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SUPERCONDUCTING HIGH-LUMINOSITY INSERTION AT THE CERN-ISR

by

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INTRODUCTION

In 1977, CERN decided to add a superconducting high-luminosity insertion, i.e. eight high-gradient quadrupole magnets, to its ISR. The idea was to assess interference between a superconducting installation and the high-energy particle storage rings and, at the same time, to give an immediate benefit of increased particle collision rates for the high-energy physics experiments¹.

All basic design and operation parameters for the superconducting quadrupoles² and their cryostats³, the helium cryogenic refrigeration and the data acquisition⁴ systems, as well as the most essential auxiliaries were defined and specified during 1977. In particular, the helium refrigeration system was specified in detail and calls for tenders were issued to industry. Subsequently, orders for the supply of subsystems and components were placed in early 1978, the contract for the helium refrigeration plant being awarded to Sulzer Brothers. The refrigeration plant was commissioned at the beginning of 1980, the superconducting quadrupoles were installed in autumn 1980 and the complete superconducting high-luminosity insertion has been operational since October 1980.

So far, the system has been operating for nearly 10'000 hours, divided in 16 running periods. Each of these periods, lasting between 200 and 2000 hours, involved cooldown of the magnets to liquid helium temperature, steady liquefaction and partial natural warmup. All faults and their operational consequences have been systematically recorded. The overall reliability of the helium cryogenic system during cooldown is 97.0 %, during steady operation 99.7 % and the availability to the ISR machine is 100 %.

SOME DESIGN FEATURES

Compressor

A reciprocating, dry, non-contaminating three-stage compressor with labyrinth-sealed pistons is used. The suction pressure is adjustable between 1.05 and 1.50 bar, so that contamination of the process stream by air impurities is prevented, whereas leaks result in helium gas losses, which can easily be monitored and cured. Varying the suction pressure from 1.05 to 1.50 bar increases the mass flow from 150 g s^{-1} to 215 g s^{-1} and hence the liquefaction capacity. The discharge pressure is adjustable up to 18 bar. A bypass valve bleeding between discharge and suction controls the suction pressure; for discharge pressure control, a pair of valves is either unloading to a gas store or loading the system from that store. In this way, the suction pressure is always kept constant, even if the total gas inventory in the system should get accidentally outside the operating range; the discharge pressure would then follow and the liquefaction rate adapt itself automatically.

Cold Box

Work is extracted from the process stream by two centripetal expansion turbines each driving directly a centrifugal brake compressor. The turbines run on self-acting magnetic and gas bearings, thus excluding contamination of the process gas. The bearings are cooled with water; there is always an overpressure from the helium to the water space, and a defect seal would not result in contamination but in loss of process gas.

Two charcoal guard adsorbers are placed at 80 K and 20 K levels to remove any air impurity which might have been introduced into the circuit, e.g. with the initial gas fill.

The refrigeration plant features one cold and one warm ejector. The cold ejector combines the function of JT-expansion with that of pressure regulation in the liquid helium storage dewar. The warm ejector, in parallel with the cold box, permits to operate the cryostats at constant low pressure of 1.02 bar independently of compressor suction.

Transfer of Refrigeration Power

Refrigeration power is fed individually to each of the eight cryostats which house the superconducting magnets. The same control valve and transfer line⁵ is used for level-controlled supply of liquid helium or for adjustable transfer of cold gas for forced-flow magnet cooldown. During normal liquid helium operation of the magnets, all vaporized cold helium is used to intercept heat in the screens of magnets, transfer lines and current leads, and is then

returned warm to the refrigeration plant. Liquid nitrogen is not used in the system. This simplifies operational procedure and precludes failures due to accidental contamination of helium or freezing of nitrogen.

Continuous Operation

The entire system has been designed to continue normal supply of liquid helium to the magnets for up to five hours in the event of a failure of main components (compressor, turbines) or main utilities (electricity, cooling water). This required the installation of a no-break electrical supply for the controls, a 1000 l liquid helium store and a 500 m³ (NTP) low pressure recovery balloon. Transfer of liquid from dewar to cryostats and of gas from cryostats to balloon is maintained by pressurizing the dewar from the medium-pressure gas store.

Closed Helium Circuit

An attempt has been made to keep the helium as far as possible in the clean closed circuit. At compressor stops, the cold box is automatically isolated from dewar and cryostats and all gas from compressor, cold box and pipes is kept at a pressure of up to 12 bar; at magnet quenches, about 80 % of the instantly vaporized helium is recuperated via the warm ejector and only 20 % is blown to the balloon.

The system is divided into sub-units which can be isolated, each being systematically provided with purge facilities to establish clean conditions. Up to now, no problem could be attributed to the presence of impurities in the process gas.

Distribution of Vaporized Cold Helium for Thermal Screening

The number of active control circuits is limited to the strict minimum and no controller or actuator is installed on the cryostats, unaccessible during operation of the ISR for reasons of radiation safety. Consequently, the vapour from each cryostat is distributed among seven parallel outlets in predetermined compromised proportions. For the five current leads, the cooling vapour flow is adjusted for nominal currents, and permanently blowing air fans reduce icing when the leads are operated below nominal currents. At zero current, a throttle, activated by a solenoid valve, reduces the flow in the current leads to another set of values, thus avoiding excessive ice formation.

