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L. Coull, D. Hagedorn, V. Remondino, F. Rodriguez-Mateos

Abstract

The quench protection system for the superconducting magnets of the CERN Large Hadron Collider (LHC) is described. The system is based on the so-called "cold diode" concept. In a group of series connected magnets if one magnet quenches then the magnetic energy of all the magnets will be dissipated in the quenched magnet so destroying it. This is avoided by by-passing the quenched magnet and then rapidly de-exciting the unquenched magnets. For the LHC machine it is foreseen to use silicon diodes situated inside the cryostat as by-pass elements - so-called cold diodes. The diodes are exposed to some 50 kGray of radiation during a 10 year operation life-time. The high energy density of the LHC magnets (500 kJ/m) coupled with the relatively slow propagation speed of a "natural" quench (10 to 20 m/s) can lead to excessive heating of the zone where the quench started and to high internal voltages. It is therefore necessary to detect quickly the incipient quench and fire strip heaters which spread the quench out more quickly over a large volume of the magnet. After a quench the magnet chain must be de-excited rapidly to avoid spreading the quench to other magnets and over-heating the by-pass diode. This is done by switching high-power energy-dump resistors in series with the magnets. The LHC main ring magnet will be divided into 16 electrically separated units which has important advantages.

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Abstract - The quench protection system for the superconducting magnets of the CERN Large Hadron Collider (LHC) is described. The system is based on the so called "cold diode" concept. In a group of series connected magnets if one magnet quenches then the magnetic energy of all the magnets will be dissipated in the quenched magnet so destroying it. This is avoided by by-passing the quenched magnet and then rapidly de-exciting the unquenched magnets. For the LHC machine it is foreseen to use silicon diodes situated inside the cryostat as by-pass elements - so called "cold diodes". The diodes are exposed to some 50 kGray of radiation during a 10 year operation life-time. The high energy density of the LHC magnets (500 kJ/m) coupled with the relatively slow propagation speed of a "natural" quench (10 to 20 m/s) can lead to excessive heating of the zone where the quench started and to high internal voltages. It is therefore necessary to detect quickly the incipient quench and fire strip heaters which spread the quench out more quickly over a large volume of the magnet. After a quench the magnet chain must be de-excited rapidly to avoid spreading the quench to other magnets and over-heating the by-pass diode. This is done by switching high-power energy-dump resistors in series with the magnets. The LHC main ring magnet will be divided into 16 electrically separated units which has important advantages.

I. INTRODUCTION

This note gives a concise presentation of the present ideas concerning the quench protection of the LHC magnets. The first chapter reviews briefly the basic quench protection principles and indicates the options which have been chosen for LHC. In the succeeding chapters the important aspects are treated in more detail.

II. BASIC PRINCIPLE

In a group of series-connected magnets, if one magnet quenches, then, unless precautions are taken, the magnetic energy of ALL the magnets will be dissipated in the quenched magnet, so destroying it. The solution to this problem is to "by-pass" the quenched magnet and then de-excite the remaining series-connected unquenched magnets. For the LHC machine it is foreseen to use silicon diodes situated inside the cryostat, so-called COLD DIODES (see III.) as by-pass elements.

The extremely high energy density of the LHC magnets, coupled with the relatively slow propagation speed of a

"natural" quench can lead to excessive heating at the zone where a quench starts. It is therefore necessary to DETECT (see IV.) very quickly the incipient quench, and fire strip HEATERS (see V.), which provoke quenching along the outer layer of the magnet coil.

In order to avoid that the quench spreads to other magnets and that the cold diode overheats a FAST DE-EXCITATION (see VI.) of the magnet chain must be initiated whenever a quench is detected.

The de-excitation system is dependent on the ELECTRICAL LAYOUT of the machine. Fig. 1 shows the proposed POWER circuit of the LHC main ring magnet. The machine is divided into 16 SUB-UNITS (half octants of both machines together), powered separately and so electrically independent.

This scheme, also proposed for the SSC, has several important advantages compared to a series connection of all magnets:

Fig. 1 LHC Powering

- During fast de-excitation, since there is only one switched resistor per circuit there is no risk of a build up of voltage to earth due to differences in switch timing and resonances.

- The earthing of the ring is much more efficient since it is at 16 points around the ring.

- If quenches occur in a limited region then only one sixteenth of the total machine has to be rapidly de-excited. This reduces the total eddy current losses during de-excitation, and decreases the risk of false quench detection and quench provocation.

- The 16 "small" autonomous sub-units, which correspond to the vacuum and cryogenic sub-divisions of the machine, give easier testing and setting-up possibilities.

- There is no passage of heavy current bus-bars through the intersection regions.

However, this whole system stands or falls on how well the 16 separate power converters can maintain the required tracking and precision which is required to be in the 10^{-5} region. This extremely difficult problem is being studied by the SL/PC group at CERN.

III. COLD DIODES

The cold diode by-pass elements are situated inside the cryostat, at liquid helium temperature, and are connected across the magnet coils such as to take over the magnet current at quench [1].

