Introduction

One of the main events in the field of particle physics at the beginning of the next century will be the construction of the Large Hadron Collider (LHC). This machine will be installed into the existing Large Electron Positron (LEP) tunnel at the CERN laboratory across the Franco-Swiss border west of Geneva, as shown in Fig. 1. The pre-existence of the LEP tunnel and of the CERN accelerator chain for particle injection will make the cost of the machine affordable.

The LHC will be the largest hadron Collider in the world and will extend the energy frontier of physics, offering a further insight in the basic mechanisms of nature, as for example the mechanism that gives masses to the fundamental constituents of matter.

LHC is a very challenging project because of the engineering constraints and of the Physics requirements. As a consequence of the fixed length of the ring, imposed by the choice of using the existing LEP tunnel, the limit to the acceleration of the colliding particles comes from the strength of the maximum bending magnetic field. A new generation of superconducting magnets will provide the magnetic field necessary to achieve the TeV energy range. A large cryostat will keep the magnets at the working temperature of 1.9 K.

The statistical significance of the scientific results will be obtained by means of the exceptional luminosity of LHC, which will insure a good number of interesting events per year. On the other hand, it will lead to a very high radiation environment for the particle detectors. Therefore, the survival of the detectors in this harsh radiation environment during 10 years of operation planned for the machine is a challenging issue for the detectors.

Part of this thesis is devoted to the radiation hardness studies of silicon detectors, mainly in view of their application to LHC experiment trackers. Nevertheless, the results can be important for other fields of science where the radiation level is important, as in nuclear reactors, radiotherapy and space applications.

The first chapter describes briefly the LHC accelerator and experiments, giving some predictions, based on simulations, of the radiation levels expected in the LHC detector cavities and it gives the motivation of this thesis.

Chapter 2 introduces some results of the semiconductor physics and describes briefly several processes of silicon production and detectors manufacturing that are relevant for the present work.

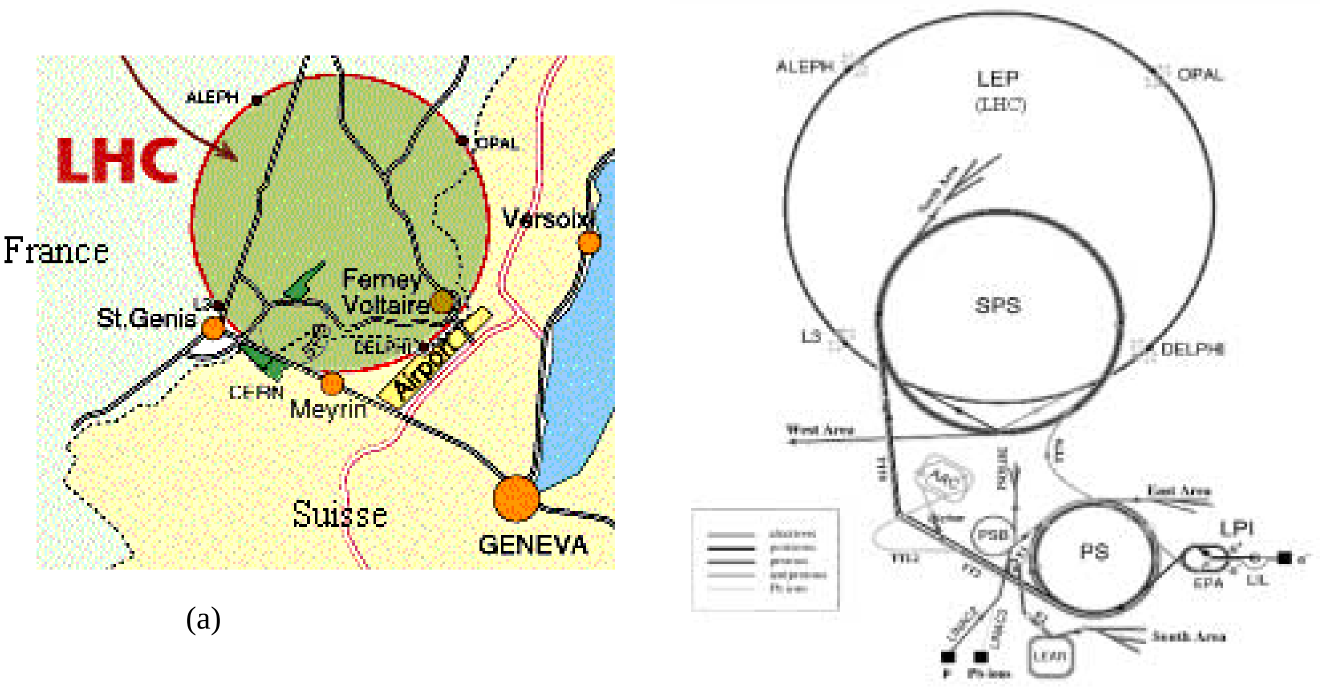
Chapter 3 describes the radiation damage mechanisms and their consequences on the operation of silicon detectors.

