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RECENT UPDATES IN THE IMPEDANCE CHARACTERIZATION OF THE CERN PS BOOSTER FINEMET RF SYSTEM

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Abstract

During the last long shutdown of the accelerators at CERN (LS2), the main radio frequency system of the Proton Synchrotron Booster (PSB) was upgraded. A wideband system with Finemet magnetic alloy cavities driven by solid-state amplifiers replaced several different ferrite-loaded cavities. In measurements post-LS2, the longitudinal beam stability did not match predictions, which triggered a survey of the PSB impedance model. This started with the Finemet RF system, which are expected to be the dominant impedance contribution. Single stretched wire measurements were carried out with a 6-cell Finemet test cavity with different amplifier configurations. Measurement results and electromagnetic simulations are presented in this paper and compared to the previous impedance model. The electromagnetic characterization presented in this contribution will complement the beam-based impedance and low-level RF measurements as an input for the simulations of beam stability.

INTRODUCTION

The Proton Synchrotron Booster (PSB) is part of the LHC injection chain. In view of the High-Luminosity (HL) upgrade [1], the PSB was equipped with a newly designed RF system which replaced a set of ferrite-loaded cavities. This system covers the frequency range from 1 MHz to 18 MHz, allowing multi-harmonic operation [2]. In each of the four rings of the PSB, there are three accelerating stations, each one composed of 12 cells. Each cell consists of a ceramic gap placed in the vacuum chamber and one Finemet [3] (magnetic alloy) core on either side of the gap (Fig. 1). For each cell, the two sides of the accelerating gap are driven in antiphase by a solid-state amplifier. As described in [4], the individual cell gap impedance dramatically changes when loaded by the amplifier circuit with integrated fast RF feedback. The internal fast RF feedback is fundamental for reducing the beam coupling impedance, and it was designed to counteract beam-induced voltage on the cavity gap (and amplifier output). During the commissioning of the PSB, and after the installation of the new RF system, the amplifier system was modified to improve its performance and reliability [5]. This modification led to an increased gap impedance for the resonance around 20 MHz. Additional beam-based measurements confirmed the increase of the maximum impedance with the upgraded amplifiers and, in addition, they show a frequency shift of the main resonance towards lower frequencies [6]. In longitudinal beam dynamics simulations, this impedance peak was shown to drive longitudinal instabilities and to potentially limit the intensity reach [7]. A dedicated feedback system of servoloops for each revolution frequency harmonic is working to reduce the induced voltage up to 20 MHz [8], beyond the direct wideband RF feedback of the amplifiers.

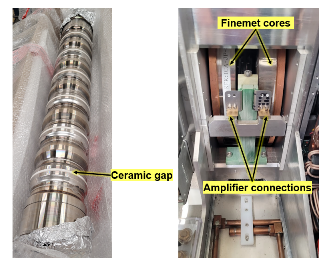

Figure 1: Vacuum chamber of a 6-cell cavity with ceramic gaps (left) and single cell gap (right), with visible pads for the connection with the amplifier. The Finemet cores are also indicated.

During post-LS2 beam commissioning, it was found that the beam stability did not match predictions, therefore a review of the PSB impedance model was started from the main RF system. The aim of the study is to evaluate the impedance of the Finemet RF system through stretched wire measurements as well as electromagnetic simulations in CST [9]. The measured beam coupling impedance is presented, and electromagnetic simulations for a single and a 6-cell cavity are shown as well.

SINGLE STRETCHED WIRE MEASUREMENTS

A stretched wire measurement setup was installed at the 6-cell cavity test stand, equipped with the upgraded amplifier units. In spite of the fixed coupling that comes with the stretched wire method, this measurement technique was chosen to properly obtain the broadband contribution of the wideband cavities [10].
In order to understand and best characterize how the cavity impedance is impacted by the connection to the amplifier system, the wire measurements were performed in three different configurations in which the Finemet system is usually operated:

- Short-circuit: the individual gaps of the cavity are short-circuited by gap relays present at the output of the amplifiers.
- Gap open: the RF gap relays are open, but the amplifier system is off.
- Gap open, Bias On: the RF gaps are loaded with the amplifier and its fast RF feedback. The RF feedback

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is active when the transistors in the amplifier circuit are biased. This feedback is implemented in the power amplifier and is able to reduce the gap impedance.

The longitudinal impedance is obtained from the measured transmission data S_{21} by using the standard log-formula [11].

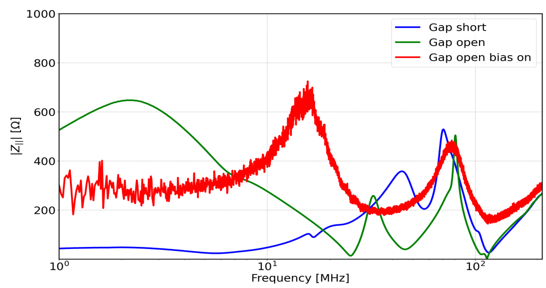

Figure 2: Absolute longitudinal impedance from 1 MHz to 210 MHz of a 6-cell cavity with three different amplifier configurations obtained from wire measurements.

