The Compact Muon Solenoid Experiment

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The Silicon Tracking System of CMS

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Abstract

The paper describes the large silicon tracking system of CMS, one of the two general purpose detectors planned at the Large Hadron Collider of CERN. The system consists of three layers of silicon microstrip detectors instrumenting the interaction region as part of the Inner Tracking Detector of CMS. The expected performance of the system is discussed together with preliminary test beam results on single and double-sided prototype detectors.

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1 Introduction

The Large Hadron Collider (LHC) will produce high energy collisions of protons at a center-of-mass energy of 14 TeV and luminosities in excess of $10^{34} \text{cm}^{-2} \text{s}^{-1}$. The CMS experiment consists of a robust muon spectrometer instrumenting a large, 13m long, 6m diameter, superconducting solenoid. The hadronic and electromagnetic calorimeters are located inside the 4T field produced by the superconducting coil, while a sophisticated tracking system performs track reconstruction, momentum measurement and pattern recognition [1] (Fig. 1). The main goal of CMS will be to exploit the peak luminosity of LHC to allow the search for the Standard Model Higgs boson in a range of mass from about 100 GeV (the maximum reach of LEP) to approximately 1TeV. The physics potential of the experiment will include the search for alternative models for the electroweak symmetry breaking mechanism, the search for supersymmetric partners of quarks and gluons, high precision studies on CP-violating decays of the b quark and on the production and decay properties of the top quark.

2 The CMS Central Tracking System

The CMS central tracker is designed to ensure high quality momentum resolution, precise e/γ separation and excellent isolation of calorimeter showers. A coarse measurement of the z coordinate is required to distinguish among different interaction vertices at very high luminosity, while a precise measurement of the impact parameter in the $r - \phi$ plane is crucial for heavy quark physics and b -tagging in general.

The high rate of interactions at the full luminosity of LHC is a challenging environment for an advanced tracking system. At $\sqrt{s}=14\text{TeV}$ we expect a total inelastic cross section around 70mb which corresponds to an overall inelastic event rate of 700MHz at full luminosity. Bunches of protons collide every 25ns but only a tiny fraction of collisions produce interesting events with high transverse momentum particles; on average 18 'minimum bias' events are superimposed on each interesting event which means that a few thousands charged and neutral particles are produced in coincidence. The detailed reconstruction of all these tracks would be practically impossible; fortunately most of them will be low transverse momentum particles confined in helicoidal trajectories around the beam line by the strong solenoidal magnetic field.

The main problem for the tracker will be pattern recognition: about 500 soft tracks will usually be superimposed on the few tracks with transverse momentum above 2 GeV/c, the only ones which are really relevant for most of the physics channels we want to investigate. The hits produced by these high p_t tracks should be identified within a large population produced by the accompanying events, by the soft tracks background and by the effects of secondaries.

The levels of radiation due to primary interactions will be very high around the collision region; in addition a high flux of neutrons will affect the tracking volume due to backscattering of neutrons evaporated from nuclear interactions in the material of the electromagnetic calorimeter. Assuming an integrated luminosity in the first 10 years of running of $5 \times 10^5 \text{pb}^{-1}$, the neutron fluence in the inner part of the tracker is expected to be higher than $5 \times 10^{13} \text{cm}^{-2}$ whereas the charged particles fluence will vary between 10^{15}cm^{-2} at 10cm distance from the beam line and $4 \times 10^{12} \text{cm}^{-2}$ at $r=1\text{m}$.

In this hostile environment fast detectors and fast read-out electronics are needed to avoid unacceptable dead-time due to the high interaction rate; radiation resistance is required both for detectors and read-out systems so that they survive the high fluence of neutrons, photons and charged hadrons in the tracking cavity; high granularity devices are needed to avoid unacceptable occupancy while only very precise detectors allow the best momentum resolution within the limited lever arm and minimize the pattern recognition problems.

These considerations lead to a tracking system based on state-of-the-art technologies: semiconductor pixel, silicon microstrip detectors and microstrip gas chambers (MSGC).

