The 2003 Tracker Inner Barrel Beam Test

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Abstract

Before starting the CMS Silicon Strip Tracker (SST) mass production, where only single component quality control tests can be done, an extensive collection of activities aiming at validating the tracker system functionality has been performed. In this framework a final component prototype of the Inner Barrel part (TIB) of the SST has been assembled and tested in the INFN laboratories and then moved to CERN to check its behaviour in a 25 ns LHC-like particle beam. A set of preproduction single-sided silicon microstrip modules was mounted on a mechanical structure very similar to a sector of the third layer of the TIB and read out using a system functionally identical to the final one. In this note the system setup configuration is fully described and the results of the test, concerning both detector performance and system characteristics, are presented and discussed.

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1 Introduction

In order to verify the basic functionalities of the Tracker Inner Barrel (TIB) of the CMS Silicon Strip Tracker (SST) [1] before starting the mass production, a number of activities has been carried out on detector structures of increasing complexity. In this framework, after the prototyping phase, a sector similar to the third TIB layer has been assembled using final production components as soon as they were available. These activities, known also under the name of “system test”, were first carried out in laboratory mainly to study the system capabilities in terms of readout performance and noise behaviour. Then the TIB layer 3 prototype has been exposed, together with a set of Outer Barrel (TOB) silicon microstrip modules and an Endcap (TEC) structure (“petal”1), to a 25 ns beam to study its response to minimum ionizing particles bunched in a LHC-like time structure. This happened during the spring of 2003 at the X5 test beam facility [2] of the SPS accelerator at CERN; the description of this test and the results obtained are the subject of the present note.

In the following, after an introduction to the SST layout together with detectors and electronics, the beam test setup will be described in detail concentrating on the TIB shell configuration, silicon microstrip modules, readout, slow controls and power supplies. Then the data analysis methods will be summarized and the main test results will be presented and discussed.

2 The CMS Silicon Strip Tracker

2.1 Detector layout

The CMS SST instruments the radial range between 20 cm and 116 cm and $|\eta| < 2.5$ around the LHC interaction point. The central region ($|z| < 118\text{ cm}^2$) is split into an Inner Barrel (TIB), made of four detector layers, and an Outer Barrel (TOB), made of six detector layers. The TIB is shorter than the TOB, and is complemented by three Inner Disks per side (TID), each disk being in turn composed of three rings. The forward and backward regions ($124\text{ cm} < |z| < 282\text{ cm}$) are covered by nine Endcap (TEC) disks per side, each one made of up to seven rings. The two innermost layers of both TIB and TOB as well as rings one, two and five of TEC and one and two of TID are instrumented with double-sided modules. A complete description of the silicon tracker layout (Fig. 1) can be found elsewhere [3].

The whole tracker region is embedded into the CMS 4 Tesla solenoidal magnetic field. Charged particle transverse momentum resolution of about 1.5% for centrally-produced muons of 100 GeV/$c$ is expected [4].

Figure 1: Longitudinal cross section of one quarter of the CMS SST. Thicker (blue) segments indicate double-sided silicon microstrip modules. The nominal beam interaction point is located in (0,0), dimensions are in mm. The pseudorapidity ($\eta$) coverage is also shown.

1) A petal is a modular structure which holds modules and services for a sector of an Endcap disk.

2) $z$ is the coordinate along the LHC beam axis.
2.2 The TIB silicon strip modules

The silicon strip module design has been kept as simple as possible to ease the mass production and integration. A TIB single-sided module is assembled from the following components: a carbon fiber support frame, a silicon microstrip sensor, the front-end multilayer Kapton hybrid, with a strip pitch adapter glued onto it, and a Kapton printed circuit biasing the sensor and insulating it from the conductive carbon fiber support frame. All these components are tested before being assembled in a module.

Figure 2 shows a single-sided TIB module identical to the ones used during the beam test. The TIB modules have strip length of approximately 12 cm and pitches of 80 \( \mu \text{m} \) (double-sided, 768 strips per module) and 120 \( \mu \text{m} \) (single-sided, 512 strips per module). These detectors are made of a single sensor 320 \( \mu \text{m} \) thick.

All silicon strip sensors [5, 6] are of single-sided type \(^3\). Double-sided TIB detectors are built simply gluing back to back two independent single-sided modules (“R-Phi” and “Stereo”). To obtain a coarser but adequate resolution on the longitudinal coordinate the stereo module has the sensor tilted by 100 mrad \(^4\) with respect to the R-Phi one. The stereo sensor and electronics are identical to the R-Phi ones, the only difference being in the support mechanics and pitch adapters.

The module assembly is done automatically using a "gantry" pick and place machine [7]. The main module production steps are the following. The Kapton bias printed circuit is glued onto the carbon fibre frame, then the sensor is precisely glued on this support making use of the precision reference marks present on the sensor and the precision aluminium inserts located on the frame. After this operation the front-end hybrid and pitch adapter are finally glued on the frame; in this case the precision required is less stringent, being imposed only by the bondability of the sensor to the pitch adapter, and, in case of double-sided modules, by the tracker support mechanical clearance.

The module strips and the bias and ground lines are then wire-bonded to the corresponding pads. The module then undergoes a chain of tests both at room (20 °C [8]) and operating temperature (-15 °C) to identify all possible defects.

The tracker microstrip sensors have been designed keeping in mind the results of extensive research and develop-

\(^3\) The SST sensors are of 'p-on-n' type with integrated decoupling capacitors, aluminium readout strips and polysilicon bias resistors.

\(^4\) Greater stereo angles would increase the z resolution at the expenses of an increase in the "fake hit" number when the particle density increases.
of development activities [9] to obtain detectors able to survive the LHC radiation environment for at least ten years of operation \(5\). An efficient cooling system is very important to reduce the radiation damage effects on the silicon sensors and to remove the amount of power dissipated by the front-end electronics. For these reasons the CMS silicon tracker has a cooling system which uses a coolant (Perfluorohexane, \(C_6F_{14}\)) at a temperature of \(-20\ ^\circ\text{C}\) or below.

### 2.3 Silicon strip tracker electronics

A scheme of the silicon strip tracker electronics is shown in Fig. 3. The signals coming from each strip are processed by front-end readout chips (APV25 [10]) mounted on a multilayer Kapton hybrid circuit. The APV25 is a 128 channel chip built in 0.25 \(\mu\text{m}\) CMOS technology. The thin gate oxide together with special layout techniques ensure its radiation tolerance [11].

Each channel consists of a charge sensitive preamplifier coupled to a shaping stage which produces a 50 ns CR-RC pulse shape. The shaper output of each channel is sampled at 40 MHz into a 192 cell deep pipeline. The pipeline depth allows a programmable level 1 trigger latency of up to 4 \(\mu\text{s}\), with 32 locations reserved for buffering events awaiting readout. Each pipeline channel is read out by an analogue circuitry which can operate in one of two modes. In peak mode only one sample per channel is read (timed to be at the peak of the analogue pulse shape). In deconvolution mode [12] three samples are sequentially read and the output is a weighted sum of all three. The deconvolution operation results in a re-shaping of the analogue pulse shape to one that peaks at 25 ns and returns rapidly to the baseline. This operating mode is particularly important for correct bunch crossing identification during the high luminosity running phase of the LHC. A unity gain inverter, which also reduces the common mode noise contribution by subtracting \(-\) from the output signal - the common input noise, is included between the preamplifier and shaper and can be switched in or out.

