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BEAM IMPEDANCE OPTIMIZATION OF THE TOTEM ROMAN POTS

N. Minafra[1] on behalf of the TOTEM Collaboration
[1]INFN sez. di Bari, Italy and CERN, Geneva, Switzerland

Abstract

The TOTEM experiment has been designed to measure the total proton-proton cross section and to study elastic and diffractive scattering at the LHC energy. The measurement requires detecting protons at distances as small as 1 mm from the beam center: TOTEM uses Roman Pots (RP), special beam pipe insertions, to move silicon detectors close to the beams to detect particles very near the beam axis. In the first period of running of the LHC no problems were detected with retracted Roman Pots and during insertions in special runs; however, during close insertions to highest intensity beam, impedance heating has been observed. After the LS1 the LHC beam current will increase and the equipment that can interact with the beam needed to be optimized. A new RP, optimized to minimize the beam coupling, has been designed with the help of CST Particle Studio; a prototype has been used to test the simulation results in the laboratory with wire and probe measurements. Furthermore, in both the old and the new RPs, new ferrites have been installed. The new ferrite material has a higher Curie temperature than the one used before LS1 and a thermal treatment at 1000°C has been applied to reduce the out-gassing.

IMPEDANCE SIMULATIONS

A particle beam can induce resonances in any cavity created by the vacuum chamber. When the geometry of the vacuum chamber is too complex, analytical models can not be used to predict the impact of these resonances on the beam and on the environment. Thus, software like CST Particle Studio [1] are used to numerically simulate the evolution of the electromagnetic field inside the cavity after the passage of a particle beam.

A Roman Pot (RP) is a movable part of the beam pipe that allows the positioning of a detector up to a few millimeters from the beam without interfering with the primary vacuum. Especially for equipment that can approach the beam so closely, the impedance has to be optimized and numerical simulations were a key part of the development [2].

The interaction between the beam and the cavity can be harmful for the beam itself, introducing instabilities, but can also damage the equipment, for example due to excessive beam induced heating.

To foresee the instabilities it is useful to compute Z^{eff}, the impedance effectively felt by the beam; the imaginary part of the effective longitudinal impedance $(\Im Z_{\text{long}}/n)^{\text{eff}}$, where $n = f/f_{\text{rev}}$ is the harmonic number, is an indication of the dispersion of the beam through the cavity.

In a similar way, it is possible to compute the power lost by the beam and transferred to the cavity [3] [4]:

$$P_{loss} = 2\,I^2 \sum_{p=1,\,\dots,\,\infty} PS(pM' f_{\text{rev}})\Re[Z_{\text{long}}(p\,M'\,f_{\text{rev}})] \tag{1}$$

where, $PS(f)$, f_{rev}, M' and I are the power spectrum, the revolution frequency and the number of buckets of the LHC;Z_{long} is the simulated longitudinal impedance.

The goal of the optimization is to reduce both heating and effective impedance.

OPTIMIZATION OF THE DESIGN

Before the Long Shutdown 1 (LS1) all Totem RP installed in the LHC were box shaped, as shown in Fig. 1. This design has several mechanical advantages; for instance, the relatively small size of the detector housing does not require the separation between the detector and the primary vacuum to be thicker than 150 μm, reducing the secondary particles shower produced inside the steel and reducing the minimum possible distance of the detector from the beam.

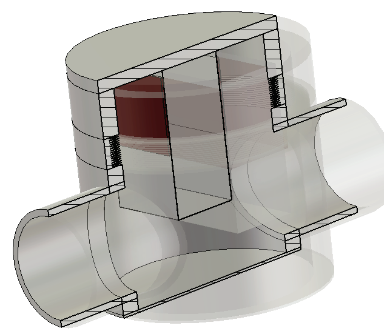

Figure 1: Before LS1 all Totem Roman Pots were box shaped. The empty space between the RP and the flange resonate at low frequency (~ 500 MHz).

However, from a RF point of view, the box RP has a considerable amount of empty space between the detector housing and the vacuum flange that resonates at low frequency (~ 500 MHz). This lead to the introduction of planes of ferrite [5].

Moreover, some of the time-of-flight detectors proposed for the the future upgrade require more longitudinal space inside the RP [6]. The new RP has been designed to increase the space available for the detector, together with reducing the impedance.

The simple solution of having a detector housing that uses all the available space would be ideal; however, the RP needs to be safely inserted and retracted and mechanical constraints and tolerances have to be considered.

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The final design, shown in Fig. 2, has a 2.5 mm gap around the detector housing to guarantee a safe movement and has a small ferrite ring to damp the resonances due to this gap.

