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Trapped modes in a dummy extraction septum for CERN Proton Synchrotron

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Summary. — The term trapped mode is usually referred to a mode that can not propagate in the beam pipe, but is localized in a particular region inside the device, producing narrow resonances peaks in the coupling impedance. They can be excited by the presence of discontinuities inside different devices of an accelerator, producing unwanted beam instabilities. It is therefore important to identify trapped modes, especially for new elements to be installed in a high-intensity accelerator. We present a recent study of the coupling impedance due to trapped modes in a new extraction septum that will be installed in the CERN Proton Synchrotron in the framework of PS Multi-turn extraction (MTE) commissioning. Simulation and theoretical calculations were performed in order to understand performance limitations of the machine, to find cures to reduce the instabilities, and to evaluate beam-induced heating.

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1. – Introduction and context

The CERN Proton Synchrotron (PS) belongs to the LHC injector chain, accelerating protons from the PS Booster from 2 GeV to 26 GeV. It has a fundamental role in the accelerator complex, supplying beams for the Super Proton Synchrotron (SPS) and to other important experiments.

The CERN PS is expected to provide beams during, at least, the next 25 years: in this prospective, the challenge is to produce higher-intensity and -brightness proton beams for collision in the LHC. Four types of LHC multi-bunch beams are prepared in the PS: differences derive from bunch spacing and intensity per bunch at PS extraction. In this framework, the PS Multi-turn extraction [1] was proposed with the aim of mitigate losses due to the shaving process that is at the heart of the Continuous Transfer (CT) technique, that has been used for years to transfer beams from the PS to the SPS. During the commissioning phase of the PS Multi-Turn Extraction (MTE) and the following operational period, a number of limitations have been observed, one in particular, the high level of activation of the magnetic extraction septum in straight section 16. The activation of the magnetic septum is the result of particles lost during the rise time of the extraction kickers. These losses are unavoidable due to the longitudinal structure of the beam that is required by the SPS. These issues have been addressed in many ways, and the solution adopted consist in installing a "dummy septum" [2] in straight section 15 of the PS ring. By "dummy septum", we mean a protection passive device, provided by a blade intercepting the beam during the rise time of the kickers. The blade is not generating any deflection, it does not interfere with the circulating beam during injection and acceleration but, during the five extraction turns, it absorbs the particles that would be otherwise intercepted by the magnetic septum blade. The activation of the extraction magnetic septum in section 16 will then be reduced. The protection septum must act in the same passive way for any kind of beam produced by the PS, and for extraction techniques different from MTE. The new device will then be enclosed in a concrete shielding, in order to minimize the level of radiation in the area.

2. – Dummy septum design

The position of the absorbing particles blade can be adjusted by means of a remote displacement system which allows accuracy of 0.1 mm. The blade can be placed between 80 and 100 mm from the PS orbiting beam during operation. Moreover, when the septum is not used, the blade can be moved to the park position at 130 mm from the orbiting beam. The 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 a water cooling. 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 designed, in order to measure the position of the extracted beam and to adjust precisely the extraction blade position.

To perform impedance simulations, several aspects of the beam operation of the dummy septum have to be considered. During operation, the beam circulates in a nominal position displaced by 27 mm from the geometrical center of the septum. During extraction, the beam moves from the circulating position to few millimeters from the copper blade in about 6 ms. The beam then circulates close to the blade for only few turns before extraction. The design of the septum used for simulations considers the blade positioned at 90 mm from the nominal circulating beam.

3. – Impedance aspects

Simulations and theoretical calculations have been performed for the septum in order to evaluate longitudinal and transverse coupling impedances due to trapped modes, and their impact on the stability of the beam. The final outcome of these studies is the basis for the acceptance for the installation of septum in section 15 of the PS ring. The importance of the study in justified by the fact that the septum design should require essentially no maintenance and, in the event of damage, a spare will be available for replacement. In fact, the very high level of activation expected in the device, is going to exclude any possibility of repairing action.