On receiving a positive level 1 trigger decision the APV25 sends out serially, at 20 MHz rate, the 128 analogue

\[5\] Equivalent to an integrated luminosity of \(500 \text{ fb}^{-1}\) or, in the innermost TIB layer, to a fluence of \(1.6 \times 10^{14} \text{ 1-MeV equivalent neutrons/cm}^2\).
signals together with information about the pipeline address and the chip error status; signals coming from two APV25 are interlaced together on a differential line by a multiplexer chip [13] which is mounted on the hybrid circuit very close to the front-end chips. When the APV25 chip is clocked but doesn’t receive any trigger it sends on the output line, every 70 LHC clock cycles, a synchronisation signal, called “tick mark”, lasting about 25 ns (after the output of 2 APVs is multiplexed, the corresponding tick mark lasts about 50 ns). This signal can also be used to make a rough measurement of the overall gain of the readout chain as its height represents the full nominal span of APVs’ output.

The analogue electrical signals are then converted to optical ones in dedicated Analogue OptoHybrids (AOH) [14] located few centimetres away from the silicon microstrip module, and transmitted to the counting room by means of single-mode optical fibres [15], where they are digitized [16]. One optical fiber carries the analogue signal coming from two APV25 chips.

With such an architecture the control signals and the analogue data are brought to the outside of the tracker using optical fibres which electrically decouple the detector from the readout system and reduce the space and the material needed to connect the instrument to the off-detector electronics.

The LHC 40 MHz clock, which drives the APV25 sampling, is synchronized at the single module level by means of a PLL (phase-locked loop) chip [17]. In this way a particle signal can be correctly sampled at its maximum regardless of the module position with respect to the LHC interaction point and of the different clock line delays. The entire readout chain is able to sustain a level 1 trigger rate of about 100 kHz. The functional parameters of the devices located inside the tracker can be uploaded from outside using the I^2C [18] standard communication protocol. They can also be read back from the chips for data integrity check. Finally a slow parameter control chip (Detector Control Unit or DCU [19]) converts, using an internal 8-channel 12-bit ADC, module temperatures, low voltage levels and high voltage currents and makes the values available to the main Data Acquisition System (DAQ) via I^2C.

2.3.1 TIB shell electronics

The TIB detectors are assembled into linear structures, called "strings", each of them made of three modules connected to a Kapton circuit which provides power and control signals ("mother cable") using controlled impedance lines and LVDS buffers for better signal quality. Data are converted to optical levels for remote digitization by means of analogue lasers mounted on the AOH and single-mode (1310 nm) optical fibres.

In the final Tracker configuration the opto-electrical conversion and the digitization will be both happen on VME-9U 96 channel boards [16] (FED-VME).

A CCU chip [20], directly mounted on the mother cable, decodes the clock and control signals from the digital frames coming from the "Digital Opto-Hybrids" (DOH [21]) which, in turn, convert the optical commands coming from the Front End Controller (FEC) [22] located in the control room. The token-ring structure made by a DOHM (a board used to host the DOHs and the routing of the ring lines) and a variable number of CCUs and mother cables, is called "control ring". Working parameters of the APV25, PLL, Multiplexer, DCU and AOH can be downloaded and read back using the control ring.

3 The Beam Test Detector Setup

3.1 The TIB shell

The TIB prototype system under test was a portion of the third layer of the tracker inner barrel (Fig. 4). This structure was equipped only on the outer side of the cylinder. A total of four strings, all of them fully provided with services, were mounted. As can be seen on Fig. 4 a "TIB string" is a longitudinal structure, parallel to the shell axis, which holds the services (opto-electrical connections, cooling and mechanical supports) for three modules. During this test two strings were fully equipped, with a total of six modules, in final configuration. All the four strings were clocked and powered, simulating, from the control electronics point of view, a portion of a complete TIB "control ring".

The shell was assembled in laboratory and then transported to CERN. For the detector transportation a simple box was used; the only important safety measure was to secure all parts to the structure and mechanically decouple it with respect to the box in order to avoid dangerous resonant frequencies which can damage the modules. The transport, being a part of the "system test", was a success: not a single strip was lost.

6) In the final TIB Layer 3 a control ring will be made of 15 strings.
The transport tested, on a small scale, the final detector assembly logistic: the TIB layers and TID disks are assembled in different clean rooms in Italy (Florence, Pisa and Turin) and then moved to the main assembly centre (Pisa). Then, when the two TIB-TID full detector halves are ready, they are moved to CERN where they are integrated into the tracker support tube together with TOB and TEC.

### 3.1.1 TIB shell prototype electronics

During this test the analogue optical signals coming from the AOHs were converted back to electrical ones by means of opto-electrical converters located in the control room and read out with Tracker PMC ADCs (FED-PMC [23]). The FED-PMC are mounted on a PCI bus using a standard PCI-PMC adapter.

For this beam test electrical FEC prototypes, mounted on PCI-PMC adapters, were used. The modules were coupled with electro-optical converters to optically drive the DOH. The DOH are located on a board different from the final one (DOHM) that is used on the final TIB-TID detector.

The rest of the detector electronics chain is made by final or pre-production components.

### 3.1.2 Power supply system

During the 2003 TIB beam test two prototypes of the CMS tracker power supplies were tested. The two systems were developed by CAEN and Laben in close contact with the INFN-Florence group.

The two prototypes were designed to work in the counting room located about one hundred metres away from the tracker 7). During this test both prototypes were used to power the TIB structure through 125 m long "low inductance cable” (LIC). An additional floating power supply was used to separately power the control ring electronics. In this test the power connections were implemented by two versions of LIC cable connected in series: LIC17, 90 metres long and 17 mm of diameter and LIC11, 35 metres long and 11 mm diameter. This configuration allows testing the system configuration where the power supplies are located outside the CMS cavern: the first 90 m long cable connects the power supplies to a patch panel placed just outside of the CMS apparatus and the second 35 m long cable reach the PP1 patch panel inside the detector; the two cable types were also designed to optimize the power dissipated on them while minimizing the material inside CMS.

One cable consists of the power lines (2.5 V, 1.25 V, common return), four high voltage pairs and other services (sense wires, temperature/humidity sensors readout). The cable is shielded by a copper-braided wire. The LIC

7) Later developments led to internal modifications of the power supply units, leaving unchanged the whole system architecture.

The aim was to place the power supply system in the experimental cavern, in presence of residual magnetic field and neutron radiation background. This choice saves a considerable amount of capital investment for the cables and human resources for the cable deployment at the expenses of additional operational risks and of maintenance drawbacks.
cables were developed for the TIB power supplies in order both to minimize the inductance and to maximize the capacitance between the power lines. The power lines consist of insulated enamelled copper wires in close contact with each other and they have sense wire pairs to allow the regulators of the supply unit to compensate the voltage drop along the cable.

The common return of both low and high voltages, the LIC external shield and the CCU ring return were connected together to the X5 experimental area main ground at a single point very close to the detectors and connected also to the TIB structure. The structure support plate and the external shielding box has been kept floating.

3.1.3 The TIB mechanics and cooling

The mechanics used to support the modules and the services is visible in Fig. 4. A prototype of a portion of the TIB Layer 3 was assembled both in carbon fiber (the layer cylindrical skin) and aluminium (the end flanges and the structure reinforce elements). In the final tracker most of the structure will be realized using carbon fiber reducing the material budget of the system, but the rest of the services will be very similar to the ones used in this test. Precisely machined aluminium plates, called "cooling ledges", are used as reference positioning elements where the silicon modules are screwed. The ledges are glued to the layer structural part using a precision mechanical mask to guarantee the requested accuracy. Aluminium cooling pipes are glued below the cooling ledges to cool the front-end and optohybrids and keep the silicon sensors below -10 °C to reduce the effects of radiation damage as well as the silicon reverse bias current and to minimize the risk of thermal runaway.

