BENCH MEASUREMENTS OF THE LOW FREQUENCY TRANSVERSE IMPEDANCE OF THE CERN LHC BEAM VACUUM INTERCONNECTS WITH RF CONTACTS

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Abstract

The low frequency longitudinal and transverse beam impedances of the CERN Large Hadron Collider (LHC) have to be specifically minimized to prevent the onset of coherent instabilities.

The LHC beam vacuum interconnects were designed as Plug In Modules (PIMs) with RF contacts to reduce their coupling impedances, but the resulting contact resistance is a concern, as this effect is difficult to estimate.

High sensitivity measurements of the transverse impedance of a PIM at low frequency using a coil probe are presented. In particular, the increase of the transverse impedance of the PIM when it is elongated to its operating position is discussed in detail. Finally, the issue of non-conforming contact resistance is also addressed.

INTRODUCTION

In order to reach nominal beam intensity in the LHC, the beam impedance of all components located in direct vicinity of the beam path have to be minimized [1].

The LHC beam vacuum interconnects are flexible bellow plug-in modules located between LHC cold elements. These PIMs are designed to ensure continuity of the vacuum chamber, both at room temperature and at operational cryogenic temperature [2].

Much effort has been made to reduce the beam impedance of these bellows - there are around 1700 PIMs per ring -, and RF contact fingers were designed to shield the distorted geometry of the bellows from the beam, while still enabling longitudinal flexibility of the whole module [3]. These contact fingers should then significantly reduce the longitudinal impedance at high frequency. However, the resulting contact resistance between these fingers and the beam pipe was a concern, as it could lead to an increase of the transverse impedance at low frequency, and therefore to a drop in the threshold for coupled bunch instability. Unfortunately, modelling or simulating this complicated geometry at low frequency did not seem possible with the available tools.

However, following beam impedance measurements at low frequency using a probe coil inserted into kickers [4] and collimators [5], this coil method was applied to assessing the transverse beam impedance of a PIM at low frequency. The cases of a contracted PIM (at room temperature) and an elongated PIM (at cold temperature) were studied, as well as different types of non-conforming contact resistance, which may happen if buckled RF fingers are not in proper mechanical contact with the beam pipe.

MEASUREMENT TECHNIQUE

Method

If the electric field contribution to the transverse beam impedance is neglected, then the following equation relates the transverse beam impedance Z_{trans} of an element to the impedance Z_{coil} of a coil inserted into the element [6]:

$$Z_{trans} = \frac{c}{\omega} \frac{Z_{coil}}{N^2 \Delta^2} ,$$

with c the speed of light, ω the angular frequency, N the number of coil windings, and Δ the width of the coil.

Setup

Contrary to collimators' aperture, the vertical aperture of a PIM is quite large (full gap 4 cm), and thick low resistance copper wires can be used (diameter 1 mm) in order to maximize the signal to noise ratio. Coils were wound around dielectric fibreglass rods of rectangular section. The number of turns and thickness of the coil were tuned to obtain a satisfying trade-off between the amplification of the measured signal (i.e. high N, high Δ), and a resonance frequency of the coil higher than the frequency range of interest (i.e. low N, low Δ). The coil was inserted into the PIM and centred using polyethylene and fibreglass blocks of known thickness.

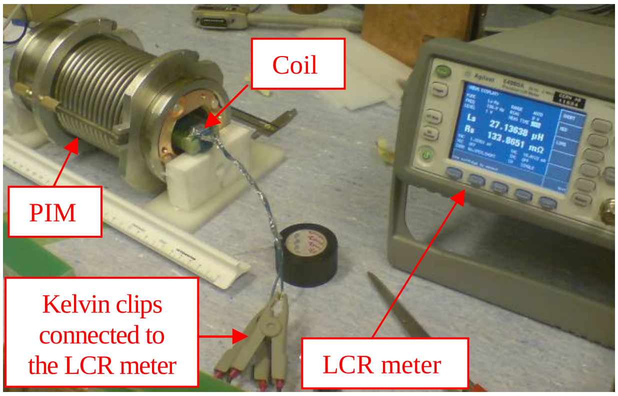

Figure 1: Setup for measuring the transverse beam impedance of a PIM. The coil is inserted into the PIM and centred. Kelvin clips connected to the LCRmeter input are plugged on each coil end.

The impedance of the coil was initially measured using a Vector Network Analyzer (HP 8751A or Agilent 4395A), but the greater accuracy at lower impedance values of the LCR meter (Agilent E4980A) lead to using this device throughout the measurement campaign.

