Abstract

The ALBA pinger magnet consists on two short kickers (for horizontal and vertical planes) installed in a single Titanium coated ceramic vacuum chamber. Single bunch measurements in the vertical plane were performed in the ALBA Synchrotron Light Source before and after the pinger installation, and by comparing the Transverse Mode Coupling Instability (TMCI) thresholds for zero chromaticity, we infer the pinger impedance and compare it with the model predictions.

INTRODUCTION

Coupling impedance calculations are a key issue when designing an accelerator, in particular for electron light sources, where the presence of numerous Insertion Devices (IDs) with very small gaps can limit the circulating beam intensity in the machine. Often, these IDs are not made of a single material, but they are composed of different materials in different layers. Therefore, it is important to evaluate the reliability of the computer codes that evaluate the impedance of these devices before their installation.

At ALBA, a pinger magnet has been installed during the summer shutdown of 2014 [1]. The pinger magnet is a multi-layer structure composed by a ceramic vacuum chamber of 6.5 mm thickness, with an inner Titanium (Ti) coating of only 400 nm. This vacuum chamber is surrounded with a ferrite yoke [1], and between the ceramic and the ferrite there is a gap of 1 mm width for air cooling. This structure is exactly the same as the one used for the four injection kickers installed since day-1, with the only difference in the ferrite thickness surrounding the ceramic chambers [2].

Figure 1 shows a picture of the pinger magnet, where the ceramic chamber is visible in the middle. The same vacuum chamber (780 mm in length) is used for the horizontal (left) and vertical kick excitations (right). The difference for each structure consists in the position of the Copper (Cu) electrodes, which are located on left/right for the horizontal excitation, and top/bottom for the vertical.

The goal of these studies is to infer the pinger magnet impedance based on beam measurements and compare it with results using different computer simulation codes (GdfidL, CST, and IW2D [3–5]). Beam-based impedance characterization of the pinger magnet are based on Transverse Mode Coupling Instability (TMCI) studies: by analysing the machine detuning and instability thresholds before the pinger installation (Autumn 2013) and after (Autumn 2014) we can infer the contribution of the new installed element to the total machine impedance.

BEAM-BASED MEASUREMENTS

TMCI Theory

Assuming a Gaussian beam bunch with $N_b$ particles and rms length of $\sigma_r$, the complex frequency shift in betatron frequency for the $l = 0$ mode is expressed by [6]

$$\Omega - \omega_B = -i Z_{\text{eff}} \frac{N_b e c^2}{4\sqrt{\pi} (E/e) T_0 \omega_B \sigma_r}, \quad (1)$$

where $\omega_B = Q_B \omega_0$ the angular betatron frequency, $Q_B$ is the betatron tune (including the integer part), $\omega_0$ is the angular revolution frequency, $E$ is the beam energy, $c$ is the speed of light, and $e$ the electron charge. The term $Z_{\text{eff}}$ is the effective impedance of the machine, defined as:

$$Z_{\text{eff}} = \sum_i \beta_i Z_i / \beta_* \quad \text{,} \quad (2)$$

where $Z_i$, $\beta_i$ refers to the impedance and beta function of the machine element $i$, respectively. Equation 1 shows that the imaginary part of $Z_{\text{eff}}$ causes a tune shift with increasing bunch current, which allows to infer the total machine impedance, as already performed in other machines [6–8].

While the vertical detuning is proportional to $\text{Im}(Z_{\text{eff}})$, the threshold at which the instability occurs decreases with increasing the impedance (approximately like $1/Z_{\text{eff}}$). In general, there is no readily available formula relating the intensity threshold and the impedance, and this has to be inferred using computer simulation codes including bunch lengthening effects.

In the following, we focus our studies on the vertical plane because the pinger transverse aperture is $80 \times 24$ mm (horizontal $\times$ vertical), and thus the effect is much more critical in the vertical plane.
**TMCI Observations**

The TMCI phenomenology is well observed on the tune monitor upon increasing the bunch current. Figure 2 compares the measurements taken (with In-Vacuum Undulators (IVUs) closed) during 2013 (blue) and during 2014 (red). In both cases, the chromaticity in the vertical plane was set as close as possible to 0 and the same rf voltage (2.1 MV) was used to keep the same synchrotron tune.

