The Status of TOTEM

The TOTEM Collaboration

October 19, 2007

1 Introduction

The TOTEM experiment [1] is dedicated to the simultaneous measurement of the total proton-proton cross-section and the luminosity, detailed studies of the elastic scattering cross-section down to a squared momentum transfer of $10^{-3}\,\mathrm{GeV}^2$, and a comprehensive menu of diffractive processes – partly in cooperation with CMS [6], located at the same interaction point, IP5.

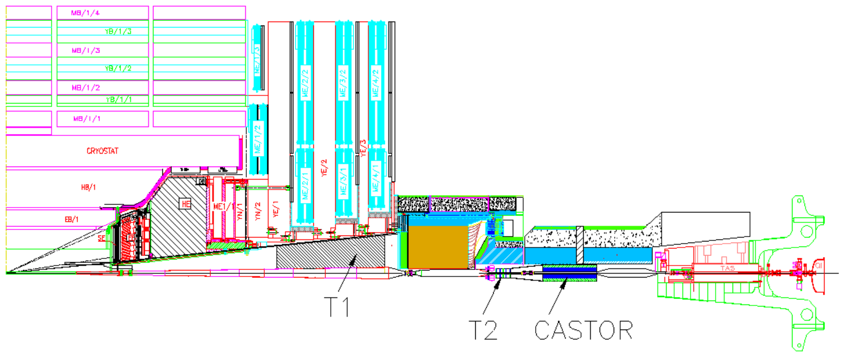

Figure 1: *The CMS detector with the TOTEM forward trackers T1 and T2. Note also the planned forward calorimeter CASTOR (under CMS's responsibility).*

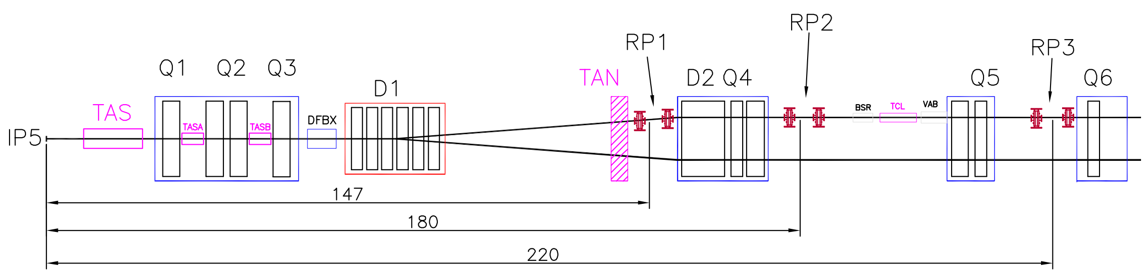

Figure 2: *The LHC beam line and the Roman pots at 147 m and 220 m.*

To perform these measurements, TOTEM requires a good acceptance for particles produced at very small angles with respect to the beam. TOTEM's coverage in the rapidity range of $3.1 \leq |\eta| \leq 6.5$ on both sides of the interaction point is accomplished by two telescopes for inelastically produced particles (Figure 1), and complemented by detectors in special movable beam-pipe insertions – so-called Roman Pots – placed at 147 and 220 m from the interaction point, designed to track leading protons at merely a few mm from the beam centre (Figure 2).

The telescope closest to the interaction point (T1, centered at $z = 9$ m) consists of well-understood and reliable Cathode Strip Chambers CSC, while the second one (T2, centered at 13.5 m) exploits newly developed Gas Electron Multipliers GEM. The proton detectors in the Roman Pots are silicon devices designed by TOTEM with the specific objective of reducing the insensitive area at the edge towards the beam to only a few tens of microns. This efficiency up to the physical detector border is an essential feature in view of maximising the experiment's acceptance for protons scattered elastically or diffractively at polar angles down to a few microradians. In addition to these detector developments, special beam optics have been conceived to optimise proton detection in terms of acceptance and resolution.

The read-out of all TOTEM subsystems is uniformly based on the custom-developed digital VFAT chip. The data acquisition system is designed to be compatible with the CMS DAQ to make common data taking possible.

2 Physics Objectives

The TOTEM apparatus with its unique coverage at high rapidities (Figure 3 left) is the ideal tool for studying forward phenomena, including elastic and diffractive scattering. Furthermore, since energy flow and particle multiplicity of generic inelastic events peak in the forward region (Figure 3 right), TOTEM accepts about 99.5 % of all non-diffractive minimum bias events.

An important application is the luminosity-independent measurement of the total cross-section based on the Optical Theorem.

