EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 153

Neutron Irradiation Tests of Calibrated Cryogenic Sensors at Low Temperatures

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Abstract

This paper presents the advancement of a program being carried out in view of selecting the cryogenic temperature sensors to be used in the LHC accelerator. About 10,000 sensors will be installed around the 26.6 km LHC ring, and most of them will be exposed to high radiation doses during the accelerator lifetime. The following thermometric sensors : carbon resistors, thin films, and platinum resistors, have been exposed to high neutron fluences (> 10^{15} n/cm^2) at the ISN (Grenoble, France) Cryogenic Irradiation Test Facility. A cryostat is placed in a shielded irradiation vault where a 20 MeV deuteron beam hits a Be target, resulting in a well collimated and intense neutron beam. The cryostat, the on-line acquisition system, the temperature references and the main characteristics of the irradiation facility are described. The main interest of this set-up is its ability to monitor on-line the evolution of the sensors by comparing its readout with temperature references that are in principle insensitive to the neutron radiation (i.e. Argon gas bulbs when working at about 84 K, and below 4.5 K, either helium gas bulbs or the saturation pressure of the superfluid liquid helium bath). The resistance shifts of the different sensors at liquid helium temperatures are presented.

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Presented at CEC-ICMC'97, Portland, USA
29 July-1August, 1997

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Geneva, 17 November 1997

INTRODUCTION

The Large Hadron Collider, LHC [1], now under construction, will include a large number of superconducting magnets operating in superfluid helium at 1.9 K. Two proton beams (0.53 A , 7 TeV each) will circulate in opposite directions and be brought in collision in four points of the circumference. The beam losses in the beam pipes (impacts on the beam screens and interactions with the residual gas) are estimated [2] to 10^7 protons m^{-1} per second. A detailed calculation gives the radiation levels at different distances from the cold mass axis (Fig. 1). In principle the cryogenic sensors will be mounted at the periphery of the cold masses (∅ = 0.57 m), where the integrated dose for ten years operation of the accelerator ranges from 10^2 to 10^3 Gy. The higher values correspond to the intermagnet gaps where the shielding effect of the cold mass is reduced. These values apply for 95% of the machine, but in several regions of the accelerator, close to the interaction points where high-luminosity beams are focused by a number of superconducting magnets, the radiation doses can be 10 times stronger.

Taking a safety margin, it has been decided to perform all the irradiation experiments at fluence values close to 10^{15} neutrons/cm^2 (corresponding to 2.10^4 Gy). During the lifetime of the accelerator, several warm-up cycles for maintenance have to be considered, and some annealing of the damaged sensors can be expected.

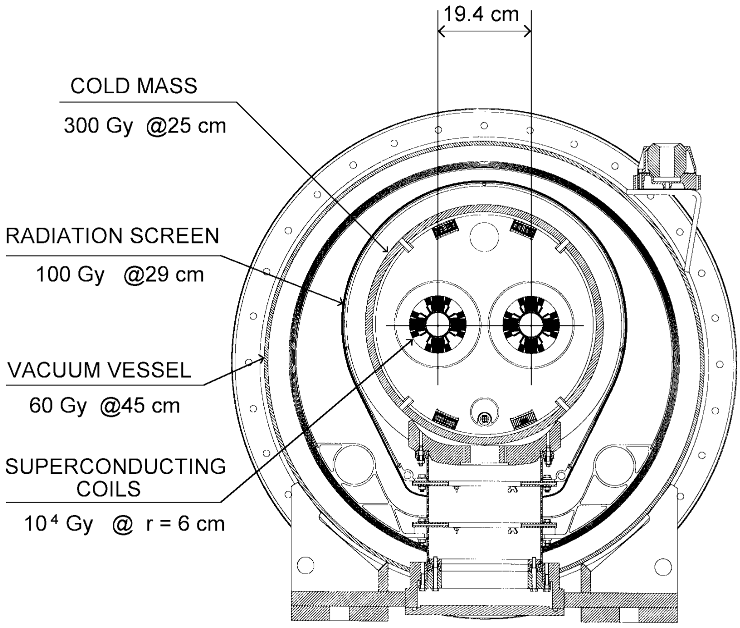


Figure1. Cross-section of a LHC magnet, the doses correspond to 10 years at nominal beam intensity.

