Available on CMS information server **CMS CR-2002/006**

CMS Conference Report

April 11, 2002

The silicon strip tracker for CMS

M. M. Angarano

Università di Perugia and I.N.F.N. Perugia, Italy

On behalf of the CMS Tracker Collaboration

Abstract

The Compact Muon Solenoid (CMS) is one of the experiments that will be installed at the new Large Hadron Collider (LHC) in construction at CERN. The Silicon Strip Tracker (SST) constitutes, in conjunction with the Pixel Tracker, the inner tracking system of CMS. It occupies a cylindrical region of 2.4 m in diameter and 5.6 m in length, instrumented with more than 24,000 micro-strip sensors for a total of about 10 millions channels. Its layout and expected performances are described in this paper.

The silicon sensors of the SST will operate in a high radiation environment. The CMS collaboration has carried out an extensive R&D program in order to minimize their radiation damage. A review of that program and the main results that determined the final choices for the sensor technology are illustrated.

Presented at *10th international workshop on vertex detectors – "Vertex 2001",* Brunnen - Switzerland,

23-28 September 2001

Submitted to *Nucl. Instr. and Meth. A*

1 Introduction

The LHC will accelerate protons up to energies never reached before in a particle accelerator (7.0 TeV/c in *pp* collisions), with a bunch crossing time of 25 ns and a luminosity that will range from 10^{33} cm^{-2} s^{-1} in the first phase ("low luminosity phase") up to 10^{34} cm^{-2} s^{-1} later on ("high luminosity phase").

CMS has been projected as a "general purpose" experiment, designed to explore the full range of "new physics" that will be accessible at LHC. Last decades of research in particle physics teach that, for such task, it is important to have a robust and versatile tracking system within a strong magnetic field. In December 1999, the CMS collaboration partially changed the detector technology of its tracking system. We decided to give up the solution (silicon + gas chambers) presented in the Technical Design Report (TDR) [1] and to adopt a "full silicon" option. In this new design, the tracker is constituted by a innermost region, instrumented with silicon pixel sensors (as in the TDR) and an external region, instrumented with silicon strip sensors, the SST, that extends up to the region once covered by gas chambers [2]. That change has been feasible because of some key reasons. First of all, the possibility to use 6" production line for silicon wafers, that results in "industrial" production, with large volume capability and cost saving. Then, the possibility to automate and use new machines with higher throughput in some steps of the module production chain (like: sensor testing, module assembly, wire bonding). Finally, the implementation of the front-end read-out chip in sub-micron technology, resulted in large cost saving.

Besides very good performances in terms of track finding quality and efficiency, the SST must also fulfil other requirements coming from the particular conditions in which it will operate. In the high luminosity phase, 24 collisions per bunch crossing are expected, which will produce more than 1000 particles, in the region of acceptance of the tracker. That requires a detector with high granularity and fast response, in order to minimize the occupancy. Silicon sensors will operate in a very high radiation environment: a fluence (normalized to 1 MeV equivalent neutrons) of 1.6×10^{14} n cm^{-2} is foreseen in its inner part after 10 years of operation. A crucial issue for a successful operation of the SST is the radiation tolerance of its sensors. Our requirement is that they ensure functionality for such fluence, multiplied by a safety factor of 1.5, to take in account for uncertainties.

Moreover, a general consideration in the construction of the SST is that we have to cope with such large numbers (24,000 sensors, 10,000,000 channels, and so on), which suggest adopting criteria of "simplicity", "automation" and "industrial point of view" in many aspects of the production.

2 Layout

The layout of the SST is shown in Fig. 1. It represents a longitudinal section of one quarter of the detector (the other three being symmetric). The SST instruments the area from 20 cm to 120 cm in *r* and from 0 cm to 280 cm in *z*, covering a region in pseudorapidity up to 2.5. It is divided in four sub-sections: Tracker Inner Barrel (TIB), Tracker Inner Disks (TID), Tracker Outer Barrel (TOB) and Tracker End Caps (TEC). Four cylindrical layers constitute the TIB; at each side of which there are the three disks of the TID. The six cylindrical layers of the TOB surround the TIB and the TID. Finally, eighteen disks (nine on each side) of the TEC complete the structure. The disks of TID and TEC are divided in 3 and 7 rings, respectively. Some of them and some of the barrel layers are instrumented with double sided modules, namely the first two layers in both the TIB and the TOB, the first two rings of the TID and rings 1,2,5 in the TEC. Double sided modules are made by single sided modules in a "back to back" configuration, where the stereo side is mounted tilted. In that way we use single sided sensors for the whole tracker and the same kind of sensors can be used for both sides of modules.