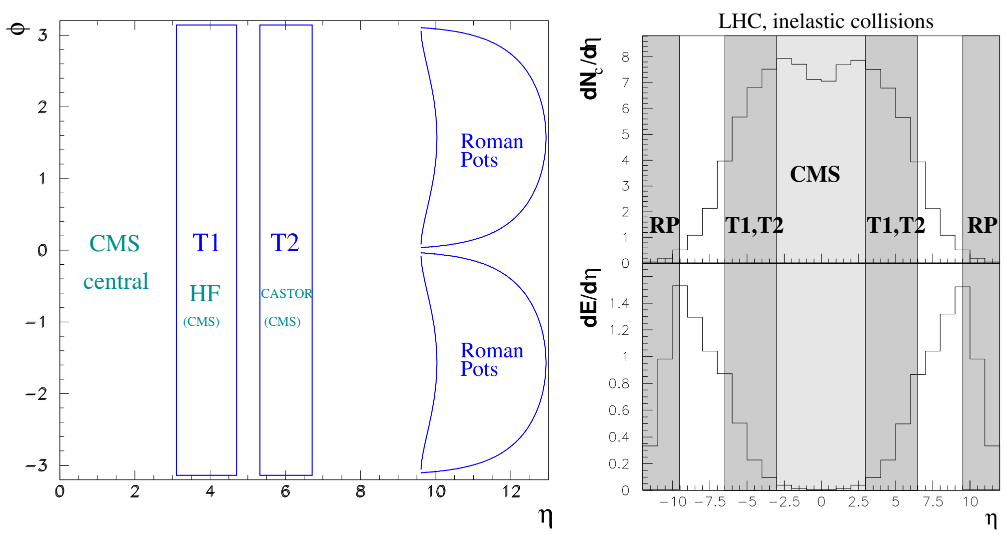

Figure 3: *Left: Detector coverage in the pseudorapidity-azimuth plane; right: pseudorapidity distribution of charged particle multiplicity and energy flow for generic inelastic collisions at 14 TeV.*

2.1 Total pp Cross-Section

A precise measurement of the total pp cross-section σ_{tot} and of the elastic scattering over a large range in the squared four-momentum transfer t is of primary importance for distinguishing between different models of soft proton interactions.
Due to the large uncertainties of the cosmic-ray data and the 2.6 standard-deviations discrepancy between the two final results from TEVATRON [2] extrapolations from existing σ_{tot} measurements to higher energies are very uncertain, leaving a wide range for the expected value at the LHC energy of $\sqrt{s} = 14\,\text{TeV}$, typically from 90 to 130 mb. Taking into account all available data, the COMPETE collaboration [3] has made an overall fit of the energy dependence of the total cross-section and the ratio ρ of the real to imaginary parts of the elastic scattering amplitude, and predicts for the LHC:

$$\sigma_{tot} = 111.5 \pm 1.2^{+4.1}_{-2.1}\,\text{mb}\,, \quad \rho = 0.1361 \pm 0.0015^{+0.0058}_{-0.0025}\,. \tag{1}$$

The precision of the extrapolation is dominated by the ambiguity in the TEVATRON data (second error).
The total pp cross-section is related to nuclear elastic forward scattering via the Optical Theorem which can be expressed as

$$\mathcal{L}\,\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2} \cdot \left.\frac{dN_{el}}{dt}\right|_{t=0} \,. \tag{2}$$

With the additional relation

$$\mathcal{L}\,\sigma_{tot} = N_{el} + N_{inel} \tag{3}$$

one obtains a system of two equations which can be resolved for σ_{tot} or $\mathcal{L}$ independently of each other. Hence the quantities to be measured are the following:

- $dN_{el}/dt|_{t=0}$: The nuclear part of the elastic cross-section extrapolated to $t = 0$. The expected uncertainty of the extrapolation depends on the acceptance for elastically scattered protons and hence on the beam optics.
- The total elastic rate N_{el} measured by the Roman Pot system and completed by the extrapolation of the nuclear part dN_{el}^{nuc}/dt to $t = 0$.
- The inelastic rate N_{inel} consisting of diffractive (~18 mb at LHC) and minimum bias (~65 mb at LHC) events. It will be measured by T1 and T2.

For the rate measurements it is important that all TOTEM detector systems have level-1 trigger capability. The parameter $\rho = \frac{\mathcal{R}[f_{el}(0)]}{\mathcal{I}[f_{el}(0)]}$, where $f_{el}(0)$ is the forward nuclear elastic amplitude, has to be taken from external theoretical predictions, e.g. [3]. Since $\rho \sim 0.14$ enters only in a $1+\rho^2$ term, its impact is small.

