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Neutron Irradiation Tests in Superfluid Helium of LHC Cryogenic Thermometers

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Abstract

For control and monitoring purposes, about 10,000 individually calibrated cryogenic temperature sensors will be installed along the 26.7 km LHC. In order to reduce maintenance constraints these sensors should be as immune as possible to the high neutron fluence environment. For selecting the sensor to be used, a radiation hardness evaluation program at cryogenic conditions is being performed in an irradiation vault of the ISN SARA Cyclotron (Grenoble, France). The set-up is capable of simulating the whole life of a LHC thermometer: same total neutron dose (10^{15} n.cm^{-2}), irradiation at low temperature (1.8 K) and thermal cycles. Bath temperature and sensor resistance are monitored on-line. This paper presents the latest results of this program.

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For control and monitoring purposes, about 10,000 individually calibrated cryogenic temperature sensors will be installed along the 26.7 km LHC. In order to reduce maintenance constraints these sensors should be as immune as possible to the high neutron fluence environment. For selecting the sensor to be used, a radiation hardness evaluation program at cryogenic conditions is being performed in an irradiation vault of the ISN SARA Cyclotron (Grenoble, France). The set-up is capable of simulating the whole life of a LHC thermometer: same total neutron dose (10^{15} n.cm^{-2}), irradiation at low temperature (1.8 K) and thermal cycles. Bath temperature and sensor resistance are monitored on-line. This paper presents the latest results of this program.

1 INTRODUCTION

The future Large Hadron Collider (LHC) at CERN needs a huge cryogenic system to maintain the magnets temperature at 1.9 K along the ring. Proton losses in the machine (produced by interaction with the residual gas in the beam pipe or by collisions with the beam pipe) will result in a high neutron fluence. Simulations [1] for the LHC arc regions give average neutron dose values ranging from 10^2 to 10^3 Gy for the 20 years of machine operation, assuming that the sensors are positioned on the cold mass at 57 cm from the beam axis. In other regions of the collider, doses can be significantly higher and further calculations are necessary. Sensors will also endure warm-up cycles to 300 K during an LHC maintenance shutdown. Ideally, the thermometer precision must remain better than 0.25% (5 mK at 2 K) during the whole machine lifetime. The main objective of the irradiation campaign is to expose the thermometers to environmental conditions as close as possible to those expected in the LHC: similar neutron energy spectra (1 MeV-10 MeV) and integrated dose, and irradiation at superfluid helium temperature. To study the influence of a thermal cycle between 1.8 K and 300 K a cryostat warm-up has been performed during three experiments and furthermore some sensors were irradiated in successive experiments. Ten models of commercial sensors from various manufacturers have been tested. They can be classified into five families: carbon resistors (Allen-Bradley (AB) and russian TVO), CERNOX™ from LakeShore Cryotronics (CX), platinum (Pt), rhodium-iron (RhFe) thin-film and wire-wound and Germanium (Ge) thin-film. In addition, some test samples have been irradiated: these are metals or alloys the behaviour of which under irradiation is well documented. These samples allow us validate our results. Since 1996, eight experiments have been performed (the first in liquid argon, the second [2] in liquid helium and the last six in superfluid helium) and 281 thermometers have been tested.

2 EXPERIMENTAL FACILITY

2.1 Irradiation aspects

The neutron beam is produced by the $^{9}Be(d,n)^{10}B$ reaction. A deuteron beam (20 MeV, iβ7 μA) hits a thin beryllium target and the gamma dose induced by this reaction is low: about 20% of the total energy emission. The sensors under test are immersed in a cryogenic bath that can be either liquid argon or helium. The minimum distance between the thermometers and the neutron source (beryllium target) is about 8 cm (see figure 1). To investigate the effects of a variable total dose, sensors are placed at different distances from the source. The total neutron dose is measured for each thermometer by using a small nickel foil (diameter: 4 mm, thickness: 0.125 mm) attached to it [3]. From the nickel foil activation data, a neutron dose map can be calculated at the end of the experiment (see figure 2). The average dose received by the sensors is about 20 kGy and the total neutron dose is 10^{15} n.cm^{-2}. In addition, the deuteron current hitting the beryllium target is measured during the irradiation and a simple normalisation gives the neutron dose at any time during the experiment.