Since all discontinuities inside the dummy septum can be potential sources of trapped modes, the model used in simulation must be as similar as possible to the real object.

The analysis has been performed on simplified 3D geometries imported from mechanical CATIA [3] drawings, assuming that simplifications have a very small impact on final results. In particular the beam observation screen, the holes in the RF beam screen and the screws inside the tanks are elements that have been neglected during simulations.

For time domain simulations, CST Particle Studio Wakefield Solver [4] has been used to obtain the wake potential generated by a Gaussian bunch circulating inside the septum. In CST the beam is always defined as a pencil beam with no transverse size, and in this context only ultra-relativistic beams have been considered. The longitudinal wake potential can be calculated by CST Particle Studio considering the beam and the integration path in the same position inside the structure; instead, the transverse dipolar wake potential can be obtained by displacing the beam in the transverse direction, while the integration path remains fixed. The beam coupling impedance components are then evaluated by Particle Studio from the Fourier transform of the wake potential. To crosscheck results obtained from time domain, CST Microwave Studio frequency domain simulations have been performed. The evaluation of the frequencies of eigenmodes resonating in the structure is done by the Eigenmode solver, while Q factor, shunt impedance R_s, and R/Q are obtained from the post-processing. The correct evaluation of the resonance parameters is fundamental to obtain good accuracy in the estimation of the impact on coupled bunch instability.

In sect. **4** we will show that beams circulating in the septum generate trapped modes, producing narrow resonances in the coupling impedance; trapped modes frequencies also correspond to the eigenfrequencies of the closed structure. Since low-frequency trapped modes are a potential source of coupled bunch instability for the PS, two different solutions for reducing their impact on the stability of the beam have been considered, and they will be discussed in sect. **7**.

4. – Impedance simulations

To perform longitudinal impedance simulations in CST Particle Studio, both the beam and the integration path have to be placed on the same axis position. Then, the longitudinal impedance can be evaluated at different distances from the location of the blade. From simulations, excitation of trapped modes in the longitudinal and transverse impedance, due to the passage of a beam of rms bunch length of 26 cm, has been observed. This bunch length corresponds to the shorter bunch for the PS at flat bottom, and has been chosen to obtain a good resolution in the desired frequency range. Trapped modes frequencies, which also correspond to the eigenvalue of the closed structure, do not depend on the beam position. On the contrary, the amplitudes of several peaks are increasing while the relative distance between the beam and the blade is decreasing. Before extraction, while the beam covers 90 mm in about 6 ms to approach the blade, a significant increase of shunt impedance for some trapped mode has been observed. During extraction, when the beam is close to the blade at a minimum distance of 5 mm, the maximum of the impedance peaks amplitude is reached. This effect is due to the strong electromagnetic field trapped at the edges of the blade after the passage of the beam.

Since the inner geometry of the dummy septum is strongly asymmetric, all trapped modes excited by the passage of the beam, have both longitudinal and transverse components. The dipolar impedance can be evaluated with CST Particle Studio by shifting the beam in the transverse direction and by performing the integration of the field along the central axis. Similarly, the quadrupolar impedance can be obtained by shifting