The entire tracker is contained in a cylindrical volume of 1.3m radius and about 6m length. The system is subdivided into barrel and forward parts which meet at around $\eta=2$. Each region consists of three subdetectors; the innermost part, close to the beam pipe, is instrumented with two layers of pixels aiming at a point resolution of $15\mu\text{m}$ in both coordinates; layers of microstrip silicon detectors in the intermediate radial region provide at least three measurements $r - \phi$ with a point resolution $\sigma = 15\mu\text{m}$ and two points in $r - z$ with $\sigma \leq 1\text{mm}$. Layers of MSGC's provide 7 precise hits per stiff track in $r - \phi$ with a point resolution around $50\mu\text{m}$ and 3 hits in $r - z$ with a coarser resolution around 3mm. The overall lever arm for momentum measurement in the barrel region is about 1.2m.

Each forward part consists of 9 layers containing only MSGC's and 6 additional 'mixed' layers partly equipped with silicon detectors in the inner region.

The total number of analog channels in this baseline design is 11×10^6 for the MSGC's and 3.7×10^6 for the silicon tracker. The number of channels of the pixel detector is about 70×10^6 heavily multiplexed and zero suppressed at the detector level.

All detectors are mounted on very light carbon fiber structures and are arranged in spiral arms to allow for easy mechanical solutions for cables and services.

3 The Silicon Tracker

The advantages and the physics potential of precise 3D tracking around the interaction region has been extensively demonstrated both by LEP experiments and CDF. In CMS we aim at similar sophisticated performance on a larger scale of apparatus and in a much more difficult environment.

Impact parameter measurements play an essential role in B -physics (CP-violation, B^0 oscillations) and in tagging b -jets in high p_t events, such as $t\bar{t}$ production, associated $b\bar{b}H$ production, in the search for $H \rightarrow b\bar{b}$ decays, as well as for modes involving τ 's ($H^\pm \rightarrow \tau\nu$ and $h, H, A \rightarrow \tau\tau$). Microvertex b -tagging played an important role also in the recent discovery of top [2].

The system of pixel and microstrip silicon detectors is the key element to provide vertexing capability in both coordinates; it is supposed to be able not only to distinguish among different interaction vertices at full luminosity but also to provide a precise measurement of the impact parameter of tracks in both coordinates and over a large range of momenta.

The first pixel layer is positioned at 7.5cm radial distance from the beam pipe to minimize the extrapolation error on the impact parameter. The second pixel layer at 11.5cm radial distance is basically used to have full efficiency and to guarantee some redundancy for pattern recognition in the highly populated innermost region of the tracker.

The microstrip silicon detectors instrument the radial region $20\text{cm} \leq r \leq 40\text{cm}$. In the barrel region three layers of rectangular silicon detectors provide accurate measurements in the bending plane with strips oriented along the beam direction. The first and the last layer are double-sided planes while the intermediate plane contains only single-sided devices.

The double-sided planes use stereo strips information to link in the $r - z$ view the pixel points with the points provided by the microstrip gas chambers instrumenting the outer layers of the tracker.

A similar structure is repeated in the forward/backward region where disks of wedge-shaped microstrip detectors measure with radial strips the bending angle and with azimuthal strips the $r - z$ position of the track.

The barrel part covers the η region up to 1.8; the forward/backward disks extend the coverage up to $\eta=2.6$. The geometry of the baseline CMS Silicon Tracker is shown in Fig. 2.

Figure 1: The CMS detector.

Figure 2: The silicon tracker: layout of the barrel region.

3.1 The Silicon Detectors

The silicon tracker is mostly made-out of two different types of detectors (single and double-sided) in two different geometries (rectangular and wedge-like).

The most critical issue for both will be the long term survivability under heavy irradiation.

In the first 10 years of running the inner detectors, at 20cm radial distance from the beam pipe, will be exposed to an integrated fluence of about $2 \times 10^{14} \text{ cm}^{-2}$ charged particles in addition to $4 \times 10^{13} \text{ neutrons cm}^{-2}$.

