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THE TESLA CRYO-PLANTS

H. Quack, M. Kauschke, C. Haberstroh, TU Dresden, 01062 Dresden, Germany
H. Lierl, B. Petersen, S. Wolff, DESY, Notkestr. 85, 22607 Hamburg, Germany

Abstract

The Tera-eV Energy Superconducting Linear Accelerator (TESLA) is a 32 km long superconducting linear electron/positron collider of 500 GeV centre of mass energy (upgradeable to 800 GeV), presently in the planning phase at DESY [1,2]. About 21000 superconducting RF 9-cell cavities have to be cooled with superfluid helium at 2 K. The cavities are assembled in groups of 12 into about 16 m long cryo-modules. The roughly 1800 cryomodules are arranged in an underground accelerator tunnel in 12 about 2.5 km long cryo-units. Except for the 2 first cryo-units every 2 cryo-units will be supplied from one refrigerator in a refrigerator hall above ground. The first two cryo-units have individual refrigerators in individual refrigerator halls.

The design goals for the cryoplants are reliability, simplicity and low installation and operating cost.

1 RELIABILITY, REDUNDANCY AND COST

The refrigeration system needs to have an availability of over 95%. Because the refrigerators in all 7 refrigeration halls have to be working at the same time, each single hall has to have an availability of at least $(0.95)^{1/7} = 99.3\%$. So availability has highest priority in all design considerations.

The first questions is, whether in each refrigerator hall one should install one large refrigerator or multiple refrigerators with e. g. 2 * 100 % or 3 * 50 % capacity including redundancy.

The sources of unavailability in existing cryogenic refrigeration systems have been investigated to find out, whether the installation of multiple refrigerators would increase the availability. Table 1 shows the main causes of unavailability in order of the frequency of their occurrence.

It turns out that concerning the four most frequent sources of unavailability the effect of multiple plants is either small, negligible or even detrimental. Only in case of a catastrophic component failure like loss of vacuum or oil spill into the cold box piping, there would be a clear advantage of multiple refrigerators, but these effects have occurred very seldom in the latest generation of helium refrigerators.

So after consultancy with CERN, which was confronted with a similar question, when a decision had to be made for the LHC cryogenic system, and with refrigerator manufacturers, we decided to go for just one single large refrigerator at each of the seven refrigerator halls with some built-in component redundancy and a clear strategy to fight impurities.

Table 1:Main Sources of Unavailability in Existing Refrigerators

	Source of Unavailability	Example	Multiple refrigerators ...
1	External utility failures	Electrical power, cooling water, instrument air	would bring no advantage
2	Blockage by frozen impurities	Air and/or water vapor	provide a little larger tolerance
3	Operational problems	Controls, instrumentation, operators	are detrimental due to higher complexity
4	Single component failure not leading to total plant shutdown	Motor burnout, compr. bearings, leaking oil pump seal, turbine bearing trouble	would bring no advantage over part redundancy within a single refrigerator
5	Catastrophic component failure leading to plant shutdown	Loss insulation vacuum, rupture heat exchanger, oil spill into CB	would have a positive effect

Further discussions with manufacturers showed that the required size of the refrigerator is about 20 % larger than the largest existing LHC refrigerator, but the cold components still fit into one single horizontal cold box, which is transportable across the road.

2 REFRIGERATOR SIZE

Table 2 shows the cooling requirements of the 7 halls.

Table 2: Design Heat Loads [kW]

T	Hall 1	Hall 2	Hall 3	Hall 4	Hall 5	Hall 6	Hall 7
2 K	3.70	3.07	4.23	4.21	3.87	5.13	4.22
5 K	4.73	4.60	7.42	7.39	6.88	8.25	7.36
40 K	44.6	53.5	80.7	79.6	74.4	78.6	80.5

The design refrigeration loads in halls 3, 4, 5, and 7 are about equal, whereas the requirements in halls 1 and 2 are somewhat smaller and in hall 6 somewhat larger. It is suggested to install seven refrigerators, which are identical in those components, which are difficult to replace or to modify (coldbox, heat exchangers, expander and cold compressor housings, adsorbers and piping). Adjustment to the special needs, like the lower design loads of the refrigerators in halls 1 and 2, can be covered by a different number of compressors and special turbine and cold compressor nozzles and wheels.

As usual for refrigerators of this size, the plants will be designed for very high energy efficiency at the design point, i. e. the highest expected refrigeration load.