2.2 Elastic pp Scattering

Much of the interest in large-impact-parameter collisions centres on elastic scattering and soft inelastic diffraction. High-energy elastic nucleon scattering represents the collision process in which the most precise data over a large energy range have been gathered. The differential cross-section of elastic pp interactions at the LHC, as predicted by different models, is given in Figure 4.
Increasing $|t|$ means looking deeper into the proton at smaller distances. Several t-regions with different behaviour can be distinguished:

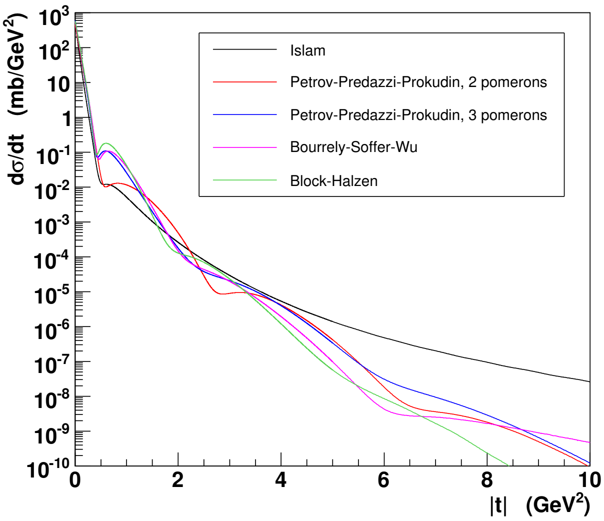

Figure 4: *Differential cross-section of elastic scattering at 14 TeV as predicted by various models.*

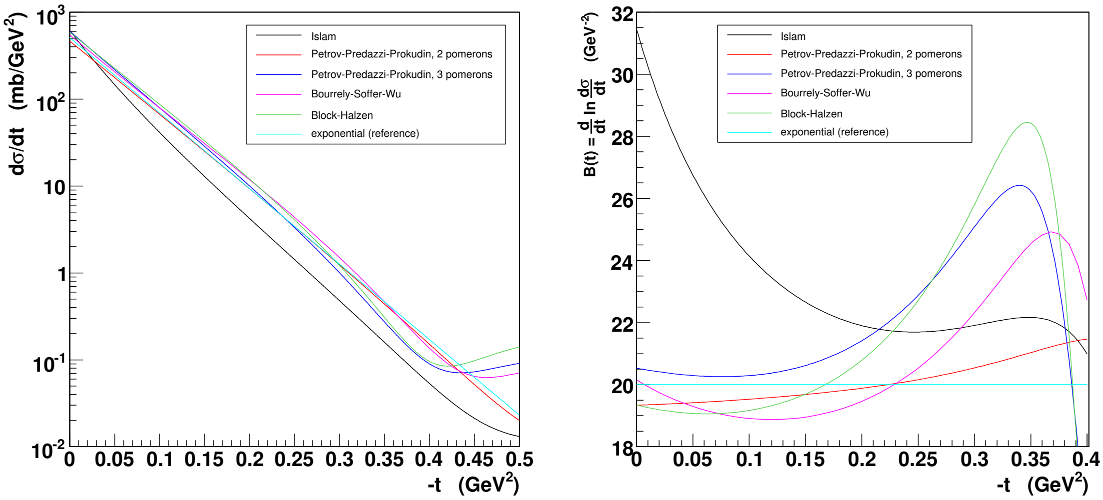

Figure 5: *Left: Differential cross-section of elastic scattering at 14 TeV as predicted by various models, focussing on the quasi-exponential domain at low $|t|$. Right: Exponential slope of the differential cross-section. The deviations from a constant slope show how the cross-sections differ from a pure exponential shape.*

- The Coulomb region where elastic scattering is dominated by photon exchange; for $\sqrt{s}$=14 TeV this region lies at $|t| < 6.5 \times 10^{-4}\,\mathrm{GeV}^2$.

- The nuclear/Coulomb interference region.

- The "single-Pomeron exchange" region with an approximately exponential cross-section $d\sigma/dt \sim \mathrm{e}^{-B\,|t|}$ (Figure 5, left). This quasi-exponential domain is important for the extrapolation of the nuclear part dN_{el}^{nuc}/dt to $t = 0$, needed for the measurement of σ_{tot}. The t-dependence of the exponential slope $B(t) = \frac{d}{dt} \ln \frac{d\sigma}{dt}$ reveils slight model-dependent deviations from the exponential shape (Figure 5, right). This theoretical uncertainty contributes to the error of the total cross-section measurement.