To support the TIB structure an aluminium cradle has been built; this holder can be adjusted to expose the modules at different beam incident angles. Finally a copper-covered fiberglass-epoxy box has been used to shield the entire setup from external electrical interference and light. To reduce the module temperature variations during the data taking period, the shell cooling circuit has been connected to an external chiller which provides coolant (glycolic alcohol) at a constant temperature of 18 °C.

3.1.4 The TIB modules

The six silicon microstrip detectors installed on the TIB shell came from the preproduction set, the only differences with respect to the final production modules being in the Kapton hybrid circuit: one of the two connectors has been reinforced and the hybrid layout has been changed to cure a problem which was believed to affect its long term reliability. The single-sided modules are assembled starting from IB2 type, final design [5, 6], silicon microstrip sensors to be used in layers 3 and 4 of the TIB and produced by Hamamatsu Photonics [24].

In Table 1 the main characteristics of IB2 type sensors are reported. Most of these numbers are directly taken from the sensor mask design. Table 2 shows the relative positions of the six modules in the experimental setup and their depletion voltages as measured before their assembly using the sensors C-V characteristics (i.e., the bias voltage value above which the sensor total capacitance does not change anymore).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall width (after cutting)</td>
<td>63 288 μm</td>
</tr>
<tr>
<td>Overall length (after cutting)</td>
<td>118 961 μm</td>
</tr>
<tr>
<td>Active area width</td>
<td>61 500 μm</td>
</tr>
<tr>
<td>Active area length</td>
<td>116 885 μm</td>
</tr>
<tr>
<td>Strip length</td>
<td>116 823 μm</td>
</tr>
<tr>
<td>Width of strip p+ implant</td>
<td>30 μm</td>
</tr>
<tr>
<td>Pitch</td>
<td>120 μm</td>
</tr>
<tr>
<td>Number of strips</td>
<td>512</td>
</tr>
<tr>
<td>Width of metal strip</td>
<td>40 μm</td>
</tr>
<tr>
<td>Silicon thickness</td>
<td>320 μm</td>
</tr>
<tr>
<td>Silicon crystal orientation</td>
<td>&lt; 100 &gt;</td>
</tr>
</tbody>
</table>

3.2 Beam Test Trigger

The trigger system used during the test described in this note was implemented with two plastic scintillators placed downstream of the setup. The coincidence of the signals coming from the two PMTs, in addition to the SPS 25 ns
Table 2: Module position on the Layer 3 prototype structure (as seen from the beam line) and depletion voltage of each sensor. The names (TIBn) are the ones used to identify the modules in Sect. 6.

<table>
<thead>
<tr>
<th>String</th>
<th>Mod. TIB1</th>
<th>Mod. TIB2</th>
<th>Mod. TIB3</th>
</tr>
</thead>
<tbody>
<tr>
<td>String #1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>String #2</td>
<td>183.8</td>
<td>183.4</td>
<td>190.8</td>
</tr>
<tr>
<td>String #3</td>
<td>188.0</td>
<td>137.9</td>
<td>143.5</td>
</tr>
<tr>
<td>String #4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

beam clock, was used as input either to a TSC [25] (Trigger and Sequencer Card) or to a TTC [26] (Trigger Timing and Control) trigger card system providing both a trigger pattern selector and a FED and APV25 clock line fan out.

3.3 TOB and TEC setup

Downstream of the TIB two additional SST substructures were present. The first one was a thermally insulated box containing six TOB modules with the strips oriented vertically. The second one was a partially equipped TEC petal.

4 Data Acquisition System and Interlocks

4.1 DAQ software

The XDAQ [27] architecture was used to control the various data acquisition components. The main part of the system is based on the event builder, which reads data from the FEDs and assembles them in an event structure. The events are then sent to an application which writes a ROOT [28] tree for storage or sends them to a monitoring system.

4.2 DAQ electronics

The beam test readout system was composed by three parallel chains (TIB, TOB and TEC) each one composed of:

- one PC with one TSC and two (or three) FEDs;
- a second PC with a FEC (and an external opto-FEC which converts the FEC electrical signal into an optical one and vice-versa) and a mass storage unit.

The individual subsystem integration was easy and was done using the following procedure. First an I^2C scan of the control ring was done checking that all the devices present in the system responded correctly. Subsequently, the FED ADC sampling point was tuned for each module synchronizing it with the LHC clock, and the optical gain and bias of all AOH was adjusted. Both procedures did not require the presence of beam particles, since they rely on the measurement of the APV25 tick marks: the sampling point should be on the tick mark flat top and the AOH functional parameters are adjuster to obtain a proper gain in a linear working region of the electro-optical converter (for details about this procedure see Sect. 6.2). Finally, using the 25 ns structured beam, a latency scan was performed in order to identify the trigger position in time followed by a PLL scan to refine the sampling: the chosen point in latency and PLL delay is the one that maximizes the total cluster charge for each silicon microstrip module.

Once independently commissioned the TIB and TOB detectors were then read out synchronously. This integration was also performed in a rather short amount of time despite of the fact that the two subsystems have different control rings and that the optical fiber lengths differed by up to 15 metres.

Up to 2500 events per SPS spill^{8)} were read out, corresponding to a data rate of about 20 Mb per spill. Limitations to this rate were mainly due to the ROOT compression algorithm performance.

^{8)} During the 25 ns LHC-like beam operation the SPS cycle length was 21.6 s with an extraction duration (spill) of 2.2 s.
4.3 Slow control system and interlocks

Throughout the beam test, the temperature and the relative humidity inside the detector volumes were monitored almost continuously. In addition, an interlock system was installed and protected the detectors under test from potentially dangerous environmental conditions (such as excessive temperature, or the risk of condensation, or rapidly variable conditions).

Another requirement was to protect the devices against the possibility of mains blackouts: a small Uninterruptible Power Supply (UPS) afforded the short time margin necessary for an orderly ramp-down of the low-voltage power on the front-end electronics and of the high-voltage bias on the sensors.

A human-machine interface program was provided for the visualization of the instantaneous values of the monitored quantities and of their recent history. All values were timestamped and committed to permanent storage for future access.

4.3.1 Temperature sensing

For the temperature measurements, specially calibrated thermistors from Fenwal, similar to the ones that will be installed permanently within the tracker volume, were used. Ad-hoc electronic circuitry was developed to condition these sensors and produce signals compatible with the industry-standard Programmable Logic Controller (PLC), belonging to the Siemens S7 family, which supervised the environmental measurements and implemented the interlock logic.

A partial history of the temperature of the gas filling the TIB box is shown in Fig. 5. A second thermistor, not shown here, was placed on the detector cooling pipe, monitoring the inlet coolant temperature.

![Temperature history for the gas inside the TIB volume](image)

Figure 5: Temperature history for the gas inside the TIB volume

The interruptions in this and in the following relative humidity plot were caused by a scheduled upgrade of the software running on the PLC and of the visualization program. Since every data point is accompanied by a timestamp, it is very easy to correlate the variations in the sensor dark currents with the environment temperature.