We expect several effects from radiation damage on silicon [3, 4, 5, 6]:

- With the irradiation the leakage current per strip will increase with time up to a level of about $1 \mu\text{A}$ per strip. AC coupling to the read-out chips and fast shaping time of the front-end amplifiers can keep the increase in noise under control and avoid baseline shifts.
- The charge concentration at the interface between silicon and the thin dielectric layers at the surface of the detectors will be heavily affected by the flux of neutral and charged particles. This effect may influence key elements of the detectors (interstrip capacitance, interstrip isolation, bias circuit components etc.) which could become uncontrolled sources of noise at the input of the amplifiers. The impact of these factors on the overall performance can be kept under control with a careful design of the detectors themselves.
- The effective doping concentration of the silicon will change with time producing type inversion of the bulk thereafter increasing the depletion voltage. The risk here is to loose tracking efficiency for the reduced thickness of the layer of depleted silicon and for the effects of trapping centers and low field regions that may slow down the signals in damaged silicon. To avoid all of this it is important to operate the devices from the very beginning at a reverse bias high enough to guarantee full depletion for the entire lifetime of the detectors. Extensive tests show that this can be achieved provided that the devices can reliably stand a bias voltage above 250V.
- With detectors heavily irradiated and subject to high leakage currents one should take into account the possibility of thermal runaway and other long-term effects affecting irradiated silicon. In particular long-term anti-annealing processes can play an important role in degrading the detector performance. These effects are known to be strongly temperature-dependent, therefore each silicon detector module is expected to be cooled down around 0°C , a temperature at which the most important reactions affecting anti-annealing phenomena seem to be frozen.

Taking all this into account we have defined a set of detector characteristics as baseline requirements:

- A standard thickness of $300 \mu\text{m}$ is maintained for several reasons, including a safety margin in the signal-to-noise ratio and higher compatibility with the more common processing technologies on 4 in. wafers with a possible extension to 5 and 6 in. processes. An option of using $250 \mu\text{m}$ thick silicon, which would extend the lifetime of the detectors in terms of depletion voltage, is under evaluation.
- The processing techniques should be compatible with high breakdown performance of the detectors before and after irradiation. In particular we request operating voltages, $V_{bias} \geq 300\text{V}$ for the detectors of the inner layers and $V_{bias} \geq 250\text{V}$ for the outer layers. Several solutions for guard-ring structures are under evaluation. A total number of 1% noisy or dead strips at V_{bias} are considered acceptable at the beginning of the operation for non-irradiated devices. This percentage should not exceed 5% for devices irradiated at levels corresponding to 10 years of LHC.
- The 'double-sided' layers will be built with real double-sided detectors. The use of back-to-back single-sided detectors could be a back-up solution in case of technical problems or cost issues.
- The high resolution side will be the traditional junction side of the conventional microstrip devices. The choice of having the high resolution pattern implemented on the ohmic side (the high field region after type inversion), although attractive may be painful for CMS considering the 4T magnetic field (difficult to compensate for the Lorentz angle on electrons) and also additional costs related to the need of some patterning of the junction side also for 'single-sided' devices.
- We consider as the baseline a 'radiation resistant' design featuring integrated coupling capacitors, polysilicon resistors as bias elements, individual p-stop structures to control the interstrip resistance on the ohmic side of double-sided detectors.

- A read-out pitch of $50\mu\text{m}$ on the junction side with no floating strip in between is considered a good compromise to minimize the interstrip capacitance while maintaining a space resolution for stiff tracks better than $15\mu\text{m}$. Solutions with larger read-out pitch, with and without floating strips, are under evaluation in an effort of cost reduction. On the ohmic side axial strips at a stereo angle of 60mrad are read out on a $200\mu\text{m}$ pitch. To avoid large dead regions at the lateral edges of the stereo detectors, we are evaluating the use of the double metal technology.

