COHERENT TUNE SHIFT AND INSTABILITIES MEASUREMENTS AT THE CERN PROTON SYNCHROTRON BOOSTER

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Abstract

To understand one of the contributions to the intensity limitations of the CERN Proton Synchrotron Booster (PSB) in view of its operation with beams from Linac 4, the impedance of the machine has been characterized.

Measurements of tune shift as a function of the intensity have been carried out in order to estimate the low frequency imaginary part of the impedance. Since the PSB is a low energy machine, these measurements have been done at two different energies, so as to enable us to disentangle the effect of the indirect space charge and resistive wall from the contribution of the machine impedance.

An estimation of the possible resonant peaks in the impedance spectrum has been made by measuring a fast instability in Ring4.

INTRODUCTION

The PSB is made of four stacked similar rings and we measured the coherent tune shift of two of them (Ring2 and Ring4) at two different energies: 160 MeV and 1 GeV. In addition we carried out the same analysis at 1.4 GeV for Ring4 only. In order to measure the transverse tune we have used the diode-based base-band-tune (BBQ) application which excites transversely the beam in both planes.

For several beam intensities we have acquired the horizontal and vertical tunes \( Q_x \) and \( Q_y \). The two energy flat tops had different tunes \( Q_{x,0} \) and \( Q_{y,0} \) which were the same for the two rings. We shall refer now to the tune shifts \( \Delta Q \) as the measured tune, \( Q_{x,Sup.}^{\text{Sup.}} \), at the highest beam intensity \( I_{Sup.} \), minus the measured tune \( Q_i^{\text{inf.}} \) at the lowest beam intensity \( I_{inf.} \), \( i \) being either \( x \) or \( y \). The same procedure was used to calculate the tunes (e.g. for the space charge contributions) instead of measuring.

In order to disentangle the different contributions to the total tune shift, we considered the total coherent tune shift as \( \Delta Q = \Delta Q_{s.c.} + \Delta Q_{r.w.} + \Delta Q_{b.b.} \), where we took into account the contributions coming from the indirect space charge due to the image charges, the resistive wall impedance and the broad band impedance respectively. The first two contributions due to the space charge and the resistive wall impedance have been calculated using analytical formulae, whereas the broad band tune shift has been deduced allowing us to give an estimation of the effective broad band impedance of the machine. The above analysis was carried out only in the vertical plane since no clear trend of the tune shift versus the bunch intensity was observed in the horizontal.

In addition, two different instabilities were observed in Ring4 for the nominal PSB cycle and their rate of growth measured.

THE TUNE SHIFT DATA

Concerning the longitudinal dynamics we used only one single harmonic RF cavity (CO2) in order to obtain a Gaussian-like longitudinal shape of the beam. Figure 1 illustrates the bunch length \( \sigma_l \,[\text{ns}] \) acquired at the three different energies in Ring4 as a function of the beam intensity.

For the following calculations requiring the use of the bunch length we used an average value \( \bar{\sigma}_l \,[\text{m}] = \beta \bar{c} \sigma_l \,[\text{ns}] \). In the following plots (Figs. 2, 3 and 4) we show the results obtained for the vertical plane at the three different energies.

In Figs. 2 and 3 we clearly see that the total vertical tune shift is almost the same in both Ring2 and Ring4 suggesting
that they have the same effective impedance. Concerning
the measurements at 1.4 GeV only Ring4 was analyzed and
the results are displayed in Fig. 3 (left plot).

In Fig. 4 (right plot) an example of the tune shift mea-
sured in the horizontal plane is shown. Due to the scattered
behavior of the data and the small variation over the inten-
sity range (in comparison with the vertical plane tune shift),
we did not conduct further the analysis. In Table 1 we sum-
marized the observed tune shifts $\Delta Q_y$ and the slopes $A$
of the fitted lines.

THE TUNE SHIFT DATA ANALYSIS

Our main goal is to disentangle the contributions to the
cohereent tune shift coming from the space charge (im-
age charges), resistive wall impedance and broad band
impedance. Since we have not observed any drastic dis-
crepancies between the two rings we carried out the analy-
sis only for Ring4. First of all we have calculated the space
charge tune shift coming from both the electric and mag-
netic images using Zotter’s formalism as reported in [1].

