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PROTECTION AND MONITORING OF THE ISR SUPERCONDUCTING LOW- β QUADRUPOLES

by

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Abstract - The eight superconducting magnets of the high luminosity insertion, installed in the CERN Intersecting Storage Rings during autumn 1980, were designed intrinsically safe against quenches. Nevertheless, in order to prevent any damage to the windings or to the cryostats, an active interlock system will trip the power supplies in the case of quenches, overheating of current leads or abnormal liquid helium level. In addition, fast quench detectors will dump the ISR beam to prevent uncontrolled losses of protons.

To prevent the unnecessary loss of the ISR beams due to a switching off by these interlocks, a computer-controlled monitoring system helps to arrest the development of faults on the magnets or on the cryogenic system. Moreover, it provides an easy observation of the system.

In such a complex magnet system, it is of utmost importance to analyse every quench and find its reason. In addition to the conventional display of the memorized interlock pattern, a fast Quench Recorder is employed. It is based on a data-acquisition system controlled by a dedicated minicomputer.

1. INTRODUCTION

In order to increase the interaction rate in one of the intersections of the ISR, eight superconducting quadrupoles were installed during autumn 1980 [1]. The magnets have a maximum field gradient of 43 T m^{-1} at 1600 A excitation current. The diameter of the warm bore is 173 mm. Two types of magnets are installed: short magnets of 0.65 m magnetic length and a maximum stored energy of 295 kJ and long magnets of 1.15 m magnetic length and a stored energy of 540 kJ. Each magnet is equipped with auxiliary windings: a sextupole for beam chromaticity correction and a dodecapole to correct the saturation of the iron yoke at different field values. The magnets are cooled by a level controlled bath of liquid helium.

It is not possible to switch ON or OFF these superconducting magnets without losing the circulating beam in the ISR. Consequently, the system must be guaranteed fail-proof during operation. This will be even more important when antiprotons are circulating in one ring, since then, the machine will have physics runs lasting ten days with filling periods of four days.

However, the protection circuitry must switch off the excitation currents, hence provoking a beam loss, fast enough to avoid damage to the system. These contradictory requirements were already taken into account in the design of the magnets and cryostats; the windings support quenches without any need for protection, and passive elements of protection were included as far as possible.

Active circuitry must cope with these remaining risks:

- abnormally high liquid helium level,
- overheating of a current lead,
- powering of a winding in the resistive state, in particular after a quench.

It is also desirable that fast quench detection systems trigger the beam dump before the variation of the magnetic field provokes random proton losses around the ISR ring. This could in particular lead to quenches of the other magnets.

The magnet and cryogenic system will also be running unattended. Consequently, a monitoring system must warn the ISR operators if a fault starts to develop so that remedial action can be taken before a beam loss occurs.

Since this is the first time that a magnet insertion of this kind is used as part of an accelerator, it is also important to provide powerful diagnostic equipment in order to analyse operation failures. The quenches of the superconducting magnets due in particular to particle irradiation, should be studied in detail.

2. BUILT-IN PROTECTION OF THE MAGNETS

First of all, the magnet windings are designed to withstand quenches without any need for protection. It was in particular tested [2] that, at all excitation currents, a quench provoked by a local heater propagates itself fast enough to avoid overheating or overvoltages in part of the windings. Further tests showed that a quench due to lack of liquid helium did not cause damage to the magnet.

In the case of a current lead burning out, the magnet is protected by resistors connected in parallel with the magnet windings inside the cryostats.

Due to the rapid change of magnetic induction when a power supply of an auxiliary winding trips (sextupole or dodecapole), a quench can occur in a quadrupole at a high current. To prevent this, diodes were mounted near the cryostat in parallel with these auxiliary windings. This also limits the power dissipation inside the cryostat.

3. CIRCUITRY PROTECTING THE MAGNETS AND CRYOSTATS

3.1 Design principles

Nowadays, relays and probes based on mechanical contacts, although they have the advantage of always failing in the same way, are not as reliable as electronic components. Furthermore some parameters to be measured need electronic amplification. Consequently, the use of relays is limited to the minimum, and the active circuitry is based on analog and logic electronic components. This also allows easy adjustments of the triggering levels and the reaction times of the interlock chains.