The radiation resistance of cryogenic sensors has been performed at different dose levels [3, 4]. The aim of this work was to irradiate the sensors at high dose levels, and follow on-line the evolution of the sensors during the irradiation time.

In this article, we present a description of the neutron irradiation facility which is installed in a beam line of a medium-energy cyclotron in Grenoble (France). A special cryostat operating in liquid argon and liquid helium has been constructed for the test of components of the detectors and accelerator systems of the LHC. A complete irradiation program of one year has started and we give here the first results obtained with different cryogenic temperature sensors.

CRYOGENIC THERMOMETRY IN THE LHC

The superconducting magnets of the LHC accelerator will be operated at a temperature ranging from 1.8 K to 1.9 K, and their absolute value should be known better than ± 5 mK. The requirement for calibrated thermometers for the whole machine and the accuracies are presented in Table 1 [5].

A new thermometer block has been designed [6] which can be mounted on the vacuum side of the magnet cold masses. This thermometer incorporates a calibrated sensor and a microstrip printed circuit board for thermalization of the electrical leads. The complete block should be in good thermal contact with the cold masses but has to be located in hazardous regions from the point of view of radiation induced by beam losses.

Table 1. LHC cryogenic thermometry requirements

Type of sensor	Range	Total	Accuracy
Low temperature	1.6 K - 40 K	2922	1%
Low temperature	1.6 K - 300 K	3696	0.25 %
T > 50 K	50 K - 300 K	2512	1 %

NEUTRON IRRADIATION FACILITY

For irradiation tests of detector and accelerator components for the LHC, a neutron irradiation station has been recently installed at the SARA Cyclotron (CNRS-ISN Grenoble France) [7]. It is located at the end of one of its beam lines. A 5 µA beam of 20 MeV deuterons hits a 3 mm thick Beryllium target producing a high neutron flux. In the axis of the beam, the neutron yield is 5.10^{7} neutron.nA^{-1}sr^{-1}s^{-1}, and its photon contamination is low (400 Gy for 2.10^{14} n/cm^{2}). The neutron energy spectrum is well adapted for studies of accelerator components ($\langle E_n \rangle$ ~ 6 MeV). As opposed to nuclear reactors this method produces very few thermal neutrons, which drastically lowers the activity of exposed samples. At 11 cm from the Be target the measured dose was 4.3 10^{14} n/cm^{2} for an integrated charge of deuterons at the target of 1.04 C. To reach the final goal of 10^{15} n/cm^{2} it was necessary to irradiate during a period of 5 days.

THE IRRADIATION CRYOSTAT

A vertical cryostat (Fig. 2) is used to irradiate the sensors and is composed of a cold vessel, a radiation heat shield and an outer vacuum vessel :

a) The cold vessel is supported by four Epoxy-glass fiber rods. One layer of active charcoal and 10 layers of superinsulation are wrapped around the cold vessel (heat losses 200 mW).

b) The copper radiation heat shield is wrapped with 25 layers of superinsulation and it is cooled by LN_2 circulation on the top. The cylindrical part is removable and is cooled by conduction. A pumping baffle on the bottom allows an efficient pumping (heat losses 7 W).

This cryostat can operate in two modes: 1) Liquid Helium, with automatic level control and temperature regulation by a valve, 2) Liquid Argon, condensed by a LN_2 circuit and with the bath pressure controlled by the LN_2 circulation.