Chapter 4 introduces the experimental techniques, with detailed discussion of the problem inherent with the interpretation of the measurement, error sources and tolerances.

Chapter 5 describes the various silicon materials irradiated and measured.

Chapter 6 shows and comments the experimental results.

Chapter 7 studies the evolution of the electric field in irradiated detectors and gives a model to interpret several unexplained aspects emerged in electrical measurements of irradiated detectors.



(a)

(b)

Fig. 1 - *The LEP/LHC tunnel map and (b) the CERN accelerator system.*

Chapter 1. Motivation and framework

1.1 The Large Hadron Collider (LHC)

The LHC [1.1] is a two-ring machine with a total length of 27 km which will allow the head-on collision of proton beams, each with an energy of 7 TeV, and beam collisions of heavy ions, such as lead, with a total collision energy in centre-of-mass of ≈ 1,250 TeV. Joint LHC/LEP operation could supply electron-proton collisions with a centre-of-mass energy of 1.5 TeV. Figure 1.1 shows a cross-section of the tunnel with a possible installation of LHC and LEP rings.

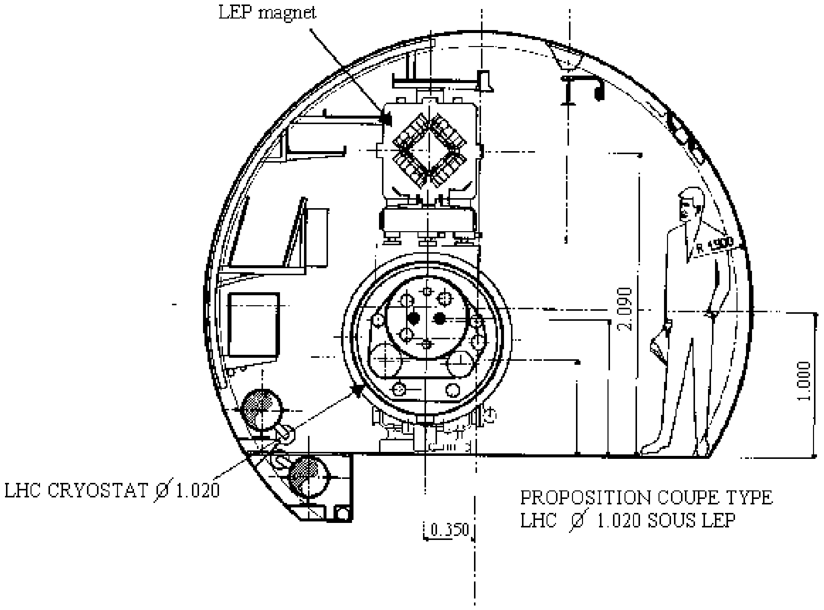


Fig. 1.1 *Cross section of the LHC/LEP tunnel. LEP magnet is hosted above the double-coil LHC magnet.*

