5th International Particle Accelerator Conference IPAC2014, Dresden, Germany JACoW Publishing
ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPRI058

IMPEDANCE STUDIES OF THE DUMMY SEPTUM FOR CERN PS MULTI-TURN EXTRACTION

S. Persichelli*, M. Migliorati, CERN, Geneva, Switzerland and University La Sapienza, Rome, Italy
O. Berrig, J. Herbst, J. Kuczerowski, M. Giovannozzi, B. Salvant, CERN, Geneva, Switzerland

Abstract

A protection septum has been installed in the CERN PS section 15 in order to mitigate irradiation of the magnetic septum 16 for fast extractions towards the SPS. Impedance studies have been performed, showing that beams circulating in the septum during extraction generate sharp resonances in the coupling impedance. Impedance measurements with the wire technique have been performed, showing a good agreement with simulations. Instability rise times of trapped modes have been evaluated and compared to extraction duration. Solutions for reducing the impact on the stability of the beam have been considered.

INTRODUCTION

The CERN Proton Synchrotron (PS) has a fundamental role in LHC injectors chain, producing high intensity and brigthness beams delivered to the Super Proton Synchrotron (SPS) for collision in the LHC. In this framework, the PS Multi-Turn Extraction (MTE) [1–3] was proposed as a new technique of beam transfer from PS to SPS. During the commissioning phase of MTE, a high level of activation of the magnetic extraction septum in straight section 16, due to particles lost during the rise time of the extraction kickers, have been observed. The adopted solution consists in installing a dummy septum in straight section 15 [4], a passive protection device, made of a thin metallic blade intercepting the beam during the rise time of the kickers. The blade does not interfere with the circulating beam but, during extraction, absorbs particles that would be otherwise intercepted by the magnetic septum blade, thus reducing its activation level. The absorbing particles blade is mounted on a solid copper support table that is also designed for transferring heating released by the beam in the blade via a copper conductor connected to water cooling. The position of the blade can be adjusted by a remote displacement system which allows an accuracy of 0.1 mm. The blade can be placed between 80 and 100 mm from the PS orbiting beam position during operation. A stainless steel RF beam screen has been integrated and connected to the upstream and downstream ends of the tank using multi-contacts. Finally, a beam observation system has been installed, in order to measure the position of the extracted beam and to adjust precisely the extraction blade position. After installation the device will be enclosed in a concrete shielding, in order to minimize the level of radiation in the area. A sketch of the septum is shown in Fig. 1.

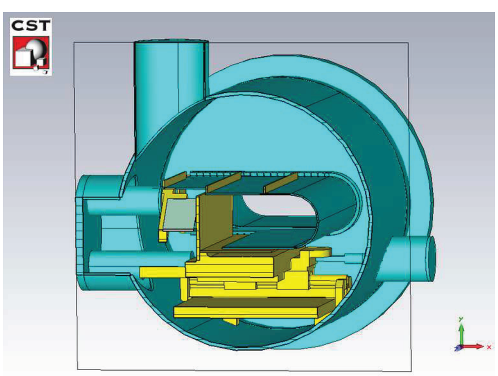

Figure 1: CST Particle Studio model used for impedance simulations.

* serena.persichelli@cern.ch

BEAM COUPLING IMPEDANCE SIMULATIONS

Longitudinal and transverse impedances of the septum have been evaluated with CST Particle Studio Wakefield Solver [5] at different distances from the location of the blade: in Fig. 2 the real part of the longitudinal impedance excited by a bunch of 26 cm (shortest r.m.s. bunch length for the PS), circulating 5 mm away from the axis of the copper blade, during extraction, is shown. Negative values of the longitudinal impedance are artefacts of the Fourier transform of a finite length non decayed oscillating signal without windowing. Trapped modes excited by the beam show longitudinal and transverse components; only numerical examples for the longitudinal component of the impedance are shown in this paper, since the transverse components have a similar behaviour. Trapped modes frequencies, which also correspond to the eigenvalues of the closed structure, do not depend on the beam position. Before extraction, while the beam covers 90 mm in about 6 ms to approach the extraction blade, a significant increase of shunt impedance for many trapped modes has been observed. During extraction, when the beam is close to the blade at a minimum distance of 5 mm, the maximum of the shunt impedance is reached. This effect is due to the strong electromagnetic field trapped at the edges of the metallic blade after the passage of the beam. The amplitude of the impedance peaks in Fig. 2 does not correspond to the shunt impedance of each resonance, since the saturation of the peaks is reached when the simulation is performed with a wake length of about 7 km. Only numerical examples of the longitudinal impedance obtained with a wake length of 100 m are shown, as qualitative output of CST Particle Studio. CST Microwave Studio frequency domain simulations have been performed to crosscheck results obtained from time domain. Frequency, Q factor and

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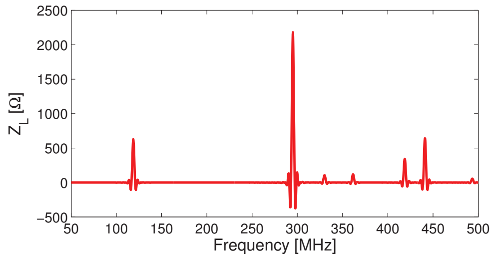

Figure 2: Longitudinal impedance during extraction evaluated with CST Particle Studio.

shunt impedance R_s were calculated for several modes post-processing the Eigenmode simulation. Results for the first trapped mode are shown in Table 1.

