TOTEM Upgrade Proposal

The TOTEM Collaboration

Abstract

During the first LHC running period 2009 – 2012 TOTEM collected a wealth of data at √s = 7 and 8 TeV, mostly in special runs at reduced luminosity, allowing a comprehensive scrutiny of large cross-section processes.

After the first Long Shutdown, TOTEM will join forces with its partner experiment CMS, creating a combined apparatus with the largest rapidity coverage and with the most performing two-arm proton spectrometer ever built at a collider. Focussing on the process of central diffraction opens unique opportunities for exploring QCD in new phase space regions and for the search for new physics.

First studies of central diffraction and, in particular, diffractive dijet production in special runs in 2012 together with CMS have provided the proof of concept, but demonstrate that even at moderate luminosities a key issue to be overcome in physics with leading protons is the pileup of several events per bunch crossing.

This document outlines the TOTEM strategy for increasing the reachable integrated luminosity and rendering its apparatus capable of resolving event pileup and multiple tracks in the proton detectors. In addition to the already approved consolidation programme including the relocation of the old Roman Pot station RP147 to the region between the quadrupole Q5 and the Roman Pot station RP220, TOTEM proposes the installation of two new Roman Pots designed to accommodate timing detectors for reconstructing the longitudinal vertex position of the leading protons in central diffractive events. Thus the protons can be assigned to the appropriate central vertex reconstructed by the CMS tracking detectors. Furthermore, the present silicon strip detectors are foreseen to be replaced by radiation-hard pixel detectors with better tracking capability.
1 Physics Motivation

Combining the TOTEM and CMS detectors at the LHC with common triggers of highest flexibility and a sophisticated read-out system creates the CMS/TOTEM experiment with an unprecedented particle coverage over 15 units of rapidity that extends further down to production angles of a few microradians for the measurement of very forward protons [1, 2, 3]. Together with very flexible beam interaction scenarios ($\beta^*$ values from 0.5 m to $\sim$2500 m) the LHC is not only optimized for highest luminosity interactions needed for new particle searches but can also be streamlined for searches in dedicated phase space regions that might lead to new physics provided the experiment is adapted to it [4, 5].

The ability of TOTEM/CMS to tag protons and study the associated production at central rapidities provides a unique opportunity to study the dynamics of Pomeron-Pomeron interactions in Central Diffraction (CD, a.k.a. Double Pomeron Exchange, DPE) in a wide range of invariant energies, essentially from the 1 GeV threshold to about 1 TeV. Measuring the momenta of the forward protons on each side determines the centre-of-mass energy of the Pomeron-Pomeron interaction. Thus, measuring the forward protons on each side turns the pp collider into a gluon-gluon collider with known energy of the initial state, allowing in particular the study of $g \to g$ interactions in the colour-singlet channel.

As already pointed out many years ago [6, 7], an advantage of the Pomeron Pomeron $\to G$ channel (where G is a gluonium state) is that the state is produced with vacuum quantum numbers in the interaction of gluon rich objects. At moderate masses, this could lead to most important hadron spectroscopy studying new composite states compatible with spin-parity quantum numbers of $J^{PC} = 0^{++}, 2^{++}$ [8]. In contrast to experiments at lower energies, contributions of secondary Regge trajectories are definitely negligible in the LHC kinematics. The ability to detect numerous final states ($\pi \pi, K K, \rho \rho, \eta \eta'$) is clearly a bonus. Tantalizing hints of structures in the mass spectrum were reported from the ISR and fixed target experiments. It is generally believed that the typical scale of low energy gluon states could be as large as 2 GeV and hence the spectrum of those exotic states may extend into the $3 \div 5$ GeV region. Therefore the ability to explore produced masses in the multi-GeV region opens up unique opportunities for discovering new QCD bound states.

At higher energy Pomeron-Pomeron interactions, the available energy allows studying properties of gluonia via processes like

$$ \text{Pomeron Pomeron } \to G \to f f' $$

(where $f, f'$ are the final states of the gluonium decay) as a function of the $ff'$ invariant mass, the transverse momenta of the gluonium states and the correlated tagged proton transverse momenta. With rising Pomeron-Pomeron energies many interesting exclusive channels will be in reach providing new tools for testing QCD dynamics in the transition region from soft to hard QCD. Background (in itself interesting) coming from the interaction of a photon (Weizsäcker-Williams photon) emitted by one of the protons with the second proton can be identified by the very small transverse momentum of the proton emitting the photon.

In general, Pomeron-Pomeron interactions should be compared with pp interactions in all aspects over the complete energy range up to 1 TeV. This includes jet and multi-jet production, transverse energy and multiplicity distributions, as well as search for missing energy or new particles. In this respect, it is important to note that the measurement of the two protons (their transverse momentum and momentum loss) significantly constrains the particle distribution expected in the central region. As an example, the total
transverse momentum of the two protons should balance the transverse momentum of the system seen in CMS and the diffractive mass should be constrained in a rapidity region defined by the rapidity gaps predicted by the momentum loss of each proton. Since the diffractive mass is well localized in the rapidity space and particles should not enter into the calculated rapidity gaps missing energy can be determined not only transversely but also longitudinally.

There are many other interesting topics in the high mass regime of CD. A most spectacular channel is the exclusive production of pairs of dijets depicted in Figure 1.

\[ \text{pp} \rightarrow p + 4\text{jets} + p \]

with \( x_{\text{gluon} 1} + x_{\text{gluon} 2} = x_{\text{Pomeron} 1} \) and \( x_{\text{gluon} 3} + x_{\text{gluon} 4} = x_{\text{Pomeron} 2} \). Correlations between the partons should enhance the cross-section of this exclusive channel, in particular in the perturbative regime when \(-t_1, -t_2\) are large enough (a few GeV\(^2\)) to squeeze the transverse sizes of the exchanged ladders. The inclusive four-jet production will predominantly arise from smaller impact parameters (< 0.7 fm) causing a large accompanying multiplicity. The cross-section for four-jet (\( p_T > 20 \text{GeV} \)) production in CD could be as high as 1 ÷ 10 nb yielding a sizeable data set for an integrated luminosity of \( 10 \text{ pb}^{-1} \). Many other channels can be imagined where correlated gluons play a major role in helping to understand Pomeron-Pomeron interactions in the vacuum channel.

These interactions might have quite different characteristics from normal pp interactions. They offer unique possibilities in the search for new physics (particle spectroscopy, dark matter search, new particles, etc.) that could be missed otherwise. The cleanliness of the topology, determined by the two leading protons, facilitates the determination of missing energy as well as particle reconstruction and identification.

Figure 1: Diagram of exclusive 4-jet production.
2 Upgrade Strategy

The experience during LHC phase I has shown that the main limitation to detect central diffractive events is the balance between the luminosity needed to access low cross-section processes and the background created by pileup events.

First measurements in July 2012 based on a special run with the $\beta^* = 90\,\text{m}$ optics showed that already an inelastic pileup level of $\mu \sim 5\%$ leads to difficulties in selecting clean samples of central diffractive events: in particular the signature of diffractive dijet events can be easily faked by an overlap of other processes with higher cross-sections. For example, the contamination of events with the right signature (two leading protons and central dijets) can be larger than 60% due to the pileup of a soft central diffractive event (or two single diffractive events) with a central non-diffractive dijets event.

At the same time, the limited luminosity ($\sim 10^{30}\,\text{cm}^{-2}\text{s}^{-1}$) led to insufficient statistics for detailed hard-diffractive studies.

Therefore the strategy for the future is two-fold:

- Upgrade the detector apparatus for resolving the pileup of multiple events in the same bunch crossing.
- Operate at higher luminosities by increasing the luminosities of special runs and later by exploiting standard LHC fills.

This can be achieved by adding timing detectors to resolve the vertex position of the forward protons, and radiation-hard silicon detectors to allow operation with high intensity beams (Section 6).

The primary aim of pileup resolution is to attribute the leading protons to the correct vertex. This is achieved by measuring the time-of-flight difference between the two outgoing protons, which yields the longitudinal vertex position $z_{pp}$ if they come from the same collision. The protons vertex has then to be matched with the $z_{central}$ of the central event. Depending on the resolution of the timing detectors several strategies can be envisaged to operate at high pile up (Section 4).

Another pileup case is the overlap of a signal proton with another proton, either from another physics event or, more likely, from beam halo. If only two projections of a track are measured, already the case of two simultaneous tracks leads to a four-fold ambiguity in the reconstruction. TOTEM will mitigate these multi-track ambiguities in two stages. The RP stations removed from the 147 m locations will be reinstalled at 210 m, with one of the two units rotated azimuthally (i.e. tilted around the beam axis) by $8^\circ$. The resulting improvement in multi-track resolution is discussed in Section 5.1. At a later stage, tracking detectors will be based on 3D pixel technology: this will allow the operation in a high-intensity and high-radiation environment as well as a complete multi-track reconstruction (Section 6.2).

RP operation at highest luminosities requires some technical adaptations in view of impedance reduction (Section 5.4.2) and the addition of a new collimator (TCL6) behind the last RP to protect downstream machine elements (in particular, Q6) against showers and losses induced by RP insertions close to the beam (Section 5.5).
3 Running Scenario

3.1 Luminosity Reach in Special and Standard LHC Fills

TOTEM will operate in a wide range of luminosities giving access to cross-sections from 100 mb down to the fb level. A rough overview is given in Table 1. Large cross-section phenomena (elastic scattering at low $|t|$, minimum-bias physics, soft diffraction) are covered by the high-$\beta^*$ scenarios with 2 to 156 bunches. To reach integrated luminosities of several pb$^{-1}$ while keeping the pileup well below 1, a crossing-angle could be introduced at $\beta^* = 90$ m, allowing to increase the number of bunches beyond 156, e.g. to about 1000, without parasitic bunch crossings near IP5. This scenario will be ideal for collecting a clean, generous sample of DPE events enabling a thorough study of centrally produced mass states: at a pileup level of a few %, 2 weeks of running are enough to obtain 400 million soft DPE events. In the same runs, $10^4$ diffractive dijet events with $p_T > 100$ GeV can be collected.

Higher luminosities required for harder DPE processes can only be obtained at the expense of an increased pileup. In this context a time measurement in vertical RPs will be very beneficial: if a pileup of $\mu \approx 0.5$ can be disentangled, the bunch charge can be raised from 0.5 to $1.5 \times 10^{11}$, yielding almost a factor 10 in luminosity. To give an example, the exclusive four-jet process mentioned in Chapter 1 will come into reach.

Standard LHC fills are foreseen to have a $\beta^*$ of about 0.5 m. In a short initial startup phase the bunch spacing will be 50 ns until the final 25 ns bunch trains will have been commissioned. No substantial luminosity production is planned for the 50 ns phase, unless unforeseen difficulties with the 25 ns bunching arise. Therefore, the 50 ns scenario – characterised by an uncomfortably high pileup up to $\mu \sim 40$ – will not be discussed for the TOTEM physics programme. However, insertion tests with the new RPs are foreseen.

