Cryogenics for Super-FRS at FAIR

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Abstract

The challenge of cooling down the huge cold mass up to 1100 tons (dominated by iron) to 4.5 K is addressed as one of the most important features for Super-FRS cryogenics at FAIR. For such large cold mass precooling with LN₂ is necessary due to the reason that approximately 80% of the cool down load is from 300 K to 80 K. The capacity of the LN₂ precooler at 80 K as well as the 4.5 K cooling power have been specified in order to reach a reasonable cooldown time of three to four weeks. In the paper we will also discuss the technical issues for Super-FRS magnet testing at CERN in terms of the limitations of the cooldown / warmup rates on magnets, interface definition, and the magnet cryostat protection against over-pressure under worst-case scenarios, i.e., quench and insulation vacuum sudden loss to air, which are the key issues for the cryogenic test facility planning and machine protection at FAIR. Meanwhile the important features of the refrigerator and the cryogenic distribution system for the Super-FRS at FAIR will be discussed.

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Peer-review under responsibility of the organizing committee of ICEC 25-ICMC 2014.

Keywords: super-ferric magnets; cooldown; precool; cryogenic distribution; cryogenic interface; cryogenic operation safety

1. Introduction

The international Facility for Antiproton and Ion Research FAIR, is under construction at the GSI Helmholtz-center for heavy ion research near Darmstadt in the state of Hessen, Germany. It will allow scientists in Europe and the rest of the world for studying matter at the level of atoms, atomic nuclei, protons and antiprotons, heavy ions and neutrons, which covers a wide variety of basic sciences including structure of matter, evolution of the universe,

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atomic physics, plasma physics, nuclear matter physics and nuclear structure physics. Its core, a double-ring accelerator SIS100/SIS300 heavy ion synchrotron with a circumference of 1100 meters, will deliver ion beams of unprecedented intensities and energies for a complex system of storage rings and experimental setups. Among them is the Super-FRS Fragment-Separator, presently one of most important radioactive secondary beam fragment separators with large-acceptance in the world.

As shown in Figure 1(a), the Super-FRS at FAIR is equipped with a number of superconducting dipole and multiplet (quadrupole, hexapole, octupole and steering dipole) magnets, Winkler et al. (2008). It consists of the Pre- and Main-separators (FFP and FMF), the three branches, i.e., the High-Energy-branch (FHF), the Low-Energy-branch (FLF), and the Ring-branch (FRF) as well as the experiments, the R³B magnetic spectrometer (GLAD dipole) and the Low-Energy-Buncher (LEB). The optical lattice of the overall Super-FRS has a length of about 460 m in total, in which the beam line with length of about 365 m belongs to the FAIR start version. It refers to the first construction phase of the Super-FRS without the Low-Energy-Buncher (LEB) and the high energy cave upgrade. The schematic of the local cryogenic distribution for the Super-FRS is illustrated in Fig. 1(b).

The superconducting dipole magnet for the Super-FRS has a super-ferric (iron dominated) design with warm iron and a warm bore of large aperture, Müller et al. (2013). Only the upper and lower coils are housed in one cryostat and cooled in a liquid helium bath at 4.5 K, Xiang et al. (2010). In the Super-FRS, each dipole stage consists of three dipole units through which the secondary beam is bended about 30°. Each dipole stage is equipped with two multiplets, one before and one behind the dipole stage. The standard long multiplet consists of three superferric quadrupoles with cold-iron and up to six hexapole and steering magnets. All magnets are assembled in a common helium vessel of the multiplet cryostat and cooled with liquid helium at 4.5 K. The cold mass and the liquid helium inventory of individual cryostats in the Super-FRS of the FAIR start version have been listed in Table 1.