3.2 The Basic Detector Module

The basic silicon microstrip half-module consists of two silicon detectors, with a size of $5.4 \times 6.4\text{cm}^2$, glued together and coupled to the read-out electronics for a total length of 15.3cm [7] (Fig. 3). 1024 strips, used to measure the $r-\phi$ coordinate, run parallel to the beam line on a $50\mu\text{m}$ pitch. The strips of two detectors are daisy-chained at each end for a total length of approximately 125mm . Two high conductivity carbon fiber support rails ($1 \times 8 \times 130\text{mm}^3$) are glued to the lateral edges of the modules for mechanical stiffening and for cooling purposes. The positioning pins inserted in the modules are used as reference for the module construction under a coordinate measuring machine. Two half-modules joint by stiff carbon fiber elements form the basic detector module. Each strip is read-out by a charge sensitive amplifier with a 45ns peaking time whose output is sampled at 40MHz . Each individual electronic chip houses 128 channels; a multiplexing unit reduces the 128 parallel inputs to a single serial output. The data are transferred at 40MHz to an analogue optical link, where they are sent, with no data suppression, to an external receiving module. This module digitises the hits in a fast ADC and stores the result in a local memory until they are required by the data acquisition and higher level triggering system [8].

Figure 3: The basic microstrip detector half-module.

Figure 4: Detail of the mechanical structure of a barrel wheel.

Considering the noise performance of the front-end chip, a strip length of 12.5cm on the junction side is foreseen as baseline choice, although further direct tests will be needed once the full electronics chain will be available. The wider read-out pitch on the ohmic side ($200\mu\text{m}$) allows us to handle the additional capacitance eventually introduced by a second metal layer.

The read-out unit, housing front-end amplifiers and control chips, is supported by a high conductivity carbon fibre substrate which also acts as a heat bridge for the power dissipated by the electronics. The front-end chips are directly glued on the substrate to maximize the heat transfer to the cooling pipe incorporated in the supporting structure. A low mass hybrid circuit provides the connections needed to distribute power lines, clocks and output signals. The hybrid is made of 5 layers (each one $25\mu\text{m}$ thick) of metallized kapton with aluminum strips. Aluminized kapton is also used for power cables.

A low mass connector couples each module to an interconnect card, housing the optical link, which distributes communication and output signals through a bundle of optical fibers.

3.3 The Mechanical Structure

The detector modules are assembled together in high modulus carbon fibre structures incorporating cable and services (Fig. 4).

To increase the modularity during the assembly of the system, the barrel structure is subdivided into 9 individual 'wheels' and the forward part into 6 'disks'. The space available for cables and services becomes larger in the barrel region if the detector modules are arranged in spiral arms.

No dead region is foreseen in the tracking volume. Detector modules overlap in $r - \phi$ for a few millimeters to allow for intermodule alignment, while adjacent wheels overlap in z allowing longitudinal interpenetration of detector modules.

The dimensions of the supporting elements have been carefully evaluated taking into account the effects of gravity, thermal cycles and heavy irradiation. Once installed and kept in the operating conditions the structure is supposed to be stable within $10\mu m$. The position of each individual wheel and disk is surveyed by optical means during data taking. The position of each individual module in the structure is recorded during the assembly procedure and measured during data taking using tracks for alignment purposes.

The silicon tracker acts as an independent volume. A thin cylindrical shield, mainly used for electromagnetic shielding defines the inner diameter while a thick thermal shield isolates the silicon volume, permanently kept below $0^\circ C$, from the MSGC's cylinder operated at room temperature.

3.4 The Cooling System

The main heat sources in the silicon tracker are the power dissipated by the front-end electronics and the heat produced by the leakage current in the silicon detectors.

The average power dissipation for an electronics channel has been fixed at less than 2mW, so a total power of about 4W is dissipated per detector module (5W for double-sided modules); the heat contribution due to the leakage current of silicon detectors is considered negligible in the initial period of running; it becomes sizeable only when the leakage current per strip increases due to radiation damage. A conservative approach evaluates this contribution as an additional 15% in power consumption ; each single-sided module is therefore considered to produce about 4.6W (5.6W for double-sided) and this power must be removed locally to avoid heating-up of the silicon detectors.