Once safe RP positions close to high-current beams will have been established, regular fills with 25 ns bunch trains will be usable in two ways:

- Colliding the beams while staying in the injection optics would offer the opportunity to run for a few hours in the beginning of regular fills at moderate luminosity and pileup ($\mu = 1.3 \div 2.5$ for $\beta^* = 11$ m or $\mu = 2 \div 4$ for $\beta^* = 7$ m). In this way, integrated luminosities of the order of 100 pb$^{-1}$ are reachable in an accumulated running time of $\sim 30$ h, possibly sufficient to catch a first glimpse at diffractively produced unknown states.

- Ultimately, after completion of the full instrumentation upgrade including timing at the $\sim 10$ ps level and tracking with radiation-hard pixel detectors, the range of (many) fb$^{-1}$ will become accessible by continuous RP operation in all standard high-luminosity fills.

<table>
<thead>
<tr>
<th>$\beta^*$ [m]</th>
<th>cr. angle [µrad]</th>
<th>$\varepsilon_N$ [µm rad]</th>
<th>$N$ [$10^{11}$ p/b.]</th>
<th>$k$ bunches</th>
<th>$\mu$ [cm$^{-2}$s$^{-1}$]</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500</td>
<td>0</td>
<td>2</td>
<td>0.7 ± 1.5</td>
<td>2</td>
<td>0.004 ± 0.02</td>
<td>(1.2 ± 5.6) $\times 10^9$ = (0.1 ± 0.5) nb$^{-1}$/24h</td>
</tr>
<tr>
<td>90</td>
<td>0</td>
<td>2</td>
<td>0.7 ± 1.5</td>
<td>156</td>
<td>0.06 ± 0.5</td>
<td>(1.3 ± 12) $\times 10^9$ = (0.1 ± 1) pb$^{-1}$/24h</td>
</tr>
<tr>
<td>90</td>
<td>100</td>
<td>2</td>
<td>0.7 ± 1.5</td>
<td>1000</td>
<td>0.06 ± 0.5</td>
<td>(0.9 ± 1.7) $\times 10^{10}$ = (0.8 ± 2) pb$^{-1}$/24h</td>
</tr>
<tr>
<td>310 ÷ 390</td>
<td>1.9 ± 3.75</td>
<td>1.15</td>
<td>2520 ÷ 2760 ($\Delta t = 25$ ns)</td>
<td>1.3 ± 2.5</td>
<td>(3.3 ± 9.5) $\times 10^{11}$ = (46 ± 82) pb$^{-1}$/24h</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>310 ÷ 390</td>
<td>1.9 ± 3.75</td>
<td>2520 ÷ 2760 ($\Delta t = 25$ ns)</td>
<td>19 ± 34</td>
<td>(0.8 ± 1.3) $\times 10^{13}$ = (0.7 ± 1) fb$^{-1}$/24h</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Overview of expected running scenarios with their respective ranges of inelastic pileup $\mu$ and delivered luminosity. The precise values depend on the bunch size, the number of bunches, and the emittance.
3.2 Schematic Experimental Setup

The layout of the consolidated and upgraded RP system in Sector 5-6 is shown in Figure 2. The station RP220 (with units at 215 m and 220 m from IP5) will remain unchanged as it was before LS1.

Within the already approved consolidation, the former station RP147 is removed from cell 4 to make space for the new collimator TCL4 and relocated into the free space between the quadrupole Q5 and the station RP220. The units of the relocated station RP210 are placed at 202 m (“210-N”) and 213 m (“210-F”). The entire far unit is rotated by 8° around the beam axis in order to introduce two additional track projections for resolving multi-track events (see Section 5.1). All pots of the RP210 and RP220 stations are initially equipped with the existing edgeless silicon strip detectors. This consolidated RP spectrometer will enable – immediately after LS1 – the continuation of the low-luminosity physics programme at $\beta^* = 90$ m, using the unmodified RP220 stations with their well-established performance. These early runs will at the same time offer the opportunity to successively insert the RP210 stations and gain experience with their properties. Adding the unit 210-N will provide an extended lever arm for precise elastic scattering-angle measurements. Moving on to the luminosity-enhanced $\beta^* = 90$ m scenario with crossing-angle and about 1000 bunches, the tilted 210-F unit will contribute its stereo effect for resolving multiple tracks.

The upgrade proposal foresees during LS1 the installation of an additional horizontal RP – intended to house timing detectors for operation at low $\beta^*$ – between the near and far units of the RP220 station. A second new RP immediately downstream of the first one will be added in a winter technical stop. Figure 3 shows the new station with two horizontal RPs.

The new RPs have been designed with a cylindrical rather than rectangular pot geometry providing sufficient space to accommodate quartz Čerenkov bars, one of the possible technologies for timing detectors. The high material budget of the quartz bars and the longer beam-facing RP window will result in multiple scattering of the signal protons and in showers, precluding the usage of the downstream tracking unit 220-F simultaneously with the timing RPs. Early after LS1, operation at low $\beta^*$ will serve mainly for insertion tests with the old rectangular and the new cylindrical RPs to study their interactions with the beam environment in terms of impedance effects and showers. In the very first stage the new pots will be equipped with only temperature sensors which will give way to timing detectors as soon as they become available. In addition to Čerenkov detectors, other technologies with less material budget will be investigated.

As soon as a satisfactory timing detector technology will have been established, one of the vertical RP pairs (e.g. 220-F-V) will be equipped with timing detectors to resolve pileup at $\beta^* = 90$ m where signal protons are primarily deflected into the vertical detector planes. Furthermore, a vertical timing measurement can be beneficial for elastic scattering measurements in all running scenarios with high background, be it single diffractive pileup at low $\beta^*$ or intense beam halo in high-$\beta^*$ runs with extremely close insertions ($\sim 3\sigma$) for low-$|t|$ measurements.

In case the Čerenkov technology will be retained for the timing measurement, full time resolution at highest pileup will require the equipment of both new horizontal pots with such detectors, to have the necessary total length of quartz bars.

Another upgrade objective is the replacement of the strip detectors in the tracking pots with radiation-hard pixel detectors (e.g. in 3D technology) which will inherently provide
Figure 2: Layout of LHC Cell 6L5 in Sector 4-5, showing the RP spectrometer and the location of the new collimator TCL6 downstream of it.
Figure 3: 3-dimensional view of the new station of 2 horizontal RPs to be installed between the units 220-N and 220-F.

multi-track separation capability at high luminosities.

The final configuration of horizontal RPs having to stay inserted at highest luminosities for very long times will ideally consist of a combination of thin timing detectors and pixel trackers in the same pot. Thus merely two inserted RPs would suffice, keeping impedance and material budget to a minimum.

The global design strategy to compose the proton detection system of 14 independent RPs offers considerable flexibility advantages:

- The detector package of a given pot, placed in a secondary vacuum, can be quickly exchanged or upgraded without breaking the primary machine vacuum.

- The set of RPs to be inserted will be adapted to the details of the given running scenario. Any unforeseen experience or difficulty with specific beam conditions can be taken into account *ad hoc* by inserting more or fewer RPs.
The trigger objective is the selection of central diffractive (CD) events with optimized efficiency and purity. The reduction of the trigger rate to an acceptable level is achieved in two steps, at level 1 (L1) and in the higher-level trigger (HLT).

The RP trigger signal has to arrive at the CMS L1 trigger on time to be mixed with the experiment’s trigger algorithms (‘alogs’) in order to generate the L1-accept signal that will allow the detectors to send their data information into the L1 buffer. The L1 latency is fixed at around 100 clock cycles. To match this requirement, the RP trigger data are transmitted to the central TOTEM trigger through LVDS parallel busses, enhanced by local repeaters for the signal integrity over a long path (~300 m long cables).

The relocated station RP210 is foreseen to serve as trigger station in the RP spectrometer, instrumented, as the station RP220, with edgeless silicon strip detectors and VFAT readout chips [9]. This chip has a special, fast, 8-bit output bus that can be used in a programmable coincidence chip to generate fast trigger roads to search for almost parallel tracks in the telescope. In the current setup the coincidence chip sends, two clock cycles after the detection, a trigger pattern to the central TOTEM trigger where the full list of observed roads seen by the station is written in parallel into the receiving FPGA. The information is pipelined so that no collision is lost. Each trigger road, made by 16 consecutive strips, has a lower resolution but it is enough for track counting. In the past an algorithm searching for single and multiple tracks had been implemented in the central trigger FPGA, counting in a single clock cycle the number of active roads.

Trigger roads are not the only information available for the L1 trigger in the upgrade. Two timing detectors are foreseen, read by a multihit TDC, to measure the time of flight of the protons. The TDC readout can be used in the trigger to select vertices compatible with the CD events. A fast data transmission line has to be implemented to send in one clock cycle the full list of the arrival times of the protons. This information has to be mixed in the CMS L1 algo with the track multiplicity in order to select the good events.

To define an optimal trigger strategy for central diffractive events at high luminosity and to determine the conditions which can give an acceptable trigger rate, a simulation of inelastic events plus background has been performed.

The estimate of the RP background coming from particles generated by the interaction of the beam halo and collision debris hitting the surrounding hardware (cf. Section 5.4.1) has been performed looking at the data taken in April 2012 during a low-intensity fill (for RP alignment) with $\sqrt{s} = 8$ TeV, $\mu \approx 9$, $\beta^* = 0.6$ m and the horizontal RPs inserted at 6$\sigma$. It is assumed that the dominant background component, i.e. the collision debris, increases with the luminosity and is almost on time with the physics vertex.

An event sample where only one arm of the T2 detector is active has been selected. This sample is rich in Single Diffractive events (about 70% according to Pythia8) and has a low pile-up incidence. However, in this topology, the RPs placed on the same side of the active T2 arm ($RP_{T2\_SAME}$) are richer in background tracks than the RPs placed on the opposite side of the active T2 arm ($RP_{T2\_OPPOSITE}$). With these assumptions, an equation system allows the determination of the acceptance $A$ and of the RP background $B_1$ in the $RP_{T2\_SAME}$ case:

$$RP_{T2\_SAME} = N_1 \times A + B_1, \quad RP_{T2\_OPPOSITE} = N_2 \times A + B_2,$$

where $N_1$ and $N_2$ are the numbers of physics protons generated in the RP, according to Pythia8 Monte Carlo. With the approximation that the RP background in the $RP_{T2\_OPPOSITE}$ case is $B_2 \ll B_1$, the acceptance has been found to be $A \sim 10\%$,
while the average number of background tracks per bunch crossing, in the RP.T2.SAME configuration, is of the order $B_1 \sim 0.1$.

Having established the incidence of the background in the RP, a simulation with $\mu = 30$ and $A = 0.1$ is then performed and the same probability of generating RP-background as measured in the data is assigned to each vertex. The track multiplicity in the RPs is shown in Fig 4.

![Figure 4: Track multiplicity (signal + background) per bunch crossing in the Roman Pot sectors in the case of $\mu = 30$.](image)

Protons arriving at the RP have a time that is the sum of the generated vertex time, the travelling time to the detector ($t_d$) and an additional smearing due to the detector resolution. For background particles attributed to secondary interactions a small delay is added. This is computed considering the time spent by the particles to travel an extra-path length of $\sim 3$ cm before hitting some material (of any aperture limitation in the LHC lattice).

For each pair of protons detected in opposite arms, the relevant observables are the sum and the difference of the arrival times. To avoid a large number of combinations when a shower develops just in front of the RP, it has been decided to limit the search on events in which the number of tracks detected on each side is not greater than 2. This cut has an efficiency of 0.3. Having reduced the track multiplicity to $2 \times 2$, the trigger can compute in one clock cycle the four combinations of the sum and difference of the arrival times.

