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Analysis of quench safety and cryogenic energy recovery for FRIB High Transmission Beam Line magnets

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Abstract. The High Rigidity Spectrometer (HRS) will be the centrepiece experimental tool of the Facility for Rare Isotope Beams (FRIB) fast-beam program. The HRS project is staged in two phases: the High Transmission Beam Line (HTBL) phase followed by the Spectrometer (SPS) phase. The HTBL will contain 24 superconducting quadrupole magnets (in 8 triplet cryostats), four superconducting dipole magnets, and three (non-superconducting) vertical corrector magnets. In general, these magnets will store a peak energy of 300-400 kJ and the cryogenic boil-off flow from a quench induced heat release will be primarily handled by the novel FRIB quench energy recovery system. The magnet cryostats will be also equipped with pressure safety devices as auxiliary protection. A thermodynamic model to estimate a magnet cryostat pressurization due to quench, and subsequent release of cryogenic helium flow to the FRIB quench energy recovery system has been developed and validated using test data. The HTBL magnet cryogenic system response (heat release, subsequent pressurization and boil-off flow) during a quench is simulated using this model. The results are utilized to predict the overall system response and address relevant design issues e.g. sizing of magnet cryostat relief devices and relevant HTBL cryogenic system components.

1. Background

The high rigidity spectrometer (HRS) and the associated beamline will be a new experimental system segment at the Facility for Rare Isotope Beams (FRIB). For project management, scheduling and phased commissioning of this segment, it is separated into the high transmission beam line (HTBL) and the spectrometer segments (SPS). HTBL will have twelve (12) superconducting magnet cryostats (8 quadrupole triplets and 4 dipoles) requiring liquid helium cooling at 4.5 K. These cryostats along with the associated cryogenic distribution system is designed to utilize the FRIB quench energy recovery system [1]. This novel system can absorb the pressure pulse and energy from a magnet quench and contain the helium without venting and then recycle (*i.e.* depressurize and reliquefy) using the cryogenic refrigerator without affecting operation of the other loads within the same cryogenic distribution. The superconducting magnets for FRIB target and pre-separator segments were commissioned and presently being operated with this system. Based on the operational experience [2], the recovery time from a

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quench event (quench, energy dissipation, containment and re-fill) with this system is approx. 30 to 45 minutes.

The present paper discusses the design methodology for the over-pressure protection system of the HTBL superconducting magnet cryostats. A multi-layered over-pressure protection system is used – the preliminary one utilizing the FRIB quench energy recovery system and then the secondary one relying on independently sized traditional over-pressure protection devices. A brief description of the FRIB quench energy recovery system and its operating sequence following a quench is provided. The mathematical model developed to estimate the thermal energy release following a superconducting magnet quench and the associated system response is also described. The overall system response under different relieving modes (e.g. single coil quench, multiple coil quench, loss of vacuum) are evaluated and their results are presented.