Logic components are only used to group the outputs of all discriminators that have to interlock the same output function. Separately, in order to diminish

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the complexity of the interlock chains themselves, electronic memories allow to trace back the causes of triggers, and are then linked to the quench recorder (see section 5.).

Although they use the same sensors, the interlock circuitry and the amplifiers conditioning the signals for the quench recorder or for the monitoring system are independant, in order to increase the reliability of the interlocks.

The protecting circuitry was designed with built-in redundancy to avoid damage to the system. It was also made fail-proof with regard to faults in the cabling and electronics. Indeed, the protection of the magnets and cryostats is more important than the risk of unnecessary proton beam losses.

3.2 Description of the interlock chains

Liquid helium level - Although a lack of liquid helium cannot provoke damage, a quench can lead to dangerous overpressures when the level is too high. The protective circuitry acts in two steps: first it closes the valve that controls the transfer of liquid helium, then, if the level continues to rise, it switches off the power supplies related to the faulty cryostat.

The measurement is done with continuous level probes, the different levels of triggering are thus easily adjustable in the analog electronics.

Overheating of a current lead - Accidental fluctuations of the cooling system might provoke the overheating of a lead.

Platinum temperature probes are mounted at the top of each lead, and the electrical resistance of the lead is also measured. Warnings and alarms are sent to the ISR operators via the monitoring system to request intervention before the hardwired circuitry switches off the power supplies. This trigger takes place when the temperature at the top of the lead reaches 340 K.

Detection of coils in the resistive state - The magnet interlock system must also prevent the powering of a non-superconductive coil in order to avoid damage to the protection resistors or to the coil itself. The power supply of the quadrupoles and sextupoles is switched off by quench detectors, which, because of their short response time, are suitably used with the beam dump system of the ISR.

The principle of the quench detectors is based on a voltage difference measurement; the voltage of one pole is subtracted from that of the neighbouring pole, the resulting signal remaining zero in the case of charge of the magnets. A resistive transition having exactly the same rate of propagation in these two poles would not be detected, but the probability of such an event is negligible; a beam loss should heat the different poles identically, and the wires of these poles should have critical currents identical. In fact, numerous quenches produced during the reception tests of the magnets, and the few quenches obtained up to now by beam losses in the ISR, show that these detectors are sensitive enough to dump the beam before any noticeable change occurs on the magnetic field. Overall response times are below 50 ms.

The redundancy for the coil protection is ensured by independant slow circuits. They measure the voltages across the windings or the currents in the protecting diodes and they must cope with the period needed to charge a winding.

For the quadrupole, this period ranges from 100 s if the power supply is at its full voltage to more than 300 s during normal conditions. The tests show that the power supply cannot put more than 100 A into the quadrupole when in the resistive state. The circuit detects whether a voltage higher than 0.8 V is applied for more than 60 s and whether the current remains below 300 A. The reaction time is reduced to reasonable and easily obtainable values whilst the triggering of the interlock due to normal charge rates or ramping up and down the magnet is completely avoided.

In the case of the sextupole and dodecapole windings some protection is necessary due to the local free-wheeling diodes.

Current may flow in these diodes for three reasons:

- i) if more than 600 mV is applied to the winding during the charge or the discharge of the magnet (this cannot last for more than 10 s);
- ii) if the winding is not superconductive;
- iii) if a diode is damaged.

Tests showed that an irradiated diode has a higher leakage current at low voltage and higher resistance at high current. Hence, current may flow under normal conditions, whilst the diode's function of limiting the voltage is no longer assured. If a current is detected in one of the diodes for a period longer than the normal time to fully charge these windings, the power supply in question is tripped. The principle of the measurement is based on a d.c. transformer. The direct current to be measured saturates a ferrite torus, thereby altering the inductance of an a.c. winding on the same core. These detectors are also used by the monitoring system.

4. THE MONITORING SYSTEM

The monitoring system has the following functions:

- Display of the actual status of any part of the system.
- Memorizing all data sampled periodically for a certain duration (logging).
- Selective retrieval of logged data.
- Generation of alarms and warnings if critical situations are detected and operator intervention is required.

The computer used is a NORD-10S, interfaced with CAMAC standard equipment. An alphanumeric terminal, a graphical display, an alarm printer and a touch panel are available in both the ISR Control Room and in the building housing most of the service hardware (Fig. 1).