Each module is constituted by a supporting frame in carbon fibre, a kapton insulator and bias carrier, the silicon sensors (one or two) and the front-end and read-out hybrid. The modules in the inner region (TIB, TID and the first four rings of the TEC) host one micro-strip sensor, while the modules of the outer region (TOB and the last three rings of the TEC) host two daisy-chained. In that way, we cover the larger external region with longer strips (up to 21 cm), so reducing the number of channel. The use of longer strips increases the noise of sensors. In order to recover an adequate ratio of signal to noise, thicker sensors (500 μm) will be used in the outer region. That is possible there, because of reduced radiation damage with respect to the inner region. A specific chip, the APV25, has been designed in 0.25 μm CMOS technology for the read-out of the signal and has been proved to be radiation hard. It has 128 channels and works as a charge sensitive amplifier, with 50 ns shaping time, sampled at the bunch crossing rate (40 MHz); deconvolution is used to restore the 25 ns timing accuracy. Signals are then transmitted outside of the Tracker for data acquisition, by mean of an analogue optical link.

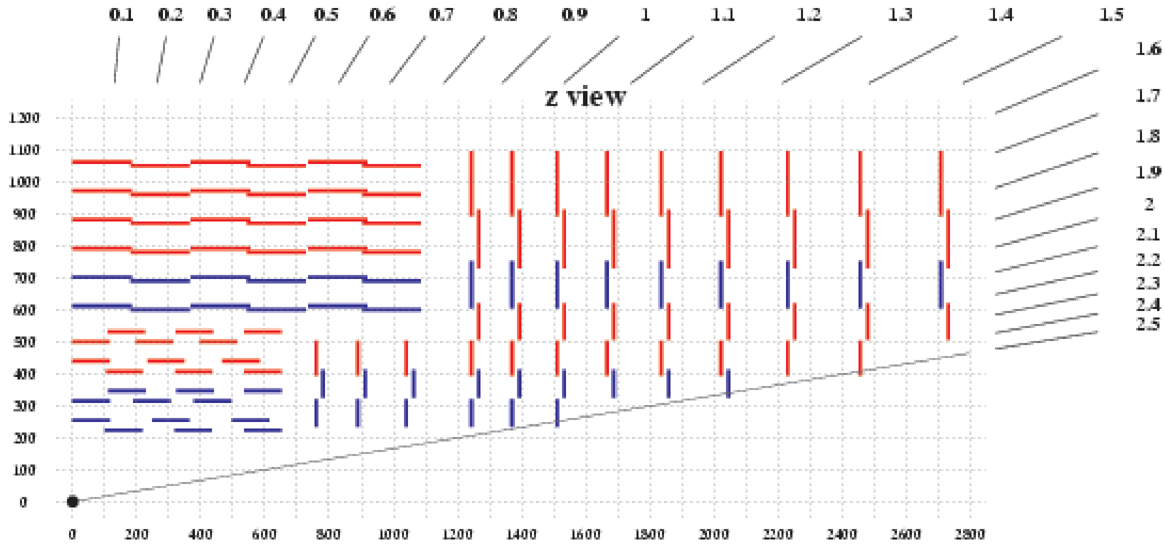

Figure 1: SST layout: longitudinal section of one quarter.

The whole Tracker volume will be held at –10 °C temperature, in order to reduce the detector current and, hence, the power consumption. That low operating temperature will also be useful in keeping the depletion voltage of irradiated sensors near the minimum of the annealing curve.

3 Expected performances

Performances of the CMS Tracker have been studied using dedicated simulation software [3]. Some main results are reported hereafter, while more details can be found in [1-2].

The amount of material that a particle will pass trough is one of the issues to take in account in the design of the Tracker. Great effort has been devoted in the choice of materials for support structures, cables, cooling pipes and so on in order to minimize the material budget, and their positioning has been designed trying to optimise its distribution. Material budget has been estimated from detailed GEANT simulation, in terms of radiation length, following the procedures specified in [1]. Results, including the contribution of the pixel system, are shown in Fig. 2.

