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CONCLUSIONS ON 8 YEARS OPERATION OF THE LEP 4.5 K REFRIGERATION SYSTEM AT CERN

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ABSTRACT

After 11 years of operation the Large Electron/Positron collider (LEP) was stopped in November 2000. Since 1993 a cryogenic system has been used to supply up to 72 superconducting (SC) cavity modules, using four large liquid-helium refrigerators at 4.5 K. We review eight years of operation of one of the world's largest helium cryogenic systems, its evolution and cooling capacity availability correlated to the LEP increasing energy program. Failure statistics, availability, recovery time after breakdowns and reliability are analyzed, and the most relevant problems encountered during the operation and their cure exposed. The operational organization is also briefly described.

INTRODUCTION

The LEP collider was a 26.6 km circumference e+/e- storage ring. Originally equipped with a room temperature radiofrequency (RF) system, it underwent an energy upgrade (LEP2) from 1992 by gradually installing up to 72 superconducting cavity modules. The beginning of 1996 marked the start of LEP2 [1,2], the progressive increase of beam energy from 45 GeV to well beyond the threshold of the W boson production. In the last year of LEP2 operation a maximum colliding energy of 104.6 GeV was achieved and a total of 1000 pb^{-1} of integrated luminosity was delivered to the experiments.

For the cryogenics of the LEP2 accelerator, four cryoplants of 12 kW equivalent cooling power at 4.5 K were purchased in 1991. A 6 kW unit was initially installed and operated in IP2 for preliminary tests until it was replaced by a 12 kW cryoplant. Installed, commissioned and operated from 1993 to 1998, they were upgraded during the winter shutdown of 1998/99 to 18 kW according to the LEP2 increasing energy program and for

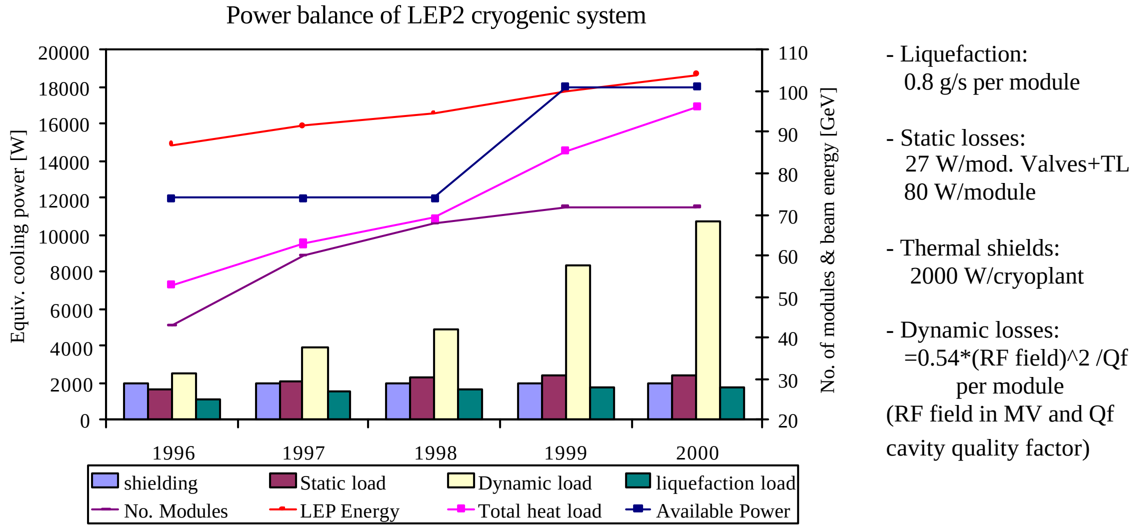

FIGURE 1. Power balance evolution of the cryogenic system from 1996 to 2000.

future LHC use. For the last two years of operation the cooling capacity of the cryoplants was pushed to its maximum limits in order to exploit the ultimate potential of the LEP collider. Figure 1 shows the power balance evolution of the cryogenic system for LEP2 from 1996 to 2000.

