STUDY OF THE BEAM-CAVITY INTERACTION IN THE PS 10 MHz RF SYSTEM

G. Favia*[1,2], H. Damerau[1], M. Migliorati[2], M. Morvillo[1], C. Rossi[1]
[1]CERN, Geneva, Switzerland
[2]Sapienza Universita' di Roma and INFN-Roma1, Rome, Italy

Abstract

The eleven main accelerating cavities of the Proton Synchrotron (PS) at CERN consist of two ferrite-loaded coaxial lambda/4 resonators each. Both resonators oscillate in phase, as their gaps are electrically connected by short bars. They are in addition magnetically coupled via the bias loop used for cavity tuning. The cavities are equipped with a wide-band feedback system, limiting the beam loading, and a further reduction of the beam induced voltage is achieved by relays which short-circuit each half-resonator gap when the cavity is not in use. Asymmetries of the beam induced voltage observed in the two half-cavities indicate that the coupling between the two resonators is not as tight as expected. The total cavity impedance coupling to the beam may be affected differently by the contributions of both resonators. A dedicated measurement campaign with high-intensity proton beam and numerical simulation have been performed to investigate the beam-cavity interaction. This paper reports the result of the study and the work aiming at the development of a model of the system, including the wide-band feedback, which reproduces this interaction.

INTRODUCTION

The PS is equipped with different cavities covering on a wide frequency range (2.8-10, 20, 40, 80 and 200 MHz) for acceleration, RF gymnastics and longitudinal emittance blow-up. Among them the 10 MHz RF system plays a crucial role for the beam dynamics, since it is the one responsible for beam acceleration and also performs beam manipulations, such as bunch splitting and rotation. It has been shown that it represents the main source of longitudinal beam instabilities in the PS, namely coupled bunch instabilities [1].

The parameter relevant to the beam-cavity interaction can be modeled as an impedance excited by the beam current crossing the cavity. The reduction of this impedance is already achieved by a wide-band feedback system [2]. However, with the increasing intensity expected in the PS in the framework of the Injectors Upgrade (LIU), a further reduction of the equivalent impedance is wished to improve longitudinal beam stability.

BEAM LOADING AND LONGITUDINAL IMPEDANCE

A beam travelling in a synchrotron loses part of its energy at each turn, generating an electromagnetic (EM) wake field that acts back on the beam itself. Depending on the intensity this may cause significant modification in the dynamics of the particles motion [3].

A cavity can be modeled as a complex impedance Z. When a bunch of current I_b travels across the cavity, a beam induced voltage V_b develops at the cavity gap [4]:

$$V_b = -Z \cdot I_b, \quad (1)$$

where the minus sign indicates that the induced voltage leads to an energy loss.

10 MHz *RF System*

Each 10 MHz cavity is driven by a tetrode based amplifier, which provides the necessary current to reach up to 10 kV$_\mathrm{p}$ per gap. In addition the system is equipped with a direct wide-band feedback, which reduces the cavity impedance [5]. The evaluation of the cavity impedance has to take into account the effect of the electronics of the amplifier driving the cavity as well as the reduction due to the wide-band feedback. Figure 1 presents a simplified model of the 10 MHz system. A detailed description of the RF amplifier and its upgrade

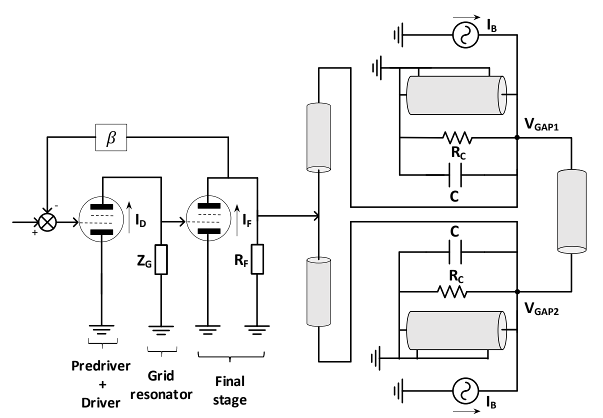

Figure 1: Simplified model of the 10 MHz RF system, including two cavity shorted coaxial line resonators and the driving amplifier.

