EVALUATION OF LONGITUDINAL BEAM IMPEDANCE IN THE BEAM GAS IONIZATION MONITOR OF THE CERN-PS ACCELERATOR

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Abstract

The recently observed beam induced heating issues in the BGI monitors of the LHC which could have been occurred due to a strong coupling between the beam and the localized modes at the sensor location showed the general importance of a thorough evaluation of the beam coupling impedance and the corresponding heat deposit in beam monitoring equipments. This paper is devoted to the examination of the beam coupling impedance and beam induced heating for a currently under development beam gas ionization (BGI) monitor which is intended to be a part of the CERN Proton Synchrotron (PS) beam monitoring equipment. Details of the EM and wake field simulations for this BGI monitor together with the RF measurement results and power loss calculations will be presented.

INTRODUCTION

To extend the discovery potential of the LHC, a major upgrade is currently under development to increase LHC luminosity by a factor of 10. The challenging High Luminosity LHC (HL-LHC) parameters have led CERN to initiate an ambitious upgrade program of the full LHC injector chain (LIU project). As part of this program, the transverse beam profile monitors in the proton synchrotron will be upgraded to provide continuous and non-destructive bunch-by-bunch measurement of the transverse emittance. Measurements of the transverse beam profile are currently performed by fast rotational wire scanners. These scanners cannot provide continuous bunch-by-bunch measurements and the expected future increase of the beam brightness will lead to an accelerated sublimation of the wire. A BGI monitor which is a fast non-destructive transverse profile monitor is currently under development [1]. In this beam monitor, the transverse beam profile is measured by four Timepix3 hybrid pixel imaging detectors [2]. The nanosecond time resolution of these chips will facilitate bunch-by-bunch measurement of the beam profile. This will be the first application of a pixel detector-based technology directly inside a CERN accelerator beam-pipe. It necessitates the development of an instrument that is compatible with several stringent considerations regarding ultra high vacuum, radiation and the beam coupling impedance issues. In this paper, longitudinal beam coupling impedance of this beam profile monitor will be examined. In the following sections, RF measurements, the beam coupling impedance resulted from CST wake field simulations, and the corresponding heat deposit calculations will be presented.

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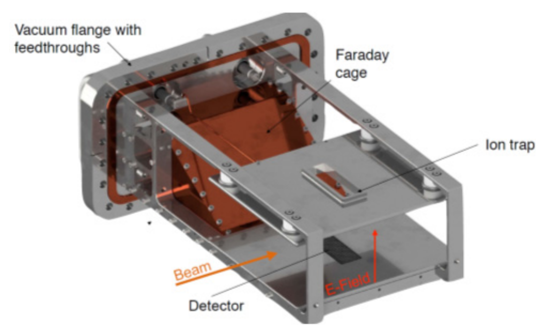
RF MEASUREMENTS AND SIMULATIONS

Figure 1 shows the BGI monitor and its vacuum vessel. This monitor measures the transverse size of the beam by monitoring the position of the electrons that are produced as a result of the rest gas ionization. As is shown in Fig. 1, the electric field between the two electrodes separates the two products of ionization, i.e., electrons and the positively charged ions. These electrodes create a vertical electric field that guides the electrons towards the detector and ions towards an ion trap. An external magnetic field of 0.2 T confines the electron movement by reducing their transverse spread.



(a)

(b)

Figure 1: (a) BGI tank and (b) BGI vacuum vessel.

Electric probes, long enough to reach the BGI tank through the long beam pipes (see Fig. 2), have been used to measure the scattering parameters of the whole structure. These results have been used to evaluate the accuracy of the CST simulation model. The variable length of the probe, which is inside the beam pipe, can help to distinguish the real eigen modes of the structure from the modes appearing due to the presence of the probe in the beam pipes. Figures 3 (a) and (b) illustrate the difference between these modes and the real eigen modes. In these figures, eigen modes of the structure without the presence of probes (shown in black bars) and its transmission coefficient (S_{21}) for different lengths of the probe are shown.

