CONSOLIDATION OF THE 45-YEAR OLD PS MAIN MAGNET SYSTEM

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Abstract

After a major coil insulation breakdown on two of the 47-year-old CERN PS main magnets in 2003, an extensive magnet consolidation program has been launched. This article reviews the analysis of the magnet state before the repair and the applied major improvements. An overview is given of the production of the new components, the actual refurbishment and the commissioning of the main magnet system after 18 months shut down.

INTRODUCTION

The CERN Proton Synchrotron (PS) installed in 1959 is now 47 years in operation. It has been used under much more demanding conditions then were foreseen at the time of its construction and it is planned to extend its existence for a long time to provide high intensity beams for LHC, CNGS and other users.

The status of the PS main magnet system has been subjected to a detailed study already twice in the past: the first time in 1974 before the SPS was built and the second time in 1983 before LEP was built in order to assure that the PS could serve as a pre-injector in the forthcoming periods. The outcome of these studies has been published in [1]. In order to deal with new challenges for the PS, many projects to reinforce, renew and repair the main magnet system have been proposed and realized in the past, including new Pole Face Windings (PFW) and new “Figure of Eight” windings.

After a relatively long period of operation without any breakdown or significant down time, in 2001 the PS main magnets have started to show alerting signs of degradation. The most recent serious accident was the breakdown of the ground insulation of two main coils during the annual high voltage test at the end of the shut down, which led to a delayed start up of the PS machine by two weeks in 2003. In view of the alarming numbers of failures, it was decided by the CERN management in March 2003 to launch a study with the following objectives:

- Analyze the present situation of the PS main magnets and the evolution in the future.
- Present proposals for a renovation and consolidation of the PS main magnets to assure reliable operation in the forthcoming LHC era.

THE PS MAIN MAGNET SYSTEM

The PS main magnet system consist of 100 magnet units (MU) installed in the tunnel plus a unit 101 used as a reference magnet. The magnets are laminated, combined function "C-shaped" magnets.

Employing two different types of pole shapes (type “open” and type “close”) for one magnetic unit produces an alternating gradient in the direction of the beam. Each unit has 10 blocks made of 1.5 mm thick laminations glued together with epoxy resin. The units are divided in two sectors of five blocks each installed on a steel girder, called the “focusing sector” or “defocusing sector” respectively.

One pair of main excitation coils is fixed around the upper and the lower pole of each unit. Each coil consists of two water cooled pancakes, which are made of five turns of hollow aluminium conductor. All main coils are connected in series by water-cooled bus bars.

So called "Pole Face Windings" (PFW) are installed to correct the undesired sextupolar field components due to both the saturation and the leakage field at high field levels. The PFW consist of an arrangement of parallel copper bars, moulded into glass fibre charged epoxy resin insulation and placed on the pole faces of each half unit. At low energy injection, they compensate also the effect of eddy currents induced in the vacuum chamber.

To adjust the quadrupole gradient to a certain degree, so called "Figure of Eight" windings are installed, which can increase the field gradient on a sector, while decreasing it simultaneously on the other half of the main unit without affecting the integrated bending field.

RISK ANALYSIS

A detailed analysis of the PS main magnets after the break-down of two main magnets in 2003 revealed that 90% of the main magnets are in the original state as in the late 50s. A relatively intensive preventive maintenance and steady efforts to upgrade and develop the system took place in the early years of the PS; but this maintenance was reduced constantly until 1987 when it was stopped completely. Since then no improvements were made and the work during the shut-downs was dedicated only to repair or replacement of faulty component in order to keep the main magnets operational.

Main Coil and Bus Bar Insulation

The expected lifetime of the coil insulation is determined by the maximum permissible integrated radiation dose which was estimated from accelerated irradiation test in a reactor to be around 10 MGy. The assumption of a “lethal” dose of 10 MGy is rather optimistic, since it does not respect that the degradation is also a function of exposure time, temperature, and the amount oxygen in the environment [2]. First tests in 1965 showed already that the insulation resistance had decreased by a factor of 2 after accumulating a dose of 2 MGy.