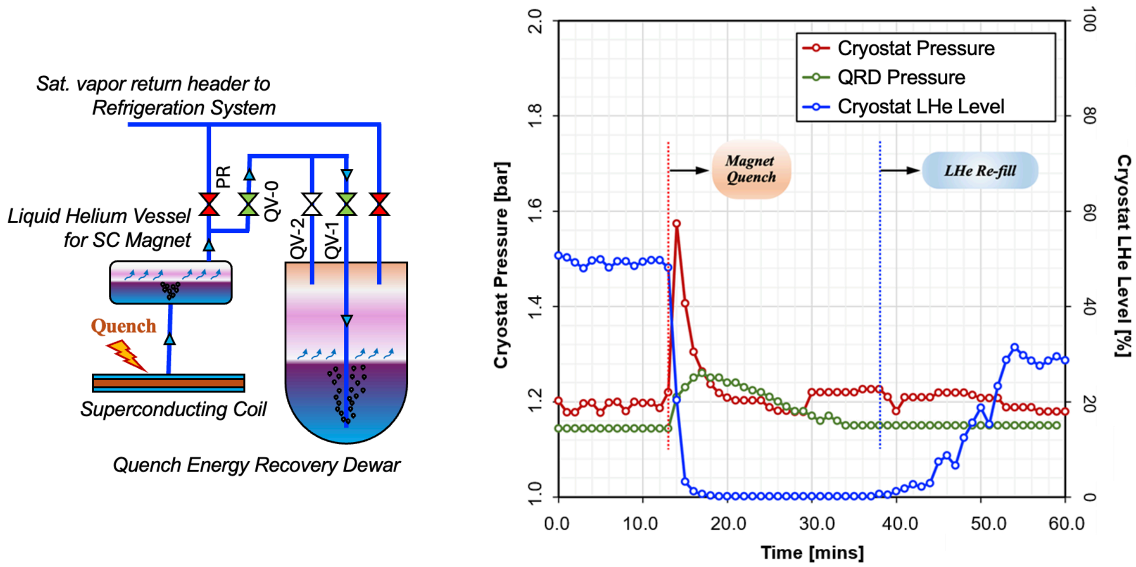

Figure 1. (left) Simplified schematic diagram of FRIB quench energy recovery system with a 10,000 liter quench energy recovery dewar (QRD) and (right) observed transient response of a FRIB pre-separator superconducting magnet cryostat (~ 100 liter LHe volume) and the QRD during a quench

2. FRIB quench energy recovery system

The energy release during a superconducting magnet quench can range from several mega-joules, up to giga-joules (magnetic field > 6T), while the stored liquid helium inventory in these magnets can range from hundreds to thousands of liters. Typically, the magnet cryostat is isolated from the rest of the cryogenic system at the onset of quench, to prevent it from affecting the operation of the rest of the cryogenic system. The subsequent pressurization of the cryostat due to the quench energy release is handled via a passive relief system (pressure relief valve or non-reclosing burst disk) and helium is vented to the atmosphere. This leads to loss of the cryogen (helium) inventory as well as refrigeration and have a significant impact on the operational cost and recovery period of the overall system.

A novel method of using a cryogenic buffer volume to absorb both the mass and energy release during the quench of a magnet has been considered in the past and implemented at the Facility for Rare Isotope Beams (FRIB) [2]. A schematic diagram for the concept of the overall quench energy and inventory management system is shown in figure 1(left). The system consists of a liquid helium buffer vessel (quench energy recovery dewar or QRD), cryogenic transfer lines for helium supply and return, and a separate cryogenic header serving as a conduit for the released flow during a quench. This header carries the released helium to the QRD (approx. 10,000-liter buffer volume) and sparges it into the liquid helium (via valves QV-0, on the cryostat and QV-1, on the QRD) in the buffer vessel. The resulting direct contact heat exchange between the liquid helium and the quench release flow cools the latter at the expense of generating more boil-off helium and hence pressurizes the buffer vessel. Practical feasibility of the quench energy and inventory management concept described above has been successfully tested and a typical observed system response is shown in figure 1 (right).