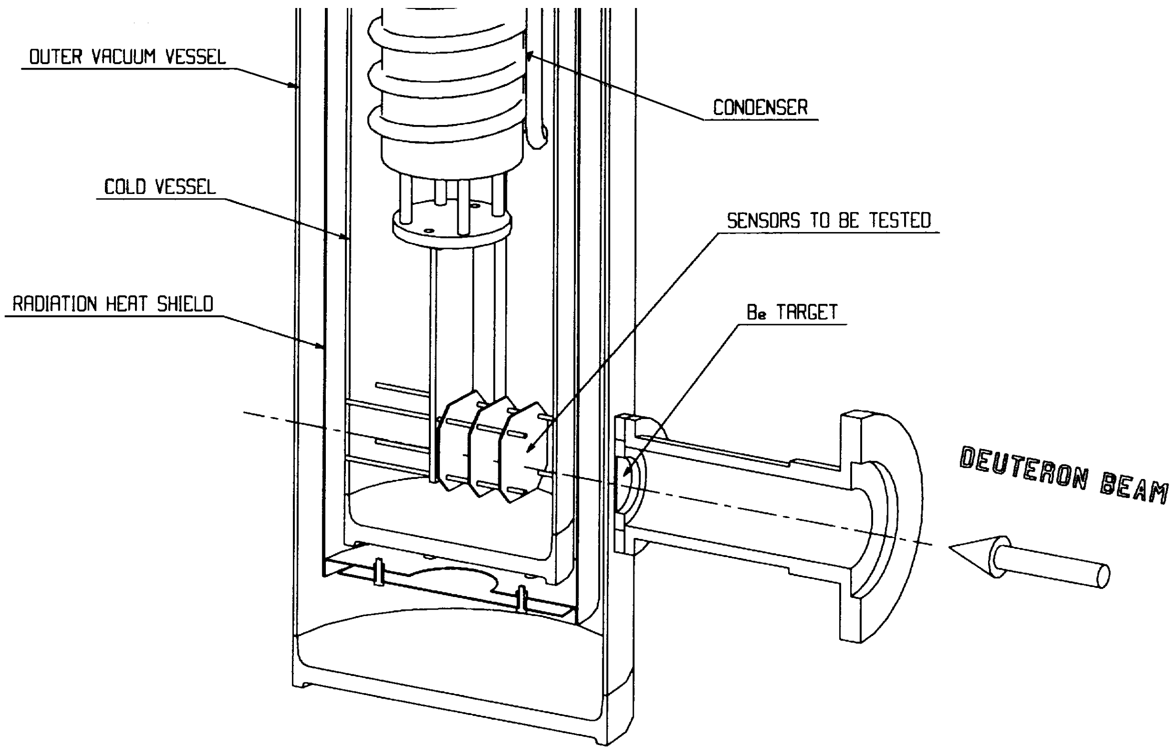


Figure 2. Cross section of the irradiation cryostat.

EXPERIMENTAL METHODS

The Temperature Reference

Three vapour pressure bulbs (argon or helium) immersed in the bath are used as temperature references. They are distributed along the vertical axis to measure any temperature gradient. These bulbs are composed of small copper cylinders (0.3 cm^3) and a stainless steel capillary tube (inside the cryostat: diam. 1 mm, length 1m, outside: int. diam. 6 mm, length 10 m) connecting the bulb to the pressure sensor (MKS ® pressure measurement system, calibrated at ±0.05 % of the reading).

Irradiated Samples

During the irradiation experiment, we have tested four types of commercial cryogenic temperature sensors, and several test samples (Table 2). Six thermometers were placed in the vacuum, on the external face of the helium vessel, six centimeters in front of the neutron source. The 47 other sensors were soldered on three plates immersed in the helium bath of the cryostat, at a distance of 8 to 12 cm from the beryllium target. The test samples are of two types : those used to confirm the behaviour of the sensitive materials of the thermometers (pure platinum wires, stripped thermometers) and an iron-boron alloy sample which has been placed for control purposes : this material has an amorphous structure and thus a very small sensitivity to irradiation. Electrical resistance variation of such a sample may indicate problems with the electronics or the data acquisition system.