4.3.2 Humidity sensing

For the beam test to which the present paper refers, a temporary solution to monitor the setup relative humidity, not suitable for operation under the LHC conditions but acceptable for the present application, was found in the Honeywell HIH-3605B sensors [29]. These sensors include active components that are used to convert the relative humidity to a voltage signal which is compatible with the standard analogue inputs of the PLC used. Figure 6 shows the history of the relative humidity measured close to the gas inlet of the TIB volume. The period over which the relative humidities are plotted is the same as for the temperatures. Starting on the evening of May 29th, the TIB was flushed with dry nitrogen, apart from a rapid intervention which required breaching the volume gastightness on the late evening of June 1st. During the initial period without dry gas flow, the influence of the weather...
conditions on the relative humidity and temperature within the TIB volume can be seen. On the contrary when the dry nitrogen is flushed the relative humidity is below 5%.

5  X5 LHC-like 25 ns Beam

The X5 [2] SPS beam line at CERN can deliver to the users pion and muon beams of momentum in the range between 5 and 250 GeV/c. The beams used during this test were low intensity muon ($\sim 10^3$ particles cm$^{-2}$s$^{-1}$) or high intensity pions ($\sim 10^5 \div 10^6$ particles cm$^{-2}$s$^{-1}$) both with 120 GeV/c momentum. This beam comes from the H3 secondary beam generated from the interaction products of the main extracted SPS proton beam on T1 primary target. During the normal SPS operation particles arriving at the test area are unbunched with an almost flat time distribution inside the 2.2 s spill time. The spill follows the CERN proton accelerator complex cycle and it is repeated every 21.6 s.

To test the LHC detectors and electronics in a condition similar to the real experiment, the SPS proton beam has been modified to have a 25 ns bunch time structure [2]. Since the SPS has no 40 MHz radio-frequency cavities, the bunched beam is prepared in the PS and it is quickly injected into the SPS at 26 GeV/c and then accelerated to 450 GeV/c. A PS bunch train of 48 packets, for a full duration of 1.2 $\mu$s, is injected into the SPS every 23 $\mu$s (SPS orbit period). After acceleration to 450 GeV/c the protons are extracted keeping the same time structure, namely 48 bunches at 40 MHz every 23 $\mu$s during the entire 2.2 s flat top duration, and sent to the primary target. A single bunch time width is determined by the 200 MHz SPS accelerating cavities’ frequency being about 5 ns. The beam intensity was regulated in such a way that the bunch particle occupancy was about one or less ($\leq 2 \times 10^6$ particles/s).

6  Beam Test Data Analysis

6.1  Data analysis methods

The particle signal is extracted from the FED digitized strip charge (raw data) by subtracting the strip pedestal and the common mode contribution. This latter quantity represents the joint shift of the baseline in a group of contiguous strips (32 in this analysis) situated on the same APV. It is computed for each event using an iterative trimmed median algorithm to avoid contribution from both particle signal and noisy strips. The pedestal of each strip is defined as the average of the raw data of that channel. Also for pedestal calculation events where the strip may have been hit by a particle have been discarded. The strip noise is calculated as the statistical fluctuation of the Common Mode Subtracted data (CMS noise). The strips are identified as bad (noisy, disconnected or shorted) when the value of their noise is outside an acceptance range; as soon as they are flagged they are excluded from further analysis.
In order to identify the passage of a particle, the offline search algorithm makes use of the previous definitions for the signal and noise of each strip and looks for clusters of adjacent strips which have a statistically significant excess of charge. First the clustering algorithm searches for "seeds", defined as strips with a signal-to-noise ratio ($R$) satisfying $R > T_1$. Once at least one such strip is found, all adjacent strips having $R > T_2$ are added to the cluster. When no more adjacent strips above threshold are found, the total cluster charge $S_C$ is computed as the sum of the pulse heights over the accepted strips. The cluster noise is then defined as $N_C = \sqrt{\sum N_i^2 / L_C}$ where $N_i$ is the noise of strip $i$ and $L_C$ the number of strips accepted for that cluster. If the condition $S_C/N_C > T_3$ is not satisfied, the cluster is discarded. For the present analysis the values used for the cuts are the following: $T_1 = 4$, $T_2 = 3$ and $T_3 = 5$. The hit position is then calculated for each accepted cluster as the pulse height-weighted mean (‘centre-of-gravity’) of the cluster strip locations.

6.2 Analogue optohybrids gain scan and signal normalization

After the DAQ system has been correctly configured for data taking the AOHs have to be tuned in order to have the lasers working in linear regions with a proper gain. This procedure is part of the DAQ program and it is executed upon operator request. If the system is kept stable, for example the optical connections are properly handled or the temperature does not change dramatically, this procedure has to be run only once at the beginning of data taking. The AOH laser parameters are accessible from the “gain” and “bias” I2C registers of the linear laser driver chip [30]: the first accepts integer values between 0 (low gain) and 3 (high gain) while the other regulates the laser diode bias current which can be trimmed, changing its value in the range 0-55 mA (corresponding to register values between 0 and 60), to set the laser in its linear region of operation. During this process the DAQ program sends clock, without triggers, to each APV25 in order to have continuous tick-marks digitization at the FED. For each “gain” a “bias” scan is performed with the DAQ software calculating the tick-mark base (called “digital 0”), its high level or “tick” (“digital 1”) and the difference. The optimal point is chosen in such a way that the difference is maximized (Fig. 7) while the two digital levels are very close to the extreme values of the AOH linear signal range (Fig. 8) but not saturated. The value for the gain register is chosen in such a way that the optical chain overall amplification is close to 0.8V/V [31].

The analogue optical signal reaches the opto-electrical converter, before entering the FED, via ~ 100 m of optical fibre crossing three optical connections. So the relative gain of each optical chain could in principle be different mainly because of possible non optimal optical contact at the connectors but also because of laser gain non uniformities and temperature induced shifts. Hence the output signal of different couples of APV25s, which are multiplexed on different fibres, should be normalized to a reference value in order to compare their pedestals, noises and cluster charge. The ADC raw values are normalized for each run in such a way that the tick marks height (digital 1 - digital 0 difference) would be equal to an arbitrary chosen value of 230 ADC counts. Table 3
Figure 8: Tick (left) and base (right) levels (ADC counts) vs. bias (register value) for the same AOH channel of Fig. 7 and the same gain value. The vertical arrow indicates the optimal point selected by the DAQ program (bias = 28).

shows the normalization factors for each APV25 couple of the six TIB detectors for a typical run. It is important to note that, if the laser works in a linear region, relative quantities, for example signal-to-noise ratios, are not affected by gain variations.

Due to the different gain of the optical chains the profile of the CMS noise normally has a step passing from the first to the second APV25 couple of the module. If the AOH normalization factors are applied the noise profile flattens (Fig. 9). Figure 10 shows the run-by-run optical chain gains. They are stable during data taking if disconnection/reconnection of the optical fibres are not done. All data reported in section 7 come from renormalized data unless specified otherwise.

Table 3: Examples of optical normalization factors used during this analysis. The high values (around 1.5) for some AOHs reflect different “gain” settings for these channels.

<table>
<thead>
<tr>
<th>Module</th>
<th>AOH 1</th>
<th>AOH 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIB1</td>
<td>1.52</td>
<td>0.89</td>
</tr>
<tr>
<td>TIB2</td>
<td>1.16</td>
<td>1.05</td>
</tr>
<tr>
<td>TIB3</td>
<td>1.14</td>
<td>0.98</td>
</tr>
<tr>
<td>TIB4</td>
<td>1.13</td>
<td>1.22</td>
</tr>
<tr>
<td>TIB5</td>
<td>1.00</td>
<td>1.49</td>
</tr>
<tr>
<td>TIB6</td>
<td>1.12</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Figure 9: Profile of the CMS noise for a module before (left) and after (right) AOH gain normalization.
Figure 10: Time evolution of the normalization factor for the second AOH of one TIB module (top: TIB alone runs, ~ 6 days of data taking, bottom: TIB-TOB runs ~ 7 days of data taking). During the second phase of data taking the analogue optical fibres were disconnected and reconnected several times.