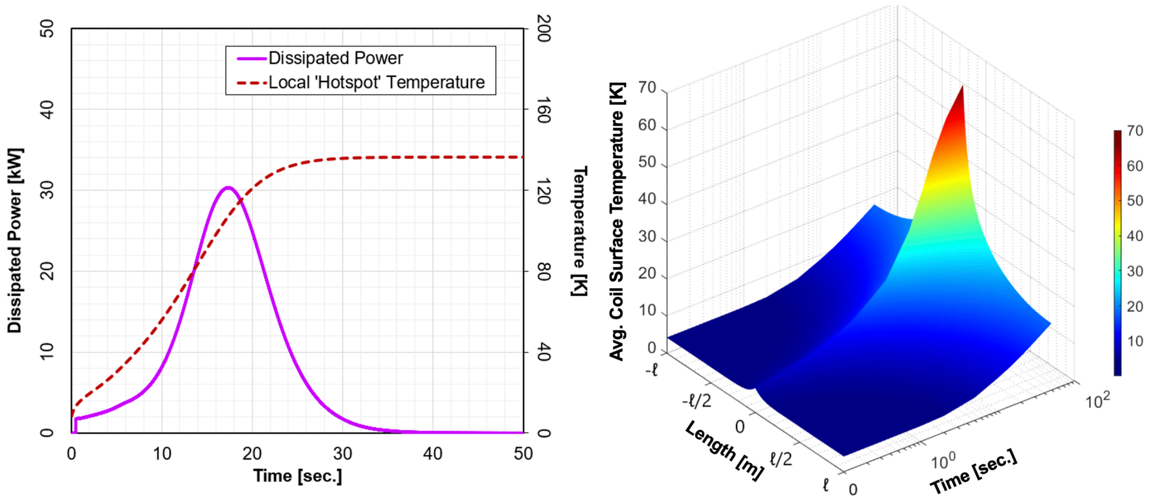

Figure 2. (left) Transient variation of dissipated power from the HTBL dipole superconducting coil and corresponding local '*hotspot*' temperature and (right) simulated spatio-temporal variation of the average coil surface temperature of the HTBL dipole magnet coil

3. Methodology and Model Development

A semi-analytical transient fluid network model for a superconducting magnet cryostat and associated quench energy recovery system discussed above was developed and published previously [3]. The model considers volume averaged properties for the magnet cryostat and the quench management dewar. Key aspects of the model are provided below.

3.1 Thermal energy release

The thermal energy released from the superconducting magnet to the helium following a quench is modelled in two different ways. The transient thermal energy release, $Q_{quech}(t)$ is independently estimated from the electromagnetic quench analysis of the superconducting coil. A fraction of this energy is consumed in raising the temperature of the coil (cold mass) and the rest is dissipated to helium, $Q_{He}(t)$.

For an intense relieving scenario (*e.g.* sizing pressure relief valve and non-reclosing burst disk), the heat transfer coefficient to the helium is considered infinite, and it is assumed that both the coil and the helium remains in thermal equilibrium. The thermal energy dissipation (to helium) function calculated with this assumption is defined as $Q_{He,A}(t)$. The overall transient internal energy of the lumped system (coil and helium), U_{sys} is calculated following energy conservation of the system:

$$U_{sys}(t,T) = U_C(t,T) + U_{He}(\rho,T) - m_{He,r}(t)h_{He,r}(\rho,T) + Q_{quench}(t) \quad (1)$$

Here, U_C is the internal energy of the coil mass, U_{He} is the internal energy of the cryostat helium mass, $m_{He,r}$ is the mass of helium relieved - which is zero until a relieving pressure is reached, and a finite calculated value to maintain the relieving pressure, $h_{He,r}$ is specific enthalpy of the relieving helium, and ρ is helium density. The transient equilibrium temperature, $T(t)$ is found solving eq. (1) at discrete times. The energy released to the helium is then found using:

$$Q_{He,A}(t) = Q_{quench}(t) - [U_C(t) - U_C(t - \Delta t)] \quad (2)$$

For a realistic relieving scenario, the realized thermal energy release to the helium is governed by finite heat transfer coefficients and the magnet coil and helium do not stay in thermal equilibrium. For such a case, a non-equilibrium thermal model comprising of a coupled three-dimensional solid conduction solver and an empirical convective heat transfer model is used. Development and numerical solution methodology for this model is described in [3]. The thermal energy dissipation (to helium) function calculated with this assumption is defined as $Q_{He,B}(t)$.

3.2 LTS magnet coil, associated piping and quench energy recovery dewar

The LTS magnet cryostat, valves and associated piping, as shown in figure 1(left), are simulated using a in-house one-dimensional, transient, hydraulic network solver. The following mass and energy conservation equations are simultaneously solved for any (cryostat) volume '*i*' –

$$V_i \frac{\partial \rho_i}{\partial t} + \sum \dot{m}_i = 0 \, ; V_i \frac{\partial \rho_i u_i}{\partial t} + \sum \dot{m}_i h_i = \dot{Q}_{He} \quad (3)$$

Here, $\dot{Q}_{He}$ is the heat dissipated from the superconducting magnet coil (obtained from either $Q_{He,A}$ or $Q_{He,B}$ discussed in Sec. 3.1, depending on the case simulated). The pipe is modelled as a one-dimensional element with a constant length (approx. 80 m long, governed by physical constraints of the associated cryogenic distribution) and hydraulic diameter. The valve is modelled as a point element with a flow resistance as specified by their respective flow coefficients. The piping hydraulic diameter and valve flow coefficients are selected from the analysis to meet an acceptable pressure drop during quench.

