RADIATION HARD MAGNETS AT THE PAUL SCHERRER INSTITUTE

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Abstract

Radiation hard magnets have been in operation at PSI for more than 30 years. Throughout this period, extensive experience was gained regarding both the conceptual design of these magnets and their operation. Worldwide, upcoming future projects for high intensity accelerators and neutron spallation sources will create an increasing need for radiation hard magnets. Through a presentation of the PSI main accelerator facilities, this paper describes the lessons learned over the years regarding the operation of radiation hard magnets and explains a few basic design concepts adopted by PSI based on this experience.

INTRODUCTION

The Paul Scherrer Institute (PSI) is the largest national research institute in Switzerland [1]. Its activities cover many fields, ranging from nuclear and general energy over biology to particle physics. The large research facilities division (GFA) is responsible for the operation of three accelerator complexes. One of them is the 1.3 Megawatt proton Ring accelerator. It produces a 590 MeV proton beam which is directed towards two graphite targets to produce pions and muons, followed by the lead target of the SINQ spallation source to produce neutrons.

The Ring cyclotron, commissioned in 1974, was initially designed for a beam current of 100 µA; it is presently operated at 2.2 mA, which corresponds to a beam power of 1.3 MW. A simplified layout of the accelerator complex is shown in Figure 1.

High Radiation Areas

While losses can be kept low along the main beam path, a high activation of the surrounding area occurs around the targets, mainly through secondary particles generated by the collision of the beam with the targets. Over the years, various measurements have been made both along the main beam path and of components that were extracted for service or replacement. Measurements of the ambient radiation inside the vacuum chamber range up to 118 Sv/h, while a value of 310 Sv/h (at 10 cm distance) was measured on the extracted collimator KHE2 behind Target E [2]. Both values were measured after a cooling time of 82 and 86 days, respectively.

Radiation Hard Magnets

The beamline between Target M and the beam dump consists almost exclusively of radiation hard magnets. Overall, over 50 radiation hard magnets are in operation, including 40 quadrupoles and seven dipoles.

This paper will explain the experience gained regarding design and operation of radiation hard magnets and propose a few basic guidelines.

DESIGN PRINCIPLES

Ranging back to the early seventies, the design of radiation hard magnets at PSI has proven to be very successful. This section describes a few basic principles which contributed to this success and lessons learned.

Material Choice

The effect of radiation on different materials [3], including thermosetting resins [4], has been thoroughly documented in the past; beyond a certain radiation level, no organic materials should be used in the magnet design. For instance, the total dose for epoxy compounds lies around 10 MGy before severe damage occurs. There are possibilities to increase the lifetime of epoxy compounds by using cyanate ester and/or mica insulation, allowing for a theoretical lifetime beyond 100 MGy [5].

However, if we consider one of the most exposed magnets in the PSI beamline immediately behind Target E, a recent 3D calculation shows an estimated

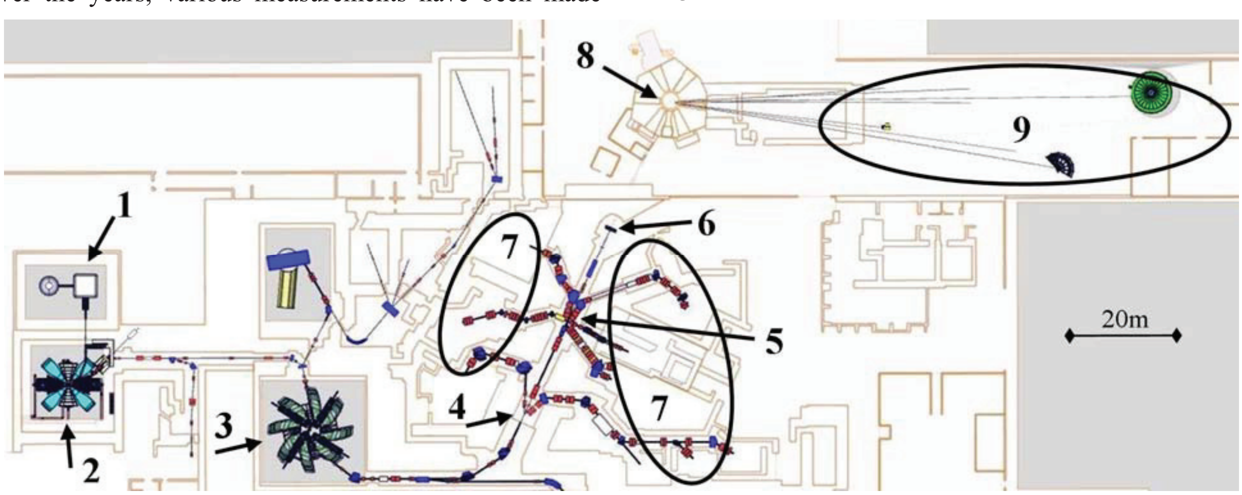

Figure 1: Overview of the main accelerator facility. (1) ECR source; (2) Injector II; (3) Ring cyclotron; (4) Target M; (5) Target E; (6) beam dump; (7) meson experimental areas; (8) SINQ spallation source; (9) neutron experimental area.

radiation deposit of 5 to 7 MGy per week [6], limiting the lifetime of a regular epoxy magnet coil to less than two weeks. Therefore, the best approach is to use metals and ceramics only, even for secondary elements like electrical or hydraulic connections away from the main beam path.