can be found in [6]. The two half cavities are modeled as two $R-L-C$ circuits: the shorted coaxial lines represent the equivalent inductances of the two cavity halves, established by the ferrite magnetic properties and variable with the magnetic bias field; C is the equivalent ceramic gap capacity and R_c is mainly given by ferrite losses. There are three short coaxial lines connecting the two cavity halves: one of them represents a copper bar which electrically couples their gaps; the other two are the two bars, through which the amplifier feeds the two gaps in parallel. The two half cavities are magnetically coupled through the circuit carrying the

* giorgia.favia@cern.ch

ISBN 978-3-95450-147-2

current biasing the ferrites, which makes a figure-of-8 loop around the two resonators.

Since the beam crosses both gaps in series, it is modeled as two current sources. The total impedance seen by the beam is then

$$Z = 2 \cdot \frac{\frac{R_F + R_c/2}{R_F \cdot R_c/2}}{1 + \beta Z_G g_D g_F \frac{R_F + R_c/2}{R_F \cdot R_c/2}}, \quad (2)$$

with Z_G being the impedance of the grid resonator loading the driver stage, g_D and g_F the effective trans-conductances of driver and final amplifier, R_F the anode resistance of the final stage, β the feedback loop transfer function. In order to better understand how the beam interacts with the whole system, a Pspice [7] model of the cavity, including the feedback amplifier, has been developed. To benchmark the model a measurement campaign of the voltage induced by the beam has been performed.

BEAM INDUCED VOLTAGE MEASUREMENTS AND SIMULATIONS

Measurements of the voltage induced by a single bunch, with high-intensity of about $8 \cdot 10^{12}$ protons, at fixed harmonic, have been performed.

The RF frequency for acceleration of protons with the 10 MHz cavities can vary from 3 MHz (h=7) to 10 MHz (h=21), slightly lower frequencies are required for ion acceleration. Several cavities have been measured, at h=8, 16 and 21 and the induced voltage has been evaluated at three stages of the beam cycle: injection, transition and ejection (Fig. 2). Since the bunch length visibly changes during the cycle, as well as its spectrum, the measurements allow to evaluate the contribution of the beam harmonic content to the total cavity impedance. The highest attention in this paper is

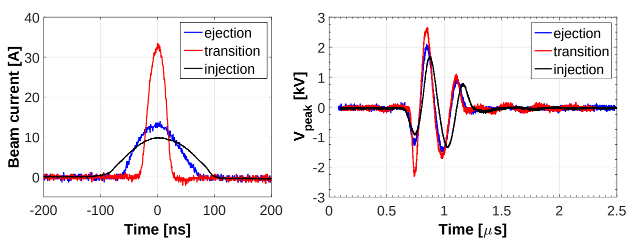

Figure 2: Measurements of the bunch current and the induced voltage across a gap, at h=8, at injection, transition and close to ejection.

posed on the effects observed during transition, since the bunch presents the shortest length, thus the highest harmonic content, during the acceleration cycle.

Simulations and measurements were carried out in parallel in order to figure out which are the main contributors to the total cavity impedance. The Pspice model, that is already able to reproduce the system behavior, has been optimized for this study. It includes dedicated libraries describing the electron tube characteristics by means of 3 to 7 order polynoms, allowing to take into account the non-linearity of the system. The cavity is modeled as sketched in Fig. 1.

The beam is simulated by means of two current sources delayed in time by 4 ns, which corresponds to the time of flight between the two gaps. The model almost perfectly matches the measurements, in each stage of the cycle, and at each harmonic.

Figure 3 shows the voltage induced by the beam across the cavity in straight section 11, when tuned to h=8 during transition, as from measurements and simulations.

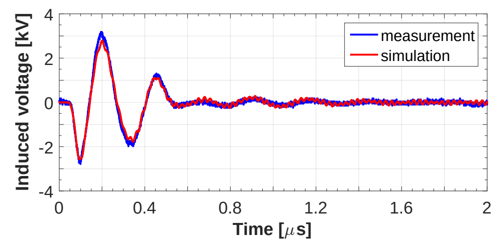

Figure 3: Comparison of measurements and Pspice simulation of the induced voltage by a bunch of ~60 ns length passing through the cavity.