Table 1: Evaluation of the resonance parameters for the first trapped mode excited by the beam.

Position	*Frequency*	*Q*	R_s
Nominal	118 MHz	2655	62 Ω
Extraction	118 MHz	2655	36.2 $k\Omega$

Coupled Bunch Instability Calculation

Longitudinal coupled bunch instability growth rate was calculated for the 118 MHz mode with the following formula, valid for a mode fully coupled with the multi-bunch spectrum [6]:

$$\alpha = \frac{c^2 \eta_c q N_b}{2L^2 E_0 \omega_s} \omega_r Re(Z(\omega_r)) \tag{1}$$

where c is the speed of light, η_c is the slippage factor, q is the bunch charge, N_b is the number of bunches, L the length of the machine, E_0 the total beam energy, ω_s the synchrotron frequency and ω_r the resonance frequency. Resonant parameters are taken into account for the calculation of the impedance:

$$Z(\omega_r) = \frac{R_s}{1 + iQ(\frac{\omega}{\omega_r} - \frac{\omega_r}{\omega})}. \tag{2}$$

Since the septum is going to be present in all operational conditions and with different types of beam, growth rates were evaluated in several conditions, also assuming worst case scenarios. Beam parameters considered for the estimations are summarized in [4] and [7]. Furthermore, to be closer to real conditions, the actual longitudinal Gaussian shape of the bunch has to be considered. Shunt impedance R_s evaluated with CST Microwave Studio was corrected with the following form factor to account for the length of the bunch:

$$R_s^{'} = R_s e^{-(\omega_r \sigma_b)^2} \tag{3}$$

When this correction is taken into account, the amplitude of the shunt impedance is drastically reduced. In Table 2, the values of growth rate for the 118 MHz mode, evaluated

Table 2: Coupled bunch instability growth rates evaluated for different beam position inside the septum (0-60 mm displacement from the geometrical center corresponding to orbit and extraction, respectively).

Position	$R_s^{'}[\Omega]$	$\alpha[s^{-1}]$ 13 *GeV*	$\alpha[s^{-1}]$ 26 *GeV*
0 mm	10	0.15	0.08
60 mm	770	11.97	6.25

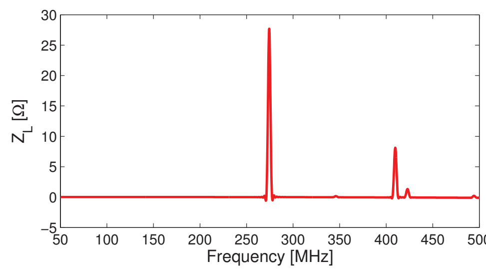

Figure 3: Longitudinal impedance at extraction evaluated with CST Particle Studio after the insertion of sliding contacts.

both at intermediate (13 GeV) and high energy (26 GeV), for different beam positions, are summarized.

These growth rates are very short compared to the typical ones in the PS [8]. Nevertheless, they become non negligible during extraction: in the final position the rise time of 170 ms evaluated at 13 GeV could sound alarming, but since the beam is extracted in 6 ms, corresponding to three PS synchrotron periods, we believe that the instability does not have time to develop. Therefore, these considerations allow to state that coupled bunch instability is not predicted to be enhanced by this mode.

Mode Dumping Solution

In the unlikely event of unexpected failure or damage of the dummy septum after installation and shielding, repairing action will not be possible because of the predicted high level of activation. This fact justifies the importance of finding preventive measures to reduce the impedance and its impact on the stability of the beam: in this respect, two proposals of modifications of the inner design have been studied with the aim of damping the 118 MHz mode. Since the resonance at 118 MHz is mainly localized in the gap between the RF been screen and the support table, the first solution consists in inserting sliding metallic contacts between them: closing the gap has the effect of cancelling the mode at 118 MHz, as shown in Fig. 3.