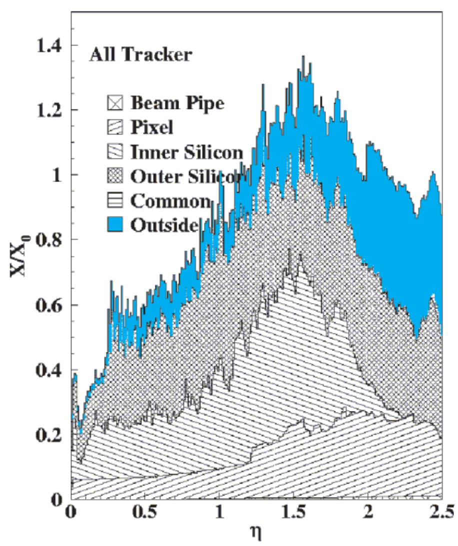

Figure 2: Radiation length in the Tracker as a function of η.

The occupancy has been evaluated in the high luminosity scenario, superimposing 24 minimum bias events per bunch crossing. It is estimated after digitisation and cluster reconstruction and is defined as $N_{fired\text{-}strips} / N_{strips}$, where $N_{fired\text{-}strips}$ is the number of strips in reconstructed cluster and N_{strips} can be either the total number of strips (*global* occupancy) or the number of strips in hit detectors (*local* occupancy). The global occupancy is relevant to data acquisition, while the local occupancy influences the pattern recognition. Both them are below a few percents in the whole Tracker, as shown in Fig. 3.

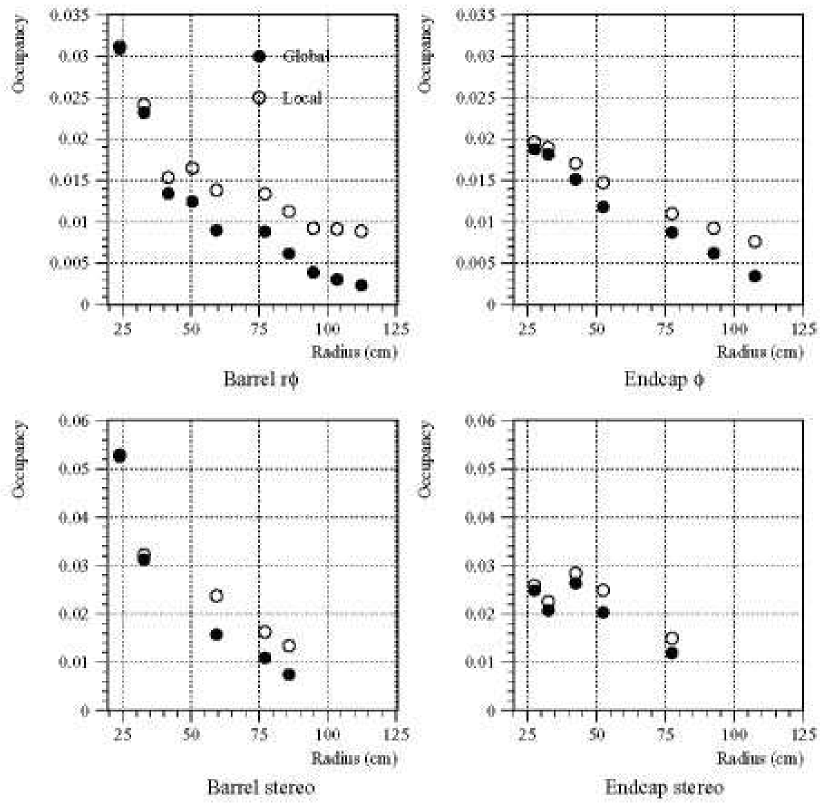

Figure 3: Global (solid circles) and local (open circles) occupancy in SST as a function of *r*, for the two sides of modules in barrel and end caps.