| SC magnet cryostats      | dipoles | long multiplets | short multiplets | GLAD dipole | Total magnet cryostat number |
|--------------------------|---------|----------------|-----------------|-------------|-------------------------------|
| Number                   | 24      | 22             | 7               | 1           | 54                            |
| Average weight of cold mass in individual cryostats [tons] | 1.7     | 42             | 15              | 25          | Total cold mass weight [tons] |
| Sum of cold mass weight of all magnets with same type [tons] | 40.8    | 924            | 105             | 25          | ~ 1,095                        |
| Liquid helium volume in individual cryostats [liters] | 25      | 1,300          | 900             | 525         | Total liquid helium volume [liters] |
| Sum of liquid helium volume in all cryostats of same type [liters] | 600     | 28,600         | 6,300           | 525         | 36,025                         |
In total, the Super-FRS with the start version consists of about 1,100 tons cold mass, mainly iron, and about 36 m³ liquid helium inventory, respectively. Because the LEB is foreseen as a further installation once the FAIR start version is complete, an additional 200 tons cold mass and 6.6 m³ liquid helium should be taken into account in the plan of the Super-FRS cryogenics. In the far future, the total cold mass up to 1,400 tons and the total liquid helium inventory of 47 m³ could be envisaged for the full version of the Super-FRS. Therefore it is a great challenge for the Super-FRS cryogenics to cooldown such a large cold mass.

2. Cooldown of the Super-FRS cold mass and LN₂ precooler

Due to the huge difference in the weight of cold masses, much higher cooling capacity is required for the long multiplets than for the dipoles. Obviously the cooldown time will be mainly dominated by the time used for cooldown of the 22 long multiplets and the seven short multiplets. In fact, there are only 40 tons cold mass from 24 dipoles which is less than 4% of the total cold mass for the Super-FRS start version. It is foreseen that the magnets are cooled down in groups, for examples, three dipoles in one dipole stage as one dipole group, and two multiplet cryostats before and after each focusing plane as one typical multiplet group. One of the special groups is the one in front of the target which consists of three final focusing multiplet cryostats. This group has the heaviest cold mass up to 102 tons. Therefore it will be intensively discussed as one example in terms of the cooldown analysis.

2.1. Cooldown of the final focusing multiplet group

The cooldown for three final focusing long multiplets is in series, which means that the cold helium gas is continuously flowing through the three multiplets one after another. This is the same arrangement as for the cooldown of the other magnet groups. Meanwhile the cooldown process is specified as three phases in time sequence in terms of different temperature stages, namely 300 K down to 100 K as phase 1, 100 K down to 6 K as phase 2 and the final cooldown to 4.5 K and liquid helium filling as phase 3.

For the epoxy-impregnated superconducting coils with racetrack shape, which have been designed and used for the Super-FRS dipole, quadrupole and sextupole coil windings, it was found out by Wilson (1983) that epoxy resin becomes brittle at low temperature and the so-called epoxy failures, i.e., micro-cracking and micro-fractures occur in resin. The reason is that the epoxy has a higher thermal contraction than the composite superconductor, to which it is glued and the resin is in tension after cooldown. A brittle material in tension may experience crack propagation under electro-magnetic forces, which cause the strain energy previously stored in the volume surrounding the crack is to be converted in heat and premature quench may be initiated. In fact no training effect is expected for the Super-FRS dipoles and multiplets.

There is evidence that epoxy failure is dependent on the temperature difference over the coil structure and the cooldown rate. Operation experience at CERN shows that one could control the cooldown / warm-up rates to keep the temperature difference upon the overall coil structure below the maximum allowed values. In fact, one of the important constraints imposed on the LHC magnets is given by the fact that the maximum temperature difference over any one magnet must not exceed 75 K, Riddone (2004). For large coil structures in the ATLAS superconducting magnet system, the maximum temperature difference must not exceed the 40 K limit from ambient to 75 K, Barth et al. (2006). According to the cooldown study for ITER, one should keep the magnet cooldown rate less than 1.0 K/hour in order to keep the temperature difference in all components below 50 K during the cool-down from 300 K to 80 K, Peng et al. (2013). A similar constraint has been specified for Super-FRS magnets cooldown from 300 K to 100 K when the individual magnets are tested at CERN and groups of them are in future operation at FAIR.