- A region with diffractive structure between 0.5 and $1\,\mathrm{GeV}^2$.

- The domain of central elastic collisions at high $|t|$, described by perturbative QCD in terms of triple-gluon exchange with a predicted cross-section proportional to $|t|^{-8}$. The model dependence of the predictions is very pronounced in this region.

With different beam optics and running conditions [1, 4, 5] TOTEM will cover the $|t|$-range from $2 \times 10^{-3}\,\mathrm{GeV}^2$ to $8\,\mathrm{GeV}^2$.

2.3 Diffraction

Diffractive scattering – comprising Single Diffraction, Double Diffraction, Central Diffraction (a.k.a. "Double Pomeron Exchange"), and higher order ("Multi Pomeron") processes – represents about 15 % of the total cross-section at 14 TeV. Many details of these processes with close ties to proton structure and low-energy QCD are still not understood. The majority of diffractive events exhibits intact ("leading") protons in the final state, characterised by their quadratic four-momentum transfer t and their fractional momentum loss $\xi \equiv \Delta p/p$. These protons can be detected in Roman Pot detectors far away from the interaction point. The other main signature of diffractive events – large gaps in the scattering products' rapidity distribution due to exchange of colour singlets (a.k.a. "Pomeron") between the interacting protons – will be optimally exploitable when the detectors of CMS and TOTEM will be combined for common data taking with an unprecedented rapidity coverage, as discussed in [6]. However, already in stand-alone running TOTEM will be able to measure ξ-, t- and mass distributions in soft Double Pomeron and Single Diffraction events.

3 The Status of the Detectors

3.1 The Roman Pots

TOTEM's Roman Pot (RP) system is symmetric w.r.t. the interaction point IP5. On each side, two stations of Roman Pots have been mounted this summer on the out-coming beam pipe. Each RP station is composed of two units separated by 2 m and 6 m respectively. Each RP unit consists of 3 pots, 2 approaching the beam vertically and 1 horizontally (Figure 6, left). Micro-stepping motors independently move each pot, and a mechanical compensation system balances the atmospheric pressure loads on the pots.

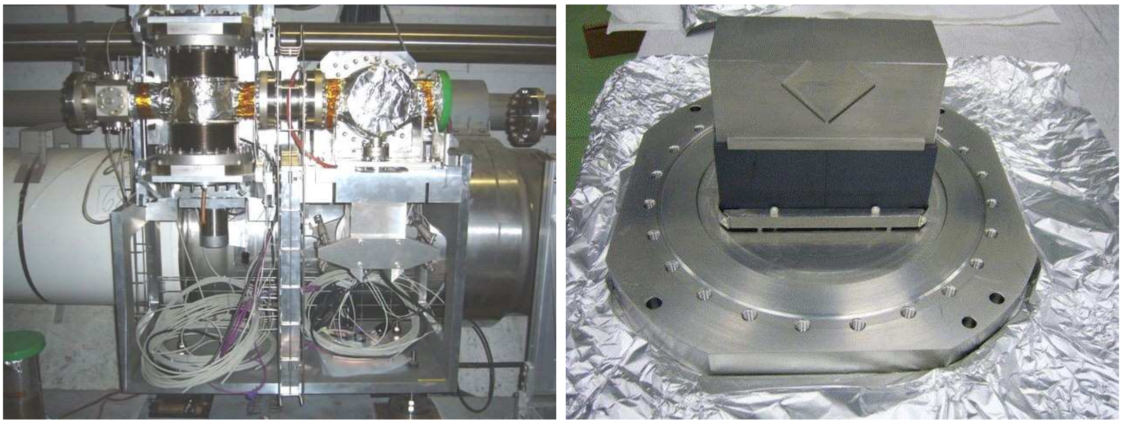

Figure 6: *left: installation of the first RP unit in the LHC; right: The pot with the thin window.*

The pot itself (Figure 6, right) provides a volume with secondary vacuum where a stack of 10 planes of novel "edgeless" silicon strip detectors and their services are enclosed. The RP window facing the beam has a thickness of 0.15 mm in stainless steel.

TOTEM and the Ioffe Institute in St. Petersburg have developed this new type of silicon detectors. These devices have a "Current Terminating Structure" on the edge facing the beam and are therefore sensitive to less than $50\,\mu$m from the edge, allowing to approach the beam centre to ≤ 1.1 mm [7]. The assembly of the 10 detectors will be cooled through an evaporative cooling system to a temperature of less than -15°C.

