



**The Protection System for the Superconducting Elements
of the Large Hadron Collider at CERN**

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Abstract

The protection system for the superconducting elements of the Large Hadron Collider (LHC) [1] at the European Laboratory for Particle Physics (CERN), and its associated equipment are presented: quench detectors, cold diodes, quench heaters and related power supplies, extraction resistors and associated current breakers. Features such as radiation resistance, redundancy and required reliability are discussed.

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THE PROTECTION SYSTEM FOR THE SUPERCONDUCTING ELEMENTS OF THE LARGE HADRON COLLIDER AT CERN

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The protection system for the superconducting elements of the Large Hadron Collider (LHC) [1] at the European Laboratory for Particle Physics (CERN), and its associated equipment are presented: quench detectors, cold diodes, quench heaters and related power supplies, extraction resistors and associated current breakers. Features such as radiation resistance, redundancy and required reliability are discussed.

1 INTRODUCTION

The LHC enters into a phase where construction started and components are being produced [2]. Injection of beam into the first sector (1/8 of the LHC) is expected for 2003, and the start-up of the completed machine is foreseen for 2005. The very flexible LHC optics requires a large number of superconducting magnet circuits, their connections with superconducting bus bars, and current leads as part of the electrical circuits. In total, about 8000 magnets connected in 1800 electrical circuits will be installed [3]. All superconducting elements require protection in case of a quench or other failures which may perturb accelerator operation or even damage equipment. Some elements require a complex system, and for others the protection can be fairly simple depending on the design of the elements and their powering.

In this paper we describe the elements of the protection system and the specific protection procedures, as well as the elements performing the monitoring of the integrity of the system, and the data acquisition of a large number of signals for analysis.

Due to the large stored energies in many of the circuits, and because of the difficulty accessing elements working at cryogenic temperatures for repair, the protection systems need to be very reliable. Equipment will be simple and robust to minimise maintenance of a large number of components. Most of the electronics will be installed in the LHC tunnel and need to be radiation tolerant at a level of some ten Gy.

The following solutions for the protection are envisaged:

- The main dipole and quadrupole magnets operate at a nominal current of about 12 kA and require protection with quench heater strips on the magnet coils, cold by-pass diodes and extraction of energy.
- The quadrupole magnets in insertions and matching sections (nominal current in the range of 6kA to 12kA) will be protected with quench heaters.
- 544 circuits with corrector magnets with a nominal current of 600A require extraction of the energy.
- If an individually powered orbit corrector magnet quenches, its power converter must be switched off.

2 ELEMENTS OF THE SYSTEM

2.1 Quench detectors

Each main quadrupole and dipole magnet will have its own protection system that is fully redundant and independent of other magnets (see Figure 1). When a quench is detected, the protection will activate the powering of the quench heater strips, shut down all power converters in the sector and open the switches across the dump resistors. For a quench in a bus bar, the system will shut down the power converter of the circuit and open the dump switches without firing heaters.

The quench detection for the dipole magnets is based on floating bridge detectors. The voltages across the two apertures are compared. A quench is detected if the absolute voltage difference exceeds a pre-set threshold. For the main quadrupole magnets, the comparison will be made between two sets of two poles, since the two apertures of the quadrupole magnets are powered separately.

Quenches in bus bars for main dipole and quadrupole magnets are very unlikely, as they are installed in regions of low field, protected from direct radiation and highly stabilised with copper. It is sufficient to detect any resistive growth on long stretches, using differential signals. Where possible, redundant detection will be performed with voltage taps at the cold side of the current leads feeding the circuit.

