Beam-induced heating in the TOTEM Roman Pot detectors at the LHC

F. Ravotti
CERN PH-DT, Geneva, Switzerland

Abstract

During 2011, temperature increase has been observed in the TOTEM Roman Pots installed in the LHC (sector 45) while the proton beams were circulating in the accelerator ring. The warming up has been recorded with the detectors in standby mode and in absence of the active detector cooling which would have guaranteed a constant operational temperature of about -25°C. This effect, induced by beam coupling impedance, is a critical issue for the operation of the Roman Pots and needs to be quantified in detail. This note describes the results of the analysis carried out on the temperature data measured in the TOTEM RP up to the maximum total beam intensity of $1.9 \times 10^{14}$ p/beam which is the limit reached by LHC in 2011 using 50ns-spaced proton bunches. Finally, the data presented here allows estimates of the maximum temperature that could build up in the detectors at LHC nominal beam intensities (25ns-spaced bunch trains).
1 Introduction

The TOTEM experiment measures the total $pp$ (proton-proton) cross section and studies elastic scattering and diffractive processes at the LHC [1]. The Roman Pots (RP), one of the TOTEM sub-detectors, are movable beamline insertions allowing detection of very forward protons which are scattered out of the LHC beam by a very small angle after their collision in the Interaction Point (IP). RP stations are located in the LHC tunnel on each side of IP5: two at ±220m and two at ±147m distance from it. Each RP station is composed of two units separated by a distance of a few meters. The units are labeled as near ($nr$) and far ($fr$) according to their distance to the IP. A unit consists of 3 RPs: two approaching the outgoing beam vertically ($top$ and $bottom$) and one horizontally ($hz$), allowing a partial overlap between horizontal and vertical detectors. A total of 24 RPs are installed at the LHC since 2010. The RP are moved to very small distances from the beams, in 2011 mainly during LHC runs with special high $\beta^*$ optics and only a few proton bunches. During the LHC runs at high luminosity with nominal (low $\beta^*$) optics the RPs remained for most of the time in their “parking” position, with the detectors about 4cm away from the beams. However, independently from their position with respect to the LHC beams, the RP insertion represents a discontinuity in the beam-pipe which interacts with the beam itself via coupling impedance [2].

Longitudinal and transverse effects related to coupling between the “cavity-like” structure of the RP insertion and the beam have been studied with laboratory measurements and numerical simulations [3]. Following those studies, ferrite tiles for absorbing RF power have been installed as collars around the pots [4]. Although this mitigation solution was applied, nowadays, significant RF power is still lost in the RP insertion and causes a warming of the detector components. The aim of this note is to summarize the observations of beam-induced heating made in 2011 and to use them to extrapolate the temperature which could be reached in the RP detectors at nominal LHC beam intensity (2808 bunches injected in the LHC ring, 25ns-spaced which corresponds to a total intensity of $\sim 3-4 \times 10^{14}$ p/beam).

2 Location of the temperature probes

Each RP detector is equipped with a series of temperature sensors continuously read out via the TOTEM DCS [5]. Ten PT100 sensors are installed on the ten detector hybrids (one each) while four PT1000 sensors are mounted on the two independent pipe evaporators which supply the cooling fluid to the right and left side of the detector package, as shown in Fig. 1 (right-hand side). Because of cables availability, only two out of ten PT100 sensors are read out during RP operation. For each RP, the PT100 of hybrid nr. 8 is read out directly from the DCS electronics via ELMBs (named $Temp01$) while the second probe, the one installed on the hybrid nr. 3, is directly wired to the CMS Detector Safety System (DSS). The measured value from the latter is then transmitted and made available in the TOTEM DCS via software protocol. Finally, outside the vacuum vessel, about 30cm away from the silicon detector, another temperature sensor is available in the RP. This NTC sensor (called here $RadmonNTC$) allows the correction of the temperature dependence in the radiation
monitoring devices [6]. This measurement point can thus be used to verify the extent of the temperature gradient across the whole RP structure. Calibration parameters for those sensors are applied in the DCS software, individually for each temperature probe, in order to guarantee the comparability of the measured values.