The prototyping of the Roman Pot Detectors (RPD) has been finalised in the last months. The cooling system for the RP has already been extensively tested with success on a mock-up made with the same material foreseen for the RPD assembly and applying the heat load foreseen by means of surface heaters. The silicon detectors and the VFAT chips electronics have been mounted and the RP hybrid (see also Section 4 and Figure 12, right) tested in pairs this summer with muon beams and ^{90}Sr sources showing excellent performance. The first assembly with ten plans is in preparation now to be ready end of October.

Moreover, to guarantee the proper functionality of the RPD over the whole period of activity foreseen, several tests have been defined and are being completed in these days. These tests address the major risks of failure that the RPD might face during operation. As the detector assemblies (ten detector planes for each set) will be hosted in the secondary vacuum of the RPs, in a defined pressure range eventual discharges might occur and damage the apparatus. Furthermore, the ageing of the assemblies due to repeated thermal cycles might affect the mechanical stability. Last, the radiation dose accumulated on the sensors will reduce their efficiency with the time. All these issues are being addressed by the specific material and geometrical characteristics of the RPD.

Regarding the production of the RPD assemblies, all the mechanic parts have been delivered and controlled. The VFAT chips have been produced and delivered. The first batch of 200 silicon detectors has been produced and 60 of them have been tested and delivered. The production of the second batch will start soon once the yield on the first batch will be clear.

As mentioned earlier, all RP stations have been installed in the LHC. Before mounting the pot with its thin window, pressure cycles in the range of ± 1 bar were applied to the window, followed by a vacuum test. The flatness of the windows was measured by metrology and found to be better than $50\,\mu$m. The motors and the compensation system were tested on all pots, and the window position w.r.t. the beam centre was calibrated by metrology.

When the RP station was completely assembled it was baked out and vacuum tested by the LHC vacuum group and approved.

Concerning the infrastructure, all cables have been installed inside the LHC tunnel. In LHC sector 5-6 the connectors will be mounted now, whereas in sector 4-5 this work can only be done beginning of 2008 since the tunnel is closed now. The first detector assembly, after being tested in the test beam and with cosmics will be installed in one RP station in the beginning of 2008, when the machine sectors will be open again. At that moment all motors will be tested and recalibrated. Furthermore, the first detector assembly will be cooled and its electrical functionality tested. It is the aim of TOTEM to equip in total 2 RP stations with 12 detector assemblies on either side of IP5 before the LHC commissioning starts. We hope that no radiation damage will occur due to accidental beam losses during the LHC commissioning phase. The planning is shown in Figure 9.

3.2 The T1 CSC Telescope

The T1 telescope is installed in two cone-shaped regions in the end-caps of CMS. Cathode Strip Chambers (CSCs), a proven technology, were chosen as detectors. They have trigger capability. Two "arms" form the T1 telescope, one on either side of the IP5. On both sides it will occupy the space between the beam pipe and the inner envelope of the CMS end-caps. Each of the two arms consists of five planes of CSCs, all different in size, and each arm is vertically divided in two halves, so-called half arms. To cover the circular region of each plane, the detector has been divided into six sextants. Each CSC chamber consists of a plane of parallel wires with a pitch of 3 mm inside a gas volume, sandwiched between two facing and properly segmented cathode planes. The thickness of the gas gap is 10 mm.

Figure 7: *Completed CSC chambers for T1 in a test area.*

The mass production of CSCs at PNPI (Gatchina) is ongoing. 25 out of 60 chambers (+ 10 spares) have been produced; the production rate is 0.5 chamber/day. 15 have been sent to CERN and are currently in the storage and test area at building 188 (Figure 7), on special temporary support structures. Materials needed to build all chambers have been procured.
Three out of five pre-production CSCs have also been at CERN for several months: two of them have been undergoing extensive ageing tests at the GIF; one is being tested with the complete data acquisition chain on the H8 beam line in the North Area.
All components making up the support structures for installation inside the CMS end-caps are ready, except for the spacers between adjacent layers, which are currently being machined in Genova. Mounting of the supporting trusses on the iron of the CMS magnet yoke has been successfully tested, with and without magnet field. The installation platforms, with external supporting trusses, have been produced. A complete installation test for one half arm of the telescope is being set up, which will make use of CSC mock-ups.
The anode read-out boards have been designed for all chamber types (10 in total); a sample of one type has been produced and tested on beam; samples for a second and third type are in production. Prototypes for two different types of cathode read-out boards have been produced: tests on are under way for the choice of the most suitable one. The concentrator card, gathering data from two chambers (both anodes and cathodes) and communicating with the data acquisition and the trigger systems, has been designed; prototypes are about to be sent for production. The design of a special mezzanine card for the trigger has started.