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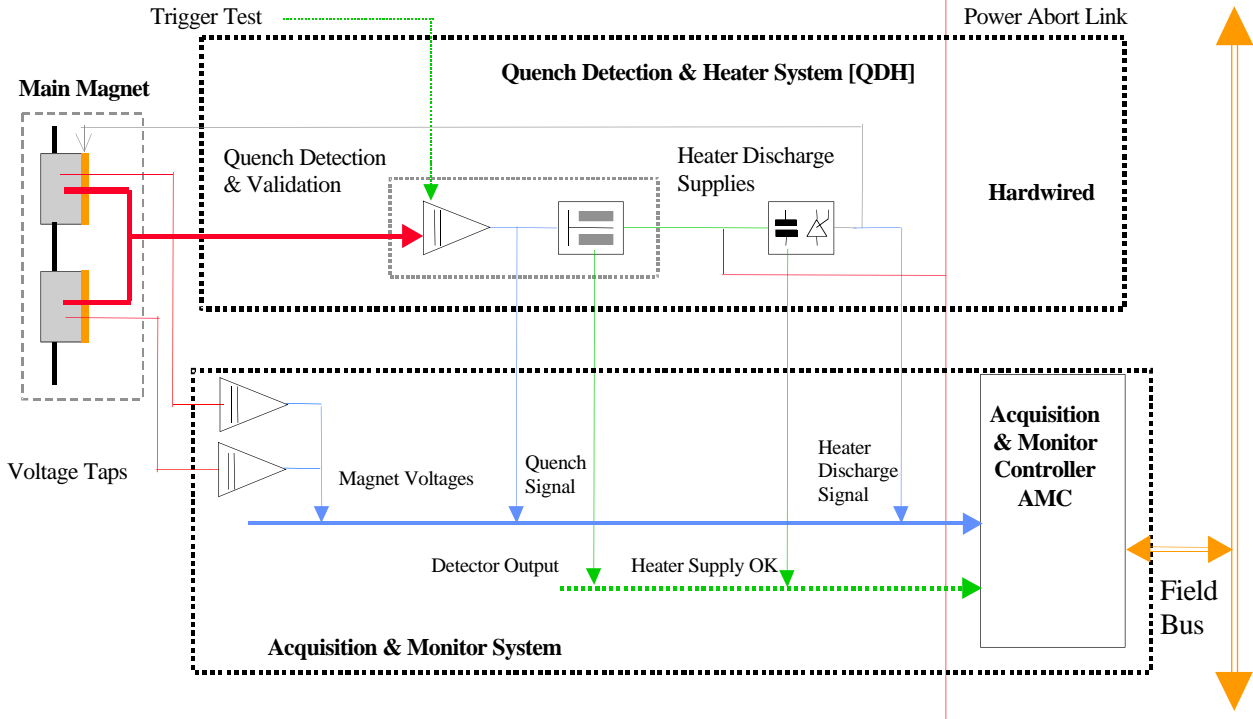


Figure 1: Block diagram for the protection system of the LHC main magnets.

For most of the circuits with corrector and insertion magnets, the voltage at the bottom of the current leads will be measured to detect a quench.

The protection of current leads (800 pairs) using high temperature superconductors depends on the quench propagation velocity. At a later stage it will be decided if they can be included into the global protection schemes

2.2 Quench heaters and their discharge supplies

The quench heater strips are sandwiched composites made of two layers of polyimide-epoxy glue embedding stainless steel strips. In order to limit the discharge voltage the strips are copper plated (a few micrometer copper thickness) to heat only a part of a strip [4].

Powering of quench heaters will be performed discharging capacitor banks by triggering thyristors in series with the strips. The heater discharge units will contain two banks of 3 capacitors connected in parallel. The capacitors will be operated at $75\% \pm 5\%$ of their rated voltage leading to an increased lifetime and a lower leakage current. The thyristors (SCR) foreseen for the power supplies are intentionally overrated in order to cope with irradiation induced changes of the device parameters.

Besides the power part, the heater power supply units require an interface to the Acquisition and Monitoring Controllers (see below) in order to monitor their status [5].

2.3 Cold Diodes

The high-current silicon diodes of the diffusion type connected in parallel to the superconducting magnets

will operate inside the magnet cryostat at a temperature of 1.9K. The quadrupole diodes have to withstand safely an estimated dose of about 400Gy and neutron fluence of about $2.4 \cdot 10^{12} \text{n/cm}^2$ during 20 years of operation. For the dipole diodes a dose of about 60Gy and a neutron fluence of about $3.0 \cdot 10^{11} \text{n/cm}^2$ has been estimated [6]. In case of a resistive transition in the superconducting magnet, the turn-on voltage of the diode is exceeded and the current commutates from the quenched magnet to the diode during the de-excitation of all magnets in the circuit.