Fig. 2 LHC half-cell with protection diodes across each double magnet.

A. Requirements

The requirements of these diodes are that they should absorb a peak current of 15 kA which then decays exponentially with a time constant of about 100 seconds. This gives an energy absorption for the diodes and their heat sinks of about 1.8 MJ. The diode reverse voltage requirement is determined by the maximum de-excitation voltage applied - this is normally about 10 volts per diode but under fault conditions may be much higher (see VI.), so a rating of at least 100 volts is required (at liquid helium temperatures). The primary requirement, however, for these diodes is that they should be radiation resistant, at liquid helium temperatures, up to a dose of 50 kGy and neutron fluences of 10^{15} neutrons per cm^2 during a period of 10 years.

B. Radiation Hardness

Several different types of diodes have been studied and radiation tested for this application [2]; firstly diffusion-type diodes, and then epitaxial diodes specially built for this purpose. Irradiation tests at 77 K in an accelerator environment showed that after a few kGy the forward voltage of the normal diffusion-type diodes increased to an unacceptable level. For the epitaxial diodes of 10 to 20 micron base width, (with a reverse breakdown voltage between 100 and 200 volts), an increase of the forward voltage from only a few percent (10 micron) up to 50 % (20 micron) was observed for a radiation dose of about 20 kGy [3]. Thermal annealing reduced the maximum deterioration to about 15 %. The reverse blocking voltages increased by up to 25 % after irradiation.

Further tests, at liquid helium temperatures, on small diode samples of the epitaxial type will be carried out in a nuclear reactor at doses up to about 50 kGy and 10^{15} neutrons per cm^2 in order to confirm that this diode type can be used for the protection of the LHC magnets.

C. Assembly and Installation

For reasons of access it has been decided to situate all the diodes for a half-cell in the short straight section of the quadrupole cryostat and so *by-pass the half-cell*. In the case of a quench in a half-cell then ALL the magnets in that half-cell will be forced-quenched by heaters, and the current will commutate from the half-cell over to the cold diodes. Since the excitation voltage of a half-cell is about 3 volts then several diodes, connected in series, are necessary. In Fig. 2 a solution is shown with 4 diodes. Connections are made to the diode stack such that each double magnet has effectively its own by-pass diode. Since the magnets are then decoupled from each other differences in the heater-induced quench delays and in the resistances between magnets do not lead to

high voltages to earth at points *between* the magnets. Calculations have shown that, without these intermediate connections, RRR variations of a factor 2 between magnets and 20 milliseconds of difference in the heater delays, could provoke up to 4kV to earth at points between the magnets. These intermediate connections can be of fairly small section (10 to 20 mm²) since they carry current only for a fraction of a second.

IV. QUENCH DETECTION

A. System

In view of the very high energy density of the LHC magnets it is necessary to detect incipient quenches, and fire the coil heaters to spread the quench quickly through a large volume of the magnet.

To detect the quench, the voltages across the two halves of the magnet are compared. If a quench occurs at a point in the magnet then a differential voltage appears and this is detected. A completely symmetrical quench of both magnet halves is extremely unlikely but this problem can also be eliminated by making a second differential comparison, this time between the adjacent magnets in the same cryostat.

A further quench detection system on the main current return bus-bar may be necessary since a quench here although unlikely, could cause considerable damage if the fast de-excitation is not quickly initiated.

In addition to the quench detection differential amplifiers a second set of amplifiers will continuously monitor and record the magnet voltage. This will detect any anomaly in the excitation or de-excitation voltage due to a deficient diode or other problem. All of these signals (excitation voltages, quench voltages) are recorded in a "sliding" memory. When a fault occurs then the previous 2 to 3 seconds are retained in memory together with the subsequent 2 to 3 seconds. This gives useful information since the form of a quench voltage can give indications as to the quench origin, and "false" quenches can be identified.

B. Components

The two basic elements of the system described above are the quench detection amplifiers and the monitoring amplifiers.

The electrical requirements of both of these amplifiers are not at first sight particularly severe. It would seem that a quench detection level of tenths of a volt and delays in the milliseconds order will suffice. These values may be lower for the detection of bus-bar quenches but with filtering and careful cabling of voltage taps the voltages should be above the expected noise levels. The common-mode voltage to earth on the magnet terminals could reach about 800 volts during de-excitation. This imposes the use of some kind of isolation amplifier.

The major problem for these amplifiers is surviving the radiation level in the LHC tunnel estimated at between 5 and 50 Gy per year of "accelerator" radiation.

A radiation hard magnetic amplifier already exists in the HERA machine at DESY and this same device is being considered also for LHC for quench detection but its non-linearity makes it unsuitable for use as a monitoring amplifier. Electronic isolation amplifiers are clearly suitable for this requirement but they must be "radiation hard" to the levels given by LHC.