Cooldown calculation results in Figure 2(a) show the temperature of three long multiplets in front of the target and gaseous helium flow during cooldown from 300 K to 6 K. One can also see that a maximum cooling power of about 5 kW is required for the magnet group when the cooldown starts. As shown in Fig. 2(b), the stress analysis for the cryogenic interface between the multiplet cryostat and the local cryogenic facilities has been done under different scenarios, e.g., pressure test, cooldown and normal operation, etc.
Fig. 2. Cooldown calculation of three long multiplets in front of the target area (a) magnet temperature and cooling power; (b) stress analysis for the process headers at the cryogenic interface between the multiplet cryostat and the local cryogenic facilities.

Table 2. LN$_2$ precooler for 1,100 tons cold mass cooldown to 100 K.

| LN$_2$ precooler           | Cooling power [kW] | Helium flow rate [g/s] | Cold mass [tons] | Cooldown energy [GJ] | Cooldown time to 100 K |
|----------------------------|---------------------|------------------------|------------------|-----------------------|------------------------|
| Super-FRS start version    | 76                  | 368                    | 1100 (Iron)      | 89                    | 15 days                |
| CMS at CERN [8]            | 30                  | 200                    | 225 (Al)         | 40                    | 14 days                |
| ATLAS at CERN [9]          | 60                  | 320                    | 680 (Al)         | 121                   | 21 days                |

2.2. LN$_2$ precooler

In order to have a reasonable cooldown time of three to four weeks for the Super-FRS, a large capacity of cooling power by using LN$_2$ precooling is foreseen for the cooldown phase No. 1 down to 100 K. Table 2 contains some of the most important parameters of the precooler for the Super-FRS. As comparison two existing LN$_2$ precooling machines for the cooldown of the CMS and the ATLAS detectors at CERN are listed as well, Delruelle et al. (2006).

3. Cryogenic distribution and heat load budget of the Super-FRS machine

The cryogenic distribution system, already schematically shown in Figure 1(b), consists of four branches A, B, C, and D. The cold helium at 4.5 K and 50 K is delivered from the cold box of the cryoplant (CRYO1) via the main transfer line to the helium distribution box, the so-called Branch box at the beam branching area. After subcooled in the Branch box, the 4.5 K supercritical helium is further distributed into the four branches in parallel. The longest Branch A extends its far end to the target area with a total length of about 250 m. To have sufficiently cold helium supply over the last 50 m distance to the three final focusing long multiplets before the target, one additional subcooler close to the target area is planned to compensate the heat in-leak over the first 200 m of transfer line.

Table 3. Heat load budget of Super-FRS cryogenics.

| Static heat loss | 4.5 K [W] | 50 K to 80 K [W] | Liquefaction [g/s] |
|------------------|-----------|------------------|-------------------|
| Magnet cryostats | 580       | 5500             | 6.2               |
| Local cryogenics | 600       | 4800             |                   |
| Total            | 1180      | 10300            | 9.3               |
| With design factor of 1.5 | 1770 | 15450            |                   |

Table 4. Sizes of four process headers.

| Process lines | DN / size [mm] |
|---------------|----------------|
| 4.5 K supply  | DN50 / 60.3    |
| 4.5 K return  | DN100 / 114.3  |
| 50 K supply   | DN50 / 60.3    |
| 80 K return   | DN50 / 60.3    |
Table 5. Pressure drop in the return header over the full length of the Branch A under different operation scenarios.

| Scenarios                       | Mass flow rate [g/s] | Pressure at return of cryoplant [kPa] | Temperature at cryoplant supply [K] | Pressure at target area [kPa] | DP calculation [kPa] | DP / P at cryoplant [%] |
|--------------------------------|----------------------|--------------------------------------|-----------------------------------|------------------------------|---------------------|------------------------|
| Normal operation /4.5 K standby | 125                  | 125                                  | 4.4                               | 125.3                        | 0.3                 | 0.2                    |
| Cool down (CD)                 | 289                  | 200                                  | 300                               | 288.1                        | 88.1                | 44.1                   |
| 80 K Cold floating (CF)        | 108                  | 1285                                 | 80                                | 1288.7                       | 3.7                 | 0.3                    |
| Warm up (WU)                   | 289                  | 200                                  | 80                                | 222.0                        | 22.0                | 11.0                   |