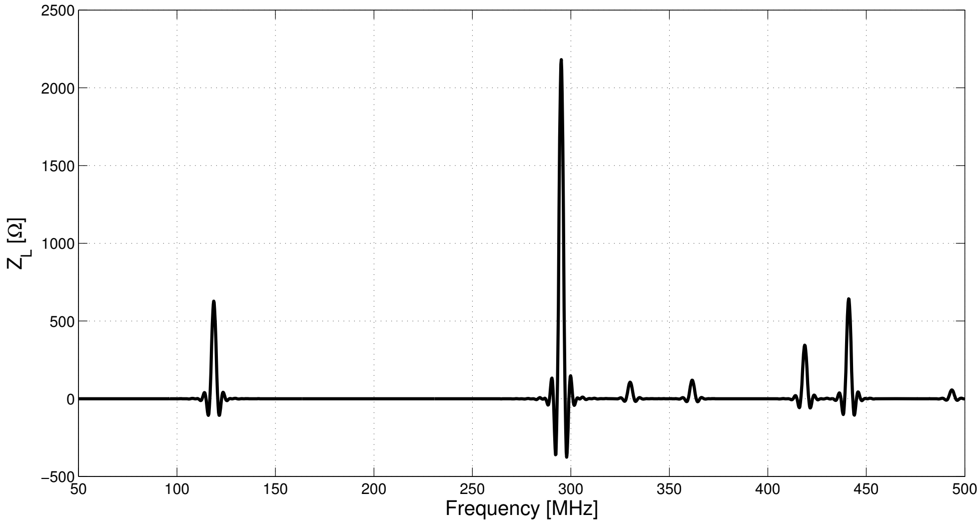

Fig. 1. – Longitudinal impedance during extraction evaluated with CST Particle Studio.

the integration path while keeping the beam in the center. The dipolar (respectively, quadrupolar) component is then obtained by subtracting from the simulated dipolar (respectively, quadrupolar) transverse impedance the same term evaluated in the center and then dividing by the displacement. For the transverse impedance, the same increase of amplitude of the peaks while the beam is approaching the blade has been observed. For this reason, only numerical examples for the longitudinal component of the impedance are shown, since the transverse one shows a similar behaviour.

Figure 1 shows the real part of the longitudinal impedance excited by a bunch of rms length 26 cm and charge $q = 1\,\text{nC}$, circulating 5 mm away from the axis of the copper blade. The wake potential has been evaluated through the Direct Integration Method using a wake length of 100 m. Perfect electric conductor (PEC) has been defined on all the outer surfaces, except for the beam entrance and exit planes that have been defined as open boundaries (perfect matching layer) due to the beam pipe aperture. No symmetry planes have been used.

Resonant parameters of the dummy septum can be easily calculated post-processing the Eigenmode simulation. The first trapped mode excited by the beam resonates at 118 MHz with a Q factor of 2616 and, since Q depends only from the geometry, it will be constant for the same mode while the beam is moving from the nominal position towards the blade during extraction. The shunt impedance for 118 MHz mode has been evaluated in the case of a beam placed in nominal position and in the case of a beam at 5 mm from the blade at extraction: in the last case it has been estimated to be approximately 50 kΩ. Between the nominal and the extraction positions, the shunt impedance increases of a factor 600. The amplitude of the impedance's peaks 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. Such a time consuming simulation has been performed and fits with the shunt impedance evaluated by the Eigenmode solver. Only numerical examples of the longitudinal impedance obtained with a wake length of 100 m are shown, as qualitative output of CST Particle Studio.

TABLE I. – *PS parameters (25 ns bunch spacing) considered for coupled bunch calculations.*

E0 [GeV]	13	26
RF voltage VRF [kV]	165	100
Harmonic number	21	84
Number of bunches	18	72
Charge per bunch [C]	$1.28 \cdot 10^{-7}$	$3.2 \cdot 10^{-8}$
Slippage factor	0.0163	0.0215
rms bunch length [ns]	3	3

For the PS, we assume that only resonant modes with a frequency lower than 200 MHz represent potential issues for coupled bunch instability: the rise time decreases significantly while the frequency of the mode is diminishing, generating high instabilities. For this reason, the mode at 118 MHz has been studied in more detail in sect. **5**, while the other trapped modes at higher frequencies are not expected to be source of coupled bunch instability.