THE LEP2 CRYOGENIC SYSTEM

The LEP2 cryogenic system described in earlier publications [3-6], located at each of the four interaction points of LEP, consisted of a cryoplant and its associated liquid helium distribution system, and a pair of 200-250 meter long supply-and-return transfer lines to feed 8 to 10 SC cavity modules on each side of the point. A description of the liquid and gaseous helium circuits inside the 11 meter long modules can be found under reference [7]. In addition to the modules, the 12/18 kW plants were also cooling the low-beta quadrupoles at two of the LEP points. A simplified layout of the LEP2 cryogenic system is shown in Figure 2.

As shown in Figure 1, the 18 kW equivalent power at 4.5 K per cryoplant was split into different loads: thermal screens, liquefaction rate for RF instrumentation, static losses of the SC cavity modules and dynamic load for compensation of beam and RF losses.

The industrial process control system was purchased by CERN separately from the cryoplants [8]. It was programmed for fully automatic operation including cool-down, warm-up, restart after utility failure and adaptation of the cryoplant capacity according to the specified load.

EXPLOITATION

The first years of commissioning and operation experience [9,10] were dedicated to tuning the cryoplants for the different operational modes and associated transients: cool

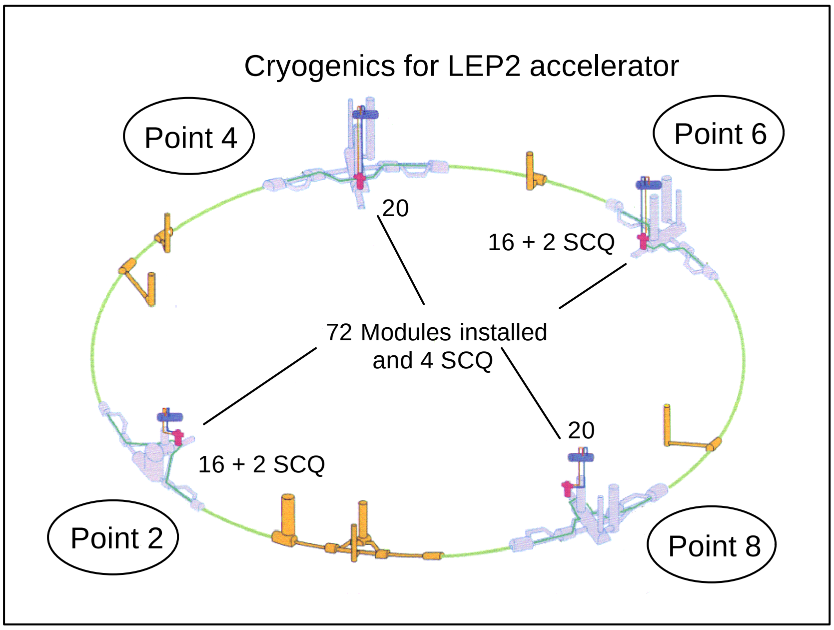

FIGURE 2. General Layout of the LEP2 Cryogenic System.

down, compensation of the RF load during normal operation, recooling and refilling of SC cavity modules, restart and recovery after failure, warm up, etc…

In order to optimize human resources for the different CERN projects, an outsourcing policy was applied for the exploitation of all CERN cryogenic systems, including the four LEP2 12/18 kW refrigerators. In 1995 an operation and maintenance contract was established between CERN and the Air Products – Thomson Consortium (APT). This contract was structured in two phases.

In a first contractual phase from 1995 to 1997, the consortium had to provide resources and infrastructure to operate and maintain the cryogenic installations under CERN's supervision and responsibility. In parallel and in close collaboration with CERN staff, the contracting consortium had the duty to define operation rules and establish the maintenance policy.

A well-defined operation philosophy based on complete operational documentation (operation procedures, control logic description, electrical and P&I Diagrams) was established with periodical follow up (checklists, logbooks, logging data). A maintenance plan adapted to the specific CERN winter shut downs (three months) was established based on common industrial knowledge.