The cables for the T1 telescopes have been laid down in the experimental hall, and connectors are being mounted now. At the moment a complete T1 telescope support is equipped with dummy chambers and should be inserted in a CMS end-cap mock-up in order to test the sliding mechanism and the precision w.r.t. the beam pipe.
The chambers delivered from Gatchina will be mounted in a test stand to verify their characteristics with cosmics before being mounted in the final support. One complete telescope should be mounted before the start-up of the LHC. The planning is shown in Figure 10.

3.3 The T2 GEM Telescope

The T2 telescopes are installed in the forward shielding of CMS between the vacuum chamber and the inner shielding of the HF calorimeter. The gaseous electron multipliers (GEM) were selected for detectors of the T2 telescope thanks to their high rate capability, good spatial resolution, robust mechanical structure and excellent ageing characteristics. In each T2 arm, 20 semi-circular GEM planes – with overlapping regions – are interleaved on both sides of the beam vacuum chamber to form ten detector planes of full azimuthal coverage. The GEMs are installed as pairs with a back-to-back configuration.
Three thin Cu-clad Kapton foils, 50 μm thick with CU layers of 5 μm and a large number of holes of $\approx 70\,\mu$m diameter, are inserted between a drift electrode and a readout board. This board is a printed circuit board covered by a polyimide foil with a pattern of strips and pads, used therefore as a two-dimensional readout board.
All the GEMs have been produced in Helsinki in clean rooms of the Detector Laboratory where a dedicated assembly line for the large GEM detectors was set up. The production of 50 GEMs (40 for T2 plus 10 spares) is terminated. A big effort was made for the quality control, which was partly automated. It includes leakage current measurements of the GEM foils, optical inspection of the foils and search for broken or short-circuited strips/pads on the readout board, and finally a ^{55}Fe source test. A half T2 telescope has been tested in the SPS beam line H8 (Figure 8).

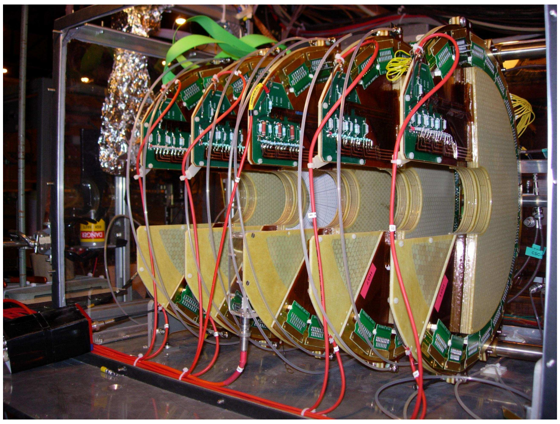

Figure 8: *Half T2 telescope in the testbeam H8.*

The cables for the T2 telescopes have been laid down in the experimental hall and connectors are being mounted now. Also the T2 telescope support has been equipped with mock-up GEM chambers in order to test the functionality of the sliding mechanism. The support structure has been delivered, and one complete telescope should be mounted in spring 2008. The planning is shown in Figure 11.