In the LHC, the energy available in the collisions between the constituents of the protons (the quarks and gluons) will reach the TeV range, about 10 times that of LEP. The particle cross section decreases like $1/E^2$, therefore a very high luminosity is required for proton-proton (pp) collision in order to maintain a physics program as effective as in LEP. At LEP the luminosity is around $L = 10^{32}$ cm^{-2} s^{-1}, whereas it will reach $L = 10^{34}$ cm^{-2} s^{-1} at LHC. This value will be obtained by filling each ring with 2835 bunches of 10^{11} particles, injected in the LHC by the Super Proton Synchrotron (SPS) at the energy of 0.45 TeV. The bunch space will be 7.48 m, corresponding to an interval between two successive bunches of 25 ns at the collision energy.

An 8.33 T magnetic field provided by 1296 superconducting dipole magnets over a total magnetic length of ≈ 15 km will guide the protons in the LHC orbits. Superconducting quadrupole correctors will make the orbit corrections to the spurious non-linear components of the guiding and focusing magnetic fields of the machine and allow the recovering of the required beam density after interactions. Special orbit correctors will be used, as sextupole, octupole and decapole magnets. The luminosity lifetime will be about 10 hours.

The two beam pipes of LHC and the superconducting coils will be hosted in the same superfluid helium cryostat at the temperature of 1.9 K.

1.2 Physics at LHC

The LHC machine and the planned experiments have been designed to study the extrapolation of the present knowledge in particle physics to the LHC energy scale and to detect the signatures of a new and possibly unexpected physics above the TeV energy threshold.

The Standard Model (SM) describes very well the results of present experiments. However some fundamental questions remain still unanswered. The most important of them is probably the origin of the mass of the Z and W vector bosons of the electroweak interactions. The most accredited explanation is the existence of a Higgs field. One of the main goals of LHC is the discovery of the associated gauge boson, the Higgs particle.

The SM does not predict the Higgs mass. The limits of the Higgs mass are set in the range $67.5\ \text{GeV} < m_H < 1\ \text{TeV}$, where the lower limit comes from the present electroweak data and the upper is theoretical. The experiments are designed to cover the different physics signatures of the Higgs, consisting in the identification of the predicted decay modes, with statistical significance over all the mass range. This requires very high luminosity because the cross section for heavy particle scales inversely with the square root of their masses. Figure 1.2 shows the energy dependence of the cross section for various processes in pp interactions [1.2]. The rate of events is obtained by the product of the cross section and the luminosity. The rate of the Higgs boson production at the expected LHC luminosity and energy is ≈ 4-5 10^{-3} s^{-1}, assuming the Higgs mass equal to 500 GeV.

Other important topics are top-quark physics, CP-violation in the B-sector, possible signals of the formation of the quark-gluon plasma (QGP) and search for supersymmetric particles. The experiments presently approved at LHC are ALICE (A Large Ion Collider Experiment), ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid). ALICE is an experiment mainly devoted to the QGP study by mean of heavy ion (Pb) collision at a centre-of-mass energy of 5.5 TeV per nucleon pair and a luminosity of about $2 \cdot 10^{27}$ cm^{-2} s^{-1}. This will create energy densities of 5-8 GeV fm^{-3}, above the QGP threshold [1.3]. CMS and ATLAS will run pp collision at the maximum centre of mass energy of 14 TeV and up to the maximum luminosity.