In 1998 the responsibility was completely transferred to APT with a new, results oriented phase of the contract. The tasks of the consortium for this new phase were:

- to provide and supervise qualified personnel ensuring efficient and uninterrupted operation of the installations with a minimum number of operators fixed within the contract
- to organize and execute preventive maintenance as defined in the maintenance plan and to perform corrective interventions in case of failure

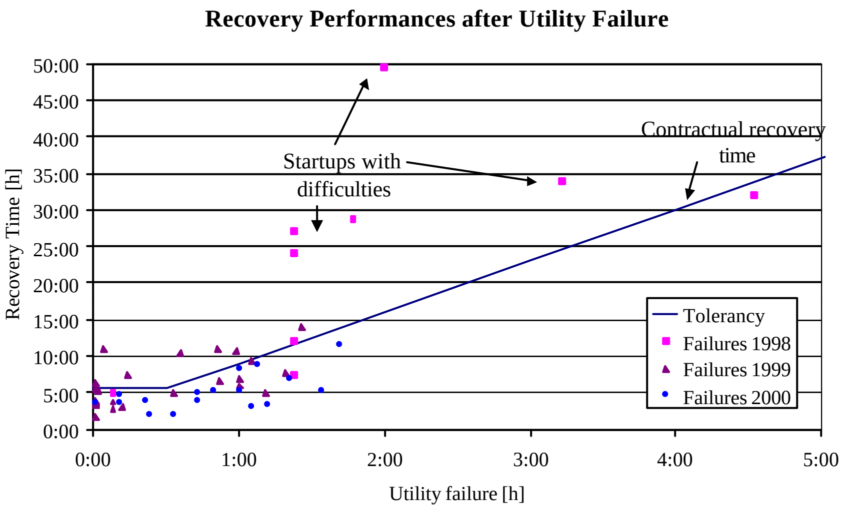

FIGURE 3. Recovery performance after utility failure during results oriented contract phase (1998-2000).

In this new phase of the contract, an important fraction of the payment was based on the cryoplants' availability, evaluated by the recovery performance after cryogenic or utility failure. The recovery performance was assessed from the integrated running time in case of cryogenic failures, and in relation to a fixed tolerance ratio between utility downtime and recovery time, in case of external utility failures.

Figure 3 presents the tolerance and recovery performances in case of utility failure as stipulated in the contract. During 1998, specific difficulties such as instrumentation and actuators faults strongly penalized the recovery time during restart. In 1999, most of the start-ups were nearly nominal with remarkable better performances in 2000. This is explained by the increase of power and recovery capacity of the upgraded 18 kW plants.

The consortium staff for all the cryogenic installations at CERN consisted of 37 persons, dedicated to contract management, maintenance and operation. For the LEP2 cryogenic system, the operation team consisted of 1 engineer and 4 operators, 6 Full Time Equivalents (FTUs) were affected for maintenance and 1 FTE for management and administration.

From CERN side, the original installation and commissioning team was reduced from 19 FTEs in 1995 to 12 FTEs during the cryogenic upgrade in 1998 and finally 5 FTEs in 2000. Apart from consolidation and upgrade work, since 1998, they were mainly involved in operation and maintenance monitoring, as well as interfacing with the LEP machine. Note that the SC modules and controls were totally CERN's responsibility.

OPERATIONAL PERFORMANCE AND STATISTICS

The LEP2 cryogenic system went through a continuous evolution all along its operational lifetime (Figure 1 and 4), hence the difficulty to evaluate its performance over the years. Figure 4 presents the total number of running hours accumulated by the LEP2 cryoplants since 1992 as well as the downtime rates from 1996 onwards.

