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 ΔQ as the measured tune, $Q_i^{Sup.}$, at the highest beam intensity $I_{Sup.}$, minus the measured tune $Q_i^{Inf.}$ 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 folmulae, 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.

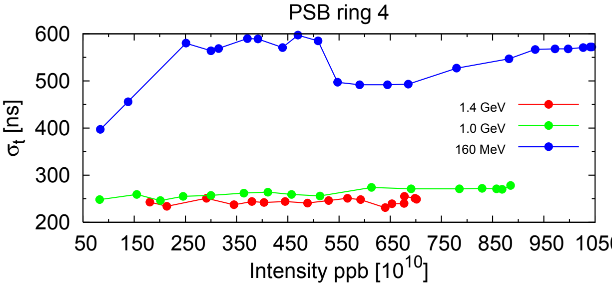

Figure 1: Measured bunch length (4σ) obtained from the longitudinal beam profile.

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 σ_t [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 $\bar{\sigma}_s[\text{m}] = \beta c \bar{\sigma}_t[\text{ns}]$. 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

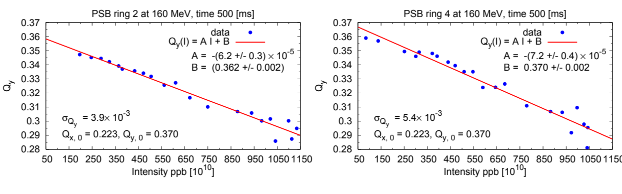

Figure 2: Tune shift measurements taken at 160 MeV ($\beta \simeq 0.519$) for Ring2 (left) and Ring4 (right).

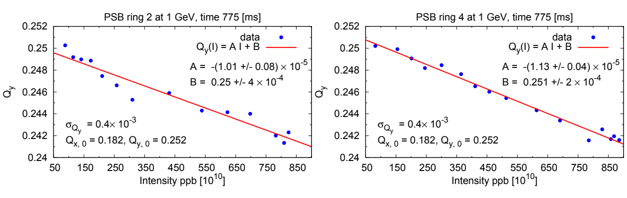

Figure 3: Tune shift measurements taken at 1 GeV ($\beta \simeq 0.875$) for Ring2 (left) and Ring4 (right).

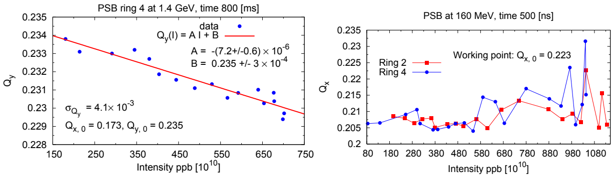

Figure 4: Tune shift measurements taken at 1.4 GeV ($\beta \simeq 0.916$) for Ring4 only (left). An example of the horizontal tune shift measurement (right) at 160 MeV for both rings.

that they have the same effective impedance. Concerning the measurements at 1.4GeV 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 measured in the horizontal plane is shown. Due to the scattered behavior of the data and the small variation over the intensity range (in comparison with the vertical plane tune shift), we did not conduct further the analysis. In Table 1 we summarized the observed tune shifts ΔQ_y and the slopes A of the fitted lines.

THE TUNE SHIFT DATA ANALYSIS

Our main goal is to disentangle the contributions to the coherent tune shift coming from the space charge (image charges), resistive wall impedance and broad band impedance. Since we have not observed any drastic discrepancies between the two rings we carried out the analysis only for Ring4. First of all we have calculated the space charge tune shift coming from both the electric and magnetic 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 elliptic 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 $\Delta Q_{s.c.} = \Delta Q^{Ellip.}_{s.c.}/3 + 2\Delta Q^{Circ.}_{s.c.}/3$ with

$$\Delta Q_{x,y,s.c.} = -\frac{N r_0 R}{\pi\gamma\beta^2\nu_{0;x,y}} \left\{ \underbrace{\frac{\xi_{x,y}}{Bh^2}}_{electric\ images} - \underbrace{\beta^2 \frac{\xi_{x,y} - \epsilon_{x,y}}{h^2}}_{ac\ magnetic\ images} - \underbrace{\beta^2 \left(\frac{1}{B} - 1\right) \frac{\xi_{x,y}}{h^2}}_{magnetic\ images} \right\} \quad (1)$$

with $B = \frac{\sigma_t \beta c}{2\pi R}$, $R = 157/2\pi$ radius of the PSB and $\epsilon_{x,y}, \xi_{x,y}$ 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