5. – Coupled bunch instability evaluation

Longitudinal coupled bunch (CB) oscillations represent a major source of instability, limiting the beam intensity and brightness that can be delivered from the CERN PS. Low frequency trapped modes with high Q factor and shunt impedance are potential source of this instability for the PS [5]. To investigate more deeply the possible impact of the 118 MHz mode, the coupled bunch instability growth rate has been calculated with the following formula, which is valid for a mode fully coupled with the multi-bunch spectrum:

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

where 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 beam energy, ω_s the synchrotron frequency, and ω_r the resonance frequency. Resonant parameters are taken into account for the calculation of the broad-band impedance:

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

Since the septum is going to work in all operational conditions and with several types of beam, growth rates should be evaluated at different beam energies, assuming worst case scenarios. The beam parameters that have been considered for the estimation are summarized in table I. Furthermore, to be closer to the real conditions, the actual Gaussian shape of the bunch has to be taken into account. Therefore, the shunt impedance R_s, evaluated with CST Microwave Studio, has to be corrected with the following form factor:

$$R'_s = R_s e^{-(\omega_r \sigma_b)}. \tag{3a}$$

TABLE II. – *Coupled bunch instability growth rates evaluated for different beam position inside the septum.*

Displacement [mm]	R_s [Ω]	R'_s [Ω]	α [s^{-1}] 13 GeV	α [s^{-1}] 26 GeV
0	640	10	0.15	0.08
20	3385	53	0.82	0.43
40	14762	231	3.59	1.87
60	49215	770	11.97	6.25

When such a correction is taken into account, the amplitude of the shunt impedance is drastically reduced. In table II, the values of growth rate for the 118 MHz mode, evaluated both at intermediate (13 GeV) and high energy (26 GeV), for different beam positions, are summarized.

6. – Contribution to the total Proton Synchroton Impedance budget

The imaginary part of the longitudinal impedance of the PS has been evaluated with measurement campaigns [6] to be

$$\frac{Z(p)}{p} = 18.4 \pm 2.2\,\Omega. \tag{4a}$$

In this simulation, a long bunch with rms bunch length of 1 m and a wake of length 100 m have been used to obtain the impedance in a low frequency range. When a bunch of such length is at the nominal circulating position, it excites an imaginary part of the longitudinal impedance that is purely inductive, and the effective impedance has been evaluated to be $\frac{Z(p)}{p} = 0.001\,\Omega$. In comparison with the measured value, 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 $\frac{Z(p)}{p} = 0.12\,\Omega$, much larger than in the previous condition. At extraction 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 complex of the PS provides a contribution of about the 4% of the total longitudinal impedance. Hence, no issue is expected under any of the operational conditions foreseen.

7. – Mode damping proposals

In the unlikely event of unexpected failure or damage of the dummy septum after installation and shielding, repairing action will not be possible. This fact justifies the interest in finding preventive measures, for example reducing the impact of a mode that, from simulation results, is not predicted to be an issue for the stability of the beam.

For this reason, 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 of inserting sliding contacts among them: closing the gap will have the effect of canceling the mode at 118 MHz, as

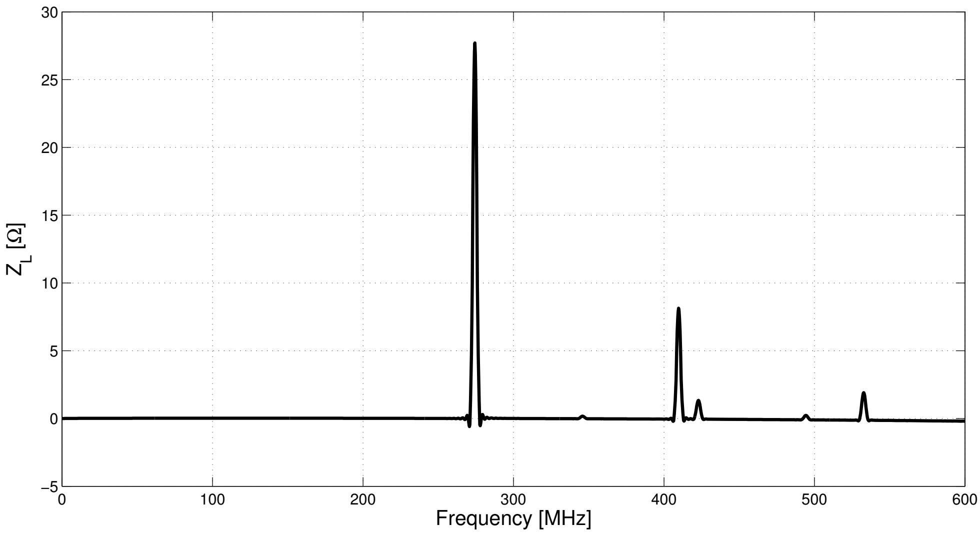

Fig. 2. – Longitudinal impedance at extraction evaluated with CST Particle Studio after the insertion of sliding contacts between the screen and the support table.