2.2 Cryogenic aspects

The irradiation cryostat is composed of a cold vessel (diameter 27 cm, height 60 cm), a radiation heat shield and an outer vacuum vessel. The heat load to the cold vessel is about 200 mW, plus 20 mW when the beam is on. The bath is re-filled daily with 4.2K liquid helium, then cooled down by pumping and its temperature is regulated by controlling the saturation pressure with a throttling valve. The reference temperature is obtained either with a helium vapour pressure bulb (volume 0.3 cm^3) or by measuring the bath pressure, both in principle insensitive to ionising radiation. The bulb is immersed in the liquid bath, at the same height as the resistive sensors and a warm sensor connected through a capillary measures the pressure. At 1.8 K, the measured bath temperature stability is $\sigma_T = 0.023$ mK, including the thermal noise and the pressure measurement incertitude.

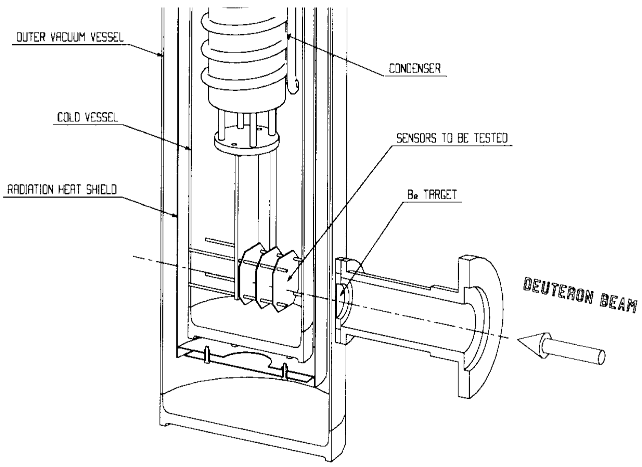

Figure 1 Irradiation cryostat

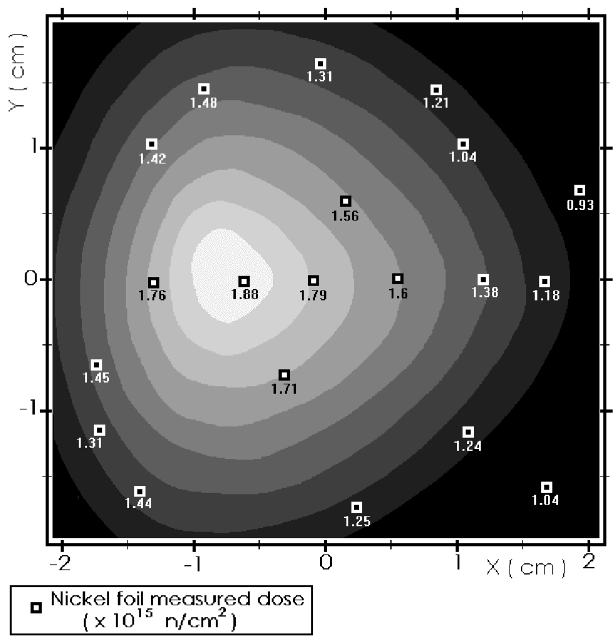

Figure 2 Neutron dose repartition at 8.5 cm from target

2.3 Acquisition and measurement systems

The measurement system is composed of a nanovoltmeter, a programmable current source (current ranges from 1 µA to 1 mA depending on the resistor type) and a scanner. The acquisition cycle duration is about 7 minutes and the temperature sensors are measured in a 4-wire configuration. In order to eliminate thermocouple effects and current source inaccuracies the voltages across the resistive-type sensors are measured with a current reversal technique and the current is measured with a high precision shunt resistor. Other parameters recorded by the acquisition system include the bath and bulb saturation pressures, the deuteron current hitting the target and various monitoring devices to verify the proper operation of the instruments. The measured relative resolution with this acquisition system is $\sigma_R/R=10^{-6}$.