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

Kinetic Energy	160 MeV	1 GeV	1.4 GeV
ΔQ_y Ring2	-0.07	-0.009	-
ΔQ_y Ring4	-0.076	-0.009	-0.0045
A Ring2 [10^{-5}]	-6.2	-1	-
A Ring4 [10^{-5}]	-7.2	-1.1	-0.72

Table 2: Calculated Space Charge Tune Shift

Kinetic Energy	160 MeV	1 GeV	1.4 GeV
$\Delta Q_{x,s.c.}$	-0.0072	0.00024	0.00025
$\Delta Q_{y,s.c.}$	-0.038	-0.0032	-0.0014

$$iZ_{Eff.} = \frac{\sum_{p=-\infty}^{\infty} Z(\omega')\, h(\omega' - \omega_\xi)}{\sum_{p=-\infty}^{\infty} h(\omega' - \omega_\xi)}, \quad \begin{cases} \omega' = \omega_0 p + \omega_\beta \\ \omega_\xi = \xi\omega_\beta/\eta \\ h(\omega) = e^{-\omega^2\sigma^2/c^2} \end{cases} \quad (2)$$

which is the sum of two different components $Z^{b.b.}_{Eff.}$ (Broad Band) and $Z^{r.w.}_{Eff.}$ (Resistive Wall). In the computation 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 $Z_\perp \simeq 2\beta c Z_\parallel / b^2\omega$, with b being the beam pipe radius, which is always valid for the value of the impedance frequencies $\hat{\omega}$ (obtained from the leading term of Eq. (2)) we observed [2]. In the calculation of the effective 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 coherent tune shift $\Delta Q_{r.w.}$ using the following formula [2] valid for Gaussian-like beam for the $l = 0$ mode

$$\Delta Q = -\frac{1}{2\pi^{3/2}} \frac{N r_0 c^2}{\gamma\omega_\beta\sigma_s} i\,(Z_{Eff.})\,. \quad (3)$$

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 $\hat{\omega}$ coming from the leading term of Eq. (2). The effective resistive wall impedance as well as the tune shifts are calculated.

Kinetic Energy	160 MeV	1 GeV	1.4 GeV
$\hat{\omega}$[MHz]	39	257	497
$Z^{r.w.}_{Eff.}$[KΩ/m]	10.7	7.1	5.5
$\Delta Q_{r.w.} \cdot 10^{-5}$	-6	-1.3	-0.6

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.

Kinetic Energy	160 MeV	1 GeV	1.4 GeV
$\Delta Q_{b.b.}$	-0.032	-0.006	-0.003
$Z^{b.b.}_{Eff.}$[MΩ/m]	5.8	2.9	2.7

shift $\Delta Q_{b.b.}$ and the effective broad band impedance $Z^{b.b.}_{Eff.}$ applying Eq. (3)

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 $I \simeq 490 \cdot 10^{10}$ 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.

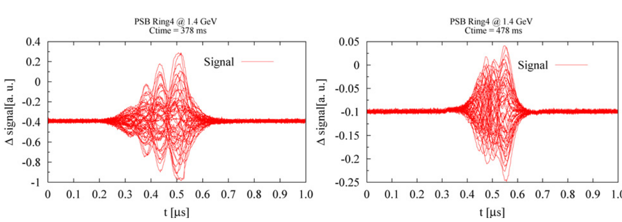

Figure 5: Delta signal of the beam from the transverse pick-up. The signal is taken few ms after the instability occurs and the trace is taken every 21 revolution periods. Only the last 50 traces have been plotted.

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 Δ signal acquisition together with the signal envelope and the fitted curve.

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.

By changing the horizontal tune Q_x, it was observed that the time when the instability appeared also changed. The Fourier analysis of the Δ signal of the bunch, acquired with a wide band pick up, showed all the Fourier components

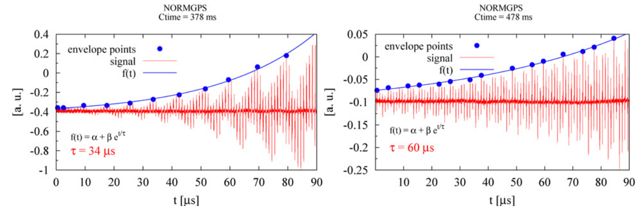

Figure 6: Delta signal of the beam during the 90μs of acquisition (90 beam traces).

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

Δt after injection [ms]	100	200
$\tau[\mu s]$	34	60

for the frequencies $(n - Q_x)\omega_0, n \in \mathbb{N}$. For each horizontal tune Q^j_x, the instability was observed at a different time of the cycle, corresponding to a bunch revolution frequency ω^j_0. While most of the lines shown by the spectrum analyzer would move with the changed tune, the line $\Omega = (2 - Q^j_x)\omega^j_0$ 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.

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