Measurement and Acquisition Systems

The measurement system is composed of a nanovoltmeter, a programmable current source (10 µA for thin film and carbon sensors, 1 mA for Pt and test samples) and the associated sensors for the cryogenic control system: helium level, pressures and temperatures in the cryostat. This system is controlled by a LabVIEW® program running under Windows NT®. The measuring cycle (reference temperatures, 50 sensors, and control devices) is 5 minutes. The measurement resolution is better than 0.2 mK at 4.2 K.

Neutron Dose Measurement

A basic problem in irradiation experiments is the measurement of the radiation dose. Three devices were used to calculate the neutron dose from indirect measurements :

1) The beam charge received by the Be target: it gives a precise on-line, not localized measure of the irradiation profile (Fig 3)

2) Nickel foils attached to each temperature sensor: the neutron activation produces ^{58}Co isotope and its activity is measured after the experiment. It gives a non-precise (±15%), off-line, localized measurement (each foil being 4 mm). A typical neutron dose map is presented in Fig. 4.

3) Nine silicon pin photodiodes were placed behind the cryostat at a distance of 42 cm of the beryllium target. The radiation-induced increase of the forward voltage gives an on-line control of the neutron beam distribution.

By comparing the data shown in Fig. 3 and 4 we can estimate the received dose as a function of time, for each thermometer. This approximation is justified by the data from the silicon diodes, which indicate that the neutron beam had a good homogeneity during the irradiation.

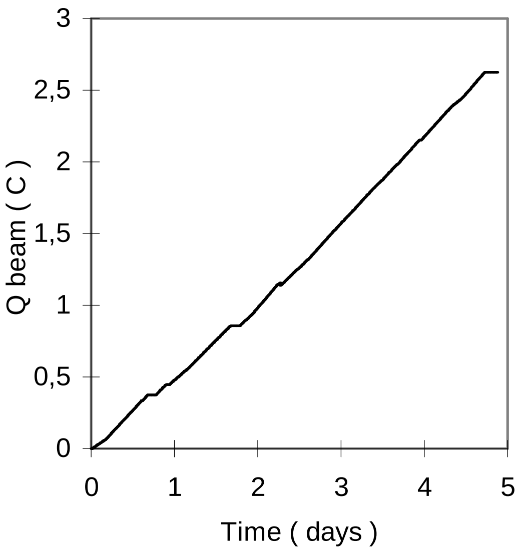


Figure 3. Deuteron beam charge on Be target.

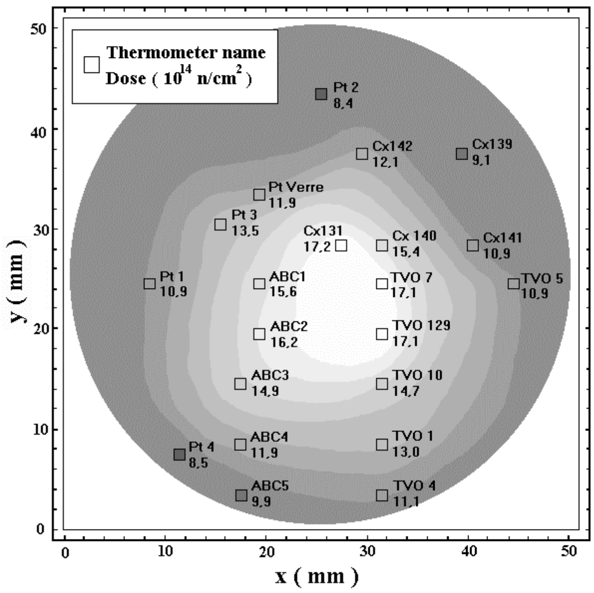
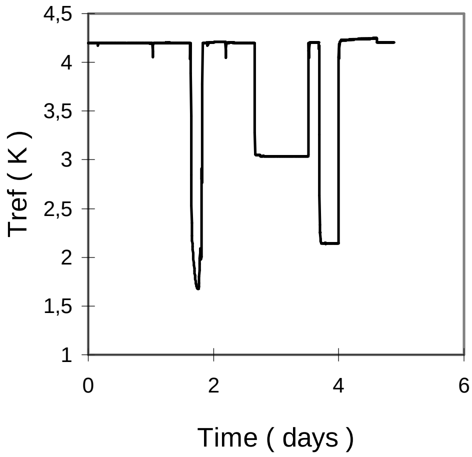


