\eta)$ for the worst-case scenario described in this section, corresponding to an initial orifice temperature of 104 K and an ambient temperature of -10°C . The dashed line gives the jet centreline temperature, which is estimated assuming that the centreline temperature difference, $\Delta T_{\max}(x)$, is twice the mean temperature difference, $\Delta T(x) = T(x) - T_{\text{amb}}$. For the dimensionless jet length $\eta = 81$, the jet centreline temperature reaches -30°C . This means that for jet lengths l above this critical value, the temperature at the wall will be above -30°C because the cold spot temperature T_{CS} is always above the wall impingement temperature $T(l)$ due to the thermal resistance between wall and fluid.

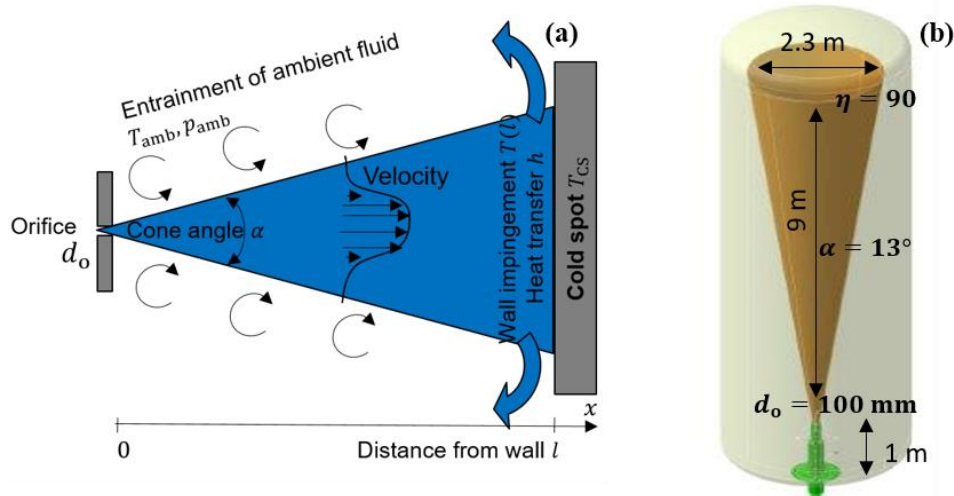


Figure 8. Schematic of a cryogenic jet and the relevant parameters (a) and visualization of the layout of the cryogenic jet in the IT String WQB (not in scale). Courtesy of J. Mouleyre (b).

Figure 8(b) shows the layout of the WQB inlet: an orifice placed 1 m above the WQB inlet flange creates a single vertical jet. The reaction forces on the short orifice inlet pipe are considerably lower compared to other studied solutions like a long vertical tube with multiple horizontal jets. This reduces the complexity of the thermal barrier between the cold orifice inlet pipe and the WQB vessel. The jet is modelled as an ideal cone with 9 m length and an experimentally determined opening angle $\alpha = 13^\circ$ [10]. To limit the pressure increase in line D to 10 bar, the required orifice diameter is 100 mm. The corresponding dimensionless jet length is $\eta = 90$; which is above the critical values shown in Figure 7 (b). At low flow rates, where buoyancy effects become important, the mixing length is sufficient to heat the cold gas to the minimum WQB wall temperature.

3.3. Recovery of operating conditions following a 39.1 MJ quench

Following a quench, the quench recovery system needs to re-establish the normal operating conditions of the IT String within maximum 12 h. The pumping capacity available in the SM18 cryogenic test facility for the exclusive use of the IT string is limited to 18 g/s. Due to the limited available pumping capacity, following a 39.1 MJ quench, the required quench recovery time cannot be met simply by re-condensing and re-filling the helium in the magnet cryostats. Instead, the magnet cryostats and line D are depressurized through two 15 kW heaters warming up a mass flow of 20 g/s, which is then recovered by the compression station. The depressurization phase is followed by the re-cool down via the cold box starting from the temperature of 28 K reached by the cold mass at the end of a 39.1 MJ quench. Table 3 details the sequence of the quench recovery phases. In total, a duration of 10.1 h is estimated to recover operating conditions following a 39.1 MJ quench, which is below the required time of 12 h.

Table 3. Quench recovery phases following a 39.1 MJ quench.

Phase	Initial temperature [K]	Duration [h]
Depressurization	28	1.2
Cold box reconfiguration	-	3
Cool down to 4.5 K	26.5	1.6
Magnet filling	4.5	2
Cool down to 1.9 K	4.5	2.3
Total	-	10.1

4. Conclusions

This paper describes the use of the EcosimPro tool for the design of the quench recovery system of the HL-LHC IT String in the SM18 cryogenic test facility at CERN. The results for a 39.1 MJ quench are detailed, which correspond to the worst-case scenarios for the sizing of the quench recovery system. The analysis demonstrates the sound and safe design of the HL-LHC IT String quench recovery system according to the requirements. Thanks to the 1-D flow modelling capabilities of EcosimPro, the complete system is modelled efficiently and dynamic effects arising during the quench can be accounted for in the design.

Installation of the HL-LHC IT String is currently underway and start of operation is planned in 2023.

5. References

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