The TESLA refrigerators would also be designed for a very good part load efficiency. So if e. g. the accelerator would be operated at part load, the electrical power consumption would be reduced proportionally down to about 60 % of the highest refrigeration load.

3 TECHNOLOGY OF LARGE HELIUM REFRIGERATORS

Over the last forty years, accelerator physics has been instrumental to push helium refrigerator technology into the direction of higher reliability, better efficiency and lower cost. All major components of the TESLA helium refrigerators have been used successfully in similar systems before.

While the design of the mechanical components is already fixed, continuous progress is going on concerning quality assurance, instrumentation, diagnostics and computer simulation of operational conditions [3].

The special challenge of the TESLA refrigeration system is the remote operation of several such refrigerators from a central operating room without any service persons at site. It is of advantage for TESLA, that the LHC cryogenic system will be in operation a number of years earlier. The TESLA refrigeration system has many similarities with the LHC system, like number of plants, distance between plants, superfluid helium cooling and the helium inventory of about 100 t. The TESLA system has about an eight times smaller cold mass, so cool-down and warm-up will be simpler.

4 HELIUM STORAGE

When in full operation the TESLA cryosystem will contain about 100 t of helium. The commercial value of the helium is about 20 EU/kg, i.e. 2,2 MEU for the total inventory. When the cryostats are warmed up, this helium has to be handled outside the cryostats.

Whereas CERN has planned for LHC to provide storage for only about 50 % of the helium, for the TESLA system it is proposed to store all helium in a combination of gaseous storage and liquid storage. Gaseous storage will be provided for about 25 % of the inventory in 31 storage vessels with a geometric volume of 250 m^3 each, working between 1 bar and 23 bar. On the other hand, nearly 100 % of the inventory can be stored in liquid form in seven 120 m^3 liquid helium dewars.

Halls 1 and 2 will be equipped with one dewar and 3 gas tanks each, whereas stations 3 to 7 will be equipped with one dewar and 5 gas tanks each. All tanks and dewars will be installed outside the refrigerator halls.

The ambient temperature helium systems of halls 1, 2, 3 and 4 on one side and 5, 6 and 7 on the other side are interconnected by ambient temperature pipes through the tunnel. In an extended standstill period, now and then one of the plants on each side of the accelerator has to be started to reliquefy the collected boil-off gas.

In case of an unplanned refrigerator shutdown and an associated pressure rise in all cold systems, the helium inventory of the portion of the system, which has a high design pressure, will be directed directly to the 20 bar buffer.

The helium of the part of the system with lower design pressure, i. e. mainly the inventory of the cavity cryostats, will be allowed to rise in pressure and temperature by the „2 K static heat load". Such a warm-up from 2 to 4,4 K will take about 10 to 20 hours. If the pressure in the cryostat exceeds a pressure of about 1,2 bar, vapor is allowed to leave the cryostat, partially also through the 5-8 K shield line. So additional static heat load to the cryostat is avoided.

5 MODEL REFRIGERATOR

A model refrigerator has been designed by the TU Dresden and DESY, with valuable advice from CERN [4,5,6] and from industry [7, 8]. The model refrigerator allows to get information on component sizes, number of compressors, flow rates in different loops etc., to get provisional data on power consumption for the specification of utility systems and the operating budget and to get the approximate size of components for the building layout.

This model refrigerator was discussed extensively with the industrial companies, which are presently building the LHC refrigerators. Industry confirmed, that the important aspects of the model refrigerator are a correct basis for the planning of TESLA and that the estimated cost is adequate.

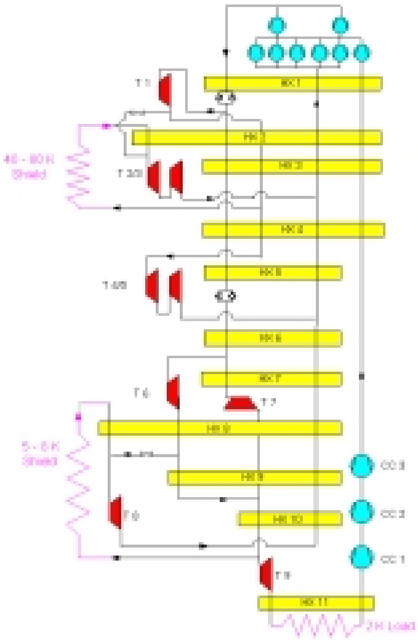

Fig. 1: Flow Diagram of Model Refrigerator

Helium is compressed at ambient temperature by a two-stage screw compressor group to a pressure in the 20 bar range. After re-cooling to ambient temperature and careful oil removal and drying from residual water vapor, the high pressure helium is cooled in heat exchanger HX 1 to 80 K, where it is purified from residual air in switchable adsorbers.