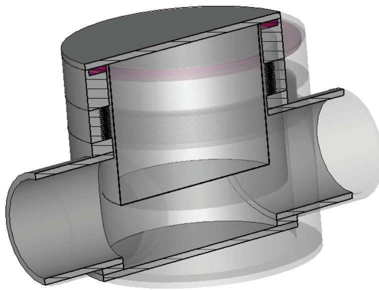

Figure 2: The Cylindrical RP has been designed to increase the space available for the detector and to decrease the impedance.

Furthermore, following the same strategy, a RF shield has been developed to optimize the impedance of the box RP (Shielded RP shown in Fig. 3) without a complete replacement of the existing RPs. The shield is made of a thin layer of copper and stainless steel; some holes on its side and bottom guarantee enough ventilation.

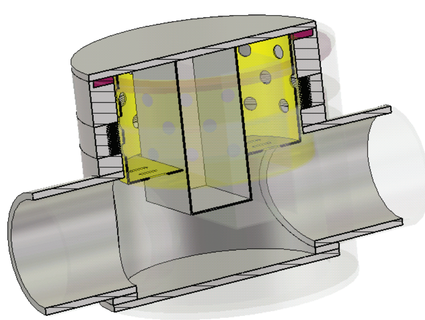

Figure 3: The Shielded RP has been designed to optimize the impedance of the box RP without a complete redesign.

The RF performances of the optimized design are undoubtedly better than the old box RP. As shown in Fig. 4 and Fig. 5 the new RP behaves better both when the RP is retracted in garage position at 40 mm and when is inserted close to the beam.

Beside the RF optimization, the new design has been improved also from a thermo-mechanical point of view. Indeed, the energy stored in the cavity is mainly dissipated inside the ferrite material that happens to be a brittle material that is not easy to cool in vacuum. The chosen ferrite material (Trans-Tech™ TT2-111R, with $T_C \sim 375°C$) is able to tolerate higher temperatures than the one used in the previous version (Ferroxcube 4s60, with $T_C \sim 100°C$) and has been treated at $1000°C$ to reduce the out-gassing.

TEST BENCH MEASUREMENTS

Tests to check the validity of the simulations were performed on a prototype of the new RP stations: the tests

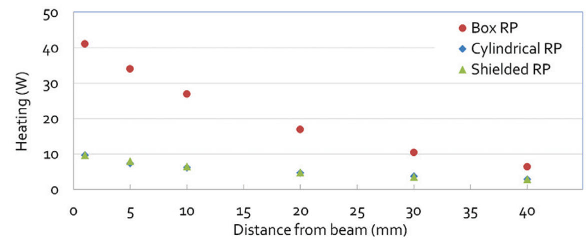

Figure 4: The cylindrical and the shielded RPs have a ~ 4 times lower heating than the box RP at 1 mm from the beam, with a 25ns beam spacing, 2800 bunches and $1.3 10^{11}$ protons per bunch (beam current of 0.65A).

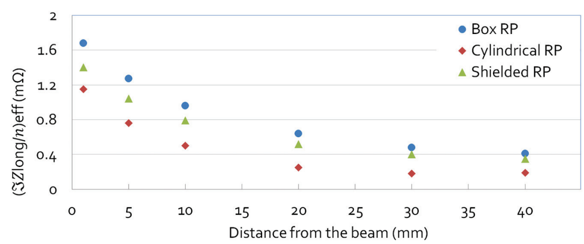

Figure 5: The cylindrical RP has a ~ 50% better $(\Im Z_{\mathrm{long}}/n)^{\mathrm{eff}}$ than the box RP at 1 mm from the beam.

consisted of studying the cavity with a probe or using one or two thin wires to simulate the presence of the beams.

In particular, one of the tests is done positioning a thin wire at the center of the beam pipe, using the setup shown in Fig. 6. A current pulse traveling through the wire perturbs the cavity in a way similar to a bunch of charged particles.

While the electromagnetic behavior of the cavity is perturbed by the presence of the wire, adapting the same models used to optimize the impedance, it is possible to simulate the behavior of the device under test and to compare the measured transmission coefficient, S_{21}, with the simulated one.

These tests represent an important milestone to ensure that the numerical model are accurate and that the details not implemented in the models (soldering, imperfections, etc.) have a negligible impact on the results.