One by-pass diode will be installed across each twin-aperture dipole magnet. As focusing and de-focusing quadrupoles will be powered separately, each single quadrupole aperture requires a diode. The two diodes assembled in one pack are galvanically separated. Each diode package must be able to conduct an ultimate current pulse of 13kA peak with a nominal decay time constant of about 100s for the dipole circuit, and about 40s for the quadrupole circuit respectively. The heat sinks have to absorb an energy of about 1.5MJ for a dipole diode; and 0.7MJ for a quadrupole diode. The diodes have to operate within a temperature range of $1.8\text{K}-450\text{K}$, withstand the associated thermal stresses, and continue to operate reliably after several cold-warm cycles.

Before installation, all diode packages will be tested at liquid helium temperature. As the differences of the electrical characteristics between 1.9K and 4.2K are rather small, most tests will be carried out at 4.2K . Only a few of the series diode assemblies will be tested at 1.8K to verify their turn-on characteristics.

2.4 Data acquisition and monitoring

The controllers for data acquisition and monitoring (AMC) will monitor the status of the protection system, allow for powering, and acquire data for both on-line and post-mortem analysis (magnet voltages, quench detector signals, signals from the heater power supplies).

The AMC units are continuously acquiring the signals and storing them in a circular buffer. When a quench is detected, the acquisition continues during a defined short period of time and then stops. On request the data is sent to the operators allowing the analysis of the event.

The integrity of the protection system is monitored, for example if heater discharge units are not correctly charged, heater discharge units are not fired, or failures of quench detectors. If an error is detected, the operators will be informed.

In terms of monitoring and data acquisition, each machine sector will be sub-divided into 5 zones, each having about 60 AMC systems and connected via a field bus to an intermediate controller (WAN-PLC). This controller acts as a bridge between the AMC units and the Control Room (see Figure 1). In order to minimise cost and development, it has been decided to use a PLC-like structure. This allows to have an Off-The-Shelf system, with only the program to be developed at CERN. Each unit will have a Data Memory exceeding 48Kbytes, an acquisition cycle less than 10ms, and analogue inputs with an accuracy of 10 bits. For the communication protocol PROFIBUS will be used.

Since the electronics will be installed in the tunnel, tests will be performed to qualify components for radiation tolerance before final selection.

3 ENERGY EXTRACTION

For a fast de-excitation in the case of a quench, many of the magnet chains will be equipped with external energy extraction systems with mechanical circuit breakers and energy-absorbing dump resistors.

The 1.33 GJ of stored energy in the dipole magnets of each sector will be extracted into two, symmetrically placed energy dump facilities, inserted in series with the two half-chains. This configuration limits the maximum voltage to ground to 500V; it halves the energy deposit in each resistor unit and allows symmetrical grounding of the power circuit (the mid-point of the mid-arc dump resistor). Transfer function analysis of the chains has shown that this grounding concept provides important advantages for ripple, ramping and transient phenomena. The resistance value (75m Ω each unit) limits the maximum current decay rate to -125A/s. Four 4.5kA D.C. circuit breakers will carry the current, fed from a current-equalising bus-way. Each cluster of breakers consists of eight individual units, with two breakers in series for redundancy. Each breaker has two independent release mechanisms (no-volt coil for slow opening and current impulse for fast release). The low-inductance

dump resistors incorporate a forced air-to-water heat exchanger, as heat dissipation into the tunnel air is inadmissible. Their cooling time is approximately one hour.

A single extraction system is foreseen for each of the quadrupole chains. The dump resistance values are 7.7m Ω and 6.6m Ω , which give a maximum decay rate of -325A/s. The same breakers as for the dipole magnets are used.

4 RADIATION TOLERANT EQUIPMENT

The equipment installed in the tunnel includes capacitor discharge power supplies for firing the quench heaters, quench detectors, breaker control electronics, data acquisition systems, programmable logic controllers (PLC) and interfaces to field buses. Due to beam losses and interactions with the residual gas in the beam tube this equipment will be exposed to radiation (order of magnitude: 1 to 10Gy per year) during LHC operation. The test of all these devices under conditions similar to those expected in LHC are performed in the newly created irradiation test zone in the northern fixed target area of the CERN SPS accelerator [7]. The dose rate in this area is about 10Gy per week corresponding to a fast neutron fluence of some 10^{11} n/cm². The zone is equipped with cable connections to a local control allowing for dynamic, on-line measurements of components and radiation levels.

In a first step the main components of the heater discharge power supplies, namely capacitors and thyristors, shall be qualified with respect to radiation tolerance, ageing and environmental influences.

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