A retrospect on the successful commissioning of the linde 18kw refrigerators for the LHC particle accelerator at CERN

Kuendig A., Chromec B., Fleck U., Voigt Th.
Linde Kryotechnik AG, Dättlikonerstrasse 5, CH-8422 Pfungen, Switzerland

Six years ago, a call for tender for four new identical refrigerators was published by CERN, the European laboratory for particle physics. Within the tender, an exergetic equivalent capacity of 18 kW at 4.5 K per unit was specified. Finally CERN split the scope between the two bidders and LINDE KRYOTECHNIK AG got the order for two units. With completion of the 18kW cold boxes end of 2001, beginning of 2002 the installation at CERN took place. Acceptance test was started and accomplished in 2003. The paper highlights their characteristic features, like the low power input, which was honored by CERN with a bonus for the performance, the excellent process stability, as well as the remarkable compact design.

INTRODUCTION

CERN, the European Laboratory for Particle Physics, is presently engaged in the construction of the Large Hadron Collider (LHC). This LHC will make use of high field super-conducting magnets operating in super-fluid helium and thus will require a huge refrigeration capacity at several temperature levels. The refrigeration capacity will be generated and distributed by eight refrigerator stations located along the colliders tunnel.

Four of these stations will be equipped with the LEP-12KW refrigerators which will be upgraded for this purpose. The Linde Kryotechnik AG got the order for two of the new refrigerators. Table 1 gives a short overview on the capacity requirements.

Table 1: The specified heat loads to the LHC 18 kW refrigerators in the main operating modes

Operating Mode	4.5 K isothermal [W]	4.5 K – 20 K cold compressors [W]	20 K – 280 K current leads [W]	50 K – 75 K radiation shield [W]
Installed	4’400	20’700	55’400	33’000
Normal	2’600	12’400	36’500	22’000
Low-Intensity	1’600	7’700	36’500	22’000
Injection Standby	1’200	5’700	14’900	22’000
75 K Standby	0	0	0	22’000

Table 2: A useful comparison: the 10 years old LEP12 KW refrigerators

	4.5 K isothermal [W]	4.5 K – 280 K current leads [W]	50 K – 75 K radiation shield [W]
Design-Values	10’000	20’500	6’700

THE OUTLINED PROCESS

The refrigeration process which the Linde Kryotechnik AG selected for the new refrigerators is outlined as follows:

- A Brayton cycle with three pressure levels and five stages of expansion with a total of 10 turbines as indicated in the schematic temperature-entropy-diagram (Fig 1) and in the cold-box flow sheet (Fig3).
- Two compressor stages with three screw compressor units in the first stage and two screw compressor units in the second stage.

- The high pressure level is automatically adjusted to the load. The medium pressure is floating, it is reached by equalizing the flow from the coldbox with the compressors capacity.
- Liquid nitrogen pre-cooling is performed for cool-down purposes and for the liquid filling of the magnets of LHC. The liquefaction rate with liquid nitrogen support is 5800 l/h.
- Two switchable full flow adsorbers at 80 K and one full flow adsorber with a bypass at 20 K. The regeneration of the adsorbers is performed automatically by one common blower system.
- The coldbox is horizontally designed. Only the heat-exchangers in the temperature range below 20 K are in vertical position. The coldbox length is 12m, the coldbox diameter 3.5 m.

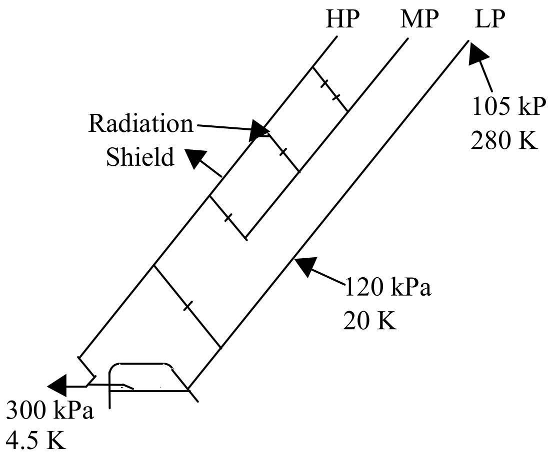

Fig.1: Schematic Temperature-Entropy diagram of the Linde LHC 18kW refrigerator.