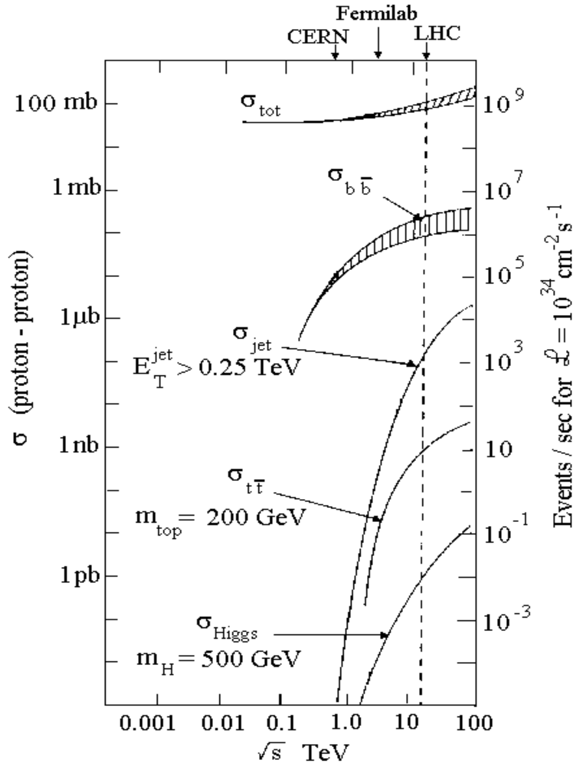


Fig. 1.2 - *Cross section for various processes expected in proton-proton interactions as a function of the centre-of-mass energy* $\sqrt{s}$

1.2.1 The ATLAS and CMS detectors

Figures 1.3(a) and (b) show the cross section of the two detectors [1.4,1.5]. Without entering into design details and the differences between the two approaches to the LHC physics, the basic common requirements are

- Good muon system
- Good electromagnetic (EM) calorimeter
- High quality inner tracker.

The muon system is crucial for the high luminosity physics and must provide good momentum resolution, safe stand-alone operation at higher luminosity, when the inner tracker might be of limited use because of the radiation damage, excellent geometrical acceptance and robust pattern recognition.

The requirement to the EM calorimeter, for the identification and measurement of photons and electron energies are:

- hermetic jet and missing transverse energy measurement
- high luminosity operation
- radiation tolerance for 10 years operation.

The inner tracker functions are essentially the reconstruction of high p_T tracks with 90-95% efficiency, high momentum resolution for leptons, electron and photon identification at high luminosity and τ and b tagging at low luminosity.

A key feature of the inner tracker is the ability to distinguish secondary from primary vertex. Short lifetime particles, as for instance the charmed particle, live for about 0.3 ps before decaying. In this case, the secondary vertex is situated some millimetres far from the interaction point. The tracks of the longer lifetime particles generated in the decay are reconstructed and allow the identification of the event. The unambiguous reconstruction of the secondary vertex requires a good spatial resolution. The use of pixel and microstrip silicon detectors satisfies the spatial resolution requirements because of their fine segmentation. Designs of the ATLAS and CMS inner tracker are shown in Fig. 1.4.