Fig. 1. Location of the temperature sensors in the Roman Pot detector assembly. PT100 probes are on board each detector hybrid (left-hand side), while the PT1000 are mounted on the evaporator pipes outside the detector assembly (right-hand side).

To allow operation after high irradiation, the RP silicon detectors are constantly kept at about -25°C to reduce the radiation-induced thermally generated bulk current and to control the reverse annealing after high irradiation [1]. Moreover, the cooling system also removes the thermal load from the sensors and the electronics. Therefore, during normal operational conditions, the effect of external heat loads, such as the one induced by coupling impedance, is eliminated.

3 Experimental data

In the event of a failure of the cooling system or whenever this is kept deliberately switched off while the proton beams are circulating in the LHC, an increase of the temperature in the detector volume is observed. During the run 2011, this occurred twice:

1. During the month of May: the cooling loop of the station 147m of sector 45 was turned off for testing purposes over several days (from 16 to 30 May 2011). In that period, the LHC ran with gradually increasing number of injected proton bunches (from 228 to 1092) and therefore with the injected peak intensity increasing from $2.5 \times 10^{13}$ to $1.3 \times 10^{14}$ [7];
2. On September 19th: warming up of the RP station 220m of sector 45 due to a problem in the vacuum system of the same station. Overnight, a train with 1380 bunches was injected, corresponding to a peak intensity of $1.9 \times 10^{14}$ p/beam.

During both periods, the intensity of every injected proton bunch ($N_b$) was constant: a maximum spread of about 20% has been calculated on the average bunch intensity measured for every fill used in this study. In the following, the event of September 19th will be described in detail, while the data recorded during May will be used later on to study the heating effect as function of the peak beam intensity injected into the LHC. All data presented in this document refers to **RP detectors in “parking” (garage) position**, e.g. $d \approx 4$ cm from the beam axis.

![Fig. 2. Temperature behavior in the RP station 45-220m in Sep. 2011. The primary y-axis refers to the total beam intensity (total # of charges = p/beam), while the temperature plots refer to the secondary y-axis.](image)

Fig. 2 shows the variation of the temperature in the Roman Pots of the station 45-220m during the night of September 19th. The violet curve represents the average of the six *Temp01* recorded on each RP detector. The temperature increase follows the injection of beam 2 in the LHC and reaches a maximum value (*Peak Temp.*) when the thermal equilibrium is achieved. An average peak $T \approx 41^\circ C$ was reached. Afterwards, the temperature decreases together with the decay of the beam intensity (red curve – data of the BCTDC extracted from TIMBER).

Fig. 2 clearly demonstrates that the heat deposition is related to the power lost by the beam in its surrounding. The blue curve represents the temperature measured by the *RadmonNTC* outside the secondary vacuum vessel of the RPs. While the temperature inside the detector rises, on average, by more than 15°C, the *RadmonNTC* is essentially stable.
within 1-2°C. Although the level of the secondary vacuum was steadily degrading inside the station 45-220m, an additional “kink” in the pressure rise is observed synchronous to the temperature increase (not shown in the picture). The pressure decreases then again once the heat source is switched off, as it happens during normal RP operation.

Fig. 3 (left-hand side) compares the temperature behaviors recorded by the Temp01 of every RP in the station. The two horizontal pots show a temperature increase 6-7°C higher than the vertical one. The plot in the right-hand panel of Fig. 3 compares the reading of the PT100 sensors with the one of the PT1000 for a couple of RP detectors. Since the sensor-to-sensor variation was less than 2°C, the plotted PT1000 curves are the averages of the four measurement points present in each pot.

Fig. 3. Individual temperature behaviors (Temp01) for each RP of the station 45-220m (left-hand side). Comparison of the PT100 vs. PT1000 readout for two RPs of the same station (right-hand side).

The lower mass of the evaporator pipes with respect to the one of the detector hybrids explains the reduced heating effect measured by the PT1000.

Fig. 4. Comparison of the peak temperature in each RP measured on the hybrid nr. 8 (Temp01) and in the hybrid nr. 3 (DSS). The dotted lines represent the average values across the six RPs.
Fig. 4 compares the peak temperatures measured by the two PT100 mounted on the different detector hybrids. Since the hybrid nr. 3 (DSS) and the hybrid nr. 8 (Temp01) are located at different positions in Z, this plot gives indications about the heat distribution among the ten detector planes. A difference of less than 2°C between the two temperatures, in all six RPs, indicates a good homogeneity of the heat distribution inside the detector assembly.