The results for the three amplifier settings are shown in Fig. 2, and they confirm the large impact of the amplifier configuration on the equivalent beam coupling impedance:

- In the case of gap relays closed (blue), two impedance peaks appear at 45 MHz and 70 MHz respectively. They are far outside the frequency range of interest for beam acceleration (RF harmonic h = 1, 1–1.8 MHz).
- When the gap relays are open (green), with fast RF feedback off, we obtain a large broadband impedance component between 2-3 MHz which is successfully suppressed in the next measurement by the fast RF feedback (red).
- The beam coupling impedance (red) of the entire cavity with the amplifier system connected when the fast RF feedback is on. Note that the noisy signal in the low frequency range can be attributed to transient effects inside the amplifier circuitry when the transistors are biased.

The results from the stretched wire measurements can now be compared with the existing impedance model. Figure 3 shows the measured impedance with the fast RF feedback active in comparison to the existing impedance model of the PSB Finemet cavities [12]. Note that the existing impedance model was obtained from beam-based measurements and simulations, and it still includes the cavity with the original amplifier units. In this case, the impedance model of the 1-cell cavity has been scaled to 6 cells to allow comparison with the measurements by multiplying it with a factor of six, i.e. each cell has been considered equally contributing to the impedance.

The comparison shows a good agreement in the overall impedance behaviour, in particular at higher frequency. The main peak of interest indicates an impedance magnitude of 660 Ω at around 16 MHz, i.e. the wire measurements confirm an impedance peak at lower frequency than expected from the model and, in addition, with a lower magnitude (Fig. 3). The frequency shift can therefore be attributed to the changes and upgrades of the amplifier system. However, the perturbation introduced by the wire does not allow the magnitude of the impedance to be quantified with high accuracy, and only a bead-pull measurement could provide an additional confirmation.

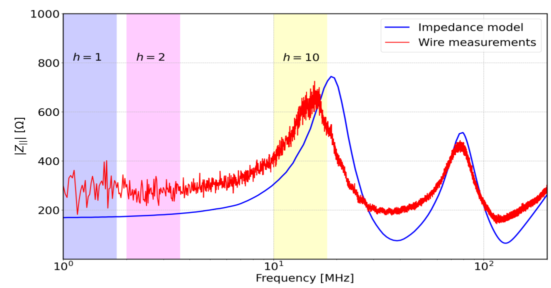

Figure 3: Wire measurements versus existing impedance model of a 6-cell cavity from 1 MHz to 200 MHz.

ELECTROMAGNETIC SIMULATIONS

Starting from the mechanical design, a simplified model of a 1-cell cavity was built in CST studio (Fig. 4).

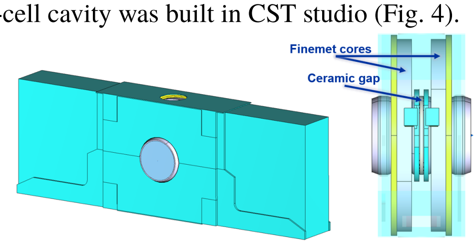

Figure 4: 3D model of the 1-cell cavity.

The geometry includes the cell assembly with the ceramic gap and the two magnetic alloy cores (Fig. 4, right) but not the amplifier unit. Instead, two empty metallic boxes are added at the left and right side of the beam pipe (Fig. 4, left) to close the geometry. In the real assembly, one of the boxes contains the amplifier system, whereas the other one is left empty for future upgrades. The Wakefield solver using a Gaussian beam with an rms bunch length of 50 cm has been set up to calculate the longitudinal beam coupling impedance. The dispersive behaviour of the Finemet material has been defined in CST by importing the measured complex magnetic permeability as a function of the frequency [13]. As the resonant behaviour of the cavity is fully dominated by the Finemet (magnetic alloy) properties, a minimum (green), maximum (blue) and mean (red) permeability curve were taken as an input to CST to observe their impact on the impedance response. The permeability was averaged over the 336 measured core samples. The magnetic properties of the material are indeed essential to properly represent the impedance behaviour, as can be seen from Fig. 5. It shows the broadband impedance behaviour of a single cell. The spread in the material properties is leading to a variation of the resonance frequency of ±0.5 MHz around a central frequency of about 4 MHz.