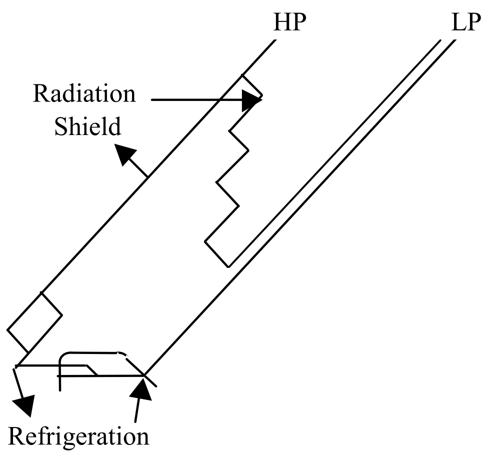

Fig.2: Schematic Temperature-Entropy diagram of the 10 years old Linde LEP 12 kW refrigerator.

There is a remarkable difference in the process design between the LHC 18 kW refrigerators and the LEP 12 kW refrigerators which now are ten years old. The figures 1 and 2 show schematically the two process versions. Here some motives which made Linde to change their design of large refrigerators and liquefiers.

- More simple piping between turbines and heat-exchangers
- More simple and consequently more efficient heat-exchangers. The old process required alternately three or four heat-exchanger streams. The redistribution of these flows was costly and it required a considerable part of cold-box space.
- More efficient heat-exchangers. In the new process the helium flow is cooled down as far as needed. In the old process the total flow was cooled to 20 K.
- More pressure ratio on the single turbines. The new process design enables the same performance with smaller turbines.
- The slightly lower efficiencies of the turbines are compensated by the increased efficiency of the heat-exchangers.
- The new process is easy to control. The different independent expan-

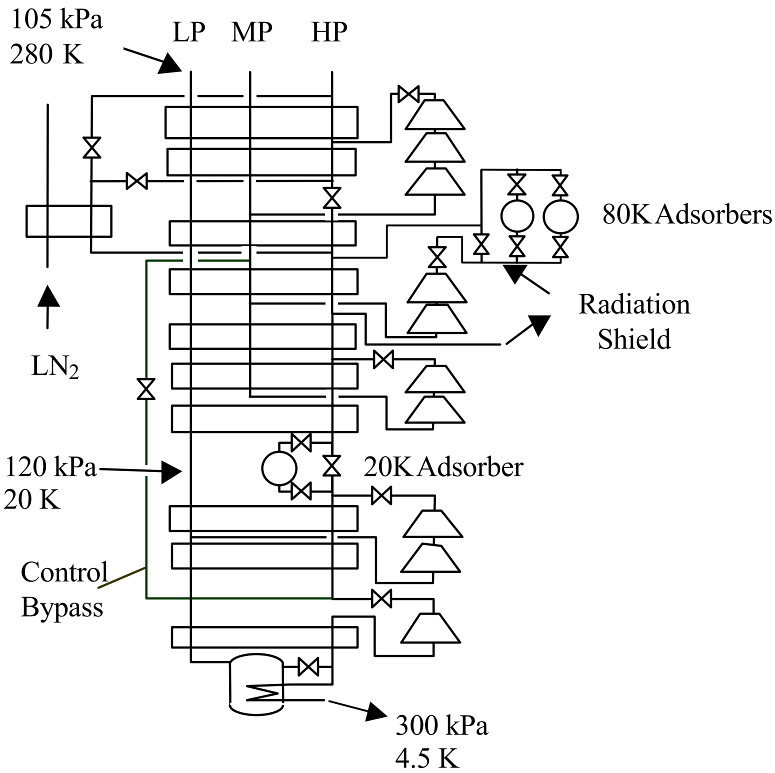

Fig. 3 Process Flow Diagram (PFD) of the coldbox

sion stages enable to maintain independently optimal temperatures for the adsorbers beds and the radiation shield.