Track reconstruction performance and efficiency have been evaluated studying single muon tracks of energy between 1 GeV and 1 TeV; detailed results are reported in [2]. Fig. 4 shows latest simulation results of track finding efficiency for isolated muons: it is better than 98% for η up to 2. For tracks in jets the efficiency is around 90% in the whole η range. For isolated tracks, a transverse momentum resolution better than $\delta p_T/p_T \approx (15 \cdot p_T \approx 0.5)$ %, with p_T in TeV, is reached in the central region ($|\eta| < 1.6$); in conjunction with muon chambers, that results in muon momentum resolution better than 10% up to 4 TeV in the region $|\eta| < 2$

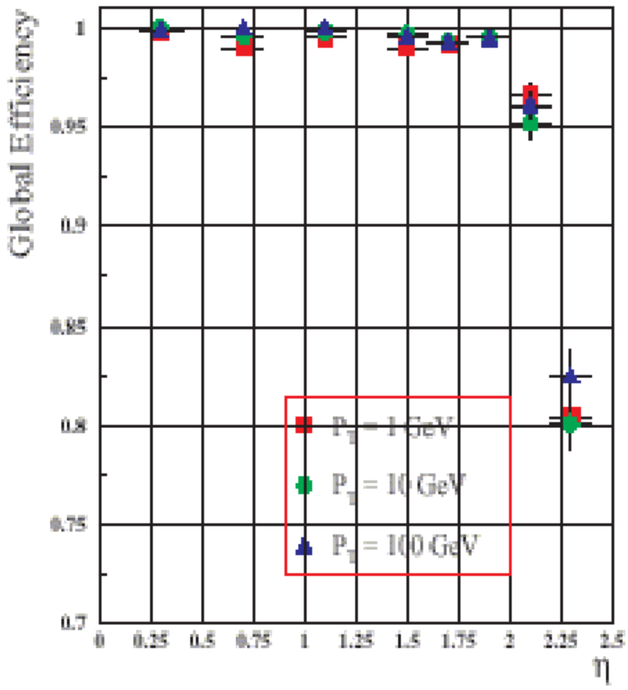

Figure 4: Simulated track finding efficiency for isolated muons.

4 Choice of silicon sensors

The SST will undergo an elevate radiation fluence in the LHC environment. To ensure functionality for at least 10 yr of operation, the CMS collaboration has performed a detailed R&D programme on silicon sensors, investigating various possibilities in terms of kind of sensors, substrates type and resistivity, geometry, mask design and so on. They have been tested after irradiations with various sources and have been studied by mean of simulations, electrical characterization, and beam-tests. The results of those studies have led to the choice of single sided silicon sensors with p^+ strips implanted on *n* type substrates, integrated AC coupling of the read-out strips, polysilicon resistor biasing of the p^+ strips, <100> silicon lattice orientation, metal overhang of the read-out strips, low resistivity (1.5-3.0 kΩ cm) thin (320 μm) substrates in the inner region and standard resistivity (4.0-8.0 kΩ cm) thick (500 μm) ones in the outer region. In this section a summary of the main choices, and relative motivations, on silicon sensors will be given.

Radiation damage can be split in bulk effects and surface effects. Bulk effects are caused by the displacement of silicon atoms out from their reticular positions. From the point of view of sensor operation, it mainly causes three effects: an increase of leakage current, a variation of depletion voltage and a decrease of charge collection. The increase of leakage current results in an increase of the noise. The variation of depletion voltage results (at high fluences, for which sensors undergo type inversion) in an increase of the operation voltage and, hence, of the breakdown risk. The decrease of charge collection results in a decrease of the signal. For what concerns surface effects, they are mainly due to charge trapping at the interface between silicon and oxide. It causes an increase of interstrip capacitance, which, in turn, results in an increase of the noise.

One important parameter for the operation of silicon sensors in a radiation environment is the substrate resistivity. Fig. 5 [4] shows the depletion voltage vs. fluence for low and high resistivity devices. After the inversion point, low resistivity substrate offers considerable advantage in terms of depletion voltage. That allows operating sensors at lower voltage, so increasing the safety margin with respect to breakdown risk. Low resistivity material will be used in the inner region of the Tracker, where the radiation damage will be higher. In the outer region the maximum fluence after 10 yr of operation will be 3.5×10^{13} n cm^{-2} (1 MeV eq.), hence sensor will not overpass the inversion point. That permits to use standard (4.0-8.0 kΩ cm) material and thicker (500 μm) substrates.