Many magnet components have now approached or are even beyond their expected life time and show heavy degradation induced by radiation and mechanical fatigue due to pulsed magnetic forces, in particular the main coils. The glass-fibre insulation of many coils was deteriorated and over larger areas it did or does not adhere anymore to the conductor. The ground insulation lost elasticity and became porous. The resin has changed colour and become brittle.

The poor state of the main coil insulation can very easily lead to further short circuits while the coils are moving due to thermal stresses or magnetic forces when pulsed. In case of water accidentally sprayed on the main coils, due to a leaking cooling circuit or broken water hose, the water will enter the porous insulation provoking a short circuit. The same concerns are relevant for the bus bars.

Considering all these facts including the recent accidents, it was obvious that the reliability of the main coils and bus bars has become very low and the risks of further serious breakdowns in the near future are significant. In case of a main coil failure the complete magnet has to be replaced.

PFW Cable Insulation

The polyurethane insulation of the PFW cables gave, at first glance, the impression to be generally in good condition. However, after an inspection it turned out that the insulation is falling apart when touched (see Figure 1). This damage results from a combined effect of degradation of the organic material submitted to high irradiation and its poor resistance against microbes.

Figure 1: Destroyed PFW cable insulation.

Once a PFW cable has been moved - accidentally or on purpose during an intervention - the insulation is completely damaged and the entire PFW has to be replaced. Since almost all PFW cables are suffering from this degradation the risk of a breakdown is considerably high. A PFW could be replaced in situ, but the vacuum chamber has to be removed, which requires a displacement of the magnet unit from its position.

Impact in Case of a Magnet Breakdown

The replacement of a magnet requires about one week assuming that an operational spare magnet is available and the induced radioactivity is low enough to permit an immediate intervention. In case the induced radioactivity is considerable and depending on the broken item to be repaired it can take up to one month to get the PS back to normal operation. In some particular cases where the radiation level is extremely high such a repair might even be excluded.

PS MAGNET CONSOLIDATION

In summer 2003 it was decided to launch the PS Magnet Consolidation Project. The 18 months shut-down of the PS in 2005/06 offered a unique chance to repair a significant number of PS magnets. The most important advantage was the long cool-down period: the radiation level of the magnets was strongly reduced and, hence, the integrated dose submitted to the personnel involved in this work was minimized. An immediate repair of a maximum number of magnets became even more important in view of the increase of induced radioactivity of the PS in the forthcoming years, which has to be expected due to high intensity proton beams for CNGS.

Financial restrictions, the narrow time window and the limited availability of human resources made it impossible to refurbish all 100 magnet units in one go. Therefore, the project had to be split into two phases. All high-risk magnets have been repaired in the first phase whereas magnets with a low failure probability stay in the tunnel and will be refurbished during the following shut-downs in the coming years. This strategy guarantees nevertheless that a maximum reliability for the future is achieved.

Magnet Selection Criteria

Before starting the refurbishment work, a detail campaign started to examine all 100 magnet units. The actual state of the components was determined as well as their future reliability in order to identify high risk magnets. The magnets were categorized in several classes according to their priorities. The following criteria were applied to find out the weakest magnets:

- Detailed visual inspection: Significant degradation of the main coil insulation, corrosion of aluminium conductor, damaged gold plating, disintegrated rubber pads, damaged PFW cable insulation, etc…
- The total integrated dose received between 1959 and 2004: Magnets close or beyond the "lethal" dose limit were given highest priority. 18 magnets were found to have received more than 8 MGy (Figure 2).
- The actual radioactivity: To profit from the exceptional long cooling down time, magnets with high radiation levels were given priority.

An electrical test (partial discharge test) was taken into consideration to measure the quality of the coil insulation on every individual magnet, but had to be omitted, because it turned out to be too time consuming.

The sequence of the magnet removal and refurbishment was mainly determined by the actual radioactivity (less radioactive magnets first) and the accessibility. Magnets difficult to uninstall or repair were removed when the personnel had acquired a sufficient level of experience.

The minimization of the radiation doses received by the personnel involved, according to the ALARA principle, was a key issue in this project. Special tools and detailed work procedures were studied to optimize and streamline all handling and repair operations.