Tests have been carried out on various isolation amplifiers in an accelerator radiation environment and it was found that a commonly used isolation amplifier (the AD289 amplifier from Analog Devices) gave very encouraging results [4]. These amplifiers continued to work satisfactorily up to an absorbed dose of about 2500 Gy, equivalent to between 50 and 500 years of LHC operation at full intensity. The deterioration showed firstly in a loss of high frequency gain, before the amplifiers finally became unusable. All amplifiers tested gave very similar results. This gives a possibility to check the amplifiers during a shut-down and to replace those which have seriously deteriorated. An amplifier which fails will almost inevitably give a high offset output which is easily detectable and "fail-safe." The radiation tests are continuing.

These results lead to the possibility that, with a continuously monitored double-security system, it may be possible to replace the magnetic amplifiers of the quench detection system by such electronic isolation amplifiers which have much superior electrical characteristics.

The output signals from the quench detection amplifiers and from the monitoring amplifiers will be sent to screened alcoves which are distributed around the LHC tunnel. In these enclosures, computer-controlled multiplexing and data-handling systems will be situated. These will monitor and record the magnet voltages from the isolation amplifiers, and the quench detection signals from the magnetic amplifiers. They will also control the fast de-excitation switches and give out the signals necessary for beam-dumping etc.. This system will be composed mainly of industrial process-control material.

V. QUENCH HEATERS

The heaters for the main lattice magnets are composed of 15 mm wide, 25 microns thick, stainless steel strips, with Kapton insulation. Four quench heaters are placed along the outer layer of the dipoles covering 12 turns of each pole along the entire length of the magnet.

The heaters are powered by a capacitor discharge. To keep the capacitor voltage low, without losing heater efficiency, the stainless steel heater strips are section-wise copper clad on one side with high RRR copper of 1 to 1.5 micron thickness, such as to alternate 25 cm lengths of clad and unclad stainless steel. This almost halves the resistance

of the strips and gives a "spot" heating along the coil which, due to quench spreading, is expected to be almost as effective as heating over the full length.

Results from 1 metre model tests [5] showed that, for a specific initial power of 36 kW per square metre of stainless steel strip, the delay time between the firing of the capacitor discharge and the start of quenching below the strips, for nominal current (14.5 kA) and at a temperature of 1.8 K, was about 35 milliseconds.

VI. FAST DE-EXCITATION

A. System

The rapid de-excitation of the magnet chain is achieved by switching a high-power resistor in series with the magnets (see Fig.1).

The fast de-excitation of the magnets must be fast enough to avoid over-heating of the diodes but should not be so fast as to provoke quenching by dI/dT in other magnets, nor should the de-excitation voltage be so high as to damage the magnet insulation. Measurements on model dipoles have shown that, at full field, the maximum allowable negative dI/dT is about 300 Amps per second. Furthermore the voltage to earth of the magnets should be kept below 1 kilovolt. A decay time-constant of about 100 seconds seems to be a good compromise. A low de-excitation rate also gives reduced eddy-current loss, less risk of provoking additional quenches, and reduced voltage disturbance to the magnet with its sensitive quench detection system.

In the event of multiple quenching then the reducing time constant (less magnets) giving higher dI/dT could provoke quenching until all magnets in the half octant had quenched. The last half-cell to quench could receive instantaneously across its extremities the full voltage being developed in the dump resistor. This voltage would exceed the breakdown voltage of the cold diode and destroy it. For this reason it may be necessary to provide additional fast switches, actuated by dI/dt , capable of being switched in quickly to short out fully or partially the dump resistor.

B. Components

i) Switches The obvious choice for these switches is to use industrial d.c. circuit breakers (as in HERA). These are well-tested, reliable, and robust elements. A 1 kV arc voltage is standard and well adapted to LHC.

ii) Resistors As shown in Fig.1) each half octant of the LHC machine is electrically separate and has one switched resistor for fast de-excitation. The inductance of the half octant is 5.5 H, which with 15 kA gives a stored magnetic energy in the half octant of about 620 Megajoules.

For a decay time constant of 100 seconds the required value of resistance is $R = L / T = 55$ milliohms. This gives an initial voltage of 825 volts across the resistor, which, with centre-point earthing, gives ± 410 volts to earth. The resistor will be constructed of stainless steel. It is presently foreseen to be situated above ground outside the LHC tunnel, and air cooled. Assuming a maximum temperature rise of 500 K, the mass of stainless steel in the resistor is about 2.7 tons.

The inductance of this resistor and of the associated cabling should obviously be kept to a minimum and it will probably be necessary to add some capacity across the switch to reduce the disturbance to the magnet and other equipment at opening. This will be defined when impedance measurements have been made on the full-length prototype magnets and transmission line and resonance effects calculated.

CONCLUSION

It is clear from the above that some aspects of the LHC magnet quench protection system still have to be defined and that much detail work remains. Equally the decision to use cold diodes has to be finally confirmed after further radiation tests. However, we feel confident that we have the basis of a satisfactory solution.

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