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As seen in this figure, the probe-related modes change their frequency with the length of the probe while a frequency variation is not observed in the case of the real eigen modes of the structure (red arrows in Figs. 3 (a) and (b) show these modes). By inserting absorbing materials in the beam pipes (see Fig. 3 (b)), the disturbing probe modes are damped to some extent, however, the frequency of the eigen modes of the BGI tank remains unchanged. Good agreement between the eigen mode simulation results and the measured results which can be deduced from Figs. 3 (a) and (b) confirms the accuracy of the simulated model. In the next section, this agreement will be examined in more detail. Similar measurements were also done for the frequency range from 800 MHz to 1500 MHz. As expected, all eigen modes cannot be excited with these excitation settings (for example, as shown in Figs. 3 (a) and (b), none of the modes within the frequency range from 600 MHz to 800 MHz are excited). On the other hand, when the probes placing in the symmetry plane of the beam pipes, only a few modes which are mainly confined to the BGI tank itself and have a significant field decay inside the beam pipe are weakly excited. Consequently, the measured quality factor (Q_m) is close to the unloaded quality factor (Q_u) only for these modes[1]. The mode with $f = 160$ MHz is one of these modes. For this mode, Q_m is close to Q_u and it is in very good agreement with the simulated Q_u which is 220. It should also be mentioned that the lowest eigen mode frequency of the structure lies at 50 MHz. This mode, due to its very small shunt impedance, is considered to be insignificant and therefore it has not been shown in Fig. 3. Figure 4 shows the simulated Q_u values. Modes with frequencies below 1 GHz are the modes that are mainly confined to the BGI tank and therefore they do not have a very high quality factor in comparison to modes above 1GHz which are of a more volumetric nature and are extended to the beam pipe region.

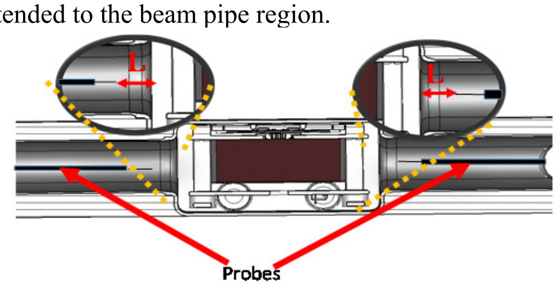

Figure 2: Cut-away view of the BGI monitor with long electric probes inside the beam pipes. The distance between the entry of the BGI tank and the probe is L (see the figure inset).

WAKE FIELD SIMULATIONS AND BEAM COUPLING IMPEDANCE

CST simulation software [3] has been implemented for calculating the longitudinal beam coupling ($Z_{||}$). A meshing scheme which is fine enough to resolve the details of the ion trap and the detector area of the BGI monitor has been used. Figure 5 shows the real and the imaginary part of $Z_{||}$. As can be seen in Fig. 5, the maximum value of the real and imaginary part of $Z_{||}$ for the BGI monitor are smaller than 2.5 kΩ and therefore this monitor does not significantly contribute to the total $Z_{||}$. Before examining the heating issues, it is interesting to assess the accuracy of the simulations. Table 1 presents an overview of the agreement between the measured and simulated (using eigen mode and wake field simulators) resonant frequencies (only modes below 1.5 GHz with non-negligible $Re[Z_{||}]$ are shown in this table). In fact, the combination of a fine mesh and long wake potential simulations resulted in a very good agreement between the eigen mode frequencies, the frequencies resulted from wake field simulations, and the measured frequencies.