The sum, $\bar{t} = \frac{t_1 + t_2}{2} - t_d$, gives a hint of the generation time of the proton collision while the difference of the arrival time ($\Delta t$) is proportional to the longitudinal position of the collision vertex ($z_{pp} = \frac{\Delta t}{c}$).

The resolution of the timing detectors can be between 10 ps (hence $\sigma(z_{pp}) \approx 3 \text{mm}/\sqrt{2} = 2.1 \text{mm}$) and 25 ps ($\sigma(z_{pp}) \approx 5.3 \text{mm}$), to be compared with the rms vertex spread of $\text{rms}_{\text{bunch}}/\sqrt{2} = 7.1 \text{cm}$. The worst detectors resolution has been considered in this study and the strategy is to search for events in which the central detector has vertices that are separated by $\geq 10 \text{mm}$ from the others. In this way the reconstructed $z_{pp}$ can be associated without any ambiguity to the vertex of the central event in CMS, $z_{\text{central}}$.

The sample of CD events on isolated vertices and at most $2 \times 2$ tracks in RP is considered the golden sample on which efficiency and purity are calculated.
Assuming the multiplicity cut (efficiency 100%) the purity is found to be $6 \times 10^{-4}$. From simulation it appears clear that colliding bunches tend to accumulate the vertices near $z = 0$ and isolated vertices tends to be seen in the tails of the distribution (Fig 5).

![Figure 5: Longitudinal distribution of vertices separated by at least 1 cm from the others.](image)

Therefore a clean way to increase the purity of the sample is to cut the central vertices and select the events that have at least one isolated vertex. This can be achieved requiring $-800 \text{ps} < \Delta t < 800 \text{ps}$. To further suppress the combination of tracks generated by secondaries which are coming with a longer path and tend to have later recording times, it is required in addition $\bar{t} < -200 \text{ps}$. With these additional cuts the purity of the sample increases up to $3 \times 10^{-2}$, and the efficiency on the golden sample is reduced to $8.5 \times 10^{-2}$.

The rate at this stage is estimated to be 82 kHz, and harder cuts are possible to achieve a better purity of the signal. Supposing that the full rate is sent to the CMS HLT (not realistic indeed), the next cut that can be performed is the matching of timing vertices with the $z_{\text{central}}$ position list of the primary vertices recognized by CMS tracker. We search for a precise match of the $\geq 4$ vertices measured by the timing detectors, out of which only one or none is a true vertex, with the list above. The event is accepted only if a timing vertex is closer than 2.5 mm to one of the CMS tracker vertices, and if the recognized vertex is more than 10 mm apart from the other vertices. This cut is highly efficient on our golden sample, and it removes most of the events in which mainly SD protons from other interactions are mimicking a CD due to the large pileup. The final rate is 10 kHz with an efficiency of 0.03 and a purity of 0.31. This means that more than 3 kHz of good events survive this cut.

The central point of this work is to demonstrate that even with a poor time resolution, such as 25 ps, we can achieve at trigger level a purity of 30%, and in the worst case of a prescaling factor to be applied at L1, still the throughput of physics is relevant. It has to be noted that with this configuration the horizontal pots can reach $|\xi|$-values from 3% up to 10%, which means that the masses created are quite high. The possibility to have a coincidence at L1 with two jets at relatively low energy (25 GeV in the past) or muons, together with a direct link of the jets or muons to the CD vertex at HLT, allows to get a high efficiency to rare hard diffractive physics processes.
5 Improvements of the Roman Pot System

5.1 The Rotated RP Unit 210-F

The RP unit 210-F, relocated from 147 m, is installed with a tilt of $8^\circ$ around the beam centre (Figure 6). This concerns both the vertical and the horizontal pots. Technically, the mechanical support of the RP unit is modified to achieve this rotation. The multi-track resolution capability achieved by this tilt is discussed in Section 7.4.

5.2 New Roman Pots for Timing Detectors

The new RPs 220-C1 and 220-C2 to be installed between the existing units 220-N and 220-F are intended to host timing detectors. Hence their design is subject to the following main requirements:

1. Among several potential detector technologies for the timing measurements (see Section 6.3.1), Čerenkov counters \cite{10, 11} are already at well advanced development stage. For the full timing resolution of $\sim 15$ ps a total length of 24 cm of quartz is needed. Distributing this length over the two new pots requires each pot to accommodate two slabs of 6 cm length, too big for the space provided by the traditional TOTEM pots. If at a later stage thinner timing detectors (e.g. diamond detectors) become available, tracking and timing functionality may be combined in the same pots, reducing the number of pots to be inserted.

2. The RPs housing the timing detectors will have to operate in high luminosity running scenarios. They will have to approach very intense beams to the same distance as the tracking RPs, i.e. down to about a mm from the centre. At that distance beam-coupling impedance effects, machine vacuum compatibility in terms of outgassing, and particle shower development have to be taken into account in the geometrical design and in the choice of materials (Section 5.4).

After considering various options and after an iterative optimisation, the following design has been adopted for the new Roman Pots (Figures 7 and 8). The volume housing the
detectors will have a cylindrical rather than rectangular box shape. This choice provides the necessary space for all potential technologies of timing detectors and at the same time reduces the beam coupling impedance by minimising resonant cavities. A further impedance reduction is achieved by a $10 \, \mu\text{m}$ thick copper coating of the cylinder surface facing the beam vacuum. The ferrite in this design will be integrated in the (stationary) flange rather than mounted on the moving detector housing. It will have a ring geometry (inner diameter = 150 mm, radial width = 15 mm, thickness = 5 mm).

Furthermore, all vacuum-side surfaces of the RP stations are foreseen to receive a $2 \, \mu\text{m}$ thick NEG coating.

### 5.3 The RF Shield for the Old Horizontal Roman Pots

Given that the existing horizontal pots housing tracking detectors will have to cope with the same high luminosity conditions as the new timing RPs, some adaptations will be made:
• To reach the same impedance reduction as for the new cylindrical pots (see Section 5.4.2), the old rectangular detector boxes will be successively equipped with 1 mm thick cylindrical copper shields (Figure 9). Holes in the shield allow for the gas flow necessary to establish a vacuum equilibrium inside and outside the shield. The number and dimensions of these holes have been defined in cooperation with the LHC vacuum group: In the lateral, cylindrical wall there are 3 rows of 15 circular holes each with a diameter of 1 cm; the wall facing the beam has 8 slits of $3 \times 12 \text{mm}^2$ with rounded corners (2 mm radius). The shield is retracted by 30 mm from the box window facing the beam, in order not intercept any signal protons with the shield material. In the first step, during LS1, only the horizontal pots of the RP210 station will receive the shields, in order to gain experience without touching the RP220 station.

• The old ferrites mounted around the rectangular box will be replaced with new elements of the same geometry but in the new material TT2-111R, as used for the new RPs. In addition, identical ferrite rings like in the cylindrical RP design will be integrated into the flange.

![Figure 9: Drawings of the cylindrical RF shield for the old horizontal RPs.](image)

5.4 Interaction with the Beam Environment

5.4.1 Experience from 2012

In October and November 2012 several test insertions of the RPs in normal high-luminosity fills at $\sqrt{s} = 8 \text{ TeV}$ with $\beta^* = 0.6 \text{ m}$ were performed. While the vertical pots had no problems to reach the target distance of $12 \sigma$ from the beam centre, the horizontal pots encountered a very intense collision debris halo, and repeatedly the beam was dumped by showers hitting the Beam Loss Monitors at a pot position of about $30 \sigma$. Separating the beams in IP5 finally reduced the luminosity and hence the debris halo by a factor 22.7, enabling the approach to the horizontal target distance of $14 \sigma = 1.6 \text{ mm}$ from the beam containing 1368 bunches of – at RP insertion time – $1.1 \times 10^{11}$ protons or a total charge of $1.45 \times 10^{14}$ protons. The trigger rate beam profiles (Figure 10) measured during these insertions can be used to benchmark shower simulations (Section 5.4.4). The first lesson for the upgrade from this exercise is that a horizontal RP approach to physics-relevant positions of $10 \div 15 \sigma$ will require to absorb the showers produced by the RPs in order to protect the quadrupole Q6. The solution envisaged is the addition of the new collimators TCL6 between the RR220 station and Q6 (see Section 5.5).
Figure 10: Left: vertical beam profile measured via the trigger rates in the detectors of the top and bottom pots of 56-220-N. Right: horizontal beam profile measured in 45-220-N; the luminosity reduction by beam separation has been corrected for. The reconstructed curve is the result of a convolution fit discussed in [20].

While the horizontal pots were stationary at 14\(\sigma\) from the beam centre, i.e. for about 30 minutes, the temperature sensors on the detector hybrid boards in those RPs registered a temperature increase by about 4\(^\circ\)C, despite the active cooling of the detector packages. This effect is explained by impedance heating of the ferrite collar mounted around the box-shaped housing on the beam vacuum side. A direct temperature measurement near the ferrite was not available, but given the long thermal conduction path from the heat source to the detector package, and the absence of convection inside the pot due to the secondary vacuum, the temperature of the ferrites may have reached values well above 100\(^\circ\)C, the Curie temperature of the ferrites (material 4S60 from Ferroxcube) above which they are ineffective. Another piece of evidence for substantial heating of the ferrites was given by the vacuum deterioration observed after the very close insertion of the horizontal RPs. First laboratory tests have shown that the ferrite material installed around the pots shows substantial outgassing at high temperatures.

Triggered by the problems and observations described above, a programme of simulations, extended laboratory tests and design optimisations was defined; it is discussed in the following section.

5.4.2 Impedance

As mentioned in the previous section, during a RP insertion to 1.6 mm from a high-intensity beam (1368 bunches of \(1.1 \times 10^{11}\) protons) a temperature increase was observed on the detector hybrid boards. This effect can probably be attributed to impedance heating. It is hypothesised that the 4S60 ferrite mounted around the RP box reached a temperature above 100\(^\circ\)C, the Curie temperature, which resulted in the loss of ferrite effectiveness and hence even stronger heating by the now non-damped cavity resonance near 550 MHz [12]. Note, however, that no other impedance effects were observed, in particular, no beam instabilities.

The aim of the work presented here [13] was the optimisation of the RP design to minimise the beam-coupling impedance, in particular at very close distances to the beam, in view of more regular and extended RP insertions in the future.

The impedance seen by a beam of particles has contributions from the shape of the
vacuum chamber (geometrical impedance) and from the finite conductivity of the material used for its construction. The latter, resistive, contribution can be reduced by coating the cavity with a good conductor, like copper or beryllium. For the new TOTEM RPs a 10\(\mu\)m thick copper coating is foreseen. The remainder of this section focusses on the geometrical contribution of three RP designs: the standard box-shaped RP, the new cylindrical RP, and the improved box-shaped RP with shield (introduced in Section 5.3).

The study was performed by simulating the passage of a charge distribution (source charge) through a cavity, in this case through a RP, and computing the wake field felt by a longitudinally or transversely displaced second charge (test charge). The potential felt by the test charge is then used to compute the longitudinal or transverse impedance using Fourier Transforms.