7 Beam Test Results

In this note the TIB detectors under test of the upper (resp. lower) string (Tab. 2) are conventionally called TIB1, TIB2, TIB3 (resp. TIB4, TIB5, TIB6); TIB1 (resp. TIB4) being the module closest to the external cooling pipes visible at the left in Fig. 4. The TIB structure has been placed in such a way that the module strips run horizontally. Except for the last data taking period, when the structure has been horizontally moved to test all the six detectors, the experimental setup was configured in such a way that the beam illuminated mainly the central modules of both strings (TIB2 and TIB5). All the other modules were powered, clocked and read out, but the number of clusters on their sensors was very low (i.e., mainly generated by noise or by highly scattered beam particles).

7.1 Beam profile

Figure 11 shows the vertical distribution of the muon (upper plots) and pion (lower plots) beams as detected by the TIB2 and TIB5 detectors. Figure 11 shows also that the pion beam was much more collimated (2 cm FWHM) than the muon one (only the 4.5 cm trigger scintillator shadow is visible in the upper plots of Fig. 11, the real muon beam dimensions being much larger). In fact the X5 muon beam is obtained by in flight decays of the pions during the ~ 300 m path from the production target to the final absorber, which is placed some metres before the detector station to stop the residual pion components when the muon beam is selected. In this way the muon transverse momentum with respect to the beam line keeps memory of the neutrinos emitted in the pion decay during the very long way from the production target to the detector, increasing the beam spot. The muon beam intensity was also much lower than the pion one.

7.2 Bias voltage scans

In this paragraph data coming from microstrip module bias voltage scans are reported. The scans were performed up to a maximum value of 500 V at 50 V steps. Particular detector behaviour when reverse (ramp-down) scans are done with short waiting time between different steps and high relative humidity conditions are described in Sect. 7.4.
Figure 11: Muon (upper plots) and pion (lower plots) vertical beam profile as measured from TIB2 (left) and TIB5 (right) modules. The dips are due to noisy and less efficient strips.

7.2.1 Current vs. bias voltage

The power supply high voltage (HV) lines are organized in such a way that the three detectors of each string are connected to a single HV channel. Figure 12 shows the reverse current of the two strings as a function of the bias voltage. The measurements were performed at room temperature (about 25 °C, see Fig. 5 where the dry gas temperature inside the TIB box is shown) with the modules’ front-end electronics powered and clocked. The current of each string of modules, measured at a bias voltage of 400 V, was about 800 nA.

7.2.2 Signal-to-noise ratio vs. bias voltage

One of the most important parameters characterizing a silicon microstrip detector is the signal-to-noise ratio. This parameter is related both to the charge collection efficiency and to the strip noise which in turn depends on the electronics, sensor capacitance and bias current. Most of these factors (charge collected, sensor capacitance and bias current) depend on the bias voltage: strongly when the silicon bulk is still not completely depleted, mildly when the depletion voltage has been reached.

Figure 13 (left) shows the mean strip noise per module and the signal-to-noise ratio (right) as a function of the bias voltage. As expected noise curves taken with the two different modules operating in the same mode almost overlap. The mean module CMS noise decreases with increasing the bias voltage and reaches the asymptotic values of 1.06 ADC counts in peak mode and 1.38 ADC counts in deconvolution mode.

Figure 13 (right) shows the signal-to-noise ratio for both detectors and APV25 operating modes as a function of the bias voltage. The increase of the S/N as a function of bias results from the bigger collected charge when the depleted region increases, but also, after the sensor has reached complete depletion, on the little increase of the APV25 response to faster charge collection at its input (ballistic effect) and to a residual noise decrement. The nominal sensor depletion voltages, as measured using the sensors C-V characteristics (Tab. 2), of TIB2 and TIB5 detectors are 183.4 V and 137.9 V, respectively. Figure 13 (right) shows that, from the signal-to-noise ratio point of view, the depletion voltage is not the optimal detector working point. In fact at this voltage the S/N reaches approximately ~ 80% of its asymptotic value. This means that the silicon microstrip modules have to be operated
Figure 12: Reverse current as a function of the bias voltage for the two strings of TIB detectors (string 1 being the structures’ upper string).

Figure 13: Strip noise (left) and signal-to-noise ratio (right) for TIB2 (squares) and TIB5 (triangles) as a function of the bias voltage. Data in peak (full symbols) and deconvolution (open symbols) mode are shown. Scattered points around 200 V in peak mode come from the *ramp-down* scans discussed in 7.4.

in “over-depletion” mode when the S/N issue becomes critical (i.e., when the tracker will be heavily irradiated and the S/N value will be considerably reduced with respect to the initial phase of the experiment).

The S/N asymptotic value measured in deconvolution mode is less than the one in peak mode by approximately 30%. In fact, as explained in [12], the deconvolution filter effectively decreases the signal duration to match the LHC bunch crossing frequency, but this at expenses of an increase of the noise level.

The signal-to-noise ratio values reached by the TIB detectors when they are overdepleted are shown in Table 4. In the same table the expected values are also shown. The expected signal-to-noise ratios are calculated using the following information. For the signal one has to take into account the energy loss in the silicon [32] by a 120 GeV/c muon, the sensor active depth (290 μm) and the energy needed to produce an electron-hole pair in silicon (3.62 eV/pair). This results in a most probable value of about 23600 e− for a normally impinging 120 GeV/c
Table 4: Measured and expected signal-to-noise ratios in peak and deconvolution mode, in overdepletion regime. Fluctuation of ±0.5 units on the S/N, depending on the run, have been observed. Uncertainties on the expected values (coming from APV25 noise characteristics, sensor capacitance and active depth) are ±0.5-1 units.

<table>
<thead>
<tr>
<th>Readout mode</th>
<th>TIB2</th>
<th>TIB5</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak</td>
<td>25.5</td>
<td>26.1</td>
<td>27.1</td>
</tr>
<tr>
<td>Deconvolution</td>
<td>18.1</td>
<td>17.8</td>
<td>17.5</td>
</tr>
</tbody>
</table>

muon\(^9\). For the noise calculation the sensor capacitances and resistances (\(C_{\text{interstrip}}\), \(C_{\text{bulk}}\), \(C_{\text{PitchAdapter}}\), \(R_{\text{Strip}}\) and \(R_{\text{bias}}\)), the bias current and the AOH noise figure are used. For a TIB IB2 type sensor the total capacitance, as measured in the Process Quality Control centre, is 14.2 pF [33]; the AOH Equivalent Noise Charge (ENC) has been estimated to be 190 electrons [34], the \(R_{\text{bias}}\) is 1.5 M\(\Omega\), while \(R_{\text{Strip}}\) is 77 \(\Omega\). The bias current contribution is negligible for a non-irradiated module.

The best noise estimation (ENC) for an IB2 type module, using the APV25 noise parametrization [10], is: 870 and 1350 electrons in peak and deconvolution mode, respectively.

### 7.2.3 Cluster width vs. bias voltage

Figure 14 shows the mean cluster width as a function of the bias voltage for TIB2 and TIB5 modules when operated in deconvolution mode. After the nominal depletion voltage the cluster width continues to decrease because of less charge sharing between strips, which is in turn driven by a decreasing strip capacitive coupling.