For 1/3 of its circumference, the PSB has an elliptic
beam pipe, and circular for the remaining 2/3. The ellip-
tic section has a half height $h = 3.2$ cm and a half width
$w = 8$ cm. The circular section of the beam pipe has a
radius $r = 8$ cm. Since the space charge tune shift has a
strong dependence on the vacuum chamber geometry, we
assumed $\Delta Q_{x,s.c.} = \Delta Q_{Ellip./3} + 2\Delta Q_{Circ./3}$ with

$$\Delta Q_{x,y,s.c.} = - \frac{Nr_0 R}{\pi \gamma \beta^2 v_0 x, y} \left\{ \begin{array}{ll}
\xi_{x,y} \frac{\varepsilon_{x,y}}{h^2} & \text{electric images} \\
\beta^2 \xi_{x,y} \frac{\varepsilon_{x,y}}{h^2} & \text{ac magnetic images} \\
- \beta^2 \xi_{x,y} \frac{\varepsilon_{x,y}}{h^2} & \text{magnetic images}
\end{array} \right\}$$

(1)

with $B = \frac{2\varepsilon_{x,y}}{\pi \gamma h^2}$, $R = 157/2\pi$ radius of the PSB and
$\xi_{x,y}, \varepsilon_{x,y}$ functions of the pipe geometry. In Table 2 we
summarized the calculated values of the space charge tune
shifts for the three different energies.

For a longitudinal Gaussian beam we can define the
effective transverse impedance $Z_{Eff}[2]$ as

Beam Dynamics and Electromagnetic Fields

Table 1: Total Measured Tune Shift in the Horizontal and
Vertical Plane, as well as the Slope of the Fitted Lines

<table>
<thead>
<tr>
<th>Kinetic Energy</th>
<th>160 MeV</th>
<th>1 GeV</th>
<th>1.4 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta Q_y$ Ring2</td>
<td>-0.07</td>
<td>-0.009</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta Q_y$ Ring4</td>
<td>-0.076</td>
<td>-0.009</td>
<td>-0.0045</td>
</tr>
<tr>
<td>$\Delta Q_y$ Ring2 $[10^{-5}]$</td>
<td>-6.2</td>
<td>-1</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta Q_y$ Ring4 $[10^{-5}]$</td>
<td>-7.2</td>
<td>-1.1</td>
<td>-0.72</td>
</tr>
</tbody>
</table>

Table 2: Calculated Space Charge Tune Shift

<table>
<thead>
<tr>
<th>Kinetic Energy</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$\Delta Q_{x,s.c.}$</td>
<td>-0.0072</td>
<td>0.00024</td>
<td>0.00025</td>
</tr>
<tr>
<td>$\Delta Q_{y,s.c.}$</td>
<td>-0.038</td>
<td>-0.0032</td>
<td>-0.0014</td>
</tr>
</tbody>
</table>

which is the sum of two different components $Z_{Eff}$
(Broad Band) and $Z_{Eff,w}$ (Resistive Wall). In the compu-
tation of the resistive wall contribution to the total $Z_{Eff}$,
we used a non-ultra relativistic approach [3]. We also made
use of the relation $Z_\perp \simeq 2\beta_0 Z_\parallel / b^2 \omega$, with $b$
the beam pipe radius, which is always valid for the value of
the impedance frequencies $\omega$ (obtained from the leading term
of Eq. (2)) we observed [2]. In the calculation of the effec-
tive resistive wall impedance we used $b = h$ for 1/3 of
the machine length and $b = w$ for the rest. In the PSB the
natural chromaticity has the value $\xi \simeq -1.1$ and we obtain
the following results and we have calculated the associated
cohereent tune shift $\Delta Q_{s,c}$. using the following formula [2]
valid for Gaussian-like beam for the $l = 0$ mode

$$\Delta Q = - \frac{1}{2\pi^3/2} \frac{Nr_0 c^2}{\gamma \beta_\perp} i \left( Z_{Eff} \right) \ .$$

(3)

We observe from Table 3 that the tune shift due to the
resistive wall is negligible. Given that $\Delta Q = \Delta Q_{s,c} +
\Delta Q_{r,w} + \Delta Q_{b,b}$, we estimate the broad band vertical tune

Table 3: Resistive Wall characteristic frequencies $\omega$ from the leading term of Eq. (2). The effective resistive wall impedance as well as the tune shifts are calculated.