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To reduce the dependency of the measurement on parameters that are difficult to control (temperature, coil winding precision, etc.), a reference measurement Z^{ref} was systematically subtracted from the measurement of the Device Under Test (DUT), i.e. we have:

$$Z_{trans} = Z^{DUT}_{trans} - Z^{ref}_{trans} = \frac{c}{\omega}\,\frac{Z^{DUT}_{coil} - Z^{ref}_{coil}}{N^2\Delta^2}$$

As in [5], a very good conductor, such as copper, was chosen as reference. It is important to note the impedance of copper is significant within a great part of the frequency range of interest [100 Hz, 10 kHz], and this copper impedance cannot be considered negligible. This is why the result of subtracting the reference can lead to negative values at low frequencies.

Finally, the temperature of the coil greatly affects the measured signal at low impedance values. It is therefore important to perform the measurement quickly, and if possible in a room with tightly controlled temperature.

MEASUREMENT RESULTS

The reference object was a copper tube of 15.7 cm length, 5.1 cm diameter, 1 mm thick. In all following plots, the impedance measured for this reference copper tube is subtracted.

Transverse Impedance of a PIM at Nominal Elongation (Warm and Cold)

Measurements were performed at cold nominal length (elongated to 19.9 cm at cryogenic temperature) and warm nominal length (closed to 16.5 cm at room temperature) on an LHC SSS/MB-type PIM equipped with elongation and contraction rods. The plot is shown in Fig. 2.

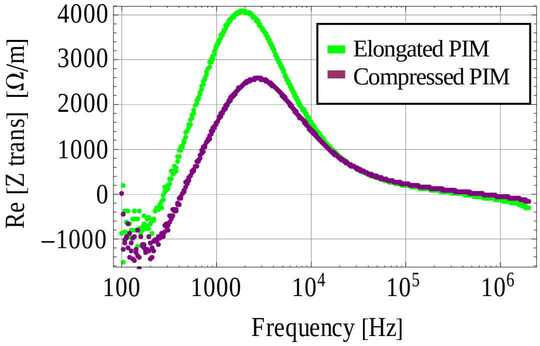

Figure 2: Comparison of the real part of the transverse beam impedance of a PIM at nominal length for cryogenic temperature (19.9 cm in green), and the same PIM at nominal length for room temperature (16.5 cm in purple). Measurement with the reference copper tube is subtracted.

It is observed that the general shape of the transverse beam impedance of a PIM is conserved when the PIM is elongated. However, we can see that elongating the PIM by 20% leads to a 40% higher impedance, with a peak at about the same frequency (~ 2 kHz). From contracted to elongated position, a larger length of RF fingers are exposed to the coil. It is therefore clear that the RF fingers (with the bellow behind them) represent a significant contribution to the global PIM transverse beam impedance.

Non-conforming Contacts

Measurements were performed at operating nominal cold length (elongated), and two types of bad contacts between the RF fingers and the vacuum chamber were measured (see Fig. 3):

- *Bad electrical contact* (a): a thin (~ 100 µm) copper sheet was inserted between the CuBe fingers and the coated vacuum chamber to reproduce an erosion of the thin gold/rhodium coating layer.
- *No electrical contact* (b): 0.5-mm-thick-fibreglass-plates were inserted between the fingers and the vacuum chamber to simulate a bent finger.

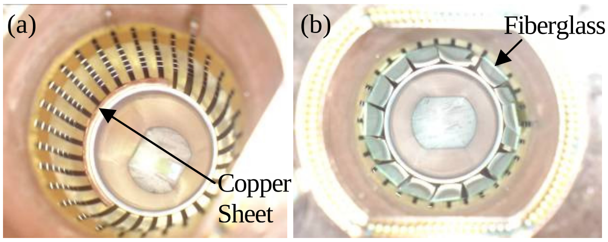

Figure 3: Pictures of the inside of a PIM with (a) a thin sheet of copper on half (left) of the RF contacts, (b) all RF contacts isolated with thin plates of fiberglass.

Measurement results for simulated bad electrical contacts (case of Fig. 3 (a)) are shown in Fig. 4.

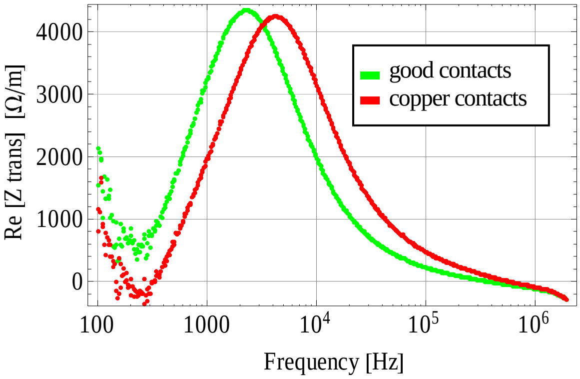

Figure 4: Comparison of the real part of the transverse beam impedance of a PIM with conform “good” contacts (in green), and the same PIM with a thin sheet of copper between half of the RF fingers and the vacuum chamber. Measurement with the reference copper tube is subtracted.