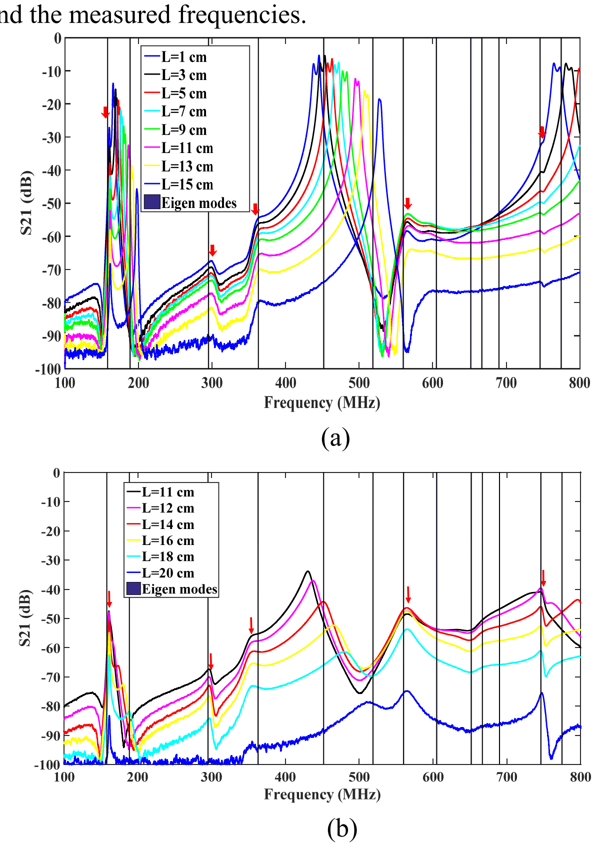

Figure 3: Measured S_{21} for different values of L (L is shown in Fig. 2) without (a) and with (b) absorbing material in the beam pipes of the BGI monitor.

HEATING ISSUES

The general formula for the beam power loss (due to an interaction with the longitudinal impedance) in circular machines can be written as [4]

$$P_{loss} = 2N_b^2 I_b^2 e^2 f_0^2 \sum_{p=0}^{\infty} Re\left[Z_{||}(2\pi p f_0)\right] \times S(2\pi p f_0) \quad (1)$$

where $Z_{||}$ is the longitudinal impedance, S is the normalized power density spectrum of the particle distribution, p shows multiples of revolution frequency (f_0), I_b is the intensity per bunch, N_b is the total number of bunches, and e is the elementary electric charge. An

[1] The quality factor which is measured from S_{21} is the loaded quality factor (Q_l). Using a very weak excitation, Q_l will be very close to Q_u.

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impedance can cause a significant amount of loss when its frequency coincides with pf_0 or is very close to this frequency.

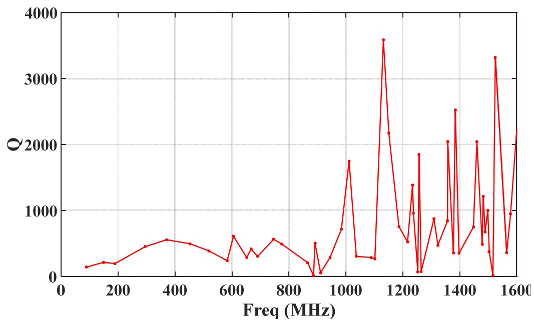

Figure 4: Simulated (using CST [3]) Q_u.

Table 1: Measured and Simulated Resonant Frequencies

$f_{measured}$ (MHz)	$f_{simulated\_eigen\ mode}$ (MHz)	$f_{simulated\_wake\ field}$ (MHz)
161.4	158	161.9
297.1	295	-----
362.2	370	370
-------	451.7	451.8
565.1	569	572
745.3	747	745
898.1	904	905
--------	1237	1240
1478.1	1480	1479