Assuming the mean value of permeability, the Wakefield solver simulation results in comparison with the impedance

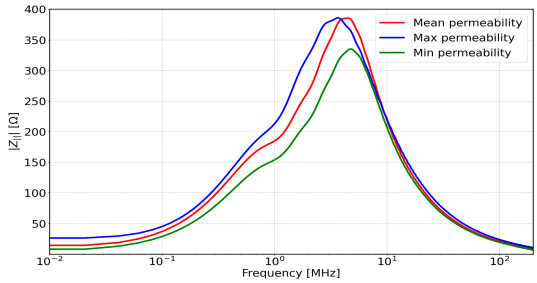

Figure 5: Longitudinal impedance magnitude from 10 kHz to 200 MHz assuming a maximum (blue), minimum (green) and mean (red) permeability curve of the Finemet material.

measurements across one gap [14] are presented in Fig. 6. The simulated impedance behaviour features a peak at 4.5 MHz while, for the measurements of one cell, this peak is at 6 MHz. Note that the impedance measurements were taken across a single gap of the 6-cell cavity test stand. They therefore include an additional contribution from adjacent cells.

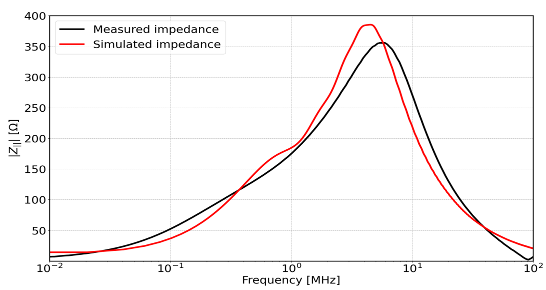

Figure 6: Simulated single-cell longitudinal impedance (red) in comparison with the measured impedance (black) from 10 kHz to 100 MHz.

Comparing both traces of Fig. 6, it can be seen that, above 7 MHz, they follow a different slope, which indicates an additional capacitive contribution. The estimated difference at about 10 MHz suggest a parallel capacity of approximately 24 pF. This capacitance value can be identified with an additional gap capacitance, whose contribution is already included in the permeability measurements. This discrepancy also needs to be taken into account when simulating an entire multi-cell cavity.

Analogously to the single cell structure, a complete 6-cell cavity was modelled in CST, and its geometry is illustrated in Fig. 7. The Wakefield solver with the same bunch parameters (Gaussian bunch with an rms length of 50 cm) was applied and the resulting longitudinal impedance of the 6-cell cavity is plotted in Fig. 8. Similar considerations made for the single-cell cavity can hence be applied to the impedance results for a 6-cell cavity, where the discrepancy between measurement and simulation is slightly more pronounced. Note that the same permeability has been assumed for all 12 Finemet cores. A more accurate comparison could be achieved by including permeability measurements for each specific core in the cavity.

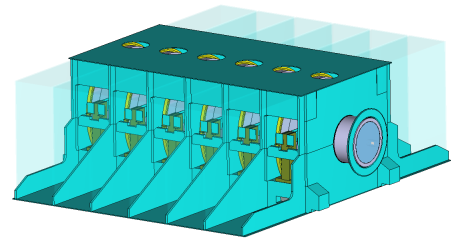

Figure 7: 3D model of a complete 6-cell cavity.

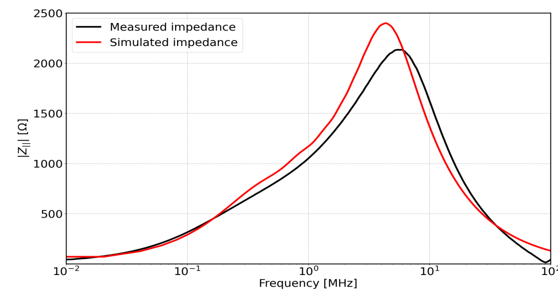

Figure 8: Simulated longitudinal impedance of the complete 6-cell cavity (red) in comparison with the measured (black) impedance from 10 kHz to 100 MHz.

CONCLUSION AND OUTLOOK

Compared to the previous impedance model, the wire measurements with the upgraded amplifier confirmed a shift of the beam coupling impedance resonance around 20 MHz towards lower frequency. This resonance is significantly reduced at the revolution frequency harmonics by the servoloops working up to 20 MHz. Complementary bead-pull measurements could be envisaged to provide additional confirmation of these results. Agreement between impedance measurements and electromagnetic simulations can be reached by adjusting the measured permeability to exclude the gap capacitance, already included in the CST impedance calculations. The correction will result in the ultimate benchmark for the 3D geometry. Based on the detailed understanding of the single-cell cavity model, a full 6-cell cavity has been simulated and compared with the bench measurements. The 3D model of the complex geometry will be the basis for a combined CST - PSpice simulation to describe the complete amplifier-cavity system, which will allow understanding the beam-RF system interaction at an unprecedented detail. A benchmarked simulation model, in agreement with the wire measurements, will enable further impedance investigations of higher frequencies.

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