![Figure 14: Mean cluster width as a function of the bias voltage for TIB2 (triangles) and TIB5 (squares) modules operated in deconvolution mode. The ratio of the two widths is reported also (full circles).](image)

The mean cluster width reaches the asymptotic values of 1.5 and 1.7 for the TIB2 and TIB5 module, respectively. This difference is explained by geometrical consideration. In the structure used for this test the modules of two adjacent strings form an angle of 7.8\(^\circ\). Due to this geometry the particles enter orthogonally to the TIB2 module, while the TIB5 module is slightly tilted with respect to the beam direction and the charge produced by the particle

\(^9\) The expected signal in the slightly tilted (7.8 deg.) TIB5 module is higher by \(\sim1\%\) with respect to the vertically placed TIB2 module. This small contribution has been neglected in Table 4.
crossing the silicon microstrip module is distributed underneath a larger path (~ 1/3 of the strip pitch). The ratio of the two widths (also shown in Fig. 14) is independent from the bias voltage when the sensor is over-depleted. A similar behaviour has been found in peak mode.

7.3 Detector overlap

In order to guarantee spatial hermeticity for particles coming from the interaction region of the CMS detector and to ease the alignment procedures for the final tracker, the sensitive part of two adjacent strings have a small overlap region. This area has a dimension of approximately 1.5 mm (~ 12 strips) in the direction orthogonal to the strips. With such geometry a small fraction of particles crosses both TIB2 and TIB5 modules and their hits are position-correlated. Figure 15 shows this correlation in the overlap region demonstrating the possibility to have double hits in the same layer of the tracker.

![Figure 15: Hit position in TIB2 vs. hit position in TIB5 for the overlap region.](image)

7.4 Hysteresis effects

During the beam test some of the voltage scans were performed with a full cycle of the bias voltage: from zero to a maximum value well above depletion and back to zero. During the "ramp-up" phase the signal and noise performance are the ones expected from previous measurements whereas in the "ramp-down" phase a clear reduction of the signal-to-noise ratio was observed ("hysteresis effect"). Figure 16 shows the S/N parameter measured in deconvolution mode as a function of the bias voltage during a bias cycle. A very similar behaviour has been observed in peak mode too. The maximum size of the effect on the S/N parameter is around 17% in both APV25 operating modes and it can be decomposed in an 8% decrease of the signal and a 9% increase of the noise (Fig. 17). The hysteresis effect is also observed in the average cluster width which increases by about 16% in the ramp-down runs (Fig. 18).

7.4.1 Laboratory measurements on TIB test-structures

The set of measurements on the module performance described in the previous paragraph can be partially explained by an increase in the inter-strip capacitance ($C_{int}$) of the sensors during the bias voltage ramp-down. A dedicated study has been carried out in the laboratory to test this assumption using test-structures extracted from the wafers of the TIB sensors and used in the Process Quality Control (PQC) of the silicon strip tracker detectors.
The IS-CAP-AC structures, used in the PQC to monitor the interstrip capacitance of the sensors, have undergone voltage cycles similar to those applied to the modules during the beam test and these operations have resulted in an increase of $C_{int}$ while bringing the bias voltage back to zero (Fig. 19).

During this study it was possible to correlate the onset of the hysteresis effect with the environmental conditions. The inter-strip capacitance depends on the bias voltage history of the structure only when the measurements are performed with high relative humidity, above 30-35%, as it was the case for the cycle shown in Fig. 19. At lower values of relative humidity (RH) no hysteresis effect was observed.

An explanation of the phenomenon could be the different arrangement of the mobile charges at the Si-SiO$_2$ interface in the presence of high RH. The effect depends on the fabrication details of the oxide layer and it is not observed for the TOB modules, installed in this beam test, built with sensors of a different producer [35].

The beam test voltage scans shown in Figs. 16, 17 and 18 were performed at values of RH around 45-50% (first part of Fig. 6). An additional voltage scan with varying RH levels confirms the hypothesis since after dry air was flowed into the system (second part of Fig. 6) the hysteresis effect ceased (Table 5). This is demonstrated by comparing the S/N pair values taken at equal voltage reached during ramp-up and ramp-down scans (e.g., run # 30147-30169, 30163-30166, 30142-30170 on Table 5).
Figure 18: Average cluster width for modules TIB2 and TIB5 as a function of the bias voltage during the voltage scan cycle in deconvolution mode. The numbers relative to each data point indicate the time order of the measurements. The systematic uncertainty on the cluster width among the two modules reflects the fact that module TIB2 is perpendicular whereas module TIB5 is inclined with respect to the beam direction (Sect. 7.2.3).

Figure 19: The interstrip capacitance measured with a IS-CAP-AC test-structure of a TIB wafer during a voltage scan cycle. The arrows indicate the time order of the measurements. Sharp edges in the plot are due to multiple measurements performed when the bias value has been kept constant for a certain amount of time (several minutes). This behaviour demonstrates that the hysteresis effect decreases with time.

7.5 TIB silicon microstrip module uniformity response

7.5.1 TIB uniformity orthogonal to the strips

In order to analyze the uniformity of the detector, the behaviour of the main variables related to the silicon microstrip module performance was studied as a function of the cluster position in the direction perpendicular to the strips.

A large number of events was collected under stable running conditions to achieve large number of clusters on each strip. The high intensity 120 GeV/c pion beam was used to reduce the data taking period. The beam centre was placed in the central module of the upper string, so that a large amount of data was collected on the third and...
Table 5: S/N parameter for the TIB2 module as function of the bias voltage during a voltage scan cycle in deconvolution mode performed at RH around 3%. The entries (run number) are time ordered.

<table>
<thead>
<tr>
<th>Run no.</th>
<th>Bias Voltage [V]</th>
<th>S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>30142</td>
<td>200</td>
<td>16.9</td>
</tr>
<tr>
<td>30145</td>
<td>250</td>
<td>17.2</td>
</tr>
<tr>
<td>30147</td>
<td>300</td>
<td>17.5</td>
</tr>
<tr>
<td>30162</td>
<td>350</td>
<td>18.4</td>
</tr>
<tr>
<td>30163</td>
<td>400</td>
<td>18.5</td>
</tr>
<tr>
<td>30164</td>
<td>450</td>
<td>18.5</td>
</tr>
<tr>
<td>30165</td>
<td>500</td>
<td>18.5</td>
</tr>
<tr>
<td>30166</td>
<td>400</td>
<td>18.4</td>
</tr>
<tr>
<td>30169</td>
<td>300</td>
<td>18.1</td>
</tr>
<tr>
<td>30170</td>
<td>200</td>
<td>17.1</td>
</tr>
<tr>
<td>30172</td>
<td>450</td>
<td>18.4</td>
</tr>
<tr>
<td>30173</td>
<td>300</td>
<td>18.0</td>
</tr>
<tr>
<td>30174</td>
<td>350</td>
<td>18.2</td>
</tr>
<tr>
<td>30175</td>
<td>350</td>
<td>18.5</td>
</tr>
</tbody>
</table>

fourth chip of TIB2 and on the first chip of TIB5. The total number of collected clusters was ~ $1.5 \times 10^6$, with a number of clusters associated to each strip which varies in the range $1 \div 8 \times 10^3$. Data were taken in peak mode with the sensors biased at 350 V.