The measurements were taken in steps of about 1 mA, when the injection was halted to perform both tune and bunch length measurements. For an easy comparison, we plot the vertical tune shift with respect to the zero-current tune, normalized to the synchrotron tune $Q_s$. It is observed that the slope becomes steeper by 3.6% after the pinger’s installation. The error bar in the data points stems from the statistical tune measurement fluctuation.

**Effective Impedance**

From Eq. 1, the imaginary part of the effective impedance is estimated from the measured tune shift as:

$$\text{Im}(Z_{\text{eff}}) = \frac{dQ}{dI_B} 4\sqrt\pi \frac{(E/e)\omega_0 \sigma_\tau}{\epsilon \beta_s},$$

where $I_B$ is the bunch current. The precision of this measurement is also limited by the precision given by the bunch length measurement given by the streak camera, which we estimate at 10%.

Considering a bunch length of $\sigma_\tau=20 \text{ ps}$ [10], the estimate before the pinger magnet’s installation is $\text{Im}(Z_{\text{eff}}^{2013}) = 216 \text{ k}\Omega/m$, and it increases to $\text{Im}(Z_{\text{eff}}^{2014}) = 224 \text{ k}\Omega/m$ after its installation in 2014. This is consistent with the results shown in Ref. [10], where thorough studies show not only measurements at 2.1 MV, but for different rf voltages (and thus varying the bunch length).

The pinger impedance is obtained from the difference between the two values, normalized by the ratio of $\langle \beta_s \rangle/\beta_p$, being $\beta_p$ the local beta-function at the pinger.

We obtain $\text{Im}(Z_{\text{eff}}^{p0}) = (14.5 \pm 4) \text{ k}\Omega/m$.

**RESULTS FROM SIMULATION CODES**

**Model Prediction with IW2D**

The impedance of the pinger magnet is estimated using an analytical code, ImpedanceWake2D [5], which is based on the exact solution of Maxwell equations. The code assumes long structures and flat geometries to model the magnet. Consistent with the pinger geometry, we simulate the pinger magnet with a 4-layer structure composed of a 6.5 mm thickness ceramic chamber with the 0.4 $\mu$m Ti coating, plus the external ferrite yoke. Between the ceramic and the ferrites, we also take into account the 1 mm thick layer of air required for air cooling. The material properties of the 4-layer structure are shown in Table 1.
Adding up geometrical and wall impedance contribution, a vertical impedance of 2.92 kΩ/m is obtained. An overview of all contributions is shown in Table 2.

Table 2: Impedance of the pinger magnet from the different contributions. The total impedance is 2.92 kΩ/m (@22 ps).

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Im(Zeff), kΩ/m</th>
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<tbody>
<tr>
<td>dipolar broadband</td>
<td>0.64</td>
</tr>
<tr>
<td>quadrupolar broadband</td>
<td>0.21</td>
</tr>
<tr>
<td>dipolar RW</td>
<td>1.35</td>
</tr>
<tr>
<td>quadrupolar RW</td>
<td>0.71</td>
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Figure 5: Real (red dashed line) and imaginary part (black) of the BBI impedance (dipolar part) computed with GdfidL.

**CONCLUSION**

The effective impedance produced by the pinger magnet has been measured by analyzing the TMCI detuning slopes and intensity thresholds before and after its installation. We evaluate \(\text{Im}(Z_{\text{eff}}) = (14.5 \pm 4) \text{ kΩ/m} \). The large (around 30% error bar) stems from the influence of the experimental machine settings in the TMCI measurements and the tune measurement spread.

On the other hand, computer simulation codes like IW2D and GdfidL provide an impedance of \(\sim 3 \text{ kΩ/m} \), which is almost a factor 4 smaller from the measured one. The difference is not understood and is currently under investigation. Several factors are under study, like the influence of the adjacent structures (tapers, bellows, etc), and the exchange of a dipole chamber for an infrared beamline.

In [10], good agreement is found regarding other multi-layer structures (in-vacuum undulators) after careful cross-check of the surrounding structures. Therefore, we will not only look at the **room-for-improvement** in the computer simulation codes, but also to a more careful analysis of the pinger surrounding structures, as well as to the experimental machine set-up and bunch length parametrisation.
REFERENCES