During the period of May 2011, several data sets like the one described in Fig. 1 to Fig. 4 are available for the station 147m of sector 45. As also visible in Fig. 1, 3h ± 20min are needed on average to reach the peak temperature after beam injection. Therefore, only beam periods lasting longer than 3h were used for the following analysis.

Fig. 5 reports the average peak temperature reached by the RP station (average of the six Temp01) as a function of the peak beam intensity injected into the LHC. As explained above, since the bunch intensity is essentially constant, the beam intensity increases because of the increasing number of bunches injected in the LHC. Table 1 summarizes the number of bunches injected in the LHC corresponding to every experimental point shown in Fig. 5. The data of both stations can be combined since they all refer to the Roman Pot detectors of sector 45 on beam 2. The error bars represent the standard deviations from the average values.

The green and red lines on Fig. 5 represent the best fits of the experimental data with a linear and second order polynomial model respectively. The first set of experimental points is consistent with a linear behavior for increasing number of bunches (e.g. increasing total beam intensity). This could be interpreted as the results of a power loss dominated by a broadband
impedance which is likely to occur when a limited number of bunches is injected in the accelerator ring (bunches not regularly distributed along the accelerator). In this configuration, the power loss ($P_{\text{loss}}$) is described by:

$$P_{\text{loss}} \propto M \times N_b^2$$  (e.g. linear with the total beam current)

where $M$ is the number of bunches per beam and $N_b$ is the bunch intensity which is a constant for the different fills [8]. At higher intensities, the behavior is instead better described by a quadratic polynomial and consistent with a power loss dominated by narrowband impedance, as it has been observed also for other elements along the LHC ring which behave as resonant cavities [9]. In such a condition, the power loss can be described by:

$$P_{\text{loss}} \propto M^2 \times N_b^2$$  (e.g. quadratic with the total beam current)

The power loss measured in the TOTEM Roman Pots is probably a superposition of both effects. A more in-depth understanding of this phenomenon and of the theoretical model underneath will require a correct modeling of the thermal capacity of the Roman Pot detector. This with the aim of calculating analytically the real impedance exposed to the beam. The resonant model, being the worst-case scenario in terms of power dissipated inside the RP detectors, has been privileged for the following calculation.

For the purposes of this document, the data are finally extrapolated to the nominal LHC beam intensity (LHC filled with about 2800 bunches) which is roughly twice as much as the maximum intensity injected in the LHC during 2011 (filling scheme limited to 1380 bunches). According to the quadratic extrapolation, a temperature near 100°C could be reached.

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Table 1. Composition of the fills used to study the heating effect as function of the peak beam intensity injected into the LHC.
4 Conclusions

The data presented in this note quantify the magnitude of the temperature increases in the TOTEM Roman Pots induced by the beam coupling impedance. The measurements refer to pots installed in sector 45 of the LHC, in “garage” position during runs with normal (low $\beta^*$) optics and increasing total beam intensities. The average temperature peak reached, over all detectors belonging to the same RP station, was ~41°C. The maximum absolute value recorded for one single RP was about 46.5°C ($45_{220 \text{ fr} \_ \text{hz}}$). While these temperature values are still within the safety limits, this will probably not be the case anymore when the LHC will run with its nominal total beam intensity. A temperature peak approaching 100°C has been extrapolated here on the base of the available 2011 data suggesting a quadratic dependence on the beam current.

Note that, under normal circumstances, all RPs are permanently cooled to -25°C and thus there is not impedance heating. Problems only arise when the cooling either fails or has to be switched off due to degradation of the secondary vacuum of the RPs. To overcome this issue, modifications on the TOTEM Roman Pot cooling system were implemented during the winter technical stop 2011-2012 [10]. These changes will allow the cooling plant to run the RP detectors at a safe “warm” temperature above the dew point, whenever the operational RP temperature of -25°C cannot be maintained.

Acknowledgement

The author would like to thank M. Deile (PH/TOT) and E. Metral (AB/ABP) for the review of the manuscript and their valuable contribution to improve it.
References