shown in fig. 2. Similarly, a small amount of energy is also trapped at the edge of the blade, in the 3 mm gap between the impedance screen and the blade itself. To avoid that resonance, it would be necessary to create contacts between the two object, filling the gap. Unfortunately this solution cannot be easily implemented.

The second solution suggests the insertion of a block of ferrite TT2-111R, a material that works very well in the frequency range of interest. This solution will not have the

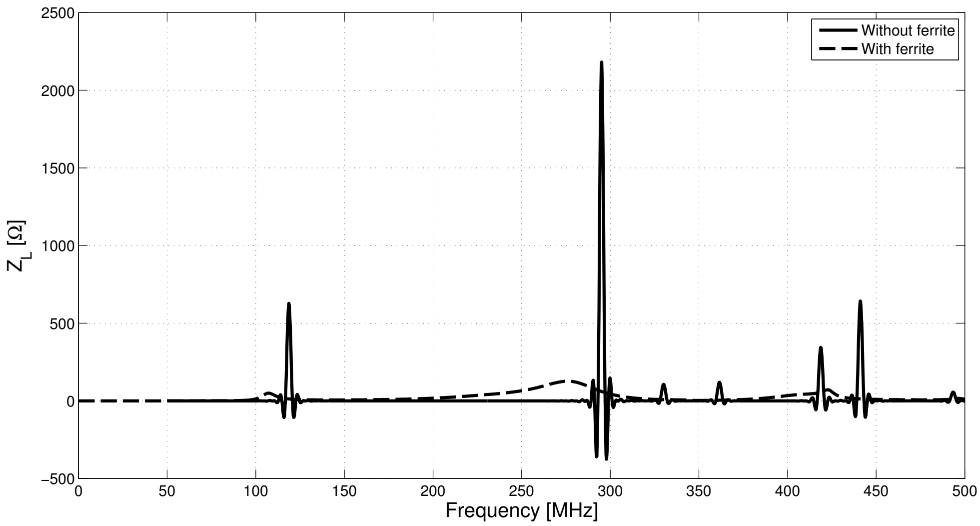

Fig. 3. – Comparison between longitudinal impedance evaluated with CST Particle Studio with and without ferrite.

effect of damping the mode, but will reduce the shunt impedance R_s and Q of the mode itself and, as a consequence, the impact of coupled bunch instability. Several simulations have been performed with CST Particle Studio, varying dimension and position of the ferrite. As a general rule, the brick of ferrite should be placed inside the tank where the magnetic field is more intense; therefore, we suggested to position a brick of $24 \times 7 \times 395\,\mathrm{mm}^3$ between the displacement system and the impedance screen. With this solution, the shunt impedance reduction of the 118 MHz mode at extraction has been estimated to be about a factor 600, as shown in fig. 3. As far as the power loss is concerned, we calculated that the heating would be about 1.8 W, as the mode falls inside the PS bunch spectrum and at 118 MHz the power is about −20 dB. The deposited heating should not represent a problem, and the foreseen cooling system should easily 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 [7]. 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.

8. – Conclusions

We have shown in this paper the beam coupling impedance due to trapped modes for a dummy septum to be installed CERN Proton Synchrotron (PS)in the framework of PS Multi-turn extraction (MTE) commissioning. Simulation with CST Microwave Studio and Particle Studio, together with theoretical calculations for the coupled bunch instability, have been performed. Two different preventive actions for reduce the instabilities have been suggested and realized in the final design of the septum, as an outcome of the impedance studies.

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