The knowledge of the beam induced voltage and the bunch current can lead to an evaluation of the 10 MHz cavities impedance as seen by beam. The real part of the impedance can be computed according to the formula [3]:

$$\Re\left(Z(\omega)\right) = -\Re\left(\frac{V(\omega)}{I(\omega)}\right) = -\Re\left(\frac{FFT\left(V_{gap}(t)\right)}{FFT\left(I_{bunch}(t)\right)}\right) \quad (3)$$

Figure 4 shows the results of the calculation of the impedance of several cavities as observed from beam induced voltage. It also contains a trace obtained from simulations, using a model whose parameters have been set to match cavity 11 properties.

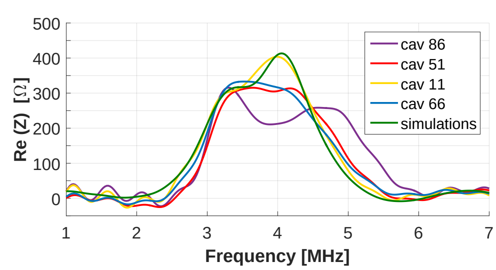

Figure 4: Computation of the beam impedance of cavities in straight sections 11, 51, 86, 66 at h=8 during transition.

Gap Relays

When the cavities are not in use two gap relays, one for each half cavity, short-circuit the gaps to strongly reduce their impedance and, as a consequence, the voltage induced by the beam.

Considering that the two half cavities are strongly coupled, one would expect to observe a similar beam induced voltage at both gaps. However an asymmetric behavior was observed [1].

ISBN 978-3-95450-147-2

The distribution of the beam induced voltage in both resonators has therefore been analyzed into more detail: measurements and simulations have been carried out in parallel to investigate the main causes of the asymmetry observed. The beam induced voltage along the beam cycle, measured across the left and right gaps at different times during the cycle, is shown in Fig. 5. The induced voltage increases

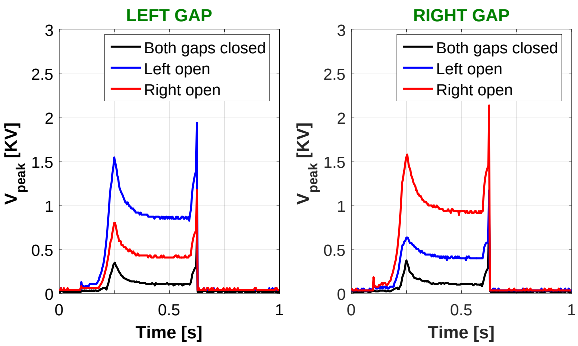

Figure 5: Beam induced voltage on left and right accelerating gaps during the acceleration of a single high intensity bunch. The first peak is the transition crossing and the second comes from bunch rotation before extraction.

when whichever gap is open: a reduction of the voltage by more than a factor of two, due to the second gap relay is observed. Moreover the voltage measured at the shorted gap is about one half of the voltage at the open gap. The same asymmetry of the beam induced voltage distribution is present in all cavities and at different harmonics. The gap relay effect on the gap voltage and the voltage distribution have been analyzed through numerical simulations.

A gap relay can be modeled as a series $R-L-C$, where L represents the leakage inductance due to the connection of the device to the gap, C is the capacitor decoupling the DC voltage, provided to generate the current biasing the ferrite discs, and R is a small resistor which reduces the cavity impedance over the whole operating frequency range. In order to simulate the gap relay effect on the cavity, a series $R-L-C$ (R=2 Ω, L=150 nH, C=67.2 nF) circuit has been included in the model, in parallel to each gap. The device increases the cavity resonance of the cavity, due to the inductance L added in parallel to the cavity, and reduces the real part of the cavity impedance because of R.

Figure 6 shows a comparison between measurements and simulations when the left gap is shorted, at h=8. An oscillation at 15 MHz is visible, as well as a modulation of the voltage due to a beat between two frequencies. According to measurements and CST [8] simulations, the cavity transfer function is characterized by its main resonant frequency and additional parallel or series resonances due to the cavity geometry and ferrite properties. If the series resonant frequency of the gap relay is close to one of the cavity resonances, there could be an additional reduction of the induced voltage and thus of the impedance seen by the beam. This is the case shown in Fig. 6 and in Fig. 7 at h=8.

