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Design Criteria of the Cryogenic System for the CERN LHC Injection Lines

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Abstract

Protons to the CERN LHC will be supplied from the SPS accelerator via two new injection lines. The lines include three bending arcs for horizontal beam deflection and are characterized by a strong inclination (7.2 % maximum slope) to overcome the difference in height (40 m) between the two machines. They will be equipped with superconducting dipoles operated at a field of 5.4 T and 4.4 K. The distribution to the magnets of liquid helium in strongly inclined channels and over a distance of several hundred meters represents a considerable cryogenic challenge. A preliminary design of the cryogenic system is under way and the cooling schemes suitable to the unusual geometry are reviewed. The basic requirements of the refrigerating system and a tentative layout of the cryoplants are presented.

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INTRODUCTION

To supply protons to the Large Hadron Collider (LHC) from the 450 GeV Super Proton Synchrotron (SPS), two new injection lines are being studied (Fig.1). The first one (TI 13, about 1000 m long) has a single arc of 650 m. The second one (TI 87, about 2400 m long) is made of two arcs (450 m and 620 m long) separated by a long straight section. The two lines extract the protons from the SPS in straight sections LSS5 and LSS4 and, after transfer along new tunnels, inject them respectively in LHC straight sections 1 and 8.

In addition to the horizontal bending, the two injection lines will deflect vertically the beam from the SPS downward to the LHC to overcome the difference in height of the two tunnels (about 40 m). The maximum slopes expected are respectively 7.2% and 3.4 %.

To provide the necessary integrated field, it is envisaged¹ to equip the three arcs with superconducting (SC) dipoles of HERA/UNK type whose performance (5.4 T) will meet the new requirements. In total, about 170 dipoles (5.7 m magnetic length) and 70 quadrupoles (1 m magnetic length) are foreseen. A preliminary layout of the present half-cell is shown in figure 2. Quadrupoles and correctors are also assumed to be superconducting.

Figure 1 : Beam transfer through the injector chain.

Figure 2 : Tentative layout of a half cell of the transfer line FODO lattice.

COOLING SCHEMES

HERA/UNK type magnets are cooled in series^{2,3} by a forced flow of supercritical helium (0.3 MPa, 4.4 K). The helium flow is split in three parallel streams at the inlet of each magnet and collected at the outlet before entering the next magnet. At the end of one string of magnets (630 m long in HERA, 680 m in UNK), the liquid is expanded and returned at about 0.11 MPa into the magnets, recooling in counterflow (almost isothermal two-phase flow) one of the single phase stream.

Reliable and stable operating conditions have been achieved² in HERA with the two-phase flow directed upward with a maximum slope of 1%. Horizontal two-phase flow conditions are planned at UNK. In both cases, the operating temperature of the magnets is below 4.6 K.

A similar solution cannot be applied to the CERN topology, since the hydrodynamic behavior of the two-phase flow in strongly inclined channels cannot be predicted. Moreover, the length of one arc (about 600 m) and the lack of modularity make it impossible to construct a facility of reasonable size to test the overall stability of the system.

Single phase cooling scheme with coolers

Single phase cooling (Fig.3) without two-phase counterflow is, at present, considered more adequate to the strongly inclined geometry. The helium stream (60 g/s), provided by the refrigerator installed in each of the three arcs, is periodically recooled by heat exchangers immersed in a saturated bath of liquid. These coolers, installed every cell (47.8 m long, six dipoles and two quadrupoles), should limit the temperature rise of the magnets to less than 0.25 K. In figures 3 and 4, the indicated pressures are for an inclined geometry (40 m difference of level) with the return gas flow directed downward.

Figure 3 : Single phase cooling scheme

To avoid long and expensive transfer lines running in parallel to the magnets, we intend to use the upper and lower existing channels (both of 5.7 cm internal diameter) located inside the cold iron. They will, respectively, collect the gas evaporated in the baths and supply the supercritical liquid to the various J-T valves at the inlet of each bath. The two single phase streams will flow in a thermally insulated pipe inside the existing 5.7 cm channels to prevent possible heat propagation from one cell to the other.