Three impedance effects have to be addressed:

- **Beam-induced heating**, i.e. the transfer of power from the beam to the lossy wall of a cavity, is determined by the frequency-dependent real part of the longitudinal impedance in conjunction with the power spectrum of the beam:

\[
P_{\text{loss}} = 2 I^2 \sum_{p=0}^{\infty} P_S(p) M' f_{\text{rev}} \Re \left[ Z_{\text{long}}(p M' f_{\text{rev}}) \right],
\]

where

- \(P_S(f)\) is the power spectrum;
- \(f_{\text{rev}}\) is the revolution frequency, 11.245 kHz for the LHC;
- \(M'\) is the number of buckets, 1782 for the LHC with a bunch spacing of 50 ns;
- \(I = M e N_B f_{\text{rev}}\) is the beam current, with \(M\) number of bunches, \(e\) charge of the proton, \(N_B\) number of protons per bunch;
- \(Z_{\text{long}}\) is the longitudinal impedance.

The main contribution to the heating comes from resonances below 1.5 GHz; at higher frequencies the beam power spectrum is attenuated by more than \(\sim 30\) dB relative to its value at \(f = 0\) [14].

- **Longitudinal instabilities** are related to the effective longitudinal impedance. The effective impedance is the impedance actually felt by the beam: it is given by the impedance convolved with a weighting function \(\sigma(f)\) which is determined by the bunch profile:

\[
Z_{\text{eff}} = \frac{\sum_f Z(f) \sigma(f)}{\sum_f \sigma(f)}
\]

A conservative estimation of the effective longitudinal impedance is the slope of the imaginary part of the longitudinal impedance at low frequencies \(Z_{\text{long}}^0 / n\):

\[
\Im Z_{\text{long}}^0 / n = \lim_{f \to 0} f_{\text{rev}} \frac{d \Im Z_{\text{long}}}{df}
\]

where \(n = f / f_{\text{rev}}\) is the harmonic number. It is possible to show [13] that

\[
\Im Z_{\text{long}}^0 / n < (\Im Z_{\text{long}} / n)^{\text{eff}}.
\]

The simulated value for \(\Im Z_{\text{long}} / n\) will be compared with the measured value for \((\Im Z_{\text{long}} / n)^{\text{eff}}_{\text{LHC}} = 90\) m\(\Omega\) [15].
- **Transverse instabilities** have, analogously, their origin in the low-frequency behaviour of the transverse impedance. Following the same approach for the effective transverse impedance, it is possible to compute the *driving* (or *dipolar*) impedance and relate it to the transverse impedance [16]:

\[
\Imag Z_{\text{driving}}^t = \frac{\partial \Imag Z_t}{\partial t_{\text{source}}} \tag{4}
\]

where \( t = x, y \) and \( t_{\text{source}} \) represents a small transverse displacement of the source charge, which creates the wake field, from the nominal position. The value is usually constant at low frequency (< 500 MHz). A normalisation with the ratio of the beta function value at the equipment under study, \( \beta_t \), and the average over the ring, \( \langle \beta_t \rangle = 70 \text{ m} \), facilitates the comparison with other equipments at different positions in the machine:

\[
\Imag Z_{\text{driving}}^t = \Imag Z_{\text{driving}}^t \beta_t \langle \beta_t \rangle \tag{5}
\]

The new RP will be horizontal (\( t = x \)); moreover, among all the RPs the highest value (worst case) of \( \beta_x = 98 \text{ m} \) is reached at the unit 210-N. This value can be compared with 25 MΩ/m, a conservative value of the value expected for the full machine [17].

For the new cylindrical pots, simulation results indicate that no low frequency resonances (< 1.4 GHz) are present if the gap between the detector housing and the flange is completely closed, which of course prevents any RP movement. Mechanical constraints require at least 2.5 mm gap between the housing and the flange. With this gap a resonance at 470 MHz appears, as shown in Figure 11; its impedance, however, is smaller than for the standard box-shaped RP. The position and the dimensions of the ferrite have been optimised through various iterations considering also vacuum and mechanical construction. The final design consists of a ferrite ring (inner diameter = 150 mm, radial width = 15 mm, thickness = 5 mm) integrated into the flange, as far as possible from the beam (Figure 12). This design is feasible and can be easily integrated in the existing design.

![Figure 11: Simulated \( \Re[Z_{\text{long}}] \) of the cylindrical RP without ferrite. The resonance at 470 MHz is due to the cavity between the flange and the detector housing. The darkened part of the graph has negligible impact on the heating due to the strongly attenuated LHC power spectrum at such high frequencies.](image)

Figure 13 shows the real and imaginary parts of the longitudinal impedances of the three RP designs with ferrites. In all cases, the 470 MHz resonance is damped and smeared beyond recognition. At low frequencies, the cylindrical and shielded RPs have a smaller \( \Re[Z_{\text{long}}] \) than the standard RP. This is also reflected by the reduced heating for the new designs (Figure 14).
Figure 12: *Detail of the geometrical model used in the impedance simulations. It shows the new ferrite ring to be integrated in the flanges of the cylindrical pots and of the improved pots with shields.*

Figure 13: *Simulated longitudinal impedance for the standard box-shaped RP (top left), the cylindrical RP (top right) and the shielded RP (bottom). Both real and imaginary part are shown.*

Figure 15 shows the effective longitudinal impedance as a function of the RP distance from the beam. Also here, the new designs have led to a significant reduction. These results are numerically summarised in Table 2.
Figure 14: *Power lost by the beam passing through the RP, for the three RP designs.*

Figure 15: *Effective longitudinal impedance as a function of the RP distance from the beam, for the three RP designs.*

<table>
<thead>
<tr>
<th>Distance from the beam [mm]</th>
<th>$\frac{\Delta Z_{\text{long}}}{\Delta Z}$ [mΩ]</th>
<th>fraction of $\frac{\Delta Z_{\text{long}}}{\Delta Z}$ [90 mΩ]</th>
<th>$\frac{\Delta Z_{\text{trans}}}{\Delta Z_{\text{LHC}}}$ [MΩ/m]</th>
<th>fraction of $\frac{\Delta Z_{\text{trans}}}{\Delta Z_{\text{LHC}}}$ [25 MΩ/m]</th>
<th>Heating [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Box RP</td>
<td>1</td>
<td>1.7</td>
<td>&lt; 1.9 %</td>
<td>0.15</td>
<td>&lt; 0.6 %</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.3</td>
<td>&lt; 1.4 %</td>
<td>&lt; 0.45 %</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>40 (garage)</td>
<td>0.41</td>
<td>&lt; 0.45 %</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Cylindrical RP</td>
<td>1</td>
<td>1.1</td>
<td>&lt; 1.2 %</td>
<td>0.11</td>
<td>&lt; 0.5 %</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.73</td>
<td>&lt; 0.81 %</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40 (garage)</td>
<td>0.18</td>
<td>&lt; 0.20 %</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Shielded RP</td>
<td>1</td>
<td>1.2</td>
<td>&lt; 1.3 %</td>
<td>0.2</td>
<td>&lt; 0.8 %</td>
</tr>
<tr>
<td></td>
<td>40 (garage)</td>
<td>0.30</td>
<td>&lt; 0.33 %</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: *Main results of the simulation of the present box RP (Box RP), the cylindrical RP (Cylindrical RP), and the Box RP with Shield. Longitudinal and transverse impedances are compared with the total values estimated for the present LHC effective impedances.*

5.4.3 Vacuum

The vacuum degradations observed in 2012 after very close horizontal RP insertions to high-intensity beams triggered the following consolidation activities for improving the vacuum compatibility of the RP system:
• Ferrite material improvements:
The 4S60 ferrites used in the RP system before LS1 are now (but not in 2006) known to show high outgassing rates unless they are baked out at 1000°C [18]. In the TOTEM RPs these ferrites were installed as received from the manufacturer and then baked out in situ at about 200°C like all other beam-pipe components, which turned out not to be sufficient. Since the 4S60 ferrites have in addition a low Curie temperature of only 100°C, alternative ferrite materials are being investigated instead of only baking out the 4S60 material at 1000°C. The most likely candidate for the TOTEM RPs is the TT2-111R material from TransTech with a Curie temperature of 375°C and an acceptable outgassing after bake-out at 1000°C [19]. Another alternative material would be 4E2 (Ferroxcube) with a Curie temperature of about 400°C; its outgassing behaviour remains to be tested.

• The new geometrical ferrite configuration reduces the ferrite surfaces exposed to the vacuum by an order of magnitude from 220 cm² per standard RP to 23 cm² per cylindrical RP.

• All components exposed to the primary beam vacuum have been proposed by the vacuum group to be coated with NEG, as far as technically possible.

5.4.4 Generation of Particle Showers

To assess the generation of particle showers by RPs interacting with the intense debris halo (see 2012 experience discussed in Section 5.4.1), Geant4 simulations implementing detailed models of the old rectangular and the new cylindrical RPs have been carried out [20].

The first goal of the study was to identify the contributions from the different structural elements of a RP to the shower creation. For this purpose, 7 TeV protons with a delta-function profile distribution, i.e. zero width and zero angular spread, were shot parallel to the beam onto three elements of a pot:

• through the beam-facing window, 50 µm from the outer surface;
• through the front window, the detector planes and the rear window, 2 cm from the outer surface of the beam-facing window;
• through the body wall of the pot, 6 cm from the outer surface of the beam-facing window.

This was performed for the standard rectangular pot geometry and for the new cylindrical one (see Table 3 for some key dimensions). For each case a sample of 2000 protons was processed. Figure 16 shows the resulting angular distributions of the secondary particles produced in the RP material.

<table>
<thead>
<tr>
<th>RP Element</th>
<th>Standard Pot</th>
<th>Cylindrical Pot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam-facing window length along beam</td>
<td>54 mm</td>
<td>145 mm</td>
</tr>
<tr>
<td>Beam-facing window thickness</td>
<td>0.15 mm</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Front / back window</td>
<td>0.5 mm</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Body wall thickness</td>
<td>2 mm</td>
<td>3 mm</td>
</tr>
</tbody>
</table>

Table 3: Comparison of the standard and cylindrical RP elements most relevant for the material budget and hence for shower production.
Figure 16: The horizontal (top) and vertical (bottom) scattering angle distribution of secondary particles produced by different elements of the standard and the cylindrical RP. Fits with the function \( \frac{dn}{d\Theta} = C (\frac{\Theta - b}{1\,\text{mrad}})^{-a} \), where \( a \approx 1 \) are superimposed (see [20] for details). The bin width is 10 mrad. Note that a particle emitted with an angle of 10 mrad travels 4 cm (= 1 beam pipe radius) transversely within a longitudinal distance of 4 m.

As expected, the number of secondary particles is mostly determined by the amount of material traversed. The key observations are:

- In both RP designs, the bottom foil produces by far the highest number of secondary particles, followed by the thick body walls with 2 to 3.5 orders of magnitude lower rates. The orthogonally traversed thin front and back windows produce the lowest numbers of secondaries.

- The bottom foil of the cylindrical pots produces more than 10 times more secondaries than the much shorter foil of the standard pots. In the other elements the shower production is similar in the two designs.

- The showers from the bottom foil of the cylindrical pot are 3 times wider than the ones from the standard pots: 99% contained in 0.6 rad = 34° rather than in 0.2 rad = 11°.
The two projections, horizontal and vertical, are almost identical.