Figure 4. Neutron dose map (Nickel foil measurements)

Bath Temperature Measurement during Irradiation

We maintained the temperature at 4.2 K most of the time during the experiment, and some measurements were made at lower temperatures (1.6 K, 2 K, 3 K) to control the resistance of the sensors.

In fig.5 we have also plotted the reference temperature during a 3-hour period. This graph allows an estimation of temperature regulation quality. The noise on the measured temperature is $<\sigma>= 0.085$ mK, and the typical temperature drift is about 1 mK per hour.



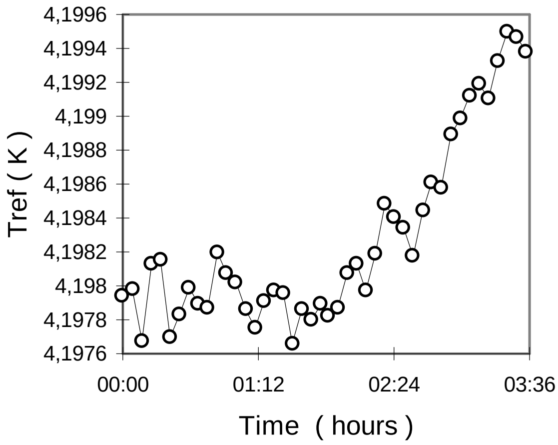
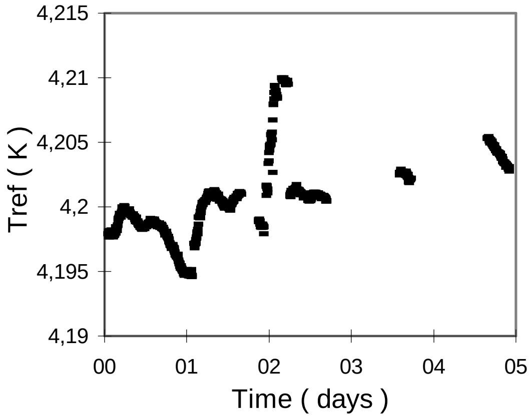


Figure 5. Measurement of the bath temperature (Reference Temperature) during irradiation.

Resistance Correction Procedure

As we want to estimate the irradiation induced resistance variations of our sensors, we must filter out the resistances changes due to bath temperature drift (Fig 6). This is done with the following correction procedure:

- We choose a correction temperature $T_{correction}= 4.200$ K.
- Rejected points: All the points outside the range 4.200 K $\pm$ 0.01K, and those considered not stable (i.e. which have changed by more than 0.5 mK in one minute).
- For each measured point we calculate $\Delta T=T_{measured}-T_{correction}$
- We obtain : $R_{corrected}=R_{measured} \pm\Delta T.(dR/dT)$, where dR/dT is the sensor sensitivity



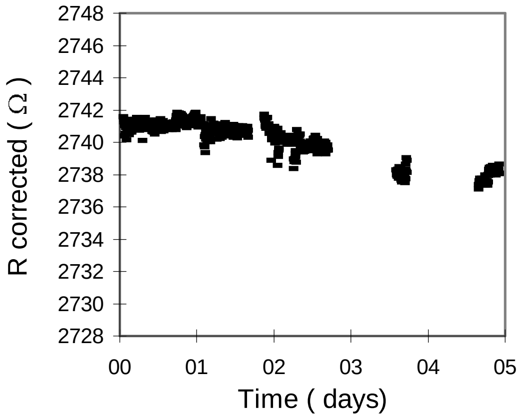


Figure 6. Resistance correction for a Cernox sensor ($T_{correction}$=4.2 K).