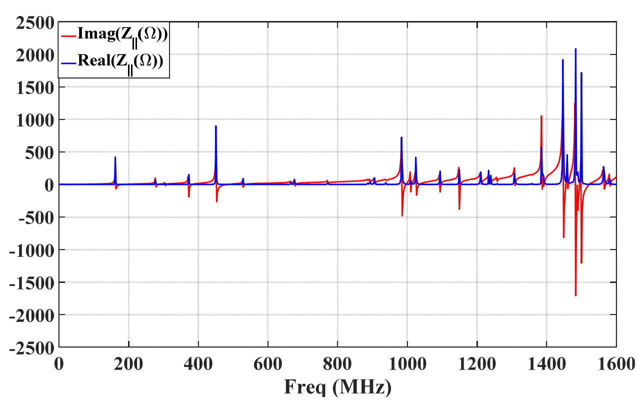

Figure 5: Real and imaginary part of $Z_{||}$ (simulated using CST [3]).

Figure 6 shows the normalized power density spectrum of the particle distribution for PS (the main beam parameters that have been used are: bunch length $(4\sigma) =$ 4.2 ns , $I_b = 1.2 \times 10^{11}$ppb, and $n_b = 72$[1].) and also the normalized $Re\ [Z_{||}]$ of the BGI monitor. As seen in this figure, a mode with a frequency of about 161 MHz coincides with one of the spectral lines in the power density spectrum of the particle distribution for PS. The total beam power loss caused by this monitor is about 8.9 W[2] (18.7 μJ/turn) where about 99.3% of this loss is related to the resonance at 161 MHz. Electric field profile of this mode is shown in Fig. 7. As seen in this figure, this mode is mostly confined to a region between the cooling plate and the outer enclosure and is not completely confined to the sensor area which is the worst scenario in terms of heating issues. However, it is still strongly advisable to remove the corresponding heating risk by slight geometrical changes which can shift the 161 MHz mode away from the maximum of the beam power density spectrum.

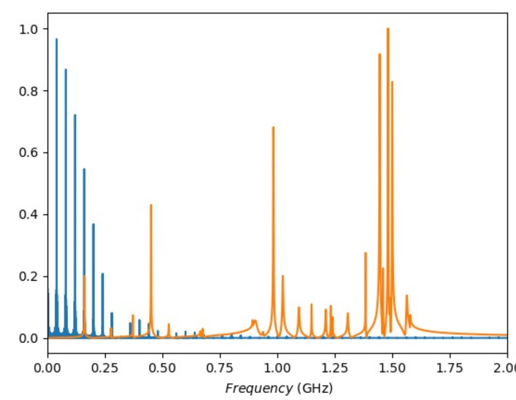

Figure 6: Normalized power density spectrum of the PS beam in blue, and normalized $Re\ [Z_{||}]$ in orange.

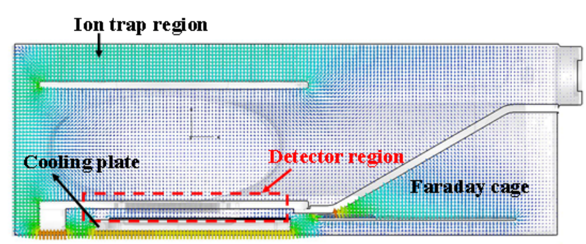

Figure 7: Simulated (using CST [3]) electric field profile for $f = 161$ MHz.

CONCLUSIONS

In this paper, the longitudinal beam coupling impedance and heating issues for the currently under development PS-BGI monitor have been examined. It has been shown that this monitor does not present significant longitudinal beam coupling impedance. Slight geometrical changes with the purpose of shifting the resonant frequency of 161 MHz mode is advisable to minimize the risk of heating issues.

[1] The power density spectrum and the losses are calculated using Blond-related tools [5]. It should be mentioned that 4.2 ns corresponds to the PS bunch length at extraction. Since usually the bunch lengths in the PS are larger than this value, P_{loss} calculations of this section correspond to the worst case scenario.

[2] It should be mentioned that increasing the I_b by approximately two times in the frame work of HL-LHC will result in increasing the calculated power loss by approximately four times.

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