Again, it is observed that the general shape is conserved. Note that the difference between the green curve of Fig. 3 and Fig. 4 can be explained by slightly different measurement conditions (temperature). This time however, the impedance peaks have the same amplitude, but the peak frequency is shifted to higher frequencies if bad contacts are simulated with a thin copper sheet on half of the fingers. As lower conductivity materials exhibit higher beam impedance peak frequency (see for instance a comparison between graphite and copper collimator jaws in [5]), this observation is consistent with a global lower conductivity of the PIM due to this bad contact.

Measurement results for a simulated absence of electrical contact (case of Fig. 3 (b)) are shown in Fig. 5.

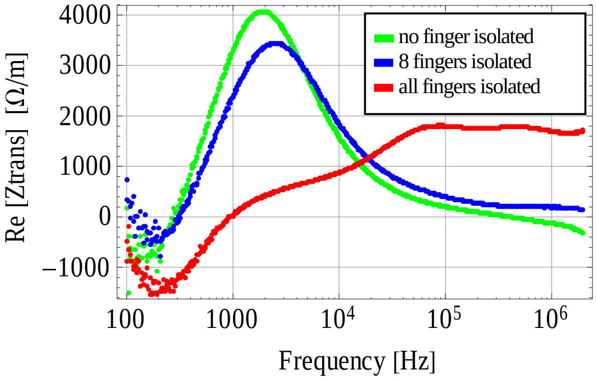

Figure 5: Comparison of the real part of the transverse beam impedance of a PIM elongated to nominal length at cryogenic temperature with all fingers in contact (green), with 8 fingers isolated out of 30 (blue), and with all fingers isolated (red). Measurement with the reference copper tube is subtracted.

If only 8 fingers out of 30 fingers are isolated, the global conductivity of the PIM is not affected too much, and the beam impedance peak is again slightly shifted to higher frequencies. When all fingers are isolated with fibreglass, the impedance peak is now clearly shifted by two orders of magnitude in frequency and smeared on a much wider range of frequencies. As the effect of the impedance on the beam is linked to the sum over the betatron frequencies of the product of the beam power spectrum with the impedance spectrum [7,8], a much larger range of frequencies where the impedance is significant can be detrimental to the beam transverse stability.

DISCUSSION

In the case of a nominal PIM at operating cryogenic temperature on Fig. 3, 4, and 5, the peak of the transverse beam impedance is observed to be ~ 4 kΩ/m at ~ 2 kHz. This peak value is consistent with a crude estimate deduced from [3], in which equation (1) in [3] used with the operating value of the contact resistance of 1 finger (3 mΩ in Fig. 1 in [3]) - i.e. 0.1 mΩ for 30 contacts in parallel - yields a transverse beam impedance of ~ 3.4 kΩ/m for one PIM (i.e. ~ 7 MΩ/m for all 1700 PIMs). In addition to being consistent with crude estimates, this measurement displays the frequency spectrum of the beam impedance, which is observed to become negligible for frequencies higher than 1MHz.

It is interesting to notice that, for the lowest betatron line frequency (8 kHz), the transverse beam impedance is lower when all contacts are removed. This behaviour is similar to the case of the LHC collimators [5]. In addition, the peak value is divided by 2 at ~ 2 kΩ/m (i.e. ~ 3.4 MΩ/m for all 1700 PIMs).

However, as already mentioned, the peak is broader, and the transverse beam impedance is not negligible over 1 MHz. Finally, the transverse beam impedance of the rest of the machine is estimated to be ~ 300 MΩ/m at 2 kHz, and constant at ~ 100 MΩ/m between 20kHz and 1 MHz [9]. Therefore, in the measured frequency range, the transverse beam impedance of the PIMs accounts for less than 4% of the total LHC beam impedance, even if all contacts are removed.

CONCLUSION

Measurements of the transverse beam impedance of a LHC SSSMB Plug in Module were performed at low frequency using a coil probe and a LCR meter, for conforming and non-conforming contacts.

These first measurements up to 2 MHz show that the low frequency real transverse beam impedance of a PIM accounts for less than 4% of the total LHC beam impedance, even if all RF contacts are removed.

However, the behaviour of the PIM transverse beam impedance at higher frequencies is not yet known, and the PIM contribution to the total LHC beam impedance may not be negligible if all RF contacts are removed.

Besides, if a solution is found to reduce the transverse beam impedance of the LHC collimators, which largely dominate over all the rest of the machine around 1 MHz [10], non-conforming PIMs could then become the major contributor to the LHC impedance around 1 MHz.

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