Then a part of the flow is split off and expanded in turbines T1, T2 and T3. After T1 a part of the stream is split off and cooled in HX 3 to 40 K. Here one part of the flow leaves the coldbox and cools the 40/80 K shield in the cryostats. It returns back, is cooled in HX 2 and enters T2. A pressure drop of about 1 bar is foreseen for this shield flow.

One part of the flow already expanded in T1 and precooled in HX 3 is further cooled in HX 4 and expanded in T4 and T5 to atmospheric pressure. The main high pressure stream leaving the 80 K adsorbers is cooled in HX 2, 3, 4, 5 and 6 and in between purified from neon and hydrogen in the switchable „20 K adsorbers“. The high pressure stream is expanded in two parallel turbines T6 and T7 to an intermediate pressure of about 5 bar. The major part is further cooled in exchangers 8, 9 and 10 and is then used for the 5-8 K shield. After return from this shield, the gas is expanded in T 8.

Another part of the 5 bar flow is expanded in T9 and subcooled in HX 11 before flowing to the cavity cryostats. After throttling to the 30 mbar pressure level and evaporation in the cryostats, the low pressure helium vapor returns to the refrigerator through the 300 mm line in the cryostats. After superheating in HX 11, the gas is compressed in a three or four-stage cold compression system to a pressure close to atmospheric pressure, but not necessarily to above atmospheric pressure. This stream is separately warmed up to ambient in exchangers 4, 3, 2 and 1 and enters its own low pressure screw compressor.

The design flow rates, pressures and power requirements of the model refrigerator are presented in Table 3.

Table 3: Process Parameters of the Model Refrigerator

		Mass flow	Outlet	Return
2 K Load	4253 W	199.4 g/s	1.1 bar 2.2 K	27.5 mbar 2.0 K
5 – 8 K Shield	7465 W	249.8 g/s	5.5 bar 5.16 K	5.0 bar 8.2 K
40 – 80 K Shield	80788 W	383.3 g/s	16.0 bar 40 K	14.0 bar 80 K

Compressors				
LP I		199.4 g/s		0.92 bar
LP II		1369 g/s		1.4 bar
HP		1568.4 g/s	24.0 bar	

Temp. Level	Refrige-ration	COP	Electric Power	% of Total Power
2 K	4.25 kW	588 W/W	2500 kW	49 %
5 – 8 K	7.46 kW	168 W/W	1254 kW	24 %
40 – 80 K	80.78 kW	17 W/W	1373 kW	27 %
Total			5147 kW	100 %

The indicated power consumption of 5147 kW is the power consumption of the biggest refrigerator for the design case. The power at smaller refrigerators or at part load operation can be calculated by using the indicated COPs for the individual temperature levels.

6 UPGRADE PHILOSOPHY

For operation at 800 GeV centre-of-mass, the refrigeration capacity has to be about doubled in each cryogenic hall. For this purpose a second cold-box can be installed in the refrigeration halls and the halls must be extended to give space for a second set of warm compressors (Fig. 2). A third cold compressor chain is also necessary for redundancy. The distribution box is already prepared for the energy upgrade.

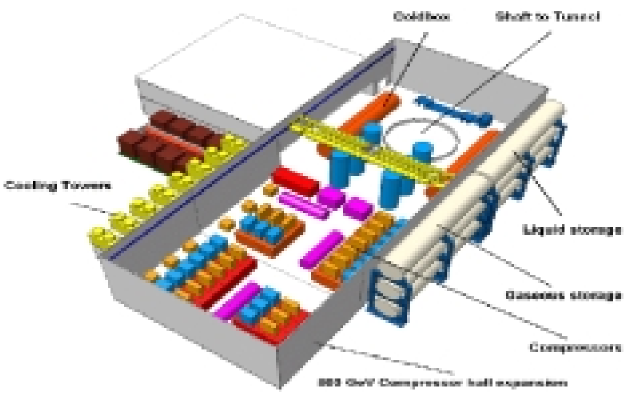

Fig. 2: Layout of the refrigeration hall

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