<table>
<thead>
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<th>1.4 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega [MHz]$</td>
<td>39</td>
<td>257</td>
<td>497</td>
</tr>
<tr>
<td>$Z_{Eff} [K\Omega/m]$</td>
<td>10.7</td>
<td>7.1</td>
<td>5.5</td>
</tr>
<tr>
<td>$\Delta Q_{r,w} \cdot 10^{-5}$</td>
<td>-6</td>
<td>-1.3</td>
<td>-0.6</td>
</tr>
</tbody>
</table>
Table 4: The effective broad band impedance as well as the respective tune shifts are calculated subtracting the space charge and the resistive wall contribution from the experimental observations.

<table>
<thead>
<tr>
<th>Kinetic Energy</th>
<th>160 MeV</th>
<th>1 GeV</th>
<th>1.4 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta Q_{b,b.}$</td>
<td>-0.032</td>
<td>-0.006</td>
<td>-0.003</td>
</tr>
<tr>
<td>$Z_{b,b.}^{Eff.}$ [MΩ/m]</td>
<td>5.8</td>
<td>2.9</td>
<td>2.7</td>
</tr>
</tbody>
</table>

From Table 4 we can see that the broad band component of the machine impedance is significant and has different values at different energies.

**INSTABILITY OBSERVATIONS AND GROWTH TIME ESTIMATIONS**

The PSB normal operation needs a transverse beam damper in order to suppress the instabilities which arise at certain times for high intensities.

In order to study those instabilities in Ring4, we switched off the transverse damper and started from the lowest beam current. We were able to accelerate with a single harmonic RF cavity (CO2). We observed that approaching a bunch intensity $I \approx 490 \cdot 10^{10}$ ppb two instabilities could develop either 100 ms or 200 ms after the injection into the PSB.

In Fig. 5 plots are shown of the superposition along the bunch of the last 50 traces before the losses took place.

![Figure 5: Delta signal of the beam from the transverse pick-up.](image)

Analyzing a set of 90 pick-up traces separated by 21 revolution periods, we have also analyzed the growth rate of the two instabilities observed. In Fig. 6 we see plots of all 90 traces during 90μs of $\Delta$ signal acquisition together with the signal envelope and the fitted curve.

![Figure 6: Delta signal of the beam during the 90μs of acquisition (90 beam traces).](image)

Fitting the signal envelope with an exponential curve $f(t) = \alpha + \beta \exp(t/\tau)$ we have calculated the growth time obtaining the results shown in Tab. 5.

Table 5: Growth Rates of the Two Observed Instabilities at Ring4 for the 1.4 GeV Cycles

<table>
<thead>
<tr>
<th>$\Delta t$ after injection [ms]</th>
<th>100</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$[μs]</td>
<td>34</td>
<td>60</td>
</tr>
</tbody>
</table>

for the frequencies $(n - Q_x)\omega_0$, $n \in \mathbb{N}$. For each horizontal tune $Q^i_x$, the instability was observed at a different time of the cycle, corresponding to a bunch revolution frequency $\omega^i_0$. While most of the lines shown by the spectrum analyzer would move with the changed tune, the line $\Omega = (2 - Q^i_x)\omega^i_0$ always stayed constant at the value of $\Omega/(2\pi) = 1.65$ MHz. This is therefore a likely candidate as frequency of a strong peak in the impedance spectrum, and it could possibly be associated to the extraction kickers.

**CONCLUSIONS**

The coherent vertical tune shift of the PSB was measured, showing that two out of the four rings exhibit the same behavior. From measurements and analytical formulae the contributions of the image charges, resistive wall impedance and broad band impedance were quantified. The resistive wall impedance was found to be a negligible contributor and the value of effective broad band impedance was estimated.

Furthermore, two instabilities were observed in Ring4 at different times of the cycle, and their growth rates were calculated. A possible impedance source was identified by observing the oscillation frequency of the instability for different working points.

**REFERENCES**