Figure 4 : Two phase cooling scheme

Alternative two-phase cooling scheme with phase separators

The single phase stream (60 g/s) is cooled by the two-phase counterflow (Fig.4) in one of the two 5.7 cm channels, as foreseen for UNK and already operating in HERA. Gas-liquid phase separators (every cell or half cell) are placed in the two-phase stream. The gas is progressively collected in the upper channel while the saturated liquid from each separator flows into the lower channel to cool the single phase. In this case, only the gaseous stream will flow into a pipe thermally insulated from the 5.7 cm channel.

One valve is required at the inlet of each phase separator to control level and pressure. The important additional function of these valves is to reduce the hydrostatic pressure head in the two-phase channel and to match it with the pressure of the return gas line.

The proposed scheme tends to separate hydraulically one cell from the next one and maintains almost isothermal cooling flow conditions. The periodic phase separation minimizes the risk of possible settling of hydrodynamic instabilities and offers the advantage of increasing the wetted perimeter of the channel by a higher liquid content in the return two-phase stream (lower average quality factor).

Common aspects

A common feature of the proposed schemes is the position of the refrigerator cold box at the bottom of the superconducting arc to take advantage of the lower average cooling temperature for a given return pressure to the refrigerator. In fact, the recooling or phase separator temperatures are established in the return gas collector by the pressure drop which is negative since the hydrostatic pressure head overcomes the friction pressure drop. Furthermore, because of the increasing hydrostatic pressure, possible liquefaction which might affect the flow stability in the gas return line is prevented (isentropic compression instead of expansion).

An exception can be made for the upper arc of the longest injection line, where it might turn out that a bottom cold box is not feasible for civil engineering reasons. Here, the hydrostatic pressure head effects are minimized because of the reduced difference in height. In particular, the phase separator solution would need, for this arc, a modification. The phase separators inlet valves must be placed at the outlet, to drive out the flow of liquid from one separator to the next one through the magnets of one cell.

Another common feature is the cooling of the thermal screen of the magnets by high pressure (maximum 2 MPa) helium gas via a 5 cm diameter pipe welded to the aluminium shield. Alternative use of liquid nitrogen is unacceptable because of safety considerations relating to underground applications and, moreover, need of a complicated subcooling system to prevent two-phase flow instabilities.

Cooldown and warm-up

Cooldown and warm-up of an arc will follow studied guidelines for HERA and UNK^{4, 5, 6} and operational sequence already successfully achieved in HERA².

Each superconducting arc will be cooled down from the two ends (100 g/s at each end) to reduce the flow impedance. One of the two pipes used for the thermal shield of the magnets will drive the cold helium at the opposite end of the arc. Outlet gas from the magnets is collected in the middle of the arc and will flow back to the refrigerator via the quench collector.

For warm-up, an additional external high pressure pipe will drive the helium at both ends. Heaters are necessary to keep at ambient temperature the gas extracted from the magnets and to increase up to 320 K the temperature at the two inlets to speed up the magnets warm-up when close to room temperature.

In both cooldown and warm-up, the helium will flow through the three annular slits of the single phase volume to improve radial heat exchange.

The proposed scheme does not allow warm-up of a limited number of magnets (for replacement or repair work of one of them) without warming up the corresponding entire arc. Limited heating of magnets (one cell) is feasible but entails excessive complication in both cryogenic and beam vacuum systems.

COOLING POWER

The cooling power will be generated by three separate cryogenic stations (one for each arc of SC dipoles).

The estimation of the cooling powers for each station is based on the following values:

- 8 W per magnet at 4.3 K.

Average value for all magnets (dipoles and quadrupoles). This value includes cryogenic end connections. The static losses only are considered, the AC losses are not included since SC magnets on injection lines do not need to be pulsed.

- 250 W at 4.3 K per arc.

For additional cryogenic components in one arc (recoolers or phase separators, valves, cold couplings, etc.).