The QRD, as shown in figure 1(left), is simulated considering a volume averaged vessel. Given the initial liquid volume fraction (y_l) and the total volume of the QRD (V_{QRD}), the initial liquid mass fraction, total fluid mass, effective density and specific internal energy of the fluid in this vessel is calculated as follows –

$$x_l = \frac{\rho_l y_l V_{QRD}}{\rho_l y_l V_{QRD} + \rho_v (1 - y_l) V_{QRD}} \, ; m_f = \rho_l x_l + \rho_v (1 - x_l); \rho_{f,e} = \frac{m_f}{V_{QRD}} \, ; u_{f,e} = u_l x_l + u_v (1 - x_l) \quad (4)$$

Once the volume averaged initial conditions are calculated, the transient response of the quench recovery dewar is calculated following the mass and energy conservation equations –

$$V_{QRD} \frac{\partial \rho_{f,e}}{\partial t} + \sum \dot{m}_{He,r} = 0 \quad (5)$$

$$V_{QRD} \frac{\partial \rho_{f,e} u_{f,e}}{\partial t} + \sum \dot{m}_{He,r} h_{He,r} = 0 \quad (6)$$

Once the effective density, ρ and specific internal energy, u for the helium in each vessel (cryostat and QRD) is found at discrete times – the transient pressure is calculated following, $p = f(\rho, u)$.

3.3 Pressure safety device sizing

There are two over-pressure protection devices – a pressure relief valve (PRV) and a non-reclosing burst disk, for each of the superconducting magnet cryostat at the HTBL segment. Both devices are independently sized considering the most intense relieving mode (*e.g.* $Q_{He,A}$, loss of insulating vacuum). Given the relieving mass flow required, $\dot{m}_{He,r}$ and the process conditions (p, T), the effective flow area, A_{eff} is calculated following the homogeneous equilibrium model prescribed by Leung [4].

4. Results and Discussion

There are three different types of superconducting coils for the HTBL segment. These are the dipole coils, quadrupole coils A (QHA) and quadrupole coils B (QHB). The stored energy in each type of coils is approx. 0.37 MJ, 0.17 MJ and 0.34 MJ respectively. The quadrupole coils are packaged in a single cryostat with a triplet configuration (QHA, QHB, QHA). There are four identical dipole cryostats each with a liquid helium inventory of ~ 55 liters, and eight identical triplet cryostats each with a liquid helium inventory of ~ 550 liters. The following relieving modes are simulated for each type of cryostats:

a) Magnet quench (one coil) – energy release and recovery to QRD
b) Magnet quench (one coil) – energy release (thermal equilibrium)
c) Cryostat loss of vacuum (air or process / helium)
d) Cryostat loss of vacuum and subsequent quench (all coils)