The static heat load budget for the magnet cryostats and the local cryogenic distribution of Super-FRS is summarized in Table 3. Taken the design safety factor of 1.5 into account, the cooling capacity of the cryoplant CRYO1 has been estimated at about 1.9 kW at 4.5 K, 17 kW at 50 to 80 K, 11 g/s liquefaction and one LN$_2$ precooler for cooldown purpose in addition. As listed in Table 4, the four process headers in the transfer line of the four branches have been sized with the acceptable pressure drops at different scenarios under the conditions of cryoplant operation. It is assumed that the process lines should be large enough to deliver the full capacity of the cryoplant CRYO1 through the longest Branch A under the following scenarios: cooldown (CD) of the full branch of magnet cryostat and local cryo-distribution together; normal operation or standby at 4.5 K of the branch; cold floating (CF) of the branch at 80 K and warmup (WU) of the complete branch. At normal operation conditions as shown in Table 5, the total pressure drop in the return header over the full length of Branch A is about 0.2% of the nominal pressure, 1.25 bar at the cold return port of the CRYO1 coldbox. Meanwhile the total pressure drop in the supply header is less than 0.3% of the nominal pressure, 4.0 bars at cold supply port of the CRYO1.

4. Interface definition for the test at CERN and magnet cryostat protection of the Super-FRS machine

The interface definition between the local cryogenic distribution system to both dipole and multiplet cryostats is one of the most important aspects for the Super-FRS machine design and the magnet test facility at CERN as well. As already shown in Figure 2(b), the process headers in the interconnection jumper line of the cryogenic distribution are connected with the counter parts in the multiplet cryostat via the interface flanges. The results of thermal stress analysis by using ANSYS 14.5 for both the vacuum barrier and the process lines with bends are also illustrated. The spring rates of the bellows are specified after optimizing of the mechanical forces on the magnet cryostat interface flanges and on the cryogenic distribution system. Concerning the magnet cryostat protection during operation, two scenarios have been investigated. In the first case, as shown in Figure 3(a), the full electromagnetic energy is deposited in the helium system of the long multiplet cryostat due to a quench by accident in the magnet. The second case, as shown in Figure 3(b), is over-pressurization of the helium vessel when an insulation vacuum loss to air occurs, Lehmann (1978). The safety devices have been specified under these two scenarios according to the European Standards DIN/BS EN 13458 and 13648 for design, fabrication, safety devices and test of static cryogenic vessel.

5. Conclusion

Cooldown of the 1,100 tons cold mass down to 4.5 K has been addressed as one of the great challenges for the Super-FRS cryogenics. For the iron dominated cold mass the advantage of using LN$_2$ precooling at 80 K is obvious in order to have a reasonable cooldown time of three to four weeks down to 4.5 K operation temperature. The size of the LN$_2$ precooler has been specified. To deliver the large cooling power over the Super-FRS under different scenarios, the process headers in cryogenic transfer line of the four branches have been sized sufficiently large upon the cryoplant conditions. Interface definitions always give critical influence on both the helium distribution system and the magnet cryostats design in terms of mechanical forces and deformation compensation. Last but not least the safe operation during the life time of the Super-FRS can only be guaranteed by correct sizing of the safety devices under the worst-case analysis, i.e., a quench by accident with full energy deposition in the helium system and the over-pressurization of the helium vessel in the case of a sudden loss to air of the insulation vacuum. The European Standards DIN/BS EN 13458 and 13648 are implemented.
Fig. 3. (a) prediction of energy deposition in helium due to a quench by accident; (b) prediction of over-pressurization in the helium vessel in the case of an insulation vacuum failure to air under the assumption that no safety release occurs.

Acknowledgements

The authors appreciate Dr. Ruggero Pengo, INFN-LNL, Italy for his consultation on the Super-FRS cryogenics.

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