Indirect cooling is the baseline option for the cooling scheme with high conductivity carbon fiber elements, incorporated in the modules, acting as heat bridges between the silicon detectors and the read-out chips and the cooling pipes.

The whole system will stay at a temperature below 0° using a distribution of chill fluid in the mechanical structure and auxiliary gas ventilation.

3.5 Material Budget and Radiation Length Studies

The radiation length budget for the Silicon Tracker has been evaluated making use of a simplified GEANT description of the detector which calculates the radiation length versus pseudorapidity.

The smearing of the beam spot has been simulated assuming a Gaussian distribution centered in the origin and with a sigma of 5.3cm. The contributions due to the different components are calculated separately, thus permitting the relative importance of each part to be determined.

The results of the simulation for the barrel part of the silicon tracker show that, including all components, each detector layer contributes with an average of $1.5\% x_0$ to the total radiation length. Similar studies performed on the forward disks yielded a corresponding value of about $1\% x_0$.

4 Expected Performance

The performance of the full tracking system, as described in the Technical Proposal, have been extensively simulated using a detailed GEANT based description of the detector geometry which includes also sophisticated detector response for pixels, silicon strips and MSGC's. A more simplified detector description is being currently used, as fast tracker simulation tool, for optimization purposes [9].

Figure 5: Momentum resolution of the tracker alone versus η for tracks of different p_t with (left) and without (right) constraint on the primary vertex position.

A random inefficiency of 10% is introduced to simulate, in a conservative approach, the effects of dead/hot channels and hits lost in silicon for any reason. For pattern recognition studies a background noise level of 0.1% is assumed, but detailed studies have been also performed with different noise levels up to 1%. A luminosity of $10^{34} \text{cm}^{-2} \text{s}^{-1}$ and bunch spacing of 25ns has been assumed. The primary vertex was smeared with $\sigma_x = \sigma_y = 20 \mu\text{m}$ and $\sigma_z = 5.3 \text{cm}$.

The main goal of the CMS detector as a whole is to reconstruct isolated, high p_t muons and electrons with a momentum resolution better than $\Delta p_t/p_t = 0.1 p_t$ (in TeV/c) and with high efficiency over the full rapidity range of $|\eta| \leq 2.5$. The high momentum resolution aims at minimizing the background under the mass peak of $H \rightarrow 4l$, while the wide angular coverage accounts for longitudinal phase space of the Higgs boson and for the boost of the decay products.

The momentum resolution of the tracker alone is shown in Fig. 5 versus η and for different p_t regions. Low momentum leptons ($p_t \leq 10 \text{ GeV/c}$) are measured before the absorber with a precision below 1% over the full rapidity region.

By using the inner tracker as well as the muon chambers we obtain an excellent momentum resolution. The combined resolution for muons of 400 GeV/c is around 3% degrading to 7% at 3TeV/c. The charge of each track could be reconstructed correctly up to 2 TeV/c p_t .

The track finding efficiency, for tracks with $p_t \geq 2 \text{ GeV/c}$, has been estimated both for isolated tracks and tracks inside 100 and 500 GeV E_t jets. The track reconstruction efficiency, averaged in different pseudorapidity regions, exceeds 90% in all cases (respectively 98, 94 and 90%) with ghosts below the 1% level.

The occupancy in the silicon tracker is always below 1% both for the barrel and the forward part. Different approaches, based on the use of Kalman filtering techniques, templates or neural networks are under study to optimize the pattern recognition algorithms.

The results for the impact parameter resolution are shown in Fig. 6.