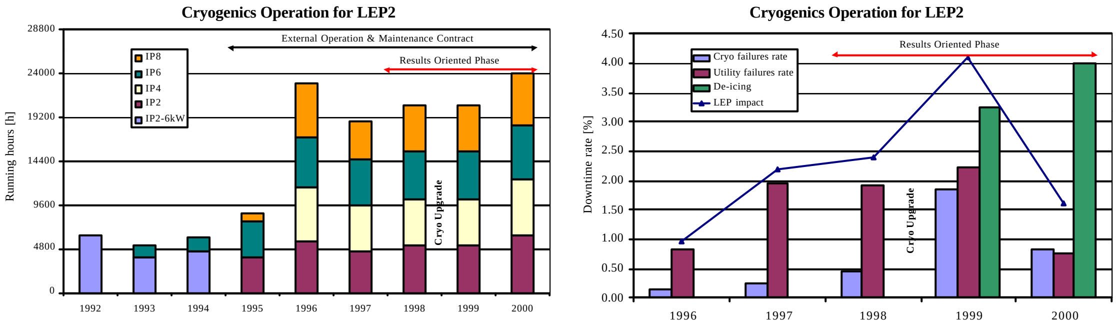

FIGURE 4. Accumulated running hours and downtime rates for LEP2 cryogenic system.

The downtime rates are calculated as the ratio of non-availability time of the cryogenic system over the total LEP running hours. They are presented by origin of the failure: 'cryo failure' when caused by failure of cryogenic equipment and 'utility failure' when caused by loss of external utilities such as electricity, cooling water or compressed air. The availability of a cryoplant was defined by the correct level of liquid helium in the SC modules and sufficient power to compensate the RF dynamic load.

A total of 120'000 hours were accumulated by the four LEP2 cryoplants. An average 'cryo failure' of 7 hours downtime per 1000 hours (0.7%) of LEP operation time could be estimated for all four refrigerators. The 'utility failure' average rate was 1.5%, being more than the double of cryogenic origin problems. The peak of 'cryo failure' rate in 1999 was due to the upgrade modifications, the new equipment (compressor stations were completely renewed) and the new behavior of the cryoplants, as the replacement of the turbines increased the mass flow through each cold box by 600 g/s.

During the last two years of operation periodical cleaning of the 1st and 2nd turbine filters of two cryoplants was necessary due to a clogging problem. These interventions temporarily reduced the available cooling power and consequently prevented LEP from running at high energy, although this time was used for machine developments. In total, 146 and 205 hours were used for filter cleaning during 1999 and 2000, respectively. Impact on LEP operation is shown in Figure 4.

Helium Consumption

Each installation needed a minimum of 17,000 Nm3 of helium. To ensure a refill of the modules after accidental loss, additional large storage tanks were installed, giving a total storage capacity of 24,000 Nm3 of helium. The annual average consumption for the four installations was about 40,000 Nm3. Half of the losses were due to the lack of utility to recover helium after accidental stops. The other half was gradually lost over the year, mostly during conditioning of the cryoplants after the annual maintenance.

MAIN CRYOGENIC PROBLEMS ENCOUTERED

The most important achievement during LEP physics running is that it was never stopped for a long period due to a failure of the cryogenic system. This was mostly due to preventive maintenance or fast repair during operation. However, some "near miss" events are worth mentioning. They are reported by type i.e. design weakness, mechanics, operation or aging of components.

Some design weakness involving turbines or plate-fin heat exchangers resulted in slightly reduced capacity. Others weaknesses such as poor efficiency of the first oil separation stage or helium leak in a vertical transfer line between the Upper Cold Box (UCB) and the Lower Cold Box (LCB) forced more risky operation with permanent monitoring of the problem. Proper engineering and prefabrication was made while operating the concerned refrigerator and replacement of components was done during the following annual LEP winter shutdown.

The most important problems resulted from recent maintenance campaign or special intervention on equipment and appeared within the first hours after restart. This was the case twice for motor bearings and once for a compressor (out of 25 units), and on a set of support structures fixing compressor skids to the building floor. The challenge was to cure the problem before the accelerator would need the maximum cooling power. On the other hand, preventive actions were scheduled yearly for sensitive components such as some motor-compressor couplings, shaft driven oil pumps and electrical relays for slide valves.