The second part of the study addressed the shower production by particles distributed according to the rate density profile \( dN/dt dx dy \) deconvoluted \(^{[20]}\) from the trigger rate profile measured in November 2012 (Figure 10). This gives a picture of the total shower distribution, in contrast to the first study that focussed on the delta-response of the individual components. Figure 17 shows the simulated secondary particle distribution and the related energy flow in a scoring plane 6 m downstream of a standard horizontal RP inserted to 2 mm from the beam centre. The position of the scoring plane relative to the RP corresponds roughly to the TCL6 position relative to the unit 220-N-H. The important message is that at the entrance point of TCL6, 91\% of the energy flow carried by 25\% of the secondary particles is contained within the beam-pipe radius and thus intercepted by TCL6. How much of this flow leaks through the TCL6 aperture and thus hits Q6 will be the subject of the FLUKA study discussed in Section 5.5.2.

Figure 17: Left: distribution of the secondary particles created by a horizontal standard RP and recorded in a scoring plane 6 m farther. Right: corresponding energy flow distribution. The particle generator is based on the measured rate profile. The white circle around the origin with radius 40 mm indicates the beam pipe.

In the final step of the study, the secondary particles created by interaction with a first RP impinge on a second RP after 4.6 m longitudinal distance. There the shower is amplified by the additional material. The amplification factor obtained from this simulation can be directly compared with the beam measurement in November 2012 (Table 4).

<table>
<thead>
<tr>
<th></th>
<th>first det. plane</th>
<th>middle det. plane</th>
<th>last det. plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>((R_{\text{far}}/R_{\text{near}})_{\text{simulated}})</td>
<td>1.5</td>
<td>1.8</td>
<td>2.5</td>
</tr>
<tr>
<td>((R_{\text{far}}/R_{\text{near}})_{\text{measured}})</td>
<td>3.5 (trigger condition: 3 out of 5 planes)</td>
<td>3.5 (trigger condition: 3 out of 5 planes)</td>
<td>3.5 (trigger condition: 3 out of 5 planes)</td>
</tr>
</tbody>
</table>

Table 4: Rate amplification factor from the near to the far RP unit in simulation and measurement.

The simulation shows how the shower size increases within the second RP by successively passing through 10 detector planes. In the data, the trigger was defined as an OR of the \( u \) and the \( v \) projection triggers, each of which was a 3-out-of-5-plane majority coincidence. The simulated amplification factor at the last detector plane agrees reasonably with the measurement.
5.5 Interplay between Roman Pots and Collimators

The modified Roman Pot system with relocated and additional units will be embedded in an upgraded collimation system. This section discusses the performance of the new combined layout in terms of physics acceptance and machine protection.

5.5.1 The New Collimators TCL4 and TCL6

LHC operation at highest luminosities may require additional protection of the quadrupoles Q5 and Q6 against collision debris from IP5 [21].

To protect Q5, new collimators, TCL4, will be installed on the outgoing beams in the old location of the RP147 station, and the already existing collimators TCL5 may be partially closed. Since both TCL4 and TCL5 are located upstream of the Roman Pot stations and can intercept diffractive protons if too tightly closed, their aperture settings of these collimators will be the result of an optimisation study maximising the physics acceptance as far as compatible with the necessary magnet protection.

Downstream of the last RP unit, 220-F, another collimator, TCL6, will be installed on the outgoing beam to protect the quadrupole Q6 against debris from IP5, thus taking over a part of the original role of TCL5 which cannot be too tightly closed without intercepting all the signal protons to be measured by the RP system. Another beneficial effect of this new collimator is its capability to absorb showers created by the insertions of the horizontal RPs close to the beam. RP operations at low $\beta^*$ and high luminosities in 2012 have demonstrated that without any absorber behind the RP stations, insertions were limited to distances greater than $30\sigma$, because the showers caused by the pots’ interaction with the debris halo brought the dose rates measured by the Beam Loss Monitors above the beam dump thresholds. The improvement by the addition of TCL6 will be the subject of a FLUKA study.

5.5.2 Optimisation of Roman Pot and Collimator Settings

This section discusses the strategy for defining an optimal combined set of jaw positions for the RPs and the collimators TCL4, TCL5 and TCL6. Given that the TCLs are only required at highest luminosities, only the low-$\beta^*$ running scenarios are relevant for these considerations. The TCL collimators are designed to protect the quadrupoles Q5 and Q6 against debris from collisions at IP5. Their jaws approach the beam horizontally and potentially intercept diffractively scattered protons, thus interfering with the physics measurements in the RPs. Therefore, the aim of the optimisation [22] is to find

1. jaw positions for TCL4 and TCL5 that leave the aperture as widely open as allowed by the protection needs of Q5, i.e. the dose rate received by Q5 has to stay well below the magnet quench threshold;

2. RP positions as close to the beam as allowed by the protection capacity of TCL6 to prevent Q6 from quenching.

The upper limit $\xi_{\text{max}}$ for accepted momentum losses of diffractive protons is given by minimum value of the ratio $d_x/D_x$ between horizontal aperture and dispersion along the path from the interaction point to the RP. Table 5 gives the values of $10\sigma_x$ beam width and the dispersion $D_x$ in all TCL collimators and in some RP locations for the $\beta^* = 0.55$ m optics at $\sqrt{s} = 14$ TeV.

The most stringent impact on diffractive proton acceptance is made by TCL5 which at its nominal jaw position of $10\sigma$ from the beam centre would intercept all protons with
| Beam Element | Position $s$ [m] from IP5 | $10\sigma_x(s)$ [mm] | $D_x(s)$ [mm] | $|\xi(10\sigma)|$ |
|--------------|-------------------------|---------------------|--------------|----------------|
| TCL4         | 149                     | 5.2                 | -66          | 0.079          |
| TCL5         | 185                     | 2.8                 | -83          | 0.034          |
| RP 210-N     | 202                     | 2.2                 | -90          | 0.024          |
| RP 220-F     | 220                     | 0.90                | -80          | 0.011          |
| TCL6         | 221                     | 0.89                | -80          | 0.011          |

Table 5: Horizontal beam envelope ($10\sigma$) and dispersion at the TCL collimators and at the first and last RP unit. The last column gives the $\xi$-value at $10\sigma$ from the beam centre (for $t = 0$).

$\xi > 0.034$ while for the physics programme a cut-off greater than 0.1 would be desirable. Therefore collimation group developed an alternative scheme for fills with RP operation where TCL5 would be fully open and both TCL4 and TCL6 closed to $10\sigma$. However, in that scheme TCL4 would be the bottleneck producing a cut at 0.079. A new study presently carried out by the FLUKA team investigates the possibility to open TCL4 to $15\sigma$ and complement its protection by closing TCL5 to $35\sigma$. In this way, both collimators would lead to the same upper $\xi$ cut-off at 0.11.

Once the optimal settings for TCL4 and TCL5 will be fixed, another FLUKA study will focus on the impact of RP insertions on Q6 and its mitigation by closing TCL6 to $10\sigma$. It is expected that a horizontal RP approach to a minimum distance between 11 and $14\sigma$ should be possible, corresponding to minimum accepted $\xi$-values between 0.012 and 0.016.
6 Detector Instrumentation

6.1 Requirements and Strategy

TOTEM has mostly operated in stand-alone mode, but compatibility with CMS has always been a prime requirement for the system. The TOTEM system is able to provide a trigger signal to CMS within the required latency, and even includes electrical trigger transmission from the Roman Pots at 220 m to meet this requirement. TOTEM also can receive a trigger signal from CMS and can operate as a partition from CMS, and can link to the data acquisition. For the upgrade the same strategy will be followed, where new detectors in the Roman Pots, including timing detectors, will be able to operate in stand-alone mode, but will be compatible with operation together with CMS.

For the consolidation, RPs at 147 m are being moved to 210 m, and their infrastructure is also being moved/extended to this location. This infrastructure, comprising low voltage and high voltage power supplies, fibers for triggering and data acquisition, detector control and safety systems, etc. is sufficiently generally applicable so that large parts of it can be reused when new pixel detectors will replace the currently implemented strip detectors. It is also planned to make a copy of this infrastructure for the up to four additional Roman Pots to be installed for timing detectors. These latter pots will require some additional infrastructure including some fibers, monitoring and high voltage cables. The strategy is to complete the long distance cabling and patch panel installation also for these additional Roman Pots for timing detection, so that a later installation of detectors inside these RPs will be limited to a local intervention.

Pixel detectors are considered for the upgrade as a replacement of the strip detectors to provide unambiguous track reconstruction in two dimensions. Timing detectors with time resolution in the few tens of psec range are considered to associate the protons detected in the Roman Pots with the correct collision at the interaction point (Section 4). An important constraint is the radiation level of $5 \times 10^{15} \div 1 \times 10^{16}$ neutron equivalents per cm$^2$ on the sensor. In principle the detectors could be replaced from time to time as the TOTEM RPs are sufficiently accessible, but it would generate significant overhead and extra cost.

6.2 Pixel Detectors and their Performance

The ALICE, ATLAS and CMS vertex detectors at the LHC are based on hybrid pixel detectors, whereas the LHCb vertex locator (VELO) [23] uses silicon strip detectors. Hybrid pixel detector technology, in which a sensor chip is bump bonded to a number of readout chips, has reached a certain level of maturity and allows unambiguous hit reconstruction in two dimensions. At LHC particle hits are detected using this technology with a position resolution of $\sim 15 \div 20 \, \mu m$ in at least one dimension and a time binning of 25 ns, corresponding to the bunch separation in the LHC machine. The present trend is to include a very significant amount of electronics with transistor counts well beyond 1000 within each pixel, and a power consumption of several 100 mW per cm$^2$ of active area.

Readout chips in LHC pixel detectors are manufactured in 0.25 $\mu m$ CMOS technology using special layout and design techniques to increase the radiation tolerance both in terms of total dose and single event upset [24], and already now radiation tolerance for readout chips in this technology beyond 100 Mrad has been achieved. More advanced CMOS technologies are currently being investigated for the upgrades, and tolerances to
ionizing radiation over several 100 Mrad have been observed.

Radiation levels with neutron fluences or equivalent of $1 \times 10^{16}/\text{cm}^2$ or beyond significantly degrade traditional sensors of several hundred $\mu$m thickness and require novel sensor technologies such as diamond sensors for which volume manufacturing may be difficult at present (but volumes in TOTEM remain limited), thinner detectors to limit depletion voltage and power consumption in the sensor, or 3D detectors [26], in which doped pillars allow much lower operation voltages by depleting the material laterally. 3D detectors allow large signal charge to be collected for a much lower power consumption in the sensor, which otherwise becomes comparable to the consumption in the circuit for these radiation levels. The ATLAS experiment has decided to install 3D detectors in parts of the inner layer during this shutdown [27], and obtain valuable operational experience. TOTEM might now tie in with its long-standing interest in 3D detector technology, having performed the first-ever high-energy testbeam qualification of active-edge 3D detectors already in 2003 [28].