3 PROCEDURE

Before irradiation, the thermometers are calibrated between 1.6 K and 4.2 K (about 15 calibration points), furthermore around the irradiation temperature another five data points with 5 mK interval are recorded. During irradiation the bath temperature is maintained at 1.8 K and all sensors are periodically recorded. When about half the expected total dose is reached, the beam is stopped, the cryostat is warmed-up to 300 K and re-cooled down to 1.8 K in order to observe possible annealing effects. At the end of the irradiation campaign the sensors are recalibrated.

4 RESULTS

All the thermometers under investigation are resistive and they can be classified into two families: metallic (Pt and RhFe) and semiconductor (AB, TVO, CX, Ge) types. The results are summarised in Table 1.

4.1 Carbon type temperature sensors

Two carbon type sensors have been tested: TVO sensors [4] and AB resistors. For both types a beam heating effect is observed and the apparent temperature increases proportionally with the neutron dose rate. For AB and TVO the heating is respectively $\Delta T = \Phi \times 9.0^{-10}$ mK and $\Delta T = \Phi \times 3.10^{-10}$ mK (theses values are given with a 20% incertitude; Φ is the neutron dose rate given in $n.cm^{-2}.s^{-1}$). Neutron dose rate heating effects in the LHC should be negligible because the dose rate is several orders of magnitude lower than that used in these experiments. Figure 3 shows the irradiation shifts versus neutron dose after deducing beam heating.

Sensors of this type show an exponential increase in the measured temperature (resistance decrease) until reaching saturation at a total dose of 5.10^{13} $n.cm^{-2}$ for AB and 2.10^{14} $n.cm^{-2}$ for TVO. For AB sensors, the temperature measurement shift value at saturation depends on the neutron dose rate; it is 1mK for a dose rate $\Phi = 3.10^{8}$ $n.cm^{-2}.s^{-1}$ and 2 mK for $\Phi = 10^{9}$ $n.cm^{-2}.s^{-1}$. For TVO the temperature measurement shift at saturation range from 0.1 mK to 0.5 mK. Low temperature annealing was observed for AB: when stopping the irradiation while maintaining the bath temperature at 1.8 K, it is possible to observe that the sensors recover their initial resistance with a time constant of 3 to 10 hours. The 300 K annealing produced no significant healing.

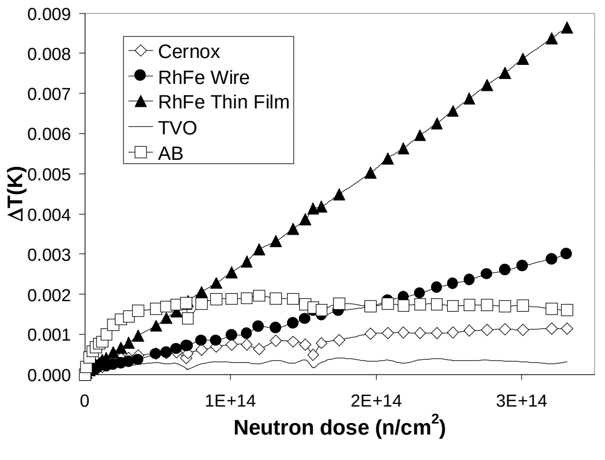

Figure 3 Error on temperature measurement on some sensors during irradiation (Tbath=1.8 K)

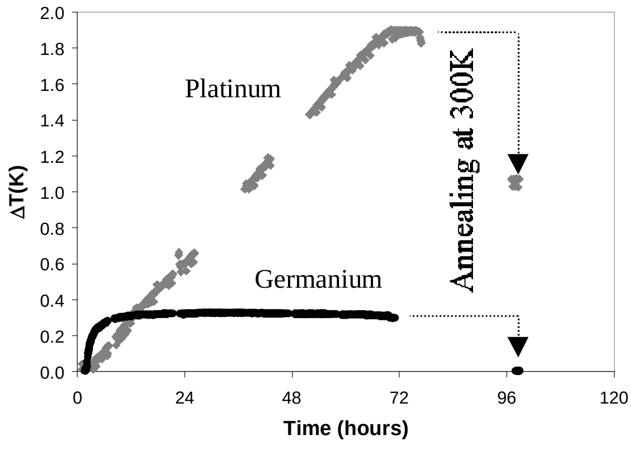

Figure 4 Irradiation-induced error on temperature read-out for Pt and Ge (T=1.8 K, dose=6 10^{14} $n.cm^{-2}$)