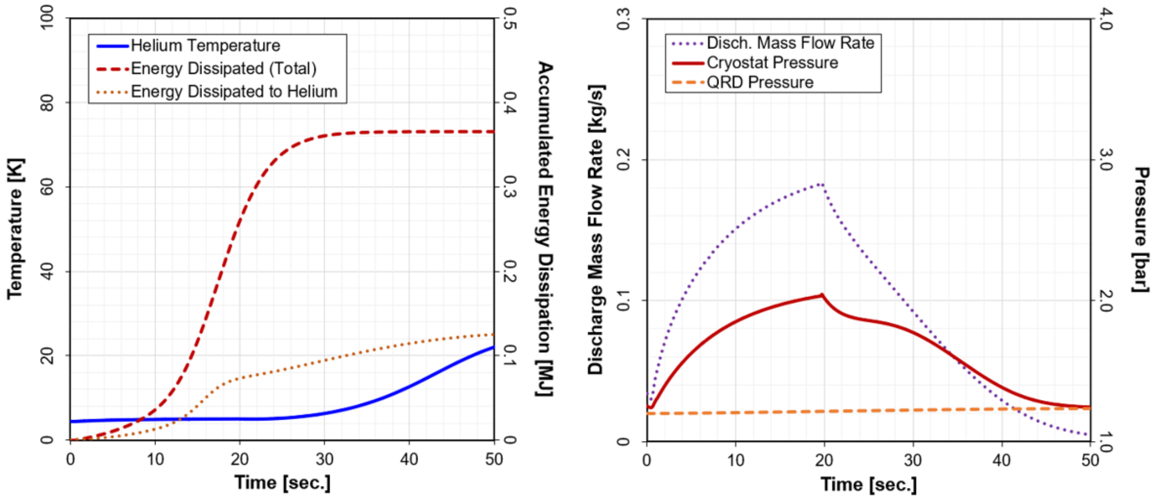

Figure 3. (left) Transient variation of dissipated energy from the HTBL dipole superconducting coil (total and to helium) with calculated helium temperature and (right) simulated transient variation of the cryostat and QRD pressures along with the discharge mass flow rate from the cryostat to the QRD under relieving mode (a)

For the sake of brevity, simulation results for only the HTBL dipole cryostat under relieving modes (a) and (b) are presented and discussed in the following sub-sections. The calculations for both type of cryostats summarizing the outcomes are presented in figure 4, tables 1 and 2.

4.1 Estimated cryostat response with quench energy recovery system

The total power dissipation and local '*hotspot*' temperature is estimated based on the electromagnetic analysis of the superconducting coil. Fig. 2 (left) shows the transient variation of the dissipated power and the corresponding '*hotspot*' temperature within the HTBL dipole coil as estimated based on the electromagnetic analysis. This coil has a 34 mm x 36 mm cross-section and approx. 6.3 m long perimeter (2ℓ). The average surface temperature at a given length of the coil due to solid conduction from the '*hotspot*' within the coil following a quench is solved using the coupled three-dimensional heat conduction solver and shown in fig. 2 (right). The corresponding energy dissipation (total and to the helium) and the helium temperature is calculated using the methodology described in Sec. 3.1 and [3]. They are shown in fig. 3 (left). It is observed that only one-third (approx. 0.125 MJ) of the dissipated energy is released to the helium (the rest is absorbed by the coil itself by conduction, there-by raising its average surface temperature substantially (up to ~ 70 K). In this case, it took approx. 22 seconds to boil-off all liquid helium in the cryostat. It is evident from the transient helium temperature shown in fig. 3 (left). The thermal-hydraulic response of the HTBL dipole cryostat and the QRD following a quench is presented in fig. 3 (right). The estimated transient variation of the cryostat pressure and the corresponding discharge mass flow rate (to the QRD via. valve QV-0 and QV-1) are shown in this figure. The transient variation of the QRD pressure is also shown. The estimated peak cryostat pressure and the corresponding peak discharge mass flow rates are 2.03 bar and 0.181 kg/s respectively. The corresponding pressure rise to the QRD is 38 mbar. Similar analysis is also carried out for the HTBL triplet cryostat. Fig. 4 (left) shows the estimated pressure rise in the QRD due to quench in the HTBL magnets based on the analysis methodology discussed in Sec. 3.1 and 3.2. The measured pressure rise in the QRD [2] during quench of the FRIB target and pre-separator magnets are also shown. A 3D model of the QRD (nominal 10,000-liter buffer vessel) is shown in fig. 4 (right). Typically, a liquid volume fraction of 40% is maintained in the FRIB QRD (operated at 1.20 bar). These initial conditions are used for the simulations. Based on the analysis, a valve with a flow coefficient, C_V of 3.25 for QV-0, and quench return piping with a hydraulic diameter of 42 mm (equivalent to 1.5 NPS Sch. 10 pipe) is selected.