One example of detectors exploiting smaller sensor thicknesses are monolithic detectors based on a high resistivity epitaxial layer of $\sim 20 \mu$m thickness. Traditional Monolithic Active Pixel Sensors or MAPS collect signal charge from this layer by diffusion and are not sufficiently radiation tolerant, but explorations to use such sensors in fully depleted mode with collection by drift have yielded very significant radiation tolerance. The challenge there is to integrate the appropriate readout circuitry with the detector without paying a large penalty in signal-to-noise or power consumption while maintaining full depletion and collection by drift. Significant progress has been made on these technologies, and they receive more and more interest from ATLAS and CMS. Monolithic sensors are currently the main candidate for the ALICE ITS upgrade [29], which does not have such stringent radiation tolerance requirements.

### 6.3 Timing Detectors and their Performance

Establishing a timing difference in particle arrivals at two distinct locations (at $\sim 220$ m on opposite sides of the interaction point) requires three components which need to match the required timing resolution: the particle sensor, the timing reference and distribution, and a way to measure the time difference between the time reference and the signal indicating a particle traversal. All three will be discussed below.

#### 6.3.1 Timing Sensors

Several sensor principles are being considered for the TOTEM upgrade: Čerenkov detectors [10, 11], diamond detectors, and even other alternatives.

The Čerenkov solution is based on quartz slabs in which the light is made to travel along the direction of the incident particles, and collected at the end. To collect a significantly large and coherent signal, the sum of the particle travel time to the point where light is generated and the travel time of the light from that point to the collection point is roughly kept constant over the full length of the scintillator. In this way, timing in the 30 ps range has been achieved for a 6 cm long quartz bar. A disadvantage of this approach is that a rather bulky setup has to be installed and moved near to the beam, but steps are being taken to be able to integrate such solution should it be retained. In particular, a new cylindrical shape for the RP is being designed (Section 5.2) which would allow to approach the beam with a detector of up to 12 cm along the beam, providing space for
two quartz bars of 6 cm length each.

A second possibility are diamond detectors [25], which have already yielded timing in the few tens of picoseconds.

Another possibility may be silicon sensors, but more development is needed. For timing resolutions well below the 1 ns level, approaches only based on time binning using counters cannot be used, and more sophisticated electronics is needed using the signal amplitude to correct for time walk of the front end\(^1\). A recent development for NA62 [30] uses the arrival time of the discriminated signal combined with time-over-threshold information to arrive at a timing resolution below 200 ps, shown to be limited by the 200 \(\mu\)m thick fully depleted silicon detector. Reducing this thickness by an order of magnitude will improve this. First studies have been done on 3D detectors, and resolutions have been reached for a \(^{90}\)Sr source varying between \(\sim 180\) and \(\sim 30\) ps depending on the signal amplitude with the perspective of several improvements. Also monolithic detectors exploit lower detection thicknesses and are expected to give better timing resolution, but more work is needed to fully quantify this.

### 6.3.2 Distribution of Timing Reference

To establish the arrival time of a particle a timing reference is needed. In TOTEM the time difference is important between proton traversals detected in the RPs on opposite sides of the interaction point. In principle therefore one could transmit the detected signal back to the counting room and measure the time difference directly. However, since the timing detector should be segmented and it is likely that several detector planes would be used, this would lead to a relatively large number of channels which would need to be accurately timing controlled. An alternative is to provide a timing reference local to the detector and establish the time difference with respect to this.

Several solutions are being envisaged to provide such local time reference: a first solution (Figure 18) – suggested to us by the TTC experts – is to convert a timing signal coherent with the beam available in the counting room to an optical signal, split it and send it to both locations. There the optical signal should be split again, sent to the detector system as the time reference, but also sent back to the counting room to allow correction for slow variations related to temperature. Timing resolutions of the order of a few ps could so be achieved.

An alternative could potentially be provided by the white rabbit development [31], which aims at adding the possibility for absolute timing to Ethernet. Traditional Ethernet does not provide for this nor does it guarantee determinism in transmission latency. The specifications for white rabbit are timing to the 20 ps level, but in practice they have reached 6 ps. The system is still under development but already offers significant functionality. One of the very significant advantages is that the system is also capable of transmitting and receiving data, and this would offer full DAQ capability. The disadvantage is that commercial components have been used in the hardware, offered now by some private companies, and that no specific effort was made towards radiation tolerance. For the RP system it is possible to remove the electronics somewhat from the beam, and also some shielding could be provided. The core of the local hardware is a Xilinx Virtex-6 FPGA, but also other components on the board can potentially be affected by radiation. Work is needed to evaluate radiation tolerance and possible mitigation techniques (refresh of firmware in the FPGA, shielding, etc), but some experience in this domain exists [32].

\(^1\)time walk is the variation in reaction time as a function of input signal amplitude
It has to be noted that apart from this time reference for precise timing purposes, the detectors receive the TTC (trigger, timing and control) information from the counting room. This will continue to be the case, i.e. it is currently foreseen that the precise timing reference would complement the standard TTC information.

6.3.3 Measurement of Time Difference between Particle Arrival and Timing Reference

To measure the time difference between two signals a time-to-digital converter (TDC) will be used. There are not very many TDCs with 10 ps time resolution but a commercially available one [33] was found capable of this time resolution in one of its operating modes. It has actually also been used for a mezzanine card to operate in conjunction with the white rabbit system. One of the issues still to be understood is its radiation tolerance.

CERN also has some experience in developing radiation tolerant TDCs [34]. Recently a prototype TDC building block implemented in a 130 nm CMOS technology came back from fabrication and demonstrated 3 ps timing precision [35]. It is planned to continue this development to obtain a full TDC.

6.4 DAQ

6.4.1 Requirements

The Data Acquisition system (DAQ) of the TOTEM experiment [2] has been designed to allow data taking in different configurations depending on the running conditions. The system accomplishes the following tasks:

- Initialisation, configuration and calibration of the front-end hardware;
- Data taking integrated with the CMS DAQ;
- Data taking in TOTEM stand-alone mode;
- Data and trigger quality monitoring and filtering.
6.4.2 Configuration of Front-End Devices

The VFAT chips and the related front-end devices need to be initialised and calibrated before a normal run can start. The parameter space of the VFAT chip is particularly large, and its calibration procedure delicate; many different parameters need to be scanned in order to compute the optimal setting in terms of threshold and latency adjustments, taking into account the specific properties of each detector in terms of signal shape and timing. During these calibrations, dedicated trigger configurations are needed along with the activation of special procedures. In these operating conditions the rates are typically much lower than in standard running mode, the limiting factor being the time needed to calculate the parameter under calibration and re-configure all the devices at every step of the parameter scan. We assume that a typical trigger rate in this running mode will be \( \approx 100 \text{ Hz} \).

At the present stage the configuration and control of the front-end devices is handled using software tools developed by TOTEM and using external library packages implementing asynchronous communication between processes and computer nodes. This architecture is fully configurable and scalable allowing the control of processing the running either in a stand-alone or distributed environment. Leveraging its modular design and the isolation between each blocks, can be easily interfaced with a distributed control and data acquisition framework such as, for example, XDAQ used by the CMS experiment.

6.4.3 Integration with the CMS DAQ

The TOTEM DAQ has been designed with a modular architecture implementing different and not exclusive data interfaces. In particular, the OptoRx mezzanine card represents the cross-connection between the various interfaces and DAQ systems. The OptoRx receives data transmitted over optical fibers directly from the detector electronics and can stream it to two different interfaces. Up to 12 Gigabit Optical Hybrid (GOH) transmitters, housed at the detector level, send data to an OptoRx module. Data processed at the level of the OptoRx can be sent to an additional mezzanine card, plugged on top of the OptoRx card; this mezzanine is called CMC S-Link64 transmitter. Furthermore the OptoRx card can be interfaced to a 192 bit wide bus, for data transmission, and a 16 bit bus for commands and controls. In this way it can be housed on a host board implementing other kinds of readout. An OptoRx card, without any mezzanine is shown in Figure 19.

![Figure 19: Left: the OptoRx card. Right: the FRL card.](image)

In the actual TOTEM DAQ a host board has been designed and built to interface the OptoRx with a VME bus. This host board is a 9U VME card that can host up to three OptoRx cards. Besides the VME interface, it implements all the needed interfaces between
the Timing Trigger and Control (TTC) system and the hosted cards. This card, named TOTEM Front End Driver (TOTFED), is actually implementing the interface with the TOTEM stand-alone DAQ. A TOTFED card is shown in Figure 20, fully equipped with the OptoRX mezzanines.

Figure 20: The TOTEM VME host board: TOTFED. The card shown is configured with three OptoRx mezzanines, one of them equipped with a CMC mezzanine.

In the CMS DAQ, the CMC transmitter is connected to the so-called CMS Front-End Readout Link (FRL), shown in Figure 19. Two CMCs are read out by an FRL and switched into a Myrinet network connected to the CMS DAQ online computer farm. The general architecture scheme of the TOTEM DAQ system integrated with CMS is shown in Figure 21.

Figure 21: CMS and TOTEM integrated DAQ architecture.
FRLs are Compact PCI boards with an internal PCI bus hosting a commercial Myrinet Network interface Card (NIC). FRLs receive data from one or two OptoRxs using 64-bit parallel LVDS links according to the S-Link64 specification. At the design clock speed of 60 MHz, the data transfer rate per link is 480 MB/s. The FRL distributes data over the Myrinet network to the following stages of the CMS DAQ infrastructure that is designed to handle event data with 2 kB fragment size at a sustained rate of 100 kHz [36].

The OptoRx is a programmable module equipped with an ALTERA StratixIIIGX device. The actual OptoRx firmware has been designed to comply with the CMS DAQ requirements. In particular, data can be transmitted to the CMC S-Link64 mezzanine using the CMS Common Data Format. At the present stage no data reduction is applied at the level of the OptoRx, the event fragment size is fixed by the number of channels connected to the OptoRx mezzanine. At full load the OptoRx event size is $\approx 4.5$ kB. The OptoRx event size will be adjusted to fulfill the FRL event size requirement scaling the number of channels appropriately or, in case it is needed, programming the OptoRx to apply a data reduction algorithm.

The TOTEM DAQ is fully compliant with the Trigger Throttling System (TTS) and Trigger Timing and Control system (TTC) adopted by the CMS Experiment. The OptoRx mezzanine generates trigger throttling signals, compliant with the CMS TTS protocol implemented in the Fast Merging Module (FMM) and can receive the TTC signals. TTS transmission is actually implemented via the TOTFED interface that is equipped with the TTCrx receiver ASIC able to decode and distribute the clock, trigger and fast command signals generated by the central CMS trigger system.

### 6.4.4 Stand-Alone DAQ Configuration

At present TOTEM adopts a stand-alone DAQ based on the VME bus. The OptoRx modules are plugged into the TOTFEDs and transmit data through them. The TOTFED cards are read out independently by TOTEM in stand-alone data acquisition mode, via VME crates. The TOTEM stand-alone data acquisition mode will be still supported and, depending on the running condition, the DAQ mode will be selected.

In view of DAQ consolidation, new OptoRx interface boards will be tested to study the performance using interfaces different from the VME one, like, for example GigaBit Ethernet, yet preserving the compatibility with the CMS DAQ.