4.2 Metallic type temperature sensors

Both Pt and RhFe thermometers have been studied. Neutron irradiation induces an increase of temperature reading that is proportional to the neutron dose (see figures 3 and 4). RhFe show a dependency on the fabrication technology and from a radiation hardness point of view wire wound is better than thin film, the temperature measurement increase is respectively DOSE $\times$ 1.25 10^{-14} [mK] ($\pm$20%) and DOSE $\times$ 3 10^{-14} [mK] ($\pm$20%). 300K annealing induces a 40 to 50% recovery of the initial sensor characteristics. For Pt a similar behaviour is observed, at 1.8 K we observe $\Delta R/R$ = DOSE $\times$ 2.5

10^{-17} (DOSE in n/cm^{-2}) and the induced temperature measurement shift is very high because of the poor sensitivity of Pt at these temperatures.

4.3 Germanium thermometers

Ge thermometers were the most sensitive to neutron radiation with a temperature measurement shift of about 300 mK. Saturation was observed at a total dose of 10^{14} n.cm^{-2} (see figure 3). Curiously during the thermal cycle to 300 K the annealing was very efficient and the sensor recovered its characteristics to within 98%. Such a behaviour can only be observed if the sensor is at cryogenic conditions and monitored on-line during the irradiation.

4.4 Cernox™

The CX sensor total temperature measurement shift range from +0.5 mK to +1.5 mK (doses between 3.10^{14} and 10^{15} n.cm^{-2}). The temperature shift and the neutron dose could not be correlated for this sensor type. The beam-heating effect is almost non-measurable and is of the order of 0.2 mK for 2 10^{9} n.cm^{-2}.s^{-1}. No annealing has been observed for this sensor type.

Thermometer (+number tested)	R @ 1.8K	dR/dT @ 1.8K	σ_T @ 1.8K	beam heating mK/(n.cm^{-2}.s^{-1})	ΔT Irradiation for 4 10^{14}n.cm^{-2}	Expected ΔT in LHC
AB (44)	6600 Ω	-10600 Ω.K^{-1}	8.10^{-5}	9 10^{-10}	+2 mK	< 2 mK
TVO (44)	5700 Ω	-3300 Ω.K^{-1}	3.3 10^{-5}	3 10^{-10}	+0.3 mK	< 0.5 mK
CX (66)	12600 Ω	-12000 Ω.K^{-1}	2.5 10^{-5}	10^{-10}	+1 mK	< 2 mK
Ge (5)	9000 Ω	-8000 Ω.K^{-1}	1.2 10^{-4}	0	+300 mK	+300 mK
RhFe thin-film (46)	15 Ω	+0.7 Ω.K^{-1}	3.10^{-5}	0	+12 mK	+3 mK/year
RhFe wire (36)	5.4 Ω	+0.6 Ω.K^{-1}	2.6 10^{-5}	0	+5 mK	+1.5 mK/year
Pt (22)	1.7 Ω	+3.5 10^{-4} Ω.K^{-1}	-	-	+1.5 K	-

Table 1 Results of irradiation at 1.8 K (average values)

5 CONCLUSIONS

The results of this irradiation programme give a good overview of radiation resistance of resistive-type temperature sensors. About 50 sensors of each type have been tested in several experiments, the results are reproducible and can be qualitatively explained by experts in radiation damage of materials. The metallic type and Ge thin-film sensors show the highest errors. It is very important to perform the measurements on-line and at low temperature in order to understand self-healing processes during annealing at room temperature.

Future plans for irradiation testing under similar conditions are foreseen for other cryogenic sensors such as level, pressure and helium flow gauges. Due to the SARA cyclotron dismantling (from the end of 1998), the irradiation cryostat will be moved to the CERI cyclotron in Orléans (France).

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