They are obtained by fitting Gaussian lineshapes to data histograms. For tracks with $p_t \geq 10 \text{ GeV/c}$ we obtain impact parameter resolutions in the transverse plane better than $30 \mu\text{m}$ in the barrel and $40 \mu\text{m}$ in the forward region. The corresponding impact parameter resolutions in the $r - z$ plane are better than $70 \mu\text{m}$ in the central region but only $400 \mu\text{m}$ at large η . Depending on the chosen algorithm and jet- E_t , the tagging efficiency for b -jets varies between 20 and 50%, while the mistagging probability is between 0.04 and 1.9%.

Further careful studies are under way to take into account more realistic description of the detector response, including uncontrolled misalignments, the effect of non-homogeneous material distribution, wrongly associated or badly reconstructed tracks etc.

5 R&D on Single and Double-Sided Detectors

Many detector prototypes have been developed within the R&D work performed by the collaboration. Here we focus on results obtained for the baseline option of single-sided axial and double-sided stereo detectors.

Figure 6: Impact parameter resolution in $r - \phi$ (left) and $r - z$ (right).

Several series of single-sided detectors have been produced [10], evaluated and tested with minimum ionizing particles. Detector modules were built using pairs of full size detectors, $64 \times 64 \text{ mm}^2$, daisy-chained together to get the total strip length of 12.5cm of the baseline design. The 1024 p^+ strips of the junction side were read-out on a $50 \mu\text{m}$ pitch without floating strip.

Using the double-metal technology it was possible to design double-sided stereo detectors with no dead region at the lateral edges. Fig. 7 illustrates the idea. The strips ending at the edges are connected together through a second metal layer and vias in a $4 \mu\text{m}$ thick dielectric layer covering the whole surface. The detector dimensions were in this case $30 \times 65 \text{ mm}^2$ with 512 p^+ strips on a $50 \mu\text{m}$ pitch on the junction side and 256 n^+ strips on a $100 \mu\text{m}$ pitch on the ohmic side at a stereo angle of 100mrad. With these detectors we built modules with two different read-out pitches on the ohmic side: 200 and $100 \mu\text{m}$ respectively with and without floating strip left in between two active read-out elements.

The detectors were produced using what we consider a standard 'radiation resistant' technology, featuring integrated AC coupling, polysilicon resistors for the bias circuits and p^+ individual blocking structures around the electrodes of the ohmic side of double-sided devices. A typical coupling capacitors yield was found to be 1% shorted capacitors on the junction side and 2% on the ohmic side.

Single and double-sided detector modules were read-out using arrays of PreMux128, front-end chips containing the same preamplifier-shaper design that will be used in the APV-series chips meant for the CMS tracker.

The main purpose of this activity was to check carefully the performance of non-irradiated devices in terms of signal-to-noise ratio and space resolution in different conditions of bias voltage and for tracks at various angle.

6 Test Beam Results

Several detector modules were installed in H2 and X7, test beam facilities of CMS at Cern equipped with precision tracking telescopes.

By defining the signal-to-noise ratio as the ratio between the most probable cluster charge and the width of the cluster noise we measured a comfortable 25:1 for the 12.5cm long strips on a pitch of $50 \mu\text{m}$ on the junction side. Although obtained with non-irradiated detectors and read-out electronics featuring only the basic elements of the final chip, this result is considered very promising and fully compatible with the performance expected for the final system after heavy irradiation.

The residuals distribution obtained for the single-sided full size module is shown in Fig. 8 (top). The width of this distribution is about $18 \mu\text{m}$ including the effects of multiple scattering produced by the material in front of the detectors and of the extrapolation errors in the tracking elements. By unfolding these components we find a detector intrinsic resolution in $r - \phi$ better than $12 \mu\text{m}$ for perpendicular tracks. Fig. 8 (bottom) shows the

Figure 7: Design of double-sided stereo detectors with no dead regions: the double-metal line crossing the stereo strips allows the readout of the first strip at the left. A similar pattern is repeated for all edge strips.

Figure 8: Residuals distribution in the $r - \phi$ plane for the full size module (top) and distribution of the residuals along the x coordinate bottom).

distribution of these residuals across the detector to check the uniformity of response of the entire module.