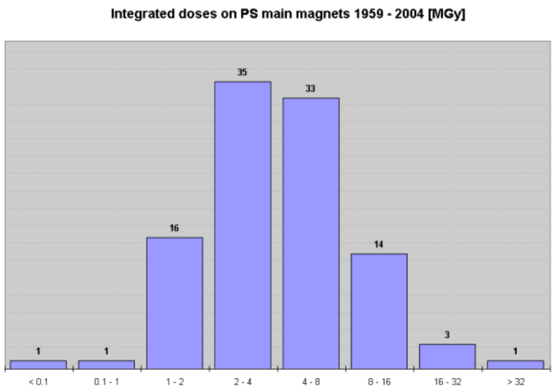

Figure 2: Histogram of integrated doses.

Main Coil and PFW Manufacture

A series of mechanical, electrical, chemical and radiation hardness test were carried out to specify the required quality of all raw materials (resin, glass fiber tape, aluminium, etc...). To study the insulation quality and to define the parameters for the impregnation, gold plating and welding processes a prototype of the main coil and the PFW were developed at CERN.

For the main coils, a total amount of 12 000 m (~ 64 t) of hollow aluminium conductor was produced by Holton/GB in a continuous rotary extrusion process. The 232 new main coils were manufactured by BINP/Novosibirsk.

The 240 PFW were produced by SIGMAPHI/ France. The main concern, in addition to the tight production schedule and the complex PFW design, was to find highly flexible and radiation resistance connection cables. A series of radiation tests led to the choice of ULTEM® (Polyetherimid) used as cable insulation material.

Systematic magnetic measurements initially foreseen to assure the tight tolerances on the PFW conductor positioning were replaced by 3D mechanical measurements, which are faster and more precise. X-ray examinations were done on some samples of the finished PFW to cross check the mechanical measurement results. A comparative magnetic measurement of the new and the old PFW confirmed that there is no evident difference in the magnetic behavior.

Loose Magnet Block Laminations

Already in February 1970, after a major breakdown of a PS magnet it was recognized, for the first time, that some laminations of the magnet blocks became loose. The araldite bonding is being destroyed slowly under the effect of ionizing radiation. At that time, the problem was solved by systematically either installing wedges or clamps except on the transition from block 5 to block 6 where the central figure of eight conductor does not permit such an installation.

During disassembly of the first PS main magnets in May 2005, it was discovered that the degradation of the glue had advanced further. Under the influence of the pulsed magnetic forces the end laminations were bend outwards in the region of the pole tips. Without repair this effect would have damaged the insulation of the figure of eight coil and led to short circuits.

Numerous repair options were studied to rescue the magnet yoke. The most promising solution found was to glue the loose lamination together and bolt them in addition with a 40 mm long M8 screw. A test with 30 000 cycles at full field showed this method to be successful.

Magnet Tests and Commissioning

After the repair, which involved a number of operations such as transport, removal and remounting of the vacuum chamber, installing new coils and PFW, replacing cables, final testing and inspection, the magnets were moved back into the PS tunnel and re-aligned.

Every repaired magnet was tested individually before re-installation in the tunnel (hydraulic, resistance, insulation, polarity, interlock, etc…). In addition, an extended hardware tests period allowed identifying and solving any possible problem before the PS start up in 2006. The commissioning included high voltage test, polarity checks on all windings, and a systematic thermographic inspection to control the electrical connections and the cooling performance of all 100 main magnets. As a result, the PS start up was extremely smooth and the beam was accelerated immediately to its maximum momentum of 26 GeV/c.

CONCLUSION

The weakest magnets were chosen for the refurbishment campaign. Thanks to the big effort and the motivation of the entire refurbishment team it was possible to repair 26 magnets and to re-install them successfully in the tunnel. Consequently, the risk of magnet failure in the future will be much lower than in the past.

A refurbishment of 8 magnets per year is planned during the next shut-downs until 2010. To continue with the second phase of the PS magnet refurbishment program without delay a corresponding decision has to be taken at the latest in 2008.

REFERENCES

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