All measured quantities, such as temperature, pressure, liquid level, gas flow, etc. are converted into analog voltage signals. The related electronic equipment for measurement and display is shown in Fig. 2.

The raw information treated consists of 140 digital and 250 analog signals each corresponding to an elementary quantity. Certain elementary quantities are combined to form compound quantities following physical laws or logical relations.

Data acquisition may be instantaneous by direct operator call or regular for ephemeral memorization and automatic monitoring. The data may be displayed or printed as single quantities or as groups of quantities. Although usually the final physical or logical quantities are desired, raw values or hardware source information may also be requested.

Fig. 1. The lay-out of the monitoring system

Fig. 2. Display and monitoring equipment

Memorization of final data for further analysis is provided by means of a 2.5 Megabyte disk storage. The interval of continuously recorded data may vary from one to several days according to the logging frequency chosen. During normal operation, all data is recorded every 6 min which allows data to be retained for the last five days.

Software is available for retrospective analysis which can graphically or textually display information as a function of time or provide groups of data from a given moment in the past.

Automatic monitoring includes alarm or warning messages to a central and a local station as well as audible and visible alarm signals.

The monitoring criteria are defined in a data base. There may be different thresholds and settings for each quantity for four operation modes (magnet operation, liquefaction, refrigeration and stand-by mode). Whenever the cryogenics operator changes the operation mode by means of a selector, the monitoring program will switch automatically the procedure.

Since an alarm requires the intervention of a specialized operator, great care has been taken to choose the alarm producing signals and conditions, in order to restrict alarms to the minimum necessary to avoid damaging the installation. Thus, the operation mode alarms are only given for abnormal cryostat pressure, cryostat screen vacuum, liquid helium level, temperature and resistance of current leads. A number of liquefier components may generate alarms when out of order.

The computer software is organized such that the dependence of programs upon user-defined facts is minimized. This is achieved by means of a data-base. In this way, names and lay-out of quantities, identification texts, physical dimensions of quantities and even calculation algorithms can be defined and changed by the user. This technique yields a high flexibility of the system.

5. THE QUENCH RECORDER

In addition to the conventional display of the memorized interlock pattern, a fast Quench Recorder is employed. It is based on a separate data-acquisition system controlled by a dedicated mini-computer. This computer is linked to a real-time computer system for permanent storage of data and for display of measured and calculated quantities.

The Quench Recorder is running continuously and unattended during magnet operation. The 108 measured analog signals include coil voltages, excitation currents and the measurement of proton losses in the magnets. A number of binary signals, including all interlock signals for power supplies and beam dumps, are also recorded. The measured quantities are stored in a circular data buffer and are retained in the event of a quench. The sampling rate is 100 measurement cycles per second. After the detection of a quench, the recording continues for a period of 7.5 s. The sampling rate is reduced at certain intervals as the time resolution becomes less critical. The total recorded period is 8 s.

The Quench Recorder permits to analyse the reasons for and the development of the magnet quenches. The propagation of the quench between the different magnet windings can be examined in detail. The influence on the beam and on the other superconducting quadrupoles of the magnet system can be observed.

In addition to these directly measured quantities, a number of relevant parameters can be deduced from the precise measurement of the decay of the excitation current.

The stored energy as a function of the excitation current was measured precisely during the acceptance tests of the magnets. The instantaneous power dissipation, the total voltage induced by the current change as well as the total resistance of the excitation winding at any moment can easily be deduced from the

measurement. The average temperature of the winding after the quench can in turn be deduced from the calculated total resistance of the winding.

Finally, the maximum possible temperature rise which could have occurred in the magnet winding can be calculated by a numerical integration of the power dissipation in the conductor [3].

An example of displayed quantities is given in Fig. 3, which shows the measured current decay, the calculated power dissipation and the calculated maximum temperature as function of time.

Fig. 3. Example of Quench Recorder display

6. OPERATIONAL EXPERIENCE

The magnets and cryogenics were installed and tested in the ISR tunnel during the autumn 1980. The protection and monitoring system was employed successfully during commissioning. Since then, several development runs with circulating proton beams have allowed to verify the usefulness of the protection and monitoring system described in this paper. The quenches which occurred during operation of the ISR were all induced by the accidental loss of particles into the magnets. Only one magnet quenched each time. The protection system functioned correctly and the analysis of the quench recordings confirmed that no voltages or temperatures exceeded the tolerable limits.

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