By tilting the detector modules we studied the $r - \phi$ resolution for tracks of different incidence angles. The resolution improves slightly with the angle, as one may expect, when the average cluster size increases from the initial value of 1.4 strips to around 2. The larger fraction of two-strip cluster allows charge sharing in most of the events yielding results better than the simple digital response. At 15° the resolution starts degrading again with the average cluster size approaching three strips.

Figure 9: Correlation plots between the telescope and the stereo detector informations for modules with different readout pitch. The position is reconstructed as ϕ coordinate (left) and true stereo coordinate (right).

The position resolution in the $r - z$ view has been studied by measuring the detector response in double-sided modules on the ohmic side. The effect of the double-metal connection of the lateral strips of the stereo detectors is shown in Fig. 9. The stereo detector information is correlated with the telescope information as ϕ coordinate in the left side plots and true stereo coordinate in the right side plots for the two cases: readout pitch of 100 and $200\mu m$. Fig. 10 shows the corresponding position resolution. Here the tracking errors and the effect of material are very small with respect to the measured values so there is no need of further corrections. The plots show that if we read out all strips on a $100\mu m$ pitch we obtain a space resolution of $325\mu m$ while the corresponding result for a read-out pitch of $200\mu m$ with a floating strip left in between is $372\mu m$. In this latter case we save the cost of half electronics channels still maintaining a good performance. Assuming a roughly linear dependence of the $r - z$ resolution versus the stereo angle can extrapolate the results obtained with these modules with 100 mrad stereo angle to the results expected for the baseline value of 60 mrad. The $600\mu m$ $r - z$ resolution that we obtain is well within the requirements. Fig. 11 shows the angle scan results for the resolution on the n side with a behavior similar to what was previously described for the junction side.

Another interesting result came from comparing the performance of the central stereo strips, directly daisy-chained and connected to the amplifiers, to the performance of the lateral strips connected to the double-metal layer and coupled in principle with the entire array of electrodes. By studying separately the two cases we can show that the lateral strips are fully working, the additional capacitance load added by the double-metal connection being fully under control. We only measured a slight worsening of the signal-to-noise ratio for the strips with double-metal, with respect to the strips without, at the level of 5% which we consider fully acceptable.

A few preliminary high voltage studies were performed on the single-sided modules. Individual detectors showed good breakdown performance when measured on wafers. Being fully depleted at $V_{dep}=40V$ it was possible to apply voltages up to 250V to all of them without reaching breakdown. Breakdown occurred on the guard-ring at V_{bias} above 350V while the strip region stayed quiet in most cases above 400V. The leakage current of the detectors was measured again after the procedure of cutting, gluing and microbonding needed to produce modules. Again the good breakdown performance was maintained. Fig. 12 shows the reverse current curve of a single-sided module tested in the beam that could be hopefully operated up to 300V. For safety reasons we reached in the beam only $V_{bias}=200V$. The module was stable with the voltage and there was no worsening of the overall signal-to-

Figure 10: $R - z$ resolution for modules with different read-out pitch: $100 \mu\text{m}$ (top) and $200 \mu\text{m}$ (bottom).

Figure 11: $R - z$ resolution versus tilt angle.

noise ratio with increasing the bias. A careful control of the cluster noise distribution showed that a non Gaussian tail appeared with the higher voltages although the overall effect was small in size (a typical factor 2 increase in noise width), and apparently interesting only a small fraction of the events at the level of .5%.

Although preliminary, incomplete and obtained with nonirradiated detectors these results are considered very encouraging to proceed further into the high voltage operation regime.

Figure 12: Reverse current of a single-sided module.

7 Conclusion

The baseline design of the silicon tracker of CMS appears to be well suited for running at the highest luminosity in search for the SM Higgs boson over a mass range from 100GeV to 1TeV. In addition the performance of the tracker in terms of impact parameter resolution allows to perform precision studies on top, beauty and tau physics at lower luminosity and to use b -tagging at high luminosity. Many details of the design are still in evolution and a further optimization process is foreseen in view of the Technical Design Report expected for the end of 1997.

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