- 200 W at 4.3 K per arc.

For transfer lines interconnecting the refrigerator cold end to the beginning of the superconducting arc.

- 30 W per magnet at 60 to 90 K.

Average value for all magnets (quadrupoles and dipoles) for magnet shielding.

- 1600 W at 60 to 90 K.

Thermal load per arc for the shield of the transfer lines.

- 3 g/s liquefaction load for current leads.

- 10 g/s liquefaction load to fill the magnets and auxiliaries of one arc in less than 48 hours.

The total cooling powers per arc are then:

- 1220 W at 4.3 K.
- 4800 W at 60 to 90 K.
- 13 g/s liquefaction capacity.

The corresponding entropy flow to the refrigerator is 710 J/(K·s) giving an equivalent total cooling capacity at 4.3 K of 3000 W per station.

Cooldown of the large iron mass (about 10^6 kg in total for the three arcs, 30% of HERA) can be done in less than 10 days using liquid nitrogen. About $8 \cdot 10^{10}$ J must be extracted by boiling off liquid nitrogen, cooling a heat exchanger in each of the three cold boxes. For the three arcs, 400'000 litres of liquid nitrogen are necessary.

The full liquefaction capacity is only needed when filling the magnets. During normal operation, this overcapacity is not used and, therefore, the above figures include a 40% cooling power redundancy.

LAYOUT

Refrigerators

It is planned to locate the three refrigeration stations at LHC points 1 and 8 and SPS point 4 to make use of existing civil engineering. Compressors and cold boxes will be independent from the LHC main facilities, improving operational flexibility and allowing mixed duties (warm-up and cooldown) for the LHC octants and the corresponding superconducting arcs of the injection lines.

As for LHC main ring, split cold boxes (upper and lower linked by lines transferring helium at 20 to 30 K) are envisaged. The slight increase of entropy input (3% of the total) and the need of additional transfer lines (about 150 m long) are largely compensated by:

- the minimization of the underground space requirements
- the elimination of vertical transfer lines to supply underground large quantities of liquid nitrogen involving considerable safety implications.

Auxiliaries

The auxiliaries (helium gas storage, liquid nitrogen supply, purifiers, etc.) can be shared with the very large ones foreseen for LHC (points 1 and 8) by adopting common solutions. Helium gas will be stored⁷ at ground level in medium pressure (2 MPa) buffer volumes installed near the compressors area for each arc. Depending on final design, a total storage capacity at room temperature for 3000 to 4000 kg of helium is needed for magnet filling or refilling after quenches. Furthermore, a liquid nitrogen storage facility at each refrigeration station (50'000 litres $\cdot$ 3 arcs to be refilled by trucks) will allow cooldown operation.

Recovery of helium after quenches or during warm-up will be done via a quench gas collector (50 cm diameter, 2 MPa) connected to the buffer volumes. The supercritical helium vessel of the magnets is designed for a maximum working pressure of 2 MPa and each of them will be protected against overpressure with a safety relief valve⁸ discharging the helium into the quench collector.

TECHNICAL DEVELOPMENTS AND CONCLUSION

Single phase cooling, without continuous heat extraction by the two-phase counterflow, eliminates the risk of hydrodynamic instabilities. However, it introduces complications (recoolers) and adopts a cooling method different from that originally foreseen for UNK magnets and already successfully operated in HERA.

Two-phase counterflow allows almost isothermal cooling and the insertion of phase separators minimizes (but not entirely eliminates) the possible settling of hydrodynamic instabilities. This solution offers the possibility of developing a new challenging cooling scheme for SC magnets with two-phase flow over very long distances in strongly inclined channels. Its modularity allows the construction of a facility of reasonable size to verify the validity. However, since it introduces several unknowns and its feasibility is still doubtful, this solution is considered as a side line of development.

Studies are already in progress for the two above-mentioned schemes and tests are planned at IHEP (Russia) to finalize the design of the cryogenic system.

Some general guidelines and the preliminary needs for the cryogenic system are presented in preparation of more detailed studies.

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