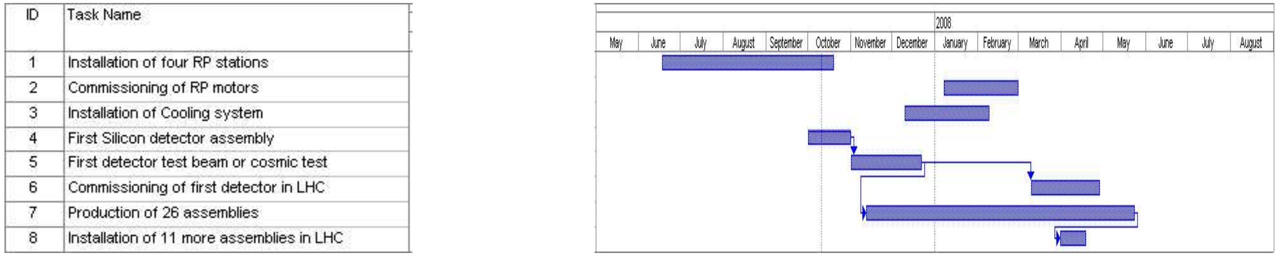

Figure 9: *RP planning.*

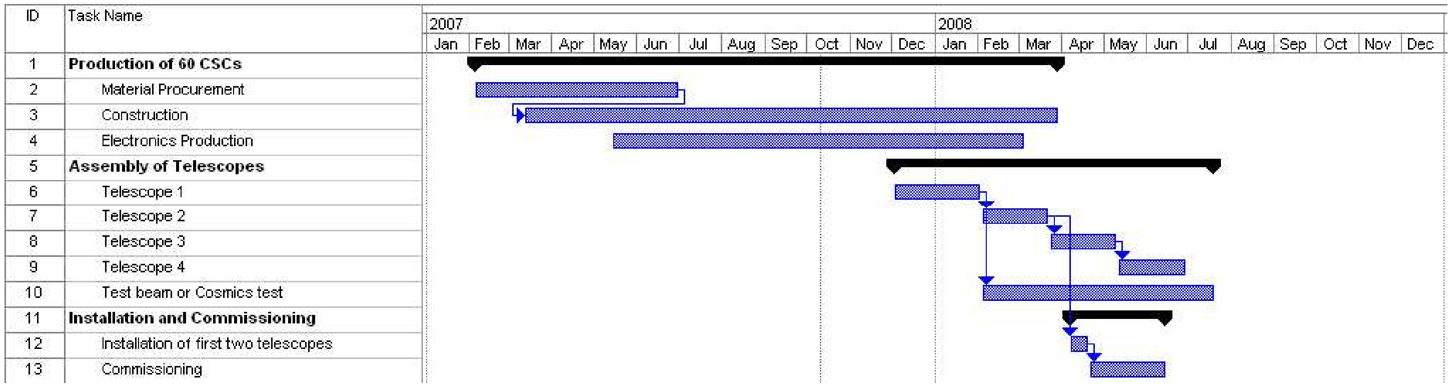

Figure 10: *T1 planning.*

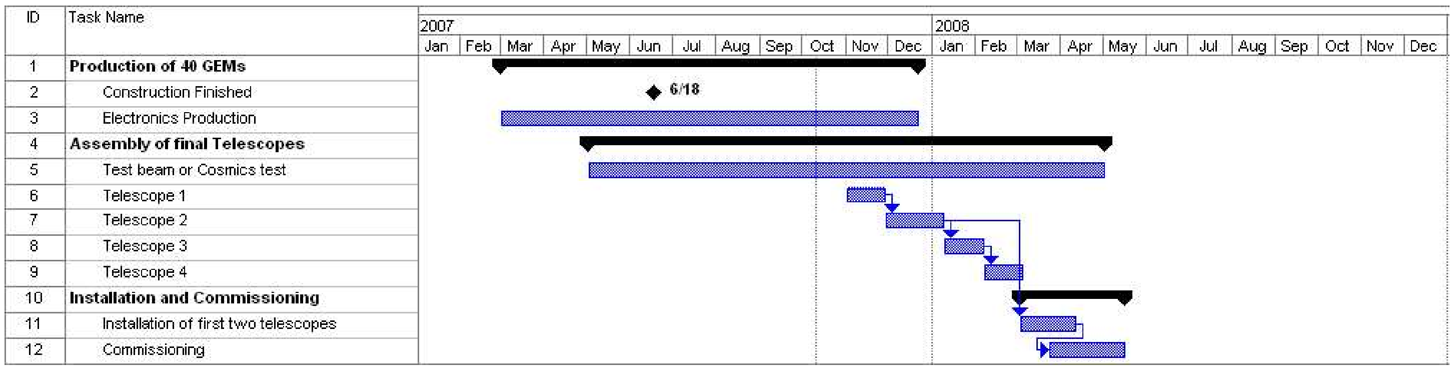

Figure 11: *T2 planning.*

4 The Electronics System

An overview of the TOTEM electronics system has been given in [8].
All three TOTEM sub-detectors provide level one trigger building signals and use the same chips: the VFAT providing both tracking data and fast trigger generation signals, the Coincidence Chip, and the LVDS repeater chip. All were designed using special layout techniques for total radiation dose tolerance, with additional measures for robustness against single event upsets.
The TTC and slow control system of CMS tracker/ECAL have been adopted for TOTEM. Both VFAT and Coincidence Chip include an I2C interface compatible with this system and counters on the fast trigger outputs to monitor hit rates.