### 6.5 Services

For the consolidation, RPs are being moved from 147 m to 210 m, and thus their infrastructure has to follow. This infrastructure consists of low voltage, high voltage supplies, optical data transmission from and to the counting room, connections for sensor signals for slow control and for safety systems, and control and power for the RP motorisation. This infrastructure is rather generally applicable, so that future detectors can be designed to be compatible with such infrastructure. For this reason it was decided to make a copy of this infrastructure also for the new RPs foreseen for the precise timing detectors. High voltage cables certified up to 2 kV will be added, as the present ones only go up to 500 V, and this may not be sufficient for some of the timing detectors considered. Also some single mode fibers dedicated to the timing reference signal and possibly white rabbit signals will be added as well. The aim is to limit the installation of new detectors at a later stage to an intervention local to the RPs.

In general all this infrastructure has been designed to guarantee compatibility of the system with CMS: one example is the detector safety system, which receives sensor information from the RPs similar to any CMS detector, and treats this in a bank of PLCs.
to take the appropriate action which can consist in switching off the power supplies, the electronics rack, etc.

Some of the infrastructure in the counting room is likely to evolve with time. For example, the TOTEM DCS (Detector Control System) is being adapted to follow the evolution of the CERN adopted technologies. Examples are the WinCC OA 3.11, new OPC servers to communicate with the hardware and using Windows 2008. This effort is linked to the EN-ICE and CMS decisions. In accordance with the general strategy, the DCS will be able to interoperate with CMS, but allowing TOTEM to run independently.
7 Physics Performance

7.1 Beam Optics

The trajectory of protons produced with transverse positions $^2 \left(x^*, y^*\right)$ and angles $\left(\Theta_x^*, \Theta_y^*\right)$ at IP5 is described by the equation

$$\vec{d} = T \cdot \vec{d}^0,$$

where $\vec{d} = \left(x, \Theta_x, y, \Theta_y, \Delta p/p\right)^T$, $p$ and $\Delta p$ denote, respectively, the nominal beam momentum and the proton’s longitudinal momentum loss. The transport matrix

$$T = \begin{pmatrix}
    v_x & L_x & m_{13} & m_{14} & D_x \\
    \frac{dv_x}{ds} & \frac{dL_x}{ds} & m_{23} & m_{24} & \frac{dD_x}{ds} \\
    m_{31} & m_{32} & v_y & L_y & D_y \\
    \frac{dv_y}{ds} & \frac{dL_y}{ds} & m_{43} & m_{44} & \frac{dD_y}{ds} \\
    0 & 0 & 0 & 0 & 1
\end{pmatrix}$$

is defined by the optical functions. The magnification

$$v_{x,y} = \sqrt{\beta_{x,y}/\beta^* \cos \Delta \phi_{x,y}}$$

and the effective length

$$L_{x,y} = \sqrt{\beta_{x,y}/\beta^* \sin \Delta \phi_{x,y}}$$

are functions of the betatron amplitude $\beta_{x,y}$ and the relative phase advance

$$\Delta \phi_{x,y} = \int_{ip}^{RP} \frac{ds}{\beta(s)_{x,y}}.$$

Together with the dispersion $D_{x,y}$ (where nominally $D_y = 0$), they are of particular importance for proton kinematics reconstruction. Table 6 lists the effective lengths, magnifications and dispersions at the first and the last RP for three different optics. These values, together with the beam widths and divergences, determine acceptance and resolution in the protons’ kinematic variables $t$ (four-momentum transfer) and $\xi = \Delta p/p$ (momentum loss of the surviving proton), discussed in the following sections.

<table>
<thead>
<tr>
<th>$\beta^*$ [m]</th>
<th>$s$ [m]</th>
<th>$\sigma_x$ [mm]</th>
<th>$\sigma_y$ [mm]</th>
<th>$L_x$ [m]</th>
<th>$L_y$ [m]</th>
<th>$v_x$</th>
<th>$v_y$</th>
<th>$D_x$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>202</td>
<td>0.614</td>
<td>0.423</td>
<td>9.6</td>
<td>178</td>
<td>-2.88</td>
<td>0.07</td>
<td>-59</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>0.398</td>
<td>0.625</td>
<td>0</td>
<td>265</td>
<td>-1.88</td>
<td>0</td>
<td>-23</td>
</tr>
<tr>
<td>11</td>
<td>202</td>
<td>0.304</td>
<td>0.223</td>
<td>12.31</td>
<td>18.23</td>
<td>-3.92</td>
<td>-2.50</td>
<td>-120</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>0.230</td>
<td>0.272</td>
<td>4.99</td>
<td>16.96</td>
<td>-3.06</td>
<td>-3.32</td>
<td>-83</td>
</tr>
<tr>
<td>0.55</td>
<td>202</td>
<td>0.208</td>
<td>0.486</td>
<td>6.49</td>
<td>15.98</td>
<td>-4.00</td>
<td>-2.87</td>
<td>-89</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>0.090</td>
<td>0.387</td>
<td>2.02</td>
<td>12.67</td>
<td>-4.02</td>
<td>-3.40</td>
<td>-80</td>
</tr>
</tbody>
</table>

Table 6: Beam widths $\sigma_{x,y}$ (for an emittance $\varepsilon_N = 3.75 \mu m \text{rad}$) and optical functions at the RP units 210-N (at $s = 202$ m) and 220-F (at 220 m) for $\sqrt{s} = 14$ TeV. Note that the nominal vertical dispersion is zero.

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2The ‘*’ superscript indicates the LHC Interaction Point 5
7.2 Proton Acceptance

The acceptance of the RP system for elastically or diffractively scattered protons depends on the optics configuration, on the distance of the RP detectors from the beam, and on any aperture limitations in machine elements between IP5 and the RP. Figure 22 shows how different the RP hit patterns are for the $\beta^* = 90 \text{ m}$ and for the $\beta^* = 0.55 \text{ m}$ optics.

At $\beta^* = 90 \text{ m}$, the large value of $L_y$ results in a good acceptance for low $|t|$-values, both in the elastic and the diffractive case. Diffractive protons with just a small minimum $|t|$ are detected in the vertical RPs (cf. Table 7). Their momentum loss $\xi$ leads to a horizontal deviation from the sharp vertical line of elastic events. Due to the very small (and in one RP unit vanishing) value of $L_x$, this horizontal deviation is almost entirely determined by $\xi$ and the vertex. The contribution from the horizontal scattering angle becomes significant only at very large $\Theta_x^*$. All values of $\xi$ are observable via the vertical RPs. The horizontal pots only detect a small kinematic region with large $\xi$ and small $|t|$.

At low $\beta^*$, diffractive protons with a certain minimum $|\xi|$, but all values of $t$, are observed in the horizontal RPs (see Table 7).

![Simulated hit maps for diffractive events in the 3 pots of the RP unit 220-F for $\beta^* = 90 \text{ m}$ (left) and $\beta^* = 0.55 \text{ m}$ (right).](image)

### Table 7: Acceptance in $t$, $\xi$, and $M$ in DPE, for the vertical (V) / horizontal (H) detectors at the RP units 210-N and 220-F. The RPs are assumed to be placed at 11 $\sigma$ from the beam centre. Empty fields represent configurations without any relevant acceptance.

| $\beta^*$ [m] | $s$ [m] | H/V | $|t|_{\text{min}}$ [GeV$^2$] | $|\xi|_{\text{min}}$ | $M_{\text{min}}$ [GeV] |
|---------------|--------|-----|----------------|-----------------|-----------------|
| 90            | 202    | V   | 0.04           | 0 for $|t| > 0.04$ GeV$^2$ | 0 for $|t| > 0.04$ GeV$^2$ |
|               | 220    | H   | 0 for $|\xi| > 0.12$ | 0.12            | 1700            |
|               |        | V   | 0.04           | 0 for $|t| > 0.04$ GeV$^2$ | 0 for $|t| > 0.04$ GeV$^2$ |
| 11            | 202    | V   | 1.3            | 0.032           | 450             |
|               | 220    | H   | 0 for $|\xi| > 0.032$ | 0.032           | 450             |
|               |        | V   | 2.1            | 0.037           | 510             |
|               |        | H   | 0 for $|\xi| > 0.037$ | 0.037           | 510             |
| 0.55          | 202    | V   | 6.5            | 0.031           | 440             |
|               | 220    | H   | 0 for $|\xi| > 0.019$ | 0.019           | 260             |
|               |        | V   | 7.0            | 0.031           | 440             |

The minimum observable values of $|t|$ (for the vertical detectors) and $|\xi|$ (for the horizontal detectors) are given by the distances of the RPs from the beam centre. This
Figure 23: Left: acceptance of the RP 220-F (vertical) for diffractive protons at $\beta^* = 90$ m in $t$ and $\xi$. Right: projection on the $t$-axis.

Figure 24: Left: acceptance of the RP 220-F (vertical and horizontal combined) for diffractive protons at $\beta^* = 0.5$ m in $t$ and $\xi$ (for beam 1). Right: projection on the $\xi$-axis for beam 1 (red solid) and beam 2 (blue dash-dotted).

Distance is defined as a multiple $K$ of the beam width $\sigma_{x,y}$ and has lower limits determined by arguments of machine protection. For regular fills, $K \geq 11$; in special runs right after a beam-based alignment, approaches as close as $K = 3$ have been realised. Taking into account that the active detector area starts at a typical distance $\delta = 0.5$ mm from the beam-facing surface of the RP window,

\[
|t|_{\text{min}} = \frac{p^2(K\sigma_y + \delta)^2}{L_y^2} \quad \text{(vertical detectors)} \tag{11}
\]

\[
|\xi|_{\text{min}} = \frac{K\sigma_x + \delta}{D_x} \quad \text{(horizontal detectors)} . \tag{12}
\]

In the case of central production, the minimum observable mass can be calculated from $|\xi|_{\text{min}}$ using the relation

\[
M^2 = \xi_1\xi_2s \tag{13}
\]
for the symmetric case $|\xi_1| = |\xi_2| = |\xi|_{\text{min}}$. Graphical representations of the acceptance ranges for $\beta^* = 90\,\text{m}$ and $\beta^* = 0.55\,\text{m}$ are given in Figures 23 and 24. Table 7 lists the lower acceptance limits for three optics. The upper acceptance limits depend on aperture limitations and the collimation scheme (as discussed in Section 5.5.2). Typically, $|t|$-values up to the order of 10 GeV$^2$ and $|\xi| \lesssim 0.1 \div 0.2$ may be reached.

### 7.3 Resolution in Proton Kinematics Reconstruction

The reconstruction of the kinematic variables ($\Theta^*_x$, $\Theta^*_y$, $\xi$) from the proton trajectory measurements in the RPs is performed by inverting Eqn. (6) with a $\chi^2$ minimisation procedure. $t$ and the azimuth $\Phi$ are then deduced from $\Theta^*_x$, $\Theta^*_y$ and $\xi$. For detailed discussions of the technique and its performance see [2, 3].

The main challenges in the reconstruction are:

1. The correlation of the reconstructed variables $\Theta^*_x$ and $\xi$ (Figure 25) that both contribute to the horizontal proton trajectory.

2. The transverse vertex positions ($x^*$, $y^*$) that represent unknown variables in the transport equation (6) in addition to $\Theta^*_x, \Theta^*_y$ and $\xi$. Due to the absence of magnetic elements in the range of the RP system, the values of the optical functions in the different pots are linearly dependent, allowing only the reconstruction of 2 variables. Therefore, in the horizontal plane, $x^*$ is either treated as a perturbation constrained by the width of the vertex distribution, or it has to be injected from the CMS tracker measurement (30 $\mu$m). In the $y$-plane, owing to the absence of a $\xi$-term, the vertex can mathematically be reconstructed, but the resolution is not better than the width of the vertex distribution.