Cooling

A very high water quality is required in case of direct cooling; even non-measurable amounts of oxygen and carbon dioxide can cause copper corrosion, ultimately causing blockages in the cooling channels due to fine copper oxide particles [7]. Additional corrosion is driven by the interaction between water and radiation [8]. This leads to the conclusion that a direct contact between copper and water should be avoided completely. In addition, direct cooling requires electrically insulating water connections; as no organic materials can be used, the only remedy is to use ceramic tubes with brazed metal ends. The special properties of this arrangement make it both very fragile and prone to corrosion [9].

Based on the experience at LAMPF [10], the approach chosen by PSI was to use a solid conductor and indirect cooling [11]. For this arrangement, mineral insulated cable (MIC) is used; it consists of a copper conductor surrounded by magnesium oxide powder inside a copper sheath. Figure 2 shows a typical cross section.

Indirect Cooling

In this coil design, additional cooling layers are introduced. The following concept has proven to be the most successful for applications at PSI.

A layer of stainless steel tubes is inserted between two double pancakes; the area between the tubes is filled with copper filler pieces to improve heat transfer. The hydraulic system is assembled using stainless steel tubing and fittings only; the complete assembly is then potted in soft solder to further increase the heat transfer. Figure 3 shows an example of a typical coil cross section.

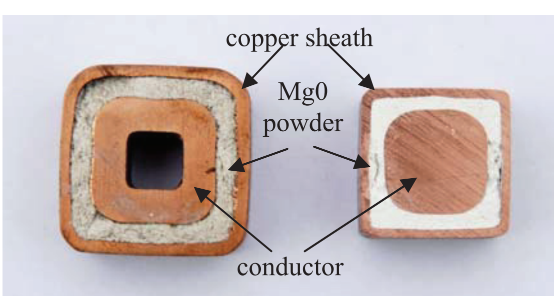

Figure 2: MIC conductor cross sections with (left) and without central cooling channel.

Manufacturing

The need for the coil to be potted in soft solder increases the manufacturing effort compared to directly cooled MIC coils, which can be bundled or clamped. However, compared to a standard coil potted in epoxy, the effort is not excessive.

Most of the winding and potting process is similar to standard coils, the most prominent differences being the sensitivity of the conductor outer copper sheath to damage and the hygroscopic properties of the insulating MgO powder, requiring the cable ends to remain sealed at all times. While temporary end seals are sufficient during the manufacturing process, ceramic end connectors are used for the final sealing, which also provide the electrical insulation.

A major advantage of the concept depicted in figure 3 is the fact that large coils can be divided into several units which can be manufactured individually, then assembled to form one coil. This makes manufacturing easier and reduces the potential loss if a catastrophic failure occurs during production or assembly.

REDUNDANCY

After several years of operation, both the magnet itself and its immediate surroundings will be highly activated, making on site servicing impossible and replacement difficult and time consuming. Based on today's experience, a concept of redundancy was created which will be implemented in the future at PSI.

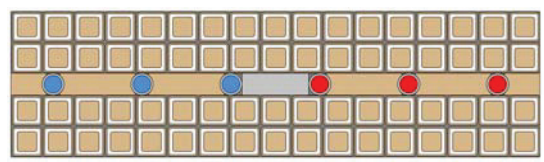

Figure 3: Coil cross section using MIC cable and indirect cooling. In this case, input and return cooling paths are inside the same cooling layer, requiring a stainless steel filler piece in the center to minimize heat transfer.

To create a time buffer, both for manufacturing a replacement magnet as well as scheduling a replacement procedure, simple modifications are introduced to allow magnet operation with modified operating parameters. Some of these modifications require additional space, which is why it can not be applied in every case.

Electric Redundancy

The most prominent type of electrical failure for magnets with MIC coils is a short to ground. The first remedy is to modify the power supply into a floating mode, effectively eliminating the current flow to ground.

This has been implemented successfully in two cases at PSI, one magnet running in floating mode for over nine years now. However, as soon as a second short to ground develops, further measures have to be taken.

An electrical redundancy is achieved by dividing each magnet coil into several sections connected in parallel; these connections are achieved by using connectors which can be removed and modified by remote access.

Disconnecting one or even several faulty circuits will allow for the magnet to stay in operation with modified operating parameters; the resistance will be higher and therefore the power consumption will rise. This has to be taken into account during the design of the power supply.