EXPERIMENTAL RESULTS

Test Samples

We have used two kinds of control samples: Pt and Fe-B alloy, in order to check the overall measurement and acquisition systems accuracy. The resistance variations of these samples are presented in Fig. 7 and 8:

- The irradiation produces a continuous resistance drift of the Pt sensors (including the wire) showing a classical response of irradiated pure metal samples at low temperature

- The Fe-B alloy sample exhibits a response in complete agreement with expectations: small influence of the temperature and near insensitivity to neutron irradiation.

Cernox® Sensors

The tested Cernox® sensors came from two different batches (Fig. 9 and 10). Sensors from the first batch (Fig.9), which are less sensitive (dR/dT≈-1kΩ.K^{-1} @4.2K) have a continuous resistance decrease. For the whole experiment, they shifted of about 4Ω (ΔR/R=-0.13%) and the equivalent measured temperature variation was of about 4mK (ΔT/T=0.1%). Sensors from the second batch (Fig.10) showed a resistance increase at the beginning of irradiation, and then a decrease. The resistance shifts for this batch were within a 3 ohm range, the equivalent measured temperature variation was of about 2.5mK. (dR/dT=1300 Ω.K^{-1}, ΔT/T=0.05%).

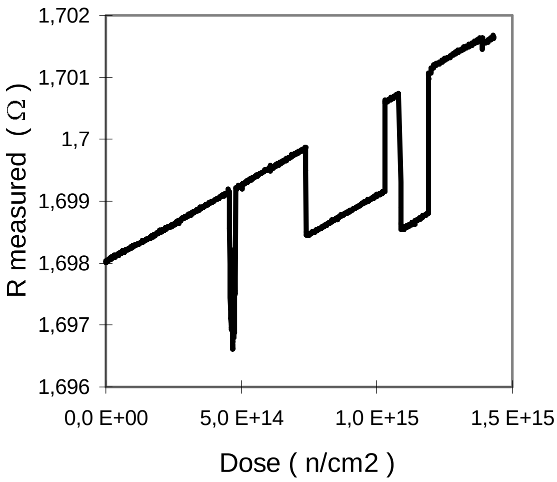


Figure7. Irradiation of a Pt sensor.

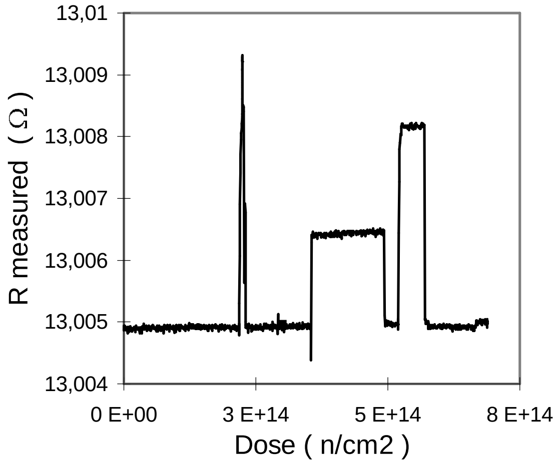


Figure 8. Irradiation of Fe-B sample.