The unknown vertex constitutes a problem mainly at high $\beta^*$ where the vertex distribution is wide ($\sigma^*_x = 200\,\mu$m at $\beta^* = 90\,\text{m}$), less at low $\beta^*$ ($\sigma^*_x = 20\,\mu$m at $\beta^* = 0.5\,\text{m}$).

3. The $\xi$-dependence of the optical functions leading to non-linearities in the transport equation and finally to $\xi$-dependent resolutions.

The key results for $\beta^* = 90\,\text{m}$ and 0.55 m are summarised in Table 8 for the most difficult case, i.e. single-arm reconstruction of protons with non-negligible $\xi$.

![Figure 25](image_url) 

**Figure 25:** Correlation between the errors in $\Theta^*_x$ and $\xi$ reconstruction for $\beta^* = 90\,\text{m}$. 

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<table>
<thead>
<tr>
<th>$\beta^*$ [m]</th>
<th>$\sigma(\Theta_x^*)$ [µrad]</th>
<th>$\sigma(\Theta_y^*)$ [µrad]</th>
<th>$\sigma(t)$ [GeV$^2$]</th>
<th>$\sigma(\Phi^*)$ [rad]</th>
<th>$\sigma(\xi)$</th>
<th>$\sigma(M)$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 (no vtx.)</td>
<td>17</td>
<td>2.3</td>
<td>$0.22</td>
<td>t</td>
<td>^{0.70}$</td>
<td>$0.075</td>
</tr>
<tr>
<td>90 (w. vtx.)</td>
<td>5</td>
<td>2.3</td>
<td>$0.13</td>
<td>t</td>
<td>^{0.70}$</td>
<td>$0.026/\sqrt{</td>
</tr>
<tr>
<td>0.55</td>
<td>32 ± 35</td>
<td>30</td>
<td>$0.45\sqrt{</td>
<td>t</td>
<td>}$</td>
<td>$0.23/\sqrt{</td>
</tr>
</tbody>
</table>

Table 8: Resolution in the reconstructed kinematic variables of the proton for two different optics, in the case of single-arm reconstruction, at $\sqrt{s} = 14$ TeV. In the parameterisations $t$ is expressed in GeV$^2$. The label “w. vtx.” ("no vtx.") means that the vertex reconstruction from CMS is (not) used. $M$ is the mass in DPE. The lower bound in the mass resolution is achieved for central masses, i.e. symmetric proton momenta ($\xi_1 \approx \xi_2$). For increasingly asymmetric momenta the resolution degrades.

In special cases, the resolution is better than the values in the table:

- For diffractive protons with very low $|\xi|$, the $\xi$-term can be neglected. Then $\Theta_x^*$ and $x^*$ instead of $\xi$ are reconstructed. At $\beta^* = 90$ m this means that the $\Theta_x^*$-resolution is no longer dominated by the vertex term but by the detector resolution. Hence the extended lever arm from adding the new RP210 station improves the $\Theta_x^*$-resolution to $\sim 2 \div 3$ µrad, i.e. the level of the beam divergence.

- In double-arm reconstruction (elastic or DPE), the common vertex of both protons removes one variable.

- For elastic protons, the collinearity constraint allows independent determination of the vertex and the scattering angle, provided the optics is symmetric in the two outgoing beams.

### 7.4 Multi-Track Resolution

Multi-track resolution capability in the RP system will be accomplished in two stages:

1. Immediately after LS1: Tilt of the RP unit 210-F:
   The multi-track resolution achieved by the $8^\circ$ rotation is demonstrated in Figure 26 which shows the fraction of true tracks out of the total number of reconstructed track candidates (including fake combinations, called ‘ghosts’), as a function of the rotation angle of the 210-F unit. The biggest improvement happens for the first few degrees of rotation; at $8^\circ$ the ratio has already reached more than 90% even for 5 true tracks. For bigger rotations the curve saturates.

2. Later: Pixel Detectors:
   The two-dimensional track detection of 3D pixel sensors inherently provides multi-track resolution capability.
Figure 26: Monte Carlo study of multi-track resolution achieved by the rotation of one RP unit. The graphs show the ratio of the number of true tracks over all reconstructed track candidates (i.e. true tracks − lost tracks + ghosts) as a function of the rotation angle. For simplicity, parallel tracks were assumed.
8 Upgrade Time Line

8.1 Introduction

As outlined in the previous chapters of this document, we foresee to install during the technical stop LS1 one new horizontal cylindrical RP on each side of IP5. Each of these newly installed RPs will be an autonomous unit, fully independent of the existing RPs (210/220) and their associated services. A RP station is composed of the RP mechanical unit with motor drive, the cylindrical pot (housing for the detectors), the service lines (fibres, LV, cooling etc.) and the detector packages. The detector packages carrying the timing detectors or tracking pixel detectors are not discussed in this section, as the final choice of technology is not yet made. However, as the detector packages can be installed inside the cylindrical housing at any time later during the standard technical stops after LS1 (5 days duration each), we do not necessarily need to perform this work during LS1. Furthermore, it was outlined already that the main emphasis will be, in the first period of LHC operation after LS1, on the testing of the RF behaviour of the new RPs and their possible impact on the LHC beams. Therefore it is mandatory that all relevant components and services that allow the insertion of the new RPs be present before the start date of the LHC after LS1.

8.2 Production of Components for New Horizontal Cylindrical RPs

The production of the RP station will be fully done by an external company (Vacuum Praha) in Prague, CZ. This company has already constructed the present RP stations of TOTEM and is fully reliable in view of quality, cost and delivery. The cylindrical RP with the thin window will be produced at CERN (EN-MME-DI) and tested by the vacuum group (TE-VSC-LBV). The partial assembly of the RP station including the installation of the motor drive with the control system, calibration, interlock and the production of the patch panel will be performed under the responsibility of PH-DT. The installation of electronics services, fibres LV, HV, cable will be coordinated by PH-ESE, the cooling system will be delivered by Czech Technical University and EN-CV-DC. The laying of cables and services will be done by different groups of CERN (EN-MEF-SI, EN-CV-DC) and TOTEM.

8.3 Time Schedule of Production and Delivery of Components

– Work Packages WP_LS1_BP and WP_LS1_SV

All installations during LS1 in the LHC sectors 4-5 and 5-6 need to be synchronised with the LHC schedule.

In general, we split the work in the tunnel and IP5 in two main work packages to separate the work related to the integration of the RP stations in the LHC beam pipe (WP_LS1_BP) from the work related to the laying of cables, installation of cooling and services (WP_LS1_SV).

The components which are at present on the critical path are those that need to be integrated in the LHC beam pipe. A clear deadline for these components is given by the bake-out of the beam pipe elements in sector 4-5 and 5-6. According to the present planning of LHC, the bake-out of both sectors starts by April 2014. As a consequence, all components integrated in the LHC beam line need to be installed by February 2014 at the latest. From April to October the sector 4-5 and 5-6 remains free for access to perform work on services, calibration and RP movement tests.
From these dates we can define backwards the deadline of the delivery and test of the different components and the scheduling of the different work packages.

8.3.1 Components Related to Work Package WP_LS1_BP

The components listed here are related to the work package WP_LS1_BP. Applying a conservative approach in scheduling the installation, we asked the different companies and workshops to deliver their contributions to the new RP system at the latest by November 2014.

- Roman Pot station:
The production time of two RP stations at Vacuum Praha (Prague/CZ) was confirmed to be about 3 months after reception of the order. All technical drawings are ready and controlled by the CMS/CERN engineer in charge.

- Cylindrical Roman Pot with thin window:
The production drawings are ready, and the base material for the bottom part, that will be treated by electro erosion to machine the thin window, was ordered by beginning of June 2013. The delivery of the prototype cylindrical RP is scheduled for August 2013. Mechanical, pressure and vacuum tests will follow in August and September this year allowing to produce and test in a safe way two RPs during September and October.

We have chosen a conservative approach in view of material composition and thickness of the thin window to reduce the risk of iterative prototyping.

- Coating of surfaces:
Depending on the final review with the colleagues of the vacuum group and the machine protection panel of LHC we will sputter a 10\(\mu\)m copper layer on the bottom part of the RP facing the LHC beam to enhance the electrical conductivity. Furthermore a NEG coating was proposed by the vacuum group on the other elements of the RP to improve the vacuum of the LHC in the vicinity of the RPs. The decision related to these surface treatments are not yet taken and therefore not yet integrated in the production plan. Final decisions will be taken in feedback with the vacuum experts of the LHC and the machine protection panel.

- Ferrite elements:
The ferrite elements TT2-111R from TransTech (material used by the LHC collimation group) have been designed and the company confirmed the delivery of the elements not more than 10 weeks after reception of the order. The bake-out can be performed by a special company or at CERN.

- Assembly of RP and calibration of movement system in a laboratory:
The assembly and calibration of the motor system in the lab will take place in the same environment and will use the same technical infrastructure as was used for the service work of the RP220 and RP210 stations. According to the present time schedule of the consolidation work, all stations of RP210 and RP220 will be serviced and ready for re-installation in the tunnel by October 2013.

- Motors, LVDTs, control:
The motors and LVDTs are available from the collimation group. The control system can be extended by additional FPGAs and PXIs.
8.3.2 Components Related to Work Package WP_LS1_SV

- **Patch Panel:**
  The production will be done by the PH-DT group. The patch panel for the RP 210/220 has already been produced by PH-DT.

- **Fibres:**
  The fibres have been selected, and the delivery is scheduled for August 2013.

- **Low voltage, High voltage, DCS:**
  The low voltage power will be taken from the existing power supplies which are located in the tunnel alcove.

  New standard HV cables (2.5 kV) have been selected and can be delivered with little delay to CERN.

  The RP will be equipped with 7 PT100 probes and 2 pressure probes that will be read out via ELMB. TOTEM has enough free ELMB cards on stock. The corresponding new standard cable will be laid in the existing cable trays starting at IP5/CMS.

- **Cooling system:**
  The new RPs will be RF optimized resulting in only several Watts of heat intake from the LHC beam. We foresee to adopt the innovative air cooling (Vortex cooling) which needs only pressured air lines (10 bar). The cooling system is presently under development at Czech Technical University.

- **Vacuum system:**
  The additional RPs will be integrated in the present vacuum system of RP220.

- **Interlock logic box:**
  The interlock box will be redesigned to integrate the newly installed RPs.

8.4 Coordination with Support Groups and LHC

After approval of the upgrade program, the corresponding work packages will be finalised with the different support groups. The ECR (TOTEM upgrade) related to the work in the tunnel is done closely together with the LTEX group (EN-MEF-LE) that interfaces the TOTEM experiment to the LHC. It should be mentioned that the work in the tunnel related to the consolidation program is discussed in a separated ECR (consolidation), and this work has already started.

8.5 Review of RP Project

As already announced in the 19th LTEX meeting (16. May 2013), TOTEM wishes to review the TOTEM RP upgrade project with relevant LHC groups, the machine protection panel and participating technical groups. The date for this review meeting is scheduled for July 2013.
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