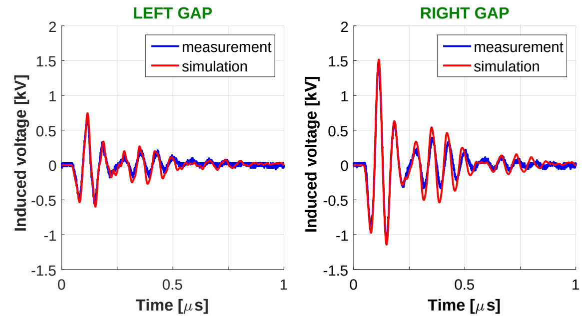

Figure 6: Beam induced voltage induced across the two cavities gaps, when the left gap is shorted.

The valid Pspice model allows to predict phenomena, as the one described, and to take them into account in the design of an improved gap relay circuit.

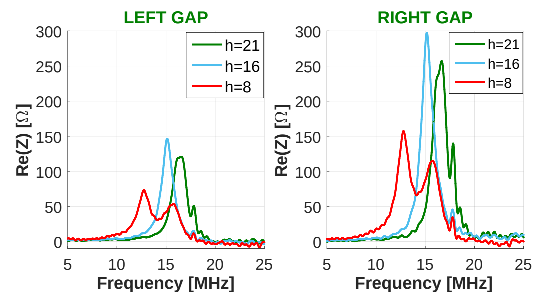

Figure 7: Measured cavity impedance at h=8, 16, 21 when the left gap is shorted.

Through numerical simulations and an analysis of the circuit, it has been found that the main contribution to the asymmetry comes from the not perfect coupling made by the bars connecting the 2 gaps. The magnetic coupling, instead, does not seem to give any contribution to the voltage distribution. In addition the grid resonator tuning position plays an important role on the total cavity impedance, since it is related to the phase stability of the wide-band feedback and power amplifier driving the cavities [5].

CONCLUSIONS

Measurements of the beam induced voltage in the PS 10 MHz cavities have been performed in order to characterize the beam-cavity interaction. Numerical simulations carried out in parallel, by means of a complete Pspice model, have allowed to fully understand how the amplifier with its feedback contributes to this interaction.

The Pspice simulations have proved to be a powerful means for the synthesis of a complex system, as well as for the characterization of single circuit elements and of their contribution to the whole system behaviour. We have been able to reproduce the measurement results and we could use the validated model for the design of new components, in the perspective of the system upgrade. A development of a CST model of the full system is presently ongoing, which could possibly lead to a further EM characterization of the system.

REFERENCES

[1] H. Damerau et al. "Longitudinal Coupled-bunch Instabilities in the CERN PS." Particle Accelerator Conference, 2007. PAC. IEEE. IEEE, 2007.

[2] R. Garoby, J. Jamsek, P. Konrad, G. Lobeau and G. Nassibian, "RF system for high beam intensity acceleration in the CERN PS", Particle Accelerator Conference, 1989. Accelerator Science and Technology, Proceedings of the 1989 IEEE, Chicago, IL, 1989, pp. 135-137 vol.1.

[3] L. Palumbo, V. G. Vaccaro, and M. Zobov. "Wake fields and impedance", CAS - CERN Accelerator School, Advanced School on Accelerator Physic, Rhodes 1994. LNF-94/041, 1994

[4] K. Schindl, "Instabilities", CAS - CERN Accelerator School: Intermediate Course on Accelerator Physics, Zeuthen, Germany, 15-26 Sep 2003, pp.321-342

[5] G. Favia et al. "The PS 10 MHz high level RF system upgrade", IPAC 2016, Busan, Korea, paper MOPOR013, this conference.

[6] D. Grier, "The PS 10 MHz Cavity and Power Amplifier", PS/RF Note 2002-073, CERN, Geneva, Switzerland, 2002

[7] OrCAD Pspice Designer, https://www.orcad.com/

[8] https://www.cst.com/