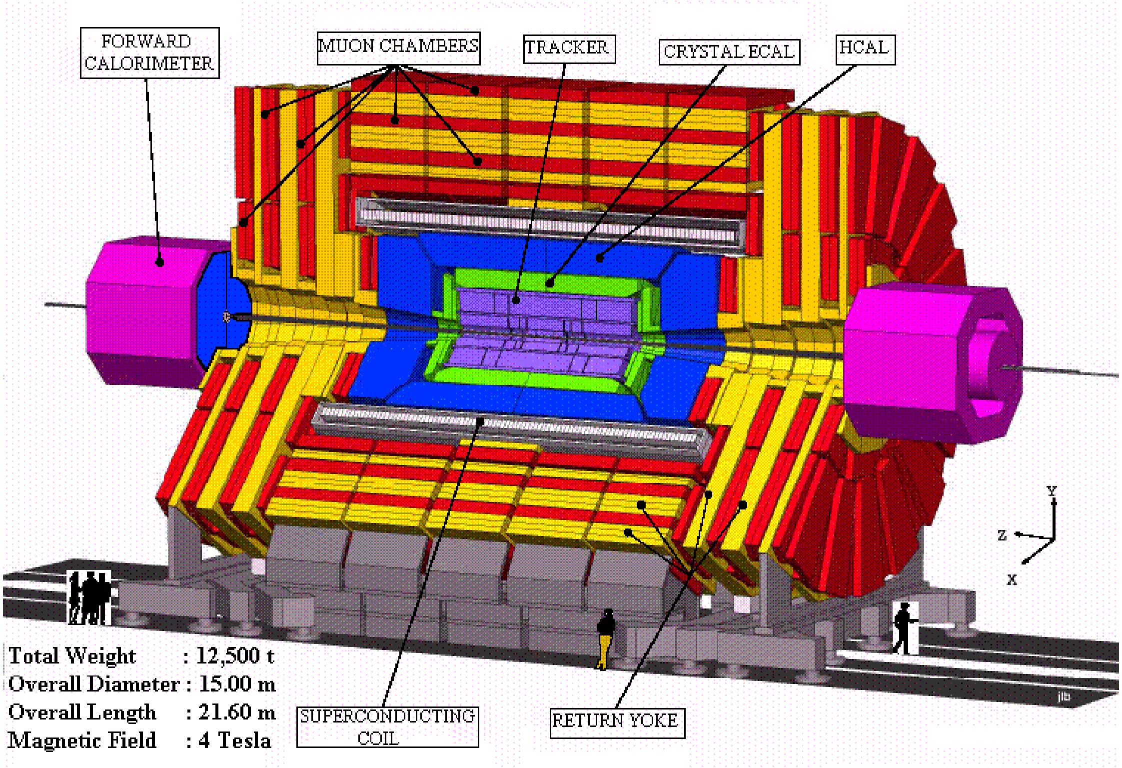


Fig. 1.3 (a) – *The CMS detector*

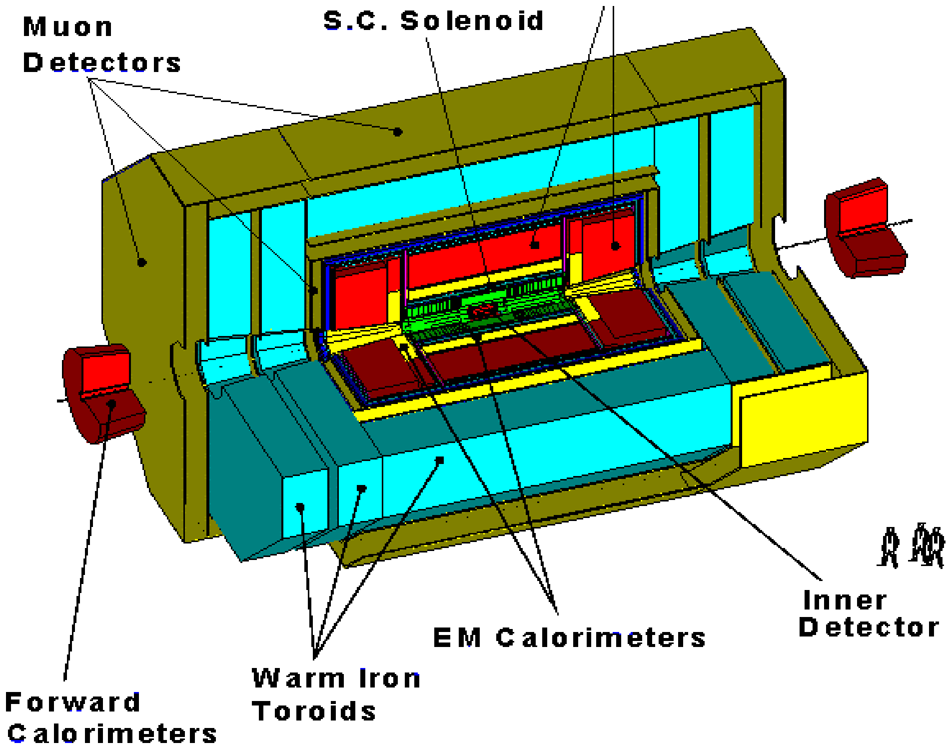


Fig. 1.3(b) – *The ATLAS detector*

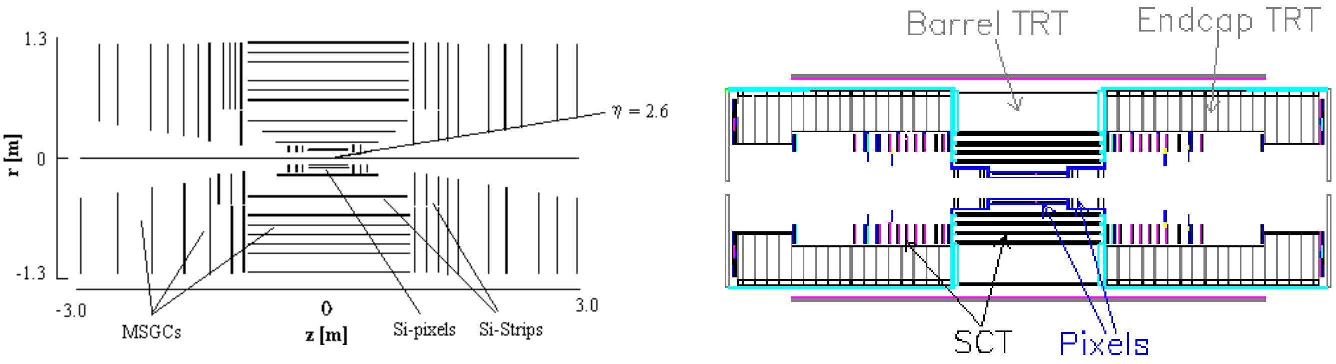
1.2.2 The radiation environment

The high interaction rate for pp collision at high luminosity at LHC (≈ 10^9 s^{-1}) will lead to a very high radiation level in the detectors, depending on its position relatively to the interaction point.

Naive calculations of the particle flux in the detector lead to a flux independent of z (the coordinate along the beam direction) and decreasing as $1/r^2$, where r is the radial distance from the beam axis. Although this estimate is very inaccurate, it indicates that the harsher radiation level is in the inner tracker region.

The particle flux is constituted by the primary particles emerging from the interaction point and by the albedo neutrons from the calorimeter.

The radiation level the detectors and electronics have to withstand can be expressed as function of 1 MeV neutron equivalent fluence. Figure1.5 [1.6] shows the neutron and charged fluxes per year at different radii in the CMS tracking cavity and Table 1.1 reports the annual 1-MeV equivalent fluence for the ATLAS inner detector region.



(a) (b)

Fig. 1.4 *(a) The CMS and (b) ATLAS inner trackers with Si pixels, SemiConductor (Si) Tracker, and TRT (Transition Radiation Tracker)*

The 1 MeV equivalent fluences range then between $0.3 \cdot 10^{13}$ cm^{-2} to $1 \cdot 10^{14}$ cm^{-2} per year of LHC operation, depending on the radial position. Almost certainly, this severe radiation environment will cause the failure of the most irradiated devices after a time of operations shorter than the 10 years planned for the LHC detectors. The improvement of the survival time of the silicon detectors has already dictated some design solution for the detector modules. Cooling pipes have been introduced in order to remove the excessive heating due to the increased leakage current caused by the radiation damage. For the same reason, the detectors will be kept at low temperature.

The use of silicon that is more radiation resistant than the high resistivity silicon presently foreseen for the detector fabrication would give an important help to the detector design in view of longer and safer operations of the LHC tracker.