- The new turbine arrangement makes possible to replace a turbine while most of the other turbines are running.

EXERGY ANALYSIS

Saving power input was a declared design criteria in the Technical Specification from CERN and the electrical power consumption in three different operating modes had to be guaranteed by the bidders in their offer. Positive deviation from the guaranteed values during the acceptance tests were sadly penalized, negative deviations were honored. The Linde Kryotechnik refrigerators were low in the guarantee and during the acceptance tests even a lower power input was realized. CERN paid a remarkable bonus.

In spite of this excellent reputation, the overall adiabatic efficiency of the Linde - LHC 18 kW refrigerator box in the installed mode is barely 30.0 %. This efficiency value is the product of the following values.

Isothermal efficiency of screw compressor and motor efficiency:	54.0%
Efficiency factor for pressure drops in after-coolers, oil removal system and warm piping	96.5%
Adiabatic coldbox efficiency	57.6%

Compared to other refrigerators, the coldbox efficiency value seems to be rather moderate. Even the ten years old LEP 12 kW refrigerator is slightly better and performes an adiabatic efficiency value of 58.2 %. Is there a design failure in the new refrigerators or is the adiabatic efficiency an inappropriate reference number in the comparison of cryogenic refrigerators for different applications?

The second is true. All the helium expansion turbines today are wasting their shaft power. The use of gas bearing turbines makes it difficult to recuperate this power. Thus, refrigeration at 4.5 K can be produced with a higher adiabatic efficiency than refrigeration at higher temperatures. By the same reason liquefiers perform a lower adiabatic efficiency than 4.5 K refrigerators. Of course, the LEP12 refrigerators, after being modified and upgraded for LHC will perform a lower efficiency too.

Table 4: Efficiency of Linde-LHC 18 kW refrigerators in different modes

Installed	Normal	Low Intensity	Injection Standby	75K standby	Liquefaction
57.6%	54.7%	48.3%	48.1%	45.4%	48%

DEVIATION BETWEEN DESIGNED AND MEASERED VALUES

The main difference between the designed process values and the measurements on site was caused by the compressor system. The total volume flow in the three first stage compressors was 4% lower than expected, the total volume flow of the second stage was 7% more than expected. The power input differed proportional to the flows, thus the compressor efficiency was as expected.

The reduced first stage flow limited the maximal heat load at 4.5 K and from 4.5 K to 20 K. Fortunately there was a margin of 5% calculated and the guaranteed capacity was still fulfilled. The higher second stage flow resulted in a lowered medium pressure and consequently a higher pressure ratio on the turbines. It finally was possible to adjust a reduced discharge pressure.

CONCLUSIONS

The acceptance of the two Linde LHC 18kW refrigerators by CERN in 2003 was a milestone in the huge project of the cryogenic system for LHC. A previous milestone was fulfilled a year before with the tests of the pre-series cold compressing system[4)5)]. This year, in the queue of orders for LHC there is the commissioning of a refrigerator for the Atlas experiment provided and the next step then will be the commissioning of the four cold compressing systems in the tunnel. The Linde Kryotechnik AG further has a order for four pre-cooling and purifying systems which are provided for the upgraded LEP 12kW refrigerators. Finally, to complete the series, an order for the upgrade of two Linde-LEP 12kW refrigerators is expected for 2005. There will be stuff for further contributions in future conferences.

Picture 1: The compressor system

Picture 2: The two Linde LHC 18kW refrigerators ready for shipping

Picture 3: The coldbox top plate

Picture 4: The purge panel (left side) and the electrical cabinets (right side)

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