Some problems were encountered due to aging of components such as oil injection piping to compressors, one oil pump and a couple of air leaks to the insulation vacuum of the cold boxes. One should note that cold boxes were extremely reliable without any turbine (out of 28) or cryogenic valve (out of 120) failures. The only minor troubles came from ancillary components such as instrumentation or actuators, which were not adapted to the cycles or type of operation they were installed for.

CRYOGENIC ISSUES FOR THE LEP MACHINE

Since the beginning of the LEP operation with SC cavity modules, several interactions of the cryogenics with the RF system, beam intensity, beam energy and accelerator operation were noticed. With the continuous energy increase of LEP, these problems became important issues for the accelerator operation. Therefore, since 1997, the cryogenic group reported yearly about cryogenic performance and the main problems [12-15].

Thermomechanical Oscillations

At the end of the 1994 run, a 100 Hz oscillation of the accelerating field of two modules was observed. Studies done during the 1995 run explained its thermo-acoustic origin [12]. This oscillation was directly affecting the accelerating field of the cavities although it had no strong impact on the cryogenic system. During the 1996/97 shutdown, Kapton™ foils were placed between the male/female part of the outlet transfer line bayonet, limiting the thermo-acoustic oscillations.

Influence of the Circulating Beam

Since 1996 an influence of the beam on the cryogenic system was noticed [13,14]. It was correlated to the beam intensity and the bunch length. An anomalous beam-induced heat load on the LEP cryogenic system was located in the cables of the RF antennas measuring the accelerating field in the cavities. During the winter shutdown of 1998/99 all faulty cables were replaced by others of larger cross sections reducing the heat losses by a factor of two and allowing LEP to increase the beam intensities.

Turbine Filter Clogging

A clogging of the turbine circuit of the UCB of two cryoplants was observed in 1996. The increase of flow through the cold box due to the upgrade strongly increased this clogging phenomenon during 1999. Based on investigations done in 1998 and 1999 it appeared that the reduction in turbine flow, and consequently the progressive reduction of the cooling power capacity, was due to the clogging of the 1^{st} and 2^{nd} turbine filters at 150 K and 90 K, respectively. For the first filter, clogging appeared to increase quite smoothly, while for the second one it occurred rapidly over a few days. Periodical de-icing (warm up for filter cleaning) was required to assure sufficient cooling capacity for the RF system and to prevent destruction of the filters (ΔP up to 3.5 bar).

Spectroscopy analyses of the gas leaving the filters during cleaning were done to identify possible impurities. Qualitative results showed traces of water in the 1^{st} turbine filter and CO_2 in the 2^{nd} turbine one. According to these results and to the operational parameters of the cold boxes, it was estimated that residual impurities in helium of the order of a fraction of ppm, probably coming from active charcoal or lubricant oil, and their accumulation in the heat exchangers were the origin of the clogging phenomenon.

Extensive cleaning of the cold box circuits, avoiding contamination during the shutdowns and extended cleaning operation immediately after start up reduced significantly the clogging phenomenon. During the last year of operation, when the maximum cooling capacity was requested for LEP, the clogging effect was more severe and presented different effects on the two cryoplants concerned. For one the cleaning interventions were required for the first turbine filter with a periodicity of about 30 days, while for the other they were required for the second turbine filter with a periodicity of 10-15 days. The duration (6-10 hours) and scheduling of each intervention were decided in close collaboration with the LEP operation coordinators in order to optimize the LEP schedule for physics and machine development (Figure 4).

CONCLUSIONS

During 8 years of operation the LEP2 cryogenic system has been operated with high reliability and remarkable performances. The acquired experience operating such cryogenic plants has showed that carefully planned maintenance with periodic checks and calibration of equipment, up-to-date documentation and well-trained operators are the keys for the success. The outsourcing experience at CERN has stressed that although operation and maintenance can be assumed by an external company with satisfactory results, it demands a long adaptation process and requires a minimum of CERN staff for consolidation works, assistance and monitoring of the contract and interfaces with other accelerator systems.

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