The second solution consists in the insertion of a block of ferrite TT2-111R, that reduces the shunt impedance and Q factor of the mode itself. As a consequence, the impact on PS coupled bunch instability would be less critical, according to Eq. (1). With this solution, the shunt impedance reduction of the 118 MHz mode at extraction has been estimated to be about a factor 600. For power loss estimation, we consider the following formula for sharp resonances [9]:

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$$P_l = 2(MI_b)^2 R_s 10^{\frac{P_{dB}(f_r)}{10}} \quad [W] \tag{4}$$

where MI_b is the total beam current, R_s is the shunt impedance (circuit convention) and $P_{dB}(f_r)$ is the power in dB read from the beam power spectrum at the frequency f_r. Heating would be about 3.6W, since the 118 MHz mode falls inside the PS bunch extraction spectrum with power of -20 dB. According to equipment experts, the deposited heating should not represent a problem, and the foreseen cooling system should cope with it. As an outcome of these studies, the decision has been taken to install the sliding contacts between the RF beam screen and the support table. The option of installing a block of ferrite is left as a fall back solution to be implemented only in case of failure of the sliding contacts. Therefore, the blade displacement system has been equipped with a support that could be used to house the ferrite block.

Impact on the PS Impedance Budget

From CST Particle Studio simulations a long bunch of r.m.s. length 1.5 m circulating in nominal position excites an imaginary part of the longitudinal impedance that is purely inductive, and the effective impedance has been evaluated to be $\frac{Z_p}{p} = 0.001\ \Omega$, where $p = \frac{f}{f_{rev}}$. In comparison with the current longitudinal impedance budget of 18.4 Ω measured in [10], the contribution of the dummy septum to the PS longitudinal impedance budget is expected to be negligible. When the bunch circulates at 5 mm from the blade before extraction, the effective impedance has been evaluated to be $\frac{Z_p}{p} = 0.12\ \Omega$. In this situation, the contribution of the dummy septum to the PS longitudinal impedance budget is less than 1%. For the sake of comparison, the 200 MHz cavities provide a contribution of about 4% of the total longitudinal impedance. Hence, no issue is expected under any of the operational conditions foreseen.

RF IMPEDANCE MEASUREMENTS

Impedance measurements have been performed to confirm the results of numerical simulations, to test the effectiveness of the sliding contacts, and to assess the need of ferrite. The well-known technique based on the coaxial wire method has been used [11], allowing to excite an electromagnetic field similar to the one generated by an ultra-relativistic point charge. This setup allows measuring the transmission coefficient S_{12} by means of a Vector Network Analyzer (VNA). The longitudinal impedance for three positions of the wire has been measured, corresponding to the wire in nominal position (orbiting beam), wire at 30 mm from the orbit beam position (geometrical center of the septum), and wire at 60 mm from the orbit beam position (extraction). During all the measurements the copper blade was positioned at 90 mm from the circulating beam position. In Fig. 4 the comparison of the impedance measured at the three different wire positions is shown. As observed in simulations, the amplitude of impedance peaks is increasing while the wire is closer to the extraction blade. Measurements also confirmed that

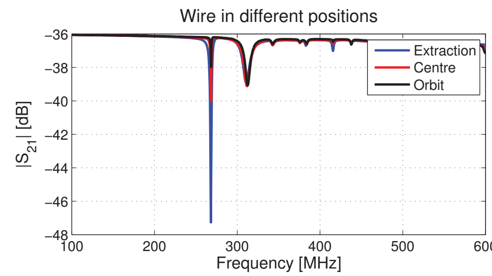

Figure 4: The S_{12} transmission coefficient measured for three positions of the wire.

trapped modes frequencies do not depend on the beam position; moreover, both measurements and CST simulations agree on the frequency of the first trapped mode resonating in the septum. The mode has a frequency of 270 MHz, thus indicating that the sliding fingers are working as expected cancelling the mode at 118 MHz. Moreover, 270 MHz is too high frequency to be a source of coupled bunch instability in the PS, even with a Q factor of 3413, shunt impedance calculated at extraction of 21.6 $k\Omega$ and power loss at extraction 9 W. Also in this case the foreseen cooling system should cope with power loss. From Eigenmode simulations it is clear that this mode is generated by resonances trapped in the gap between the RF screen and the copper blade, and it increases in amplitude when the wire is set closer to the blade, as shown in Fig. 4. Impedance measurements exhibit a slightly different behaviour with respect to CST simulations in the higher order trapped modes arrangement. The reasons for these differences are still under investigation; however the highlighted modes frequencies are outside the PS bunch spectrum and are predicted not to be a source of coupled bunch instability or heating. Nonetheless, the outcome of the measurements confirms that the dummy septum can be installed in the PS ring and that the insertion of ferrite is not needed.

CONCLUSIONS

In this paper the beam coupling impedance of a dummy septum installed in the CERN Proton Synchrotron (PS) during the Long Shutdown 2013-2014 has been discussed. Electromagnetic simulations, RF measurements and calculations for reducing the coupled bunch instability, have been performed. Preventive actions to reduce the instabilities have been suggested and realized in the final design of the septum, as an outcome of the impedance studies.

ACKNOWLEDGEMENTS

The authors acknowledge H. Damerau, S. Gilardoni and the CERN impedance team for useful discussions.

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