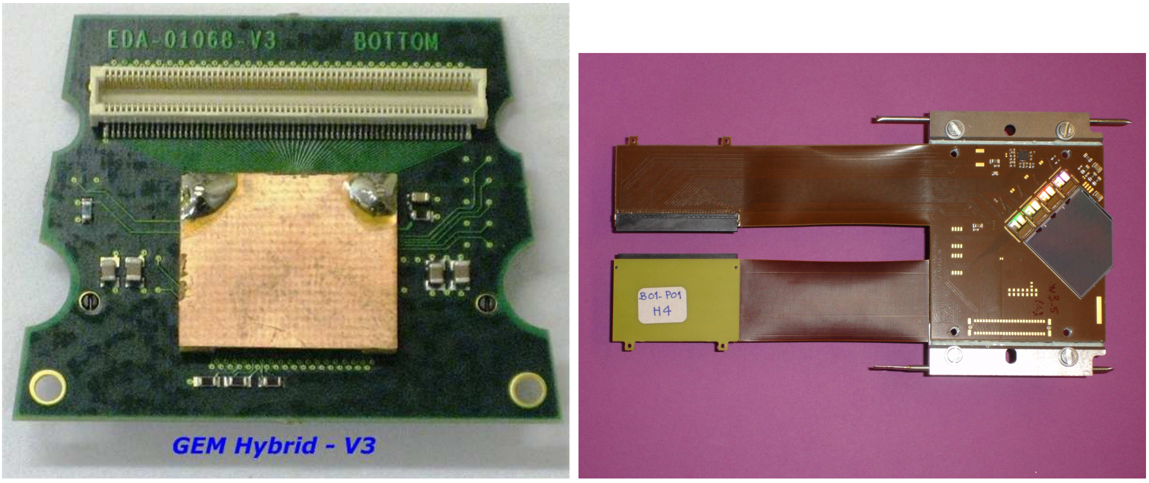

Figure 12: *Left: the TOTEM gas detector hybrid carrying one VFAT readout chip (under the cover). Right: the TOTEM Roman Pot hybrid carrying the silicon detector and its four VFAT readout chips.*

Both T1 and T2 use a common detector hybrid (Figure 12, left) with one readout chip VFAT [9]. The VFAT is equipped with a special circuit to protect itself against gas discharges. In the experiment approximately 1200 of these hybrids will be used for T1 and T2. The Roman Pot hybrid (Figure 12, right) carries one silicon strip detector and four VFAT chips. The VFAT inputs are directly bonded to the detector strips. Each of the 24 Roman Pots is equipped with 10 of these Roman Pot hybrids.
These two hybrids are fully functional and are tested using a temporary adapter board (identical for all three detectors). Final full production of these hybrids is about to start. For the experiment the functionality of this adapter board needed to be integrated in cards specific to each subdetector. These cards are now in production and will be tested in a few weeks with detectors and hybrids.
Both trigger building and tracking data are optically transmitted to the counting-room. The Roman Pots at 220 m from the interaction point are too far away for the optically transmitted trigger data to arrive within the allowed latency, and hence electrical transmission was adopted. The LVDS repeater chip is inserted at regular distances along the 270 m long cable to preserve the electrical signals.
The HOST board [10] in the counting room with opto-receiver mezzanines receives both trigger and tracking data. This was a shared development: the CMS preshower designed the opto-receiver mezzanine and TOTEM the HOST board. The fully CMS compatible system is equipped with SLINK, USB and VME interface. The level 1 trigger generation

is also carried out by HOST boards. Trigger building signals can be sent to the CMS global trigger or a level 1 trigger signal can be generated directly for TOTEM standalone operation.
In conclusion, the TOTEM electronics system, fully compatible with CMS, became possible through standardisation across its sub-detectors, adopting the same hardware for trigger building and tracking data, and through the collaboration with the CMS preshower. Despite the very limited resources significant progress has been made. The detector hybrids are fully functional. Tests with final on-detector interface cards are planned in the next few weeks before launch of final production. Counting room hardware is functional and currently in preproduction. Work on cabling and patch panels has progressed but with difficulties due to lack of technicians.

5 Data Acquisition

DAQ software components are being developed based on the XDAQ framework (from CMS). Wherever possible (like in the cases of the FEC and the TTC system software) TOTEM is re-using libraries and/or applications developed by CMS, with additions and modifications specific to our experiment. Prototype DAQ applications and libraries are being routinely used at the H8 integration facilities. Online software development and test will continue through the year 2008, with the goal of reaching full functionality in phase with the LHC physics run schedules of 2008-2009. All software and hardware components of the DAQ are being chosen or developed in view of their inter-operability with the CMS DAQ and Trigger system. In the underground counting room DAQ PCs installed, while VME crates and VME/PCI interfaces delivered and ready to be installed. Purchasing of the full set of event-builder PCs and storage for LOCAL DAQ is being set up at this moment; completion is foreseen by end 2007. During 2008 the LOCAL DAQ will be gradually installed at IP5 and its functionality tested.

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