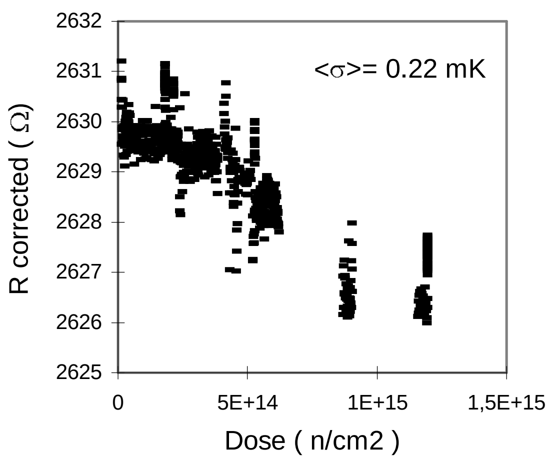


Figure 9. Cernox sensors (batch 1).

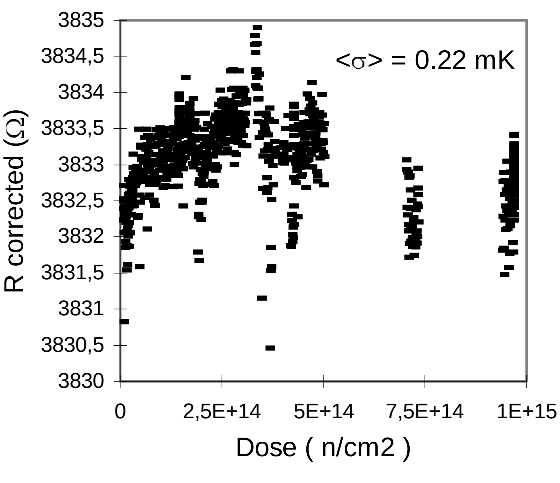


Figure 10. Cernox sensors (batch 2).

Note : the behaviour of sensors of each batch were almost the same, so the examples shown in Fig.9 and 10 are representative of the batches. The unencapulated Cernox® sensors showed the same behaviour as sensors of first batch, with a total ΔR of 9 ohm (ΔR/R= 0.3 %), and a sensitivity dR/dT= 1300ohm.K^{-1} , resulting in ΔT= 7 mK (ΔT/T= 1.6 %).

A neutron irradiation at argon temperature (85K) of the Cernox® sensors from batch #1 showed almost the same results : a continuous resistance decrease (ΔR/R≈0.1% for 1.5 10^{15} neutrons/cm^2)

Carbon Sensors

Two carbon sensor types have been tested : TVO (supplied by JINR Dubna, Russia) and the classical Allen-Bradley 100 Ω resistors.

On Fig.11 is plotted a representative graph of Allen-Bradley corrected resistance during irradiation. For this family, we see very little resistance variations (within a 0.6 Ω range), which gives an error on the measured temperature of 1.5 mK. On Fig.12 is reported the corrected resistance for a TVO sensor. We can see that this sensor has a continuous resistance drift, with a total amplitude of about 1Ω. This variation implies an error of 2 mK (ΔT/T=0.5%) on the measured temperature. (Note : the TVO sensors came from two series, but all sensors had almost the same behaviour).

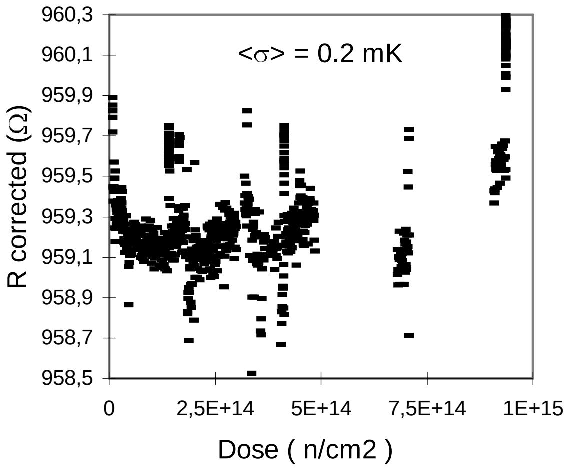


Figure 11. Allen Bradley carbon resistor.