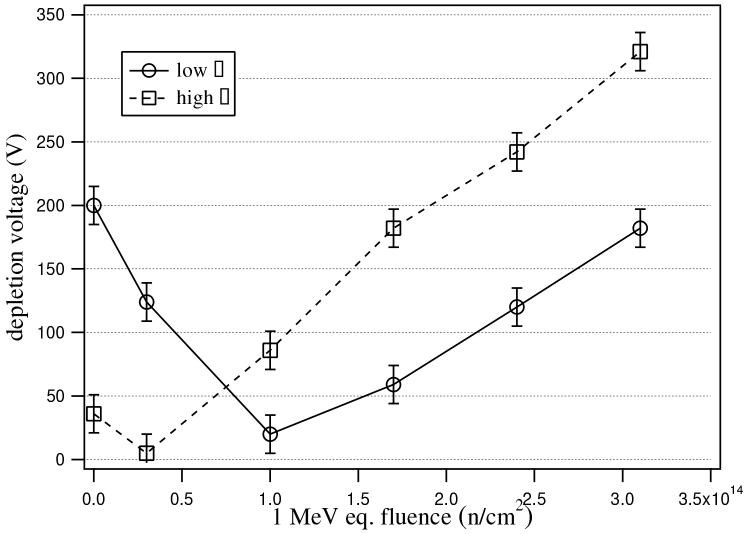

Figure 5: Depletion voltage vs. fluence for low and high resistivity sensors.

Another characteristic studied by the CMS collaboration is the crystal orientation of the silicon substrate. We have compared sensor produced on <111> substrates and on <100> ones. Before irradiation their performances are similar. After irradiation, the interstrip capacitance in <100> devices remains practically unchanged, while it increases in <111> ones, as shown in Fig. 6 [5]. For that reason we have preferred <100> silicon.

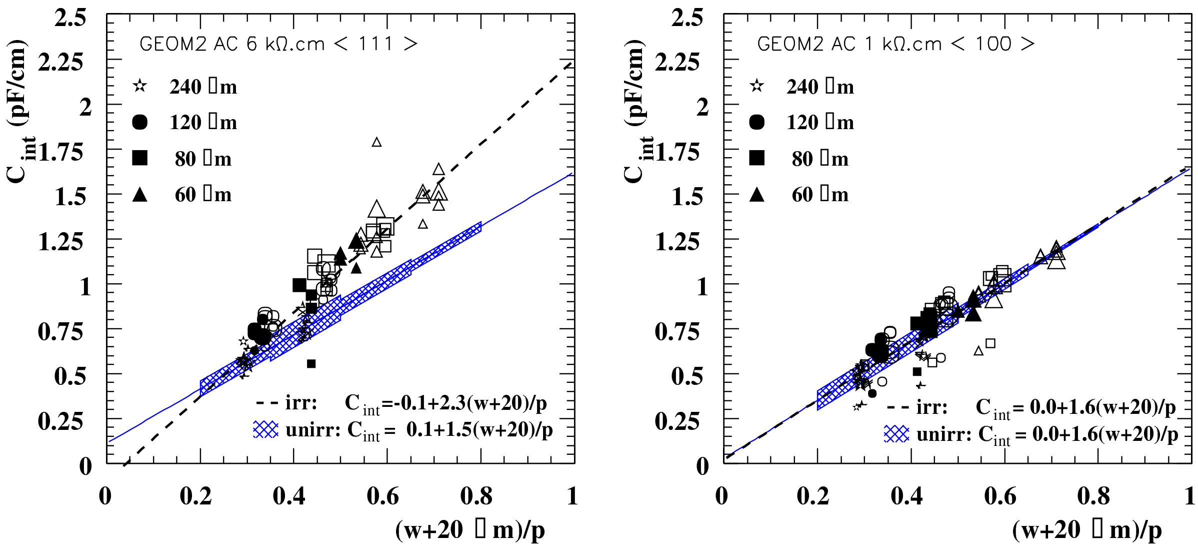

Figure 6: Interstrip capacitance before and after irradiation for <111> sensors (left) and <100> sensors (right).

Metal overhanging on the read-out strips offers sensible advantages in terms of breakdown voltage. Silicon sensors are often affected by localized, or so-called “soft”, breakdown. They happen in the regions of the sensor where the electric field is higher, that is corners on the junction side: near the implanted strips, the bias and the guard rings. The use of metal overhang, (metal strips wider than corresponding implanted ones) permits to move the maximum of the electric field from silicon substrate towards the oxide layer [6]. That results in a reduction of the electric field in the most critic regions and, as a consequence, in a higher breakdown voltage, as shown in Fig. 7 [5]. It has also been checked that the use of a small overhang does not have drawbacks from the point of view of interstrip capacitance [7].