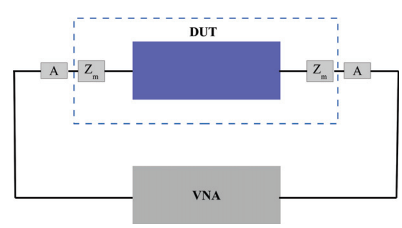

Figure 6: A single wire is stretched along the device under test (DUT) and connected to a Vector Network Analyzer (VNA). The impedance matching is ensured by the network (block "Z_m") and the series attenuator (block "A").

The tests were done on the prototypes (Fig. 7) of the new cylindrical RP and of the shielded box RP and all results were in good agreement with the simulations done using the numerical models [7]. Simulations and results for the

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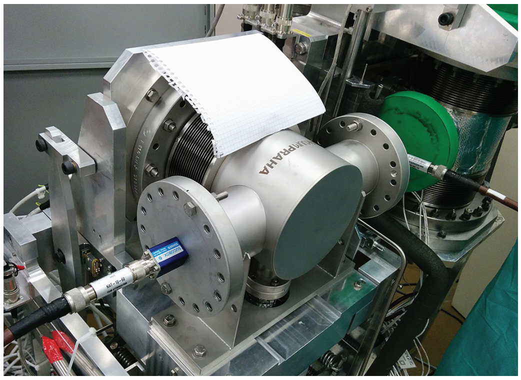

Figure 7: The RF measurement were done using a prototype station.

cylindrical RP are shown in Fig. 8 and 9, while for the shielded RP are shown in Fig. 10 and 11.

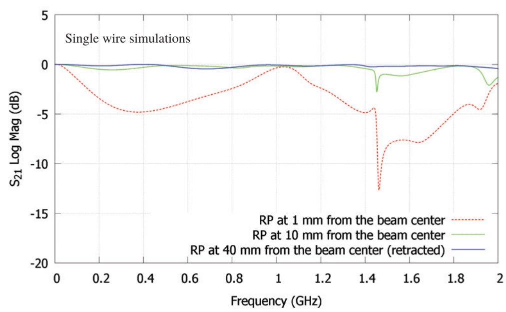

Figure 8: Simulated transmission coefficient (S_{21}) for the wire test with the Cylindrical RP at 1 mm, 10 mm and 40 mm from the center of the beam pipe.

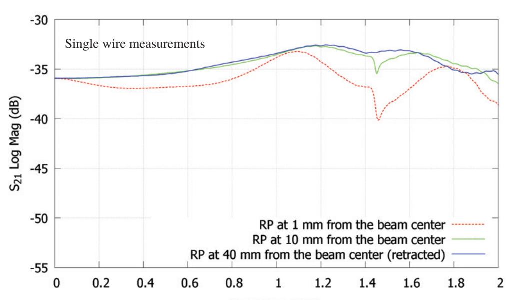

Figure 9: Transmission coefficient (S_{21}) for the wire test with the Cylindrical RP at 1 mm, 10 mm and 40 mm from the center of the beam pipe.

CONCLUSION

The TOTEM Collaboration has designed, realized and tested a new Cylindrical Roman Pot and a new RF shield has been proposed and realized to improve the RF behavior of the old RP model without requiring a complete redesign. The new design was simulated using CST Particle Studio and RF bench measurements were performed on the prototypes showing good agreement with the simulations.

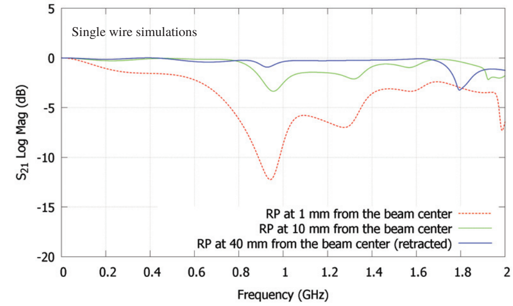

Figure 10: Simulated transmission coefficient (S_{21}) for the wire test with the Shielded RP at 1 mm, 10 mm and 40 mm from the center of the beam pipe.

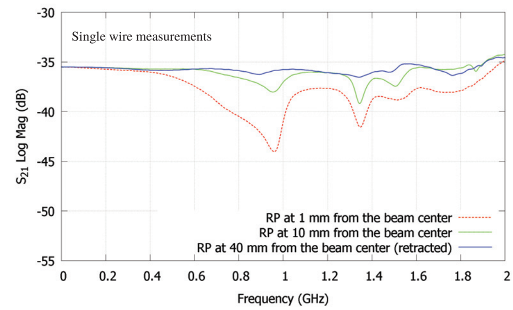

Figure 11: Transmission coefficient (S_{21}) for the wire test with the Shielded RP at 1 mm, 10 mm and 40 mm from the center of the beam pipe.

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