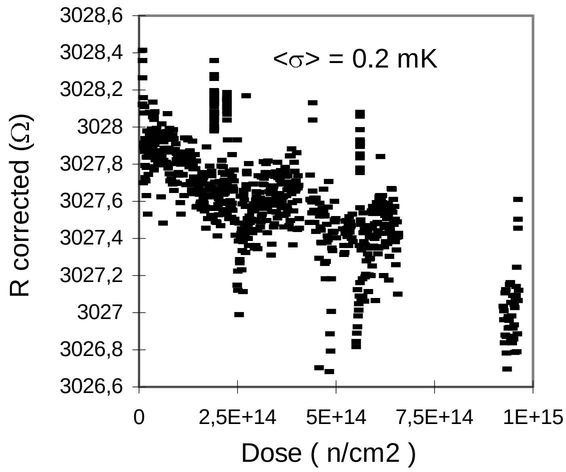


Figure 12. TVO carbon sensor.

Table 2. Summary of radiation-induced resistance shifts (all sensors receive neutron fluences between 8.10^{14} and $1.2 .10^{15}$)

Family	Type	Quantity	R@4.2K (Ω)	dR/dT@4.2K (Ω.K^{-1})	ΔR (Ω)	ΔT (mK)
CERNOX	Serie 1	5+1 (vac.)	3000	-1000	-4	4
	Serie 2	4+1 (vac.)	3800	-1300	-1.5	1
	unencapsulated	3	3200	-1300	-9	7
Carbon	Allen-Bradley	12+1 (vac.)	960	-370	-0.5	1.5
	TVO	10+2 (vac.)	3200	-600	-0.8	1.5
Platinum	type 1	5+1 (vac.)	1.7	0.0015	2.5 10^{-3}	-
	type 2	5	0.15	0.0012	2 10^{-3}	-
	Wire	2	1	0.0018	2.5 10^{-3}	-

Neutron Beam Heating Effects

During the irradiation experiments, a heating effect due to the neutron beam was observed on all sensors. When switching the beam off, an instantaneous resistance shift ranging from 0.2 to 1.5 Ω was observed on Cernox® and carbon sensors. This corresponds to temperature shifts ranging from 0.5 mK to 1.6 mK. During this transient, no significant bath temperature shift was observed. In a separate experiment we have controlled the self-heating effect of the sensors by increasing the d.c. measurement current. It allows to evaluate the beam deposited power: it ranges from 0.2 µW to 0.6 µW depending on the sensor types and their distance to the neutron source.

CONCLUSION

The whole irradiation set-up is now fully operational, most of the initial goals were reached according to schedule and the first results (i.e. bath temperature measurement and stability, neutron beam reproducibility and stability, and the quality of the measurement and acquisition systems), confirm our expectations. The complete irradiation program (more than 200 samples) will continue in the next months, including systematic on-line control of the resistance shifts, comparison of calibrated sensors before and after irradiation, and finally the test of new sensor prototypes. During the next irradiation runs, data will be sampled at superfluid helium temperatures in order to garantee a good bath temperature homogeneity, adding an extra check of the vapour pressure bulbs readings against the bath saturation pressure.

ACKNOWLEDGEMENTS

We would like to thank L.Thomé of the CSNSM (IN2P3-Orsay) for his continuous support and counsel on experimental and theoretical aspects of irradiation, and all the people at the 3 laboratories collaborating to this project: J. Collot, Ph. Martin, G. Mondin, M. Fruneau and all the cyclotron group at the ISN-Grenoble, F. Clapier, Ph. Bujard, Ch. Joly, D. Grolet, and specially S. Buhler, head of the Cryogenics group at the IPN Orsay, for his continuous support and fruithful discussions along the design phase, and finally, Ph. Lebrun, Ch. Balle, V. Datskov and all the LHC Cryogenics group at CERN.

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