Magnet Quenches

Provisions were made to avoid propagation of the quench effects from one magnet to the others. Thus, if the pressure in a cryostat exceeds a preset value, its supply valve will be closed automatical-

ly and no pressure surge will be transmitted to the supply side of the other cryostats. The return path from each cryostat is sized so that its hydraulic resistance limits the flow to values which can be coped with by the warm ejector without affecting the pressure in the common return manifold.

Instrumentation and Monitoring⁴

The system is comprehensively provided with local instrumentation for easy trouble-shooting. However, only selected variables are transformed into analog or logical electric signals and monitored by computer. A microprocessor-based event recorder lists all logical changes (valve positions, limit values, interlocks) with reference to real time.

EARLY PROBLEMS AND THEIR CURES

Commissioning went very smoothly and the whole system was rapidly operational; a few changes, however, were implemented after the initial experience gained during commissioning and early runs.

Expansion Turbines

The self-acting gas-bearing expansion turbines were the first of their size to be operated in a refrigeration system and one teething problem had to be overcome: on three occasions, when switching the plant from final cooldown to liquefaction mode at about 20 K, the upper turbine seized on its lower radial bearing. In a run dedicated to this problem, the turbine was extensively instrumented (vibration, temperature, pressure) and the cause of the fault could clearly be attributed to subcooling of that bearing. A minor design modification cured this problem definitively.

Cold Check Valves

Initially, spring-loaded cold check valves for parallel return of cooldown gas to the cold box, under low head loss, had been installed. After cooldown, the valves should have closed tightly for undisturbed running in the liquefaction mode; they were sufficiently leaky to upset the flow distribution in the current leads. These valves have been fitted with helium pressure-loaded actuators.

Cooling of Current Leads

Adequate distribution of cold helium vapour among a large number of parallel return paths of varying impedances proved difficult to achieve without any active control; in particular, the temperature at the top of the main current leads dropped below 100 K upon magnet quenches. Self-acting thermostatic control valves⁶, integrated into the top of these leads, improved the situation.

OPERATIONAL PROCEDURES

Three operators are fully conversant with the system and take weekly turns for its operation, checks and maintenance. They have been closely associated with installation and commissioning, and intensively trained during the early runs.

The normal sequence begins with some preparatory work the day before start-up, i.e. check helium inventory, prepare for refill, analyse purity and start vacuum pumps for cold box and transfer lines. Starting compressor and cold box takes approximately two hours, and for another two hours their good functioning is observed. The system is adjusted for a cooldown rate of 5 K h^{-1} by fixed settings of the turbine inlet pressure. Between 270 K and 80 K, for about 35 hours, the system is left alone. Final cooldown and filling requires some manual interventions and the presence of operators for 16 hours. Final cooldown of the cryomagnets and switchover to liquefaction mode is the only operation requiring particular skill, since a good balance of flow between turbines, JT-end of the cold box and cryomagnets has to be established without overloading the compressor. Once cryostats and dewar are at nominal liquid level, the liquefaction capacity is set 10 % in excess of the vaporization rate of the system by adjusting the turbine inlet pressure ($\sim 10 \text{ bar}$). The compressor is always run at 14 bar discharge, the pressure required for cooldown and for loading surplus helium into the buffer store.

During normal liquefaction, the operator checks the system once a day for correct operation and logs manually all significant process data. All vacuum pumps (nine turbomolecular and one diffusion), are switched off during normal liquefaction as cryopumping keeps the vacuum insulation spaces in the 10^{-7} to 10^{-5} mbar range. The cold and warm ejectors are only used during normal liquefaction. They achieve pressure stabilization in the dewar and in the cryostat return manifold to a few millibar even in the case of flow surges after magnet quenches.

To stop the system and bring it from liquefaction to standby mode also requires the presence of the operator for two periods of four hours. First, the expansion turbines are switched off and the transfer of liquid to the cryostats is interrupted. While the cold box is warming up naturally, the adsorbers are regenerated by backstream pumping which also removes all moisture trapped in the first heat exchanger. On the following day, once all liquid in the cold box, transfer lines and cryostats has vaporized and the expanded helium has been loaded to the buffer store, the compressor is stopped.

Whenever the compressor is stopped for longer periods, the water coolers are opened and dried in order to slow down progression of some slight corrosion which has been observed.

OPERATION AND FAULT STATISTICS

During the 16 recorded running periods from October 1980 to March 1983, the system has been operating in cooldown mode for nearly 800 hours, in liquefaction mode for 7700 hours and in standby, i.e. naturally warming up, for 10'500 hours. All relevant operational events and faults have been systematically recorded and made accessible for analysis (see Figs. 3 to 6). It is worth noting that the fault frequency is an order of magnitude lower during steady operation ($2.7 \cdot 10^{-3} \text{ h}^{-1}$) than during cooldown ($2.1 \cdot 10^{-2} \text{ h}^{-1}$).

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Fig. 1. Simplified Flow Scheme of Helium Cryogenic System

Fig. 2. A Typical Running Period, Showing Presence of Operator

Fig. 3. Running Periods and Faults vs. Age of System

Fig. 4. Occurrence of Faults in the Course of Running Periods

Fig. 5. Fault Distribution Accord.to Subsystem

Fig. 6. Fault Distribution According to Nature