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Hydraulic Redundancy

While the choice of indirect cooling will eliminate the problem of copper corrosion, a water leak can still occur inside or immediately around the coil. By dividing the tubes inside the coil into several groups, the faulty cooling circuit can be shut down in case of a water leak while the remaining groups stay in operation.

Each group is fitted with a separate valve both at entrance and exit; the valves will have to be positioned so that they can be operated remotely. By monitoring the pressure loss, the faulty circuit can be identified and shut down. The magnet can stay in operation, the reduced cooling leading to a higher water velocity inside the remaining cooling tubes, a higher operating temperature and therefore again a higher power consumption.

REMOTE HANDLING

Even before the magnet has completed its life cycle, servicing and manipulation of other components of the beamline might require the temporary removal of connections and sometimes removing the magnet to gain access to other components.

Connections

At PSI, electrical connections are achieved by using commercially available plug and socket systems. These plugs are attached to copper or brass rods conventionally insulated at the top of the shielding block; the sockets on the magnets are insulated using commercially available ceramic products. The connections can be removed manually from the service level above the local shielding.

A similar approach can be used for water connections, where a water pipe is screwed into a metal socket from above. Good care has to be taken to achieve tightness and avoid damage to sealing surfaces and threads.

An alternative approach would be to simply extend the leads and water tubes to an area outside the shielding to allow for manual operation of the connections and the use of organic materials. However, this will require long leads and tubes, leading to potential problems both during shielding design and in case of a removal or replacement operation.

Manipulation

The beamline at PSI was designed for vertical access; large shielding blocks cover all beamline elements which are inserted inside a concrete channel. On top of the local shielding, electric and hydraulic connections are accessible during shutdown periods. There is an additional shielding layer above this service level.

Should a magnet have to be replaced, all connections are removed manually on site and the vacuum chamber seals extracted vertically. With a remotely operated crane, the shielding above the magnet is removed; then, the magnet itself is removed vertically and transported to the high radiation servicing area. While this concept has proven to be very successful, it requires a crane and a substantial amount of headroom.

CONCLUSIONS

Being the most powerful proton accelerator in the world, the PSI Ring cyclotron and the subsequent target beamlines generate a large amount of radiation. After almost forty years of operation, the design principles adopted by PSI for the design of radiation hard magnets have proven to be very successful. The key elements are:

- Systematic restriction to non-organic materials
- Using a coil design with indirect cooling
- Careful planning of future service and replacement procedures
- Possibly increasing the magnet lifetime by introducing redundancy (where possible)

This approach allowed for the increase of the beam current by more than one order of magnitude.

A more detailed version of this document can be downloaded on the PSI website [12].

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REFERENCES

[1] L. Rivkin, “Welcome to PSI”, IMMW 16, October 2009; http://immw16.psi.ch/Presentations/

[2] B. Amrein et al., “Die wichtigsten Daten des Shutdown 2010 aus der Sicht des Strahlenschutzpersonals vor Ort“, Shutdown report 2010, PSI internal report AN-96-10-27, July 2010.

[3] P. Beynel, P. Maier, H. Schönbacher, “Compilation of Radiation Damage Test Data: Materials Used Around High-Energy Accelerators”, CERN-82-10; Geneva: CERN, 1982.

[4] M. Tavlet, A. Fontaine, H. Schönbacher, “Compilation of Radiation Damage Test Data: Thermoset and Thermoplastic Resins, Composite Materials”, CERN 98-01; Geneva: CERN, 1998.

[5] P. Fabian, N. Munshi, R. Denis, “Highly Radiation-Resistant Vacuum Impregnation Resin Systems for Fusion Magnet Insulation”, Advances in Cryogenic Engineering-Materials, Vol. 48 (2002), p. 295-304.

[6] D. Kiselev, “Absorbierte Energie in Gray für Epoxy-Glas im QTH51”, PSI internal memo, March 2012.

[7] H. Reist, D. George, “Accelerator Magnet Plugging by Metal Oxides”, PSI Scientific and Technical Report 2004 Volume VI, p. 142.

[8] DOE Fundamentals Handbook “Chemistry”, Vol. 2, DOE-HDBK-1015/2-93; Washington D.C (1993), p. 1-4.

[9] A. Harvey, “Experience with the LAMPF Mineral-Insulated Magnets”, MT-6, Bratislava (1978) p. 551-557.

[10] A. Harvey, “Radiation-Hardened Magnets Using Mineral-Insulated Coils”, LA-5306-MS Informal Report, June 1973

[11] D. George, “Magnets with Mineral Insulated Coils At SIN”, MT-5, Rome (1975) p. 719-723.

[12] D. George, A. Gabard, “Design Handbook for Radiation Hard Magnets”, (Villigen PSI: 2012); http://magnet.web.psi.ch/Archive/