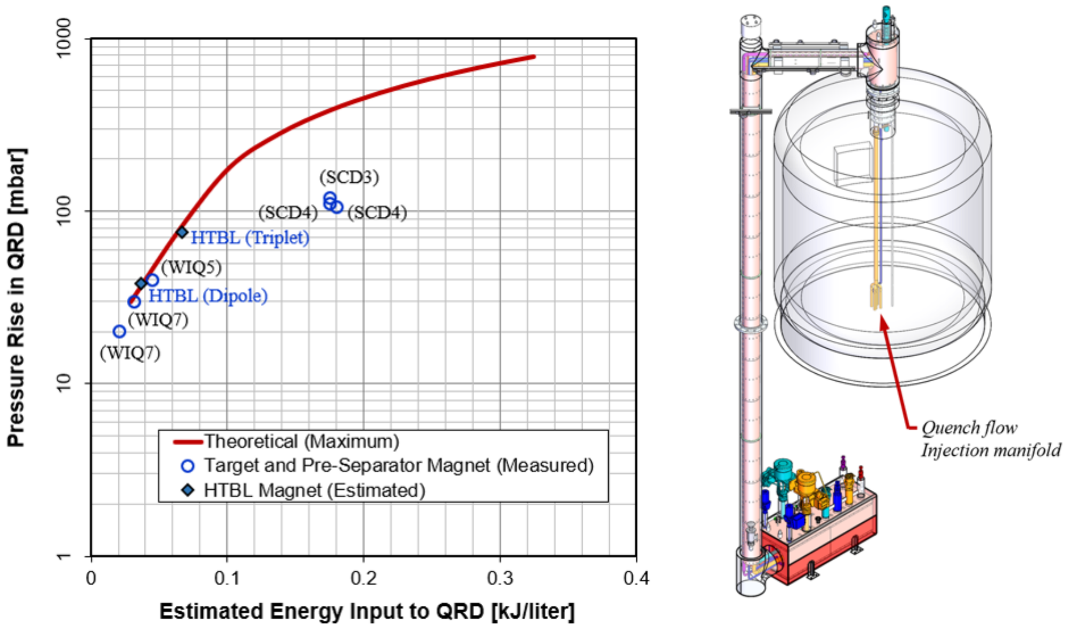

Figure 4. (left) Estimated and measured pressure rise in the QRD due to quench energy addition per unit volume and (right) 3D model of the FRIB quench energy recovery dewar (nominally 10,000 liter) and associated cryogenic distribution system.

4.2 Estimated cryostat response without quench energy recovery system

As mentioned earlier, it is considered that the thermal energy release from modes (b)-(d) are more intense in nature and are handled by over-pressure protection devices. Two pressure relieving devices are used in parallel with an offset in the relief pressure. The PRV has a relief set-point of 3.42 bar (35 psig), while the non-reclosing burst disk has a set-point of 4.11 bar (45 psig). Whether a relieving mode will be (independently) protected by the PRV or the burst disk, depends on intensity of the relieving flow rate. For example, relieving mode (b) for HTBL dipole cryostat is selected to be protected by the burst disk. Fig. 5 (left) shows the transient variation of the dissipated power, the corresponding energy dissipation (total and to the helium) and the equilibrium (helium and coil) temperature. It is observed that approx. two-thirds (0.227 MJ) of the dissipated energy is released to the helium. In this mode, it took approx. 12 seconds to boil-off all liquid helium in the cryostat. The thermal-hydraulic response of the HTBL dipole cryostat following a mode (b) quench is presented in fig. 5 (right). The estimated transient variation of the cryostat pressure and the corresponding discharge mass flow rate (to the atmosphere via. burst disk) are shown. The estimated peak discharge mass flow rate is 0.821 kg/s. The required effective flow area for this mode is estimated to be 270 mm^2 (0.42 in^2).