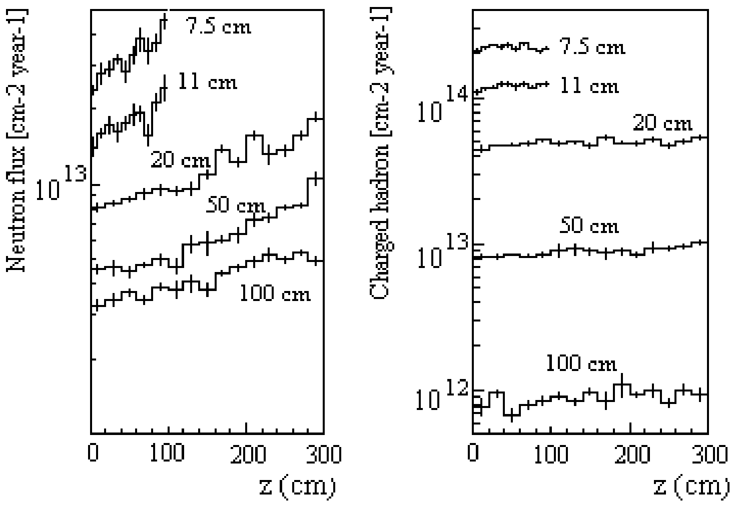


Fig. 1.5 - *Neutron and charged fluxes per year at different radii in the CMS tracking cavity* [1.6]

1.3 The ROSE (CERN-R&D 48) collaboration

The radiation damage suffered by silicon detectors at LHC can make the detector unusable above a certain fluence threshold. CERN’s RD48 or ROSE (R&D On Silicon for future Experiments) Collaboration has been started in 1996 to investigate the possible radiation hardening of silicon detectors [1.7]. The collaboration involves more than 30 institutes in Europe and in United States and has close collaboration with silicon single-crystal producers and detector manufacturers. The objectives of the collaboration are

- to develop radiation hard detectors that can operate beyond the limits of present devices and that then can insure guaranteed operation for the whole lifetime of the LHC experimental program.

- to make recommendation to experiments on the optimum silicon to be used for detectors and quality control procedures required to insure optimal radiation tolerance.

The radiation damage in silicon detector introduces electrically active defects resulting from the creation of stable complexes between the primary defects and other defects or impurities that are always present in silicon. It is impossible to affect the radiation damage itself, but it is possible to modify in a suitable way the electrical activity of the secondary permanent defects by means of the deliberate introduction of various impurities into the silicon bulk. The identification of appropriate chemical species and their optimum concentration is the key idea in the progress of the radiation hardening of silicon [1.8]. For that purpose, silicon wafers with addition of different concentrations of oxygen, carbon and tin have been produced and tested. Besides to the silicon crystal engineering, the work on the radiation hardening led to the identification of parameters able to push further the maximum tolerable fluence of standard silicon detectors. Those parameters are the choice of the initial resistivity and the operation temperature of the silicon detectors.

Radius [cm]	***n*** **Flux**	***p*** **Flux**	$\bar{p}$ **Flux**	$\pi^{\pm}$ **Flux**	**Kaon Flux**	**Total Flux**
11.5	1.3	0.74	0.57	6.1	1.3	9.9
20	0.63	0.30	0.18	2.3	0.42	3.9
52	0.30	0.065	0.027	0.46	0.055	0.91
79	0.21	0.026	0.0093	0.17	0.025	0.45
105	0.19	0.016	0.0040	0.064	0.012	0.29

Table 1.1 *Annual fluxes expected in silicon due to various damaging particles, expressed as the 1 MeV Equivalent neutron flux as a function of radial position for the ATLAS inner tracker. Flux units of the damaging particles are* 10^{13} *(1 MeV) neutrons* cm^{-2} yr^{-1}.

The work presented in this thesis has been performed in the framework of the ROSE collaboration.
The radiation tolerance studies have been performed by monitoring the electrical characteristic of detectors made from different materials as a function of the radiation fluence and the time after irradiation. Besides to the radiation tolerance, the study of the charge transport in silicon has been carried out and the results are presented in Chapter 7.