Besides the choice of sensor characteristics, we have defined a set of tests, and relative selection criteria, that every sensor must pass before entering the apparatus. We have also foreseen regular irradiation tests in order to monitor the quality and homogeneity of sensors for the whole production.

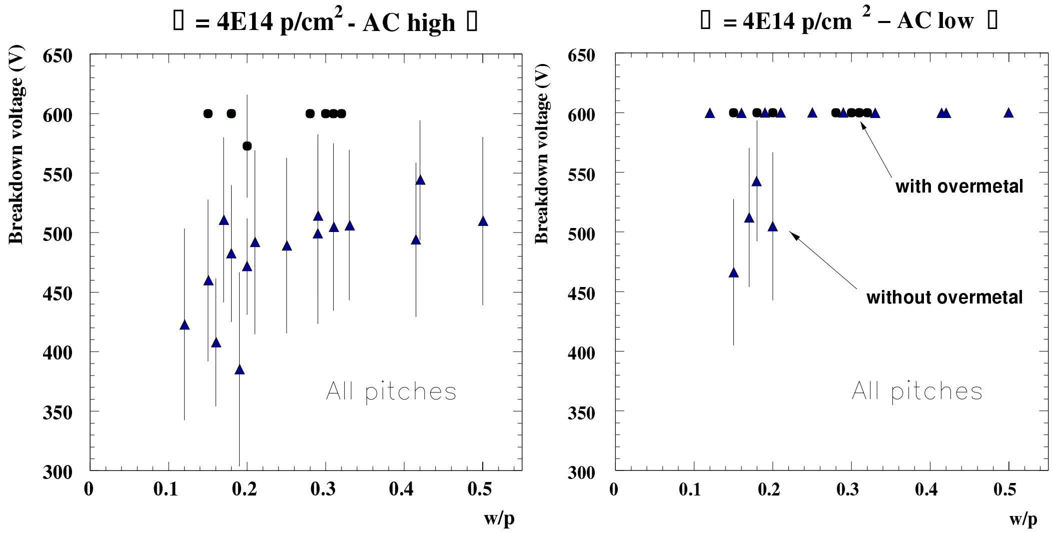

Figure 7: Breakdown voltage for sensors of different pitches and resistivity, with (triangles) and without (circles) overhang. Points at 600 V mean that no breakdown was detected (IV performed up to 600 V).

5 Conclusion

After several years devoted to the development of the project, the CMS Tracker is entering its construction phase. The new layout, with a full silicon detector, has been demonstrated to be technologically feasible and well suited to reach the required physics performances and to match the construction constraints.

The radiation hardness of silicon sensors has been deeply investigated in various R&D studies. Their results have driven the choice of technology for strip-sensors, giving now us the confidence that sensors passing the selection criteria will ensure functionality for at least 10 yr of operation at the LHC.

References

[1] CMS Collaboration, *The Tracker Project, Technical Design Report*, **CERN/LHCC 98-6, CMS TDR 5**, 15 April 1998;

[2] CMS Collaboration, *Addendum to the CMS Tracker TDR*, **CERN/LHCC 2000-016, CMS TDR 5 Addendum 1**, 21 February 2000;

[3] For update information on CMS software visit the web page: http://cmsdoc.cern.ch/cmsnicehome.html;

[4] M. M. Angarano, et al., *Characterization of neutron irradiated, low-resistivity silicon detectors*, **CMS CR 2000/006**, presented at 5th International Conference on Position-Sensitive Detectors, accepted for publication by Nucl. Instr. and Meth. A;

[5] S. Braibant, et al., *Investigation of Design Parameters and Choice of Substrate Resistivity and Crystal Orientation for the CMS Silicon Microstrip Detector*, **CMS Note 2000/011**;

[6] D. Passeri, et al., *Physical Modeling of Silicon Microstrip Detectors: Influence of the Electrode Geometry on Critical Electric Fields*, **IEEE Trans. on Nucl. Scie. 47 (2000) 1468**;

[7] M. M. Angarano, et al., *Analysis and Test of Overhanging-Metal Microstrip Detectors*, in **Proc. of IEEE Nuclear Science Symposium 2000**, Lyon (France);

M.M. Angarano, et al., *Optimization of Overhanging-Metal Microstrip Detectors: Test and Simulation*, extended version submitted to **IEEE Trans. on Nuclear Science**.