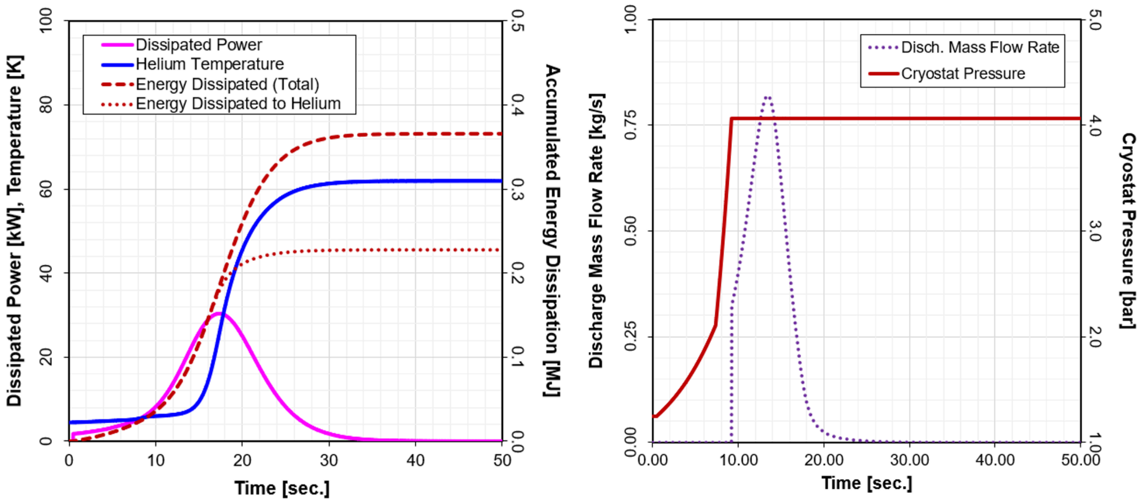

Figure 5. (left) Transient variation of dissipated energy from the HTBL dipole superconducting coil (total and to helium) with calculated equilibrium helium temperature and (right) simulated transient variation of the cryostat pressure along with the discharge mass flow rate from the cryostat to the atmosphere under relieving mode (a)

Table 1. Summary of HTBL dipole cryostat quench safety analysis under different relieving modes

Relieving Mode	Relief Device	Max. Estimated Relieving Flow, $\dot{m}_{He,r,max}$ [kg/s]	Temperature at $\dot{m}_{He,r,max}$ [K]	Required Effective Flow Area [mm^2]
(a)	QRD	0.181	5.04	N/A
(b)	Burst Disk	0.821	8.02	270
(c)	PRV	0.450	6.31	130
(d)	Burst Disk	0.711	7.42	200

Similar analyses are performed for the rest of the modes. For mode (c), a constant heat flux value of 1.7 kW/m^2 based on loss of insulating vacuum to a MLI wrapped vessel [5] is used. A summary of the outcomes of these analyses is presented in table 1. Analyses are carried out for HTBL triplet cryostat too. It is observed that individual coil quench from either QHA or QHB under mode (b) do not pressurize the cryostat to the minimum relieving pressure of 3.42 bar. Hence for mode (b), superimposed thermal energy release from all four coils of each quadrupole (QHA or QHB) is considered. Moreover, an additional case where thermal energy release from all coils of each quadrupole (*i.e.* total 12 coils) is also considered. A summary of the outcomes of these analyses is presented in table 2.

Table 2. Summary of HTBL triplet cryostat quench safety analysis under different relieving modes

Relieving Mode	Relief Device	Max. Estimated Relieving Flow, $\dot{m}_{He,r,max}$ [kg/s]	Temperature at $\dot{m}_{He,r,max}$ [K]	Required Effective Flow Area [mm^2]
(a)	QRD	0.186	5.12	N/A
(b)-QHA	PRV	1.590	5.00	240
(b)-QHB	Burst Disk	3.130	5.28	452
(b)-All	Burst Disk	7.650	5.68	1280
(c)	PRV	0.723	5.81	212
(d)	Burst Disk	8.471	5.74	1470

5. Summary

A detailed quench safety analysis for FRIB's HTBL superconducting magnet cryostats is performed using a semi-analytical transient fluid network model developed in-house. The overall methodology for designing the over-pressure protection system of such cryostats is discussed. The viability of recovering the relieving helium inventory from these cryostats under realistic scenario through a novel quench energy recovery system at FRIB is demonstrated. The associated cryogenic distribution system components are sized using the simulated thermal-hydraulic response of the cryostats. Several other relieving modes are also simulated, and the secondary (passive) over-pressure protection system components are sized based on these simulations.

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