A cluster was associated to a strip if its reconstructed position $x$ lied within a region defined by: $(n - 0.5)p < x < (n + 0.5)p$, $n$ and $p$ being the the strip number and the sensor pitch, respectively. For each measured variable in a certain region, the uniformity parameter was defined as the ratio between the RMS and the mean value of the corresponding distribution in this area. Small regions around noisy strips, usually the first and last APV25 channels, were ignored.

The cluster charge distribution as a function of the associated APV25 channel is shown in Fig. 21 (left) for the same APV25 chip of Fig. 20. An example of a fit with a Landau-like function to extract the most probable value of the cluster charge associated to a given strip is shown in Fig. 21 (right). In some cases, in the charge distributions, an inter-chip structure (modulo 32 strips) is visible. This could be due to the common mode calculation algorithm.
that operates on 32 strip groups data. In Fig. 21 (left) the last group has a charge that is in average greater than the other three by approximately 0.5 ADC counts (i.e., \( \sim 2\% \)). The global charge uniformity is of the order of 1.4\% while it is 1.9\% for TIB2 chip 3, 1.0\% for TIB2 chips 4 and 1.0\% for TIB5 chip 1. The charge uniformity calculated in groups of 32 strips is of the order of 0.5\%.

The signal-to-noise ratio distribution as a function of the associated APV25 channel for the fourth APV25 of

Figure 21: Cluster charge as a function of the strip number for the fourth APV25 chip of TIB2 module (left) and example of cluster charge distribution and Landau fit for one strip (right). Vertical lines separate 32 strips regions.

TIB2 is shown in Fig. 22. The S/N ratio is smaller near the edge of the chips due to an higher noise in these regions. The global RMS/mean ratio is around 1.6\% (1.8\%, 1.5\% and 1.7\% for TIB2 chips 3 and 4 and TIB5 chip 1, respectively) and around 1.0\% if calculated in groups of 32 strips.

Figure 22: Cluster signal to noise ratio as a function of the strip number for the fourth APV25 chip of TIB2. Vertical lines separate 32 strips regions.
The TIB module performance was also investigated as a function of the cluster position along the strip. A 120 GeV/c muon beam was used in this study since it has an uniform particles density and covers the full trigger scintillators area. Three different runs were taken with the mechanical structure in different positions in the horizontal direction to investigate the full length of central TIB modules. A total of 36000 events were collected for each APV25 chip. In these runs, modules were operated with a bias voltage of 400 V and operated in deconvolution mode.

The TIB cluster position along the strip was obtained from TOB detectors, since their strips were perpendicular to TIB ones. A linear transformation was used to obtain the TIB cluster position along the strip from the cluster position in TOB module. The transformation is of the type: \( y_{TIB} = p_{TOB} \times n_{TOB} + c_i \), where \( y_{TIB} \) is the TIB cluster position along the strip, \( n_{TOB} \) is the TOB cluster strip position, \( p_{TOB} \) is the TOB sensor pitch (i.e., 183 \( \mu \)m) and \( c_i \) is a constant coefficient for the \( i \)th TIB structure position. The \( c_i \) parameter is obtained, for each position of the TIB structure, using the "shadow" of the TIB detectors on the TOB (i.e., the falling edge of the hit position distribution in the TOB detectors, \( n_{TOB}^{shadow} \), when a hit is present in the TIB too, Fig. 23). In fact \( y_{TIB} = 0 \) when \( n_{TOB} = n_{TOB}^{shadow} - i \), so \( c_i = -p_{TOB} \times n_{TOB}^{shadow} \). The accuracy on the TIB cluster position along the strip is dominated by the width of the edge region, mainly due to the beam divergence projected over the distance between TIB and TOB detector planes. Another source of error could come from the fact the neither TIB nor TOB detector modules are perfectly aligned (only translations are considered). This accuracy has been estimated to be of the order of 2.5 mm.

TIB module clusters were grouped according to their position along the strip in 24 intervals (each one corresponding to 5 mm). The main variables related to detector performance were then plotted, with about 1500 events per interval.

The charge distribution as a function of the position along the strip is shown in Fig. 24 (left) for one of the APV chips analysed. The charge uniformity of this distribution is 1.4%. The signal-to-noise ratio distribution as a function of the position along the strip is shown in Fig. 24 (right) for the same APV25 chip. The S/N uniformity along the strip is again 1.4%.

Sometimes the numbers shown in the last two sections exceeds the pure statistical fluctuations and systematics should be taken into account to fully explain them. Certainly the common mode subtraction scheme, which uses a 32-strip grouping, is one of the systematic sources. Other possible sources can be search in APV25s, sensors and
7.6 The signal time evolution

The purpose of this study is to investigate the time evolution of a particle signal as seen by the APV25 on a TIB module. The knowledge of this behaviour will be useful to fine tune the detector front-end electronics especially when the LHC will reach the high luminosity regime. As can be seen in this section, signal amplitude, fake clusters, eta functions and cluster width depend, especially when the APVs operate in deconvolution mode, on the exact sampling time.

7.6.1 Signal shape

To reconstruct the signal time evolution a certain number of runs have been taken varying the phase difference between the APV25 clock and the SPS 25 ns beam clock using the PLL chip. Coarser variations of the clock delay (steps of 25 ns each) can be obtained by changing the APV25 latency by one or more units (i.e., the chip pipeline row which is read out).

Figure 25 (left) shows the cluster signal time evolution as a function of the delay while Fig. 25 (right) shows the Landau’s most probable value of each vertical slice of Fig. 25 (left). These pictures are prepared using data collected with TIB2 biased at 300 V operating in peak mode. The ADC counts for each APV25 have been normalized to the same reference value using the procedure described in Sect. 6.2.

Figure 25 (right) has been fitted with a CR-RC shaper transfer function. The best fit of the shaper time constant $\tau$ is, in this case, 46.5 ns, to be compared with an APV25 design value of 50 ns. The normalized signal peak amplitude is 25.2 ADC counts.

The value of the APV25 shaper time constant and the signal peak value can be trimmed changing the parameters which control the shaper input FET current bias (called $I_{sha}$) and the shaper feedback voltage bias (called $V_{FS}$). To be more specific the former affects the signal rising time, while the latter regulates the signal falling time. Table 6 reports the results of the $I_{sha}$ dependence of the shaper time constant and the signal amplitude while keeping $V_{FS}$ fixed at a value of 60 written in the corresponding APV25 register (which corresponds to $\sim 0.8$ V). The same table reports also the signal maximum variation with respect to the one measured for $I_{sha}=40$ $\mu$A (obtained with a value of 40 written in the corresponding APV25 register).

Table 6 essentially shows that increasing $I_{sha}$ the APV25 time response can be made faster and the signal higher.

---

10) The PLL can delay the clock in steps of 1.04 ns (i.e., 25 ns/24).

11) A CR-RC shaper with time constant $\tau$ has a transfer function $h(t) = S_p \times \frac{1}{\tau} \exp(-\frac{t}{\tau})$, where $S_p$ is the signal peak amplitude and $t_0$ its starting time.
Table 6: Shaper time constant ($\tau$) and peak signal ($S$) variation as function of $I_{sha}$ ($V_{FS}$ being fixed to 0.8 V). APV25 are operated in peak mode.

<table>
<thead>
<tr>
<th>$I_{sha}$ [$\mu$A]</th>
<th>40</th>
<th>45</th>
<th>60</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$ [ns]</td>
<td>48.7</td>
<td>46.5</td>
<td>46.1</td>
<td>43.4</td>
</tr>
<tr>
<td>$\Delta(S)$</td>
<td>S=25.2 ADC counts</td>
<td>+4%</td>
<td>+6%</td>
<td>+12%</td>
</tr>
</tbody>
</table>

This increase anyway drives the APV25 outside its CR-RC shaper approximation and, consequently, introduces imperfections in the deconvolution filter whose weighting parameters were calculated for an ideal CR-RC shaper. Figure 26 shows the APV25 time response function as measured in deconvolution mode when $I_{sha}$ and $V_{FS}$ were fixed to 40 $\mu$A and 0.8 V, respectively.

The rise time reported in Figure 26 is conventionally defined as the time needed for the gaussian fitted to the data points to pass from 1/10 to 9/10 of its maximum value. In this gaussian approximation the rise time is $\tau = 28.3$ ns.

The APV25 shaper time constant and the signal dependence on the bias voltage are reported in Table 7 with APVs operated in deconvolution mode. As can be seen sensor depletion increases the signal and slightly reduces the charge collection time.

Table 7: Shaper time constant ($\tau$) and peak signal ($S$) variation as function of $V_{bias}$ ($V_{FS}$ being fixed to 0.8 V and $I_{sha}$ to 40 $\mu$A). APV25 are operated in deconvolution mode.

<table>
<thead>
<tr>
<th>$V_{bias}$ [V]</th>
<th>250</th>
<th>300</th>
<th>350</th>
<th>400</th>
<th>450</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$ [ns]</td>
<td>29</td>
<td>28.3</td>
<td>27.6</td>
<td>28.5</td>
<td>27.7</td>
<td>27.5</td>
</tr>
<tr>
<td>$\Delta(S)$</td>
<td>S=23.3 ADC Counts</td>
<td>+3.2%</td>
<td>+5.7%</td>
<td>+5.7%</td>
<td>+6.6%</td>
<td>+5.3%</td>
</tr>
</tbody>
</table>

7.6.2 Cluster width

Figure 27 shows the mean cluster width as a function of the sampling time for data collected in peak (left) and deconvolution (right) mode. The two arrows indicate the maximum of the signal time response curve.

As can be seen in Fig. 27 the cluster width reaches the maximum much before the cluster charge does (25 ns in peak and 4 ns in deconvolution mode). To investigate this effect in detail the signal time evolution for the main and lateral cluster strips has been studied separately (Sect. 7.6.3).
7.6.3 Charge on lateral cluster strips and eta function

For each cluster the seed strip and the two lateral strips, regardless if they belong to the cluster or not, have been selected. The seed strip signal is called $S_{\text{Seed}}$, while $S_{\text{High}}$ and $S_{\text{Low}}$ are the highest and lowest signal on the two lateral strips. The events are divided into two categories depending on how the charge is shared among the strips. For this purpose the Eta function ($\eta$) has been used. It is defined in the following way: $\eta = S_R/(S_L + S_R)$ where $S_R$ is the strip on the right and $S_L$ is the strip on the left of the doublet of strips formed by the highest charge in the cluster and the highest of the two lateral strips (regardless if it belongs to the cluster or not).

Figure 28 shows the $\eta$ distribution for the TIB2 silicon microstrip module operated in peak and deconvolution mode. The flat region with $0.2 \leq \eta \leq 0.8$ corresponds to events where the cluster charge is shared between two or more strips, while the two edge regions are mostly populated by single strip clusters. The gaussian dispersion of the two peaks is due to the fact that $\eta$ is always calculated using two strips but in this regions only one collects
particle generated charge while the other has mainly noise. Furthermore, when the noise strip has a negative signal, the eta value can also be less than zero or greater than one.

Figure 29 shows the signal time evolution for each strip in a cluster region when the $\eta$ value is less than 0.2 or greater than 0.8 (mainly single strip clusters). Data are collected in peak mode (left side plots) and deconvolution mode (right side plots). In this $\eta$ region the cluster signal is mainly (95% of the total) due to the seed strip. The lateral strip signal peaks before the seed one: 21.3 ns in peak mode and 6.2 ns in deconvolution mode, and they are generally not included in the cluster by the search algorithm due to their very low charge. For times well after the peak the lateral strip contribution becomes negative. In the region $0.2 < \eta < 0.8$ (Fig. 30) the lateral strip with higher signal ($S_{\text{high}}$) is associated to the cluster by the search algorithm and its time evolution is very similar to the cluster seed one. The lowest lateral strip continues to peak well in advance with respect to the cluster (26.1 ns in peak and 7.4 ns in deconvolution mode) and the undershoot is also present. Furthermore when the cluster signal is spread on several strips its peaking and rising times are systematically longer than in the single strip cluster case. Figure 31 shows the cluster signal evolution as a function of the PLL delay with respect to the trigger signal on a period greater than 50 ns. Data are taken in deconvolution mode using the 25 ns bunched pion beam.

The periodic structure reflects the fact that the beam is 25 ns bunched. In case of a PLL delay multiple of 25 ns with respect to the optimal one (PLL delay = 0 ns), the APV25 detects signals coming from the bunch adjacent to the one that has generated the trigger. So there is no difference in the peak charge value, only the different population of the adjacent bunches (each bunch has a probability to contain a particle much less than one) make Fig. 31 less populated at PLL delays far from the optimal one.

### 7.7 Power supply prototypes comparison

The CAEN [36] power supply used during this beam test ran continuously for 18 days without any hardware reset or other problems. The LABEN [37] prototype has been used during the very last day: after initial setup there were no hardware resets for the following data taking period. The interlock system never triggered while connected to the power supplies. Hand-made test with artificial triggers were successful in correctly using the UPS unit to ramp-down the high and low voltages before switching off the system.

The module performance, in terms of signal-to-noise ratio, when powered using the two power supply systems were identical (Fig. 32).
Figure 29: Signal time evolution for total charge ($S_{Clu}$), seed ($S_{Seed}$) and lateral strips ($S_{High}$ and $S_{Low}$) for data collected in peak (left) and deconvolution (right) mode when $\eta$ is less than 0.2 or greater than 0.8 (single strip clusters).
Figure 30: Signal time evolution for total charge ($S_{Clu}$), seed ($S_{Seed}$) and lateral strips ($S_{High}$ and $S_{Low}$) for data collected in peak (left) and deconvolution (right) mode when $\eta$ is greater than 0.2 and less than 0.8 (multi strip clusters).
8 Conclusions

A prototype of the TIB third layer has been tested in a LHC-like 25 ns beam at CERN. Most of the setup has been assembled using final tracker components, so this test can be interpreted as a system validation experiment. The performance of the detector was excellent with a signal-to-noise ratio measured both in peak and deconvolution mode, compatible with the expectations. Detector uniformity and signal time evolution have been studied, collecting information very useful for the understanding of the final detector behaviour. A peculiar behaviour of the silicon microstrip sensors when operated during the ramping down of the bias voltage has been explained and...
traced down to an effect of the high relative humidity environment, which will hardly be reached during the real tracker operation. Together with the high valued information gained on the silicon microstrip module behaviour the test can be considered a success also from the system point of view. In fact the TIB setup was read out smoothly and the hardware and software commissioning happened in a very short time. Furthermore the data acquisition system was able to read out TIB and TOB together without problems. The commissioning procedures were also implemented and studied in view of the by far more complex final tracker implementation.

**Acknowledgements**

The work described in this note would not have been possible without the efforts of all the people involved in the R&D and the construction of the CMS Inner Barrel Silicon Strip Tracker. We would like to thank the technicians who contributed to the beam test activities working at CERN or in the INFN laboratories. We would also like to express our gratitude to the CERN accelerators crew for the excellent performance of the special 25 ns beam.

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