TUNE AND SPACE CHARGE STUDIES FOR HIGH-BRIGHTNESS AND HIGH-INTENSITY BEAMS AT CERN PS

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Abstract

The current 1.4 GeV CERN PS injection energy limits the maximum intensity required by the future High-Luminosity LHC. The bare-machine large chromaticity combined with the non-linear space charge forces make high-brightness and high-intensity beams cross betatron resonances along the injection flat bottom, inducing transverse emittance blow-up and beam losses. A scan of the working point plane (Qx,Qy) was done in order to identify beam destructive resonances, in the framework of a possible 2 GeV injection energy upgrade which would reduce the space charge effect on the tune. Experiments were carried out in order to review the maximum space charge tune shift for which no transverse emittance blow-up is observed. The results of measurements and simulations will be presented in this paper.

INTRODUCTION

The CERN Proton-Synchrotron is amongst the LHC injectors the oldest, and will continue to serve the LHC at least for the next 25 years. In view of this, an upgrade program to increase the luminosity of the LHC by reducing the beam transverse emittance for a larger intensity per bunch has been approved [1]. One of the major limitations of the PS is related to the maximum Laslett tune-shift acceptable causing losses or emittance increase that can be observed on the long injection flat bottom used for the LHC-type beams [2]. For this reason, the PS injection energy could be increased from 1.4 GeV to 2 GeV [2]. The determination of the maximum Laslett tune-shift, together with the identification of resonances that can spoil the beam quality, remains a fundamental result for future operation. This would also be an important input in case the PS will be part of a complex to accelerate high-intensity radioactive ion beams to create neutrino beams [3].

The identification of the most dangerous resonances is realized by applying the same method as proposed in [4]: a large emittance, moderate intensity, not space-charge dominated beam is kept on a 1.2 s magnetic flat bottom at constant energy. While the tune is slowly varied within a predefined interval, the beam intensity is recorded: if an excited resonance is crossed, beam losses should be observed. The emittance of the beam is chosen to be large enough to fill at maximum the vacuum chamber, in such a way that even a weak resonance produces a limited increase of the betatronic amplitude for which losses should become visible. Once the working point is scanned, a space-charge dominated beam is injected to observe the effect of the resonance crossing on the longitudinal and transverse profiles.

MEASUREMENT METHOD

The PS is composed of 100 combined-function dipoles. The working point control, linear and non-linear, is realized with two different methods depending on the beam energy. At low energy, between injection at 1.4 GeV (kinetic energy) up to about 4 GeV/c, the tune is controlled by two families of quadrupoles, limited in maximum current due their particular construction. The natural chromaticity is left uncorrected. In this case, the working point can be adjusted within the interval $0.1<Q<0.4$ for both planes. Above about 4 GeV/c, the working point is controlled by a set of four extra windings located on main-magnet poles (Pole-Face Windings, PFW), plus an extra winding of the main coil, the Figure-of-Eight loop (F8L). The five controllable free currents are used to set the horizontal and vertical tunes and chromaticities, leaving and extra parameter to control either one non-linear chromaticity or to miminize the RMS current of the different circuits. A detailed description of the working point controls can be found in [5]. These extra windings can also excite different resonances due to the non-linear magnetic-field components they generate. For this reason, the measurements at 1.4 GeV were carried out by varying the tune exclusively with the dedicated quadrupoles, whereas for the case at 2 GeV an hybrid working point was produced: the tunes and chromaticities were fixed with the PFWs and F8L, trying to linearize at maximum the non-linear chromaticity, and then the scan was realised by the low-energy quadrupoles. In some cases, Landau octupoles located in the large vertical beta function sections were used to correct for large vertical non-linear chromaticity. A moderate intensity single bunch beam of about 130 10^{10} is injected at 1.4 GeV and eventually accelerated to 2 GeV. The bunch length chosen was 180 ns, with transverse emittances of ϵ_h=12 mm mrad (1σ normalised) and ϵ_v=4 mm mrad (1σ normalised). With these beam parameters, the maximum Laslett tune shift would correspond to ΔQ_h=-0.051 and ΔQ_v=-0.095, small enough to scan the tune diagram without space-charge effects. An example of the magnetic cycle used for the measurements at 1.4 GeV is shown in Fig. 1. Once the desired energy is reached, the beam is eventually de-bunched if desired, and the tune scan is started. During the scan, beam losses are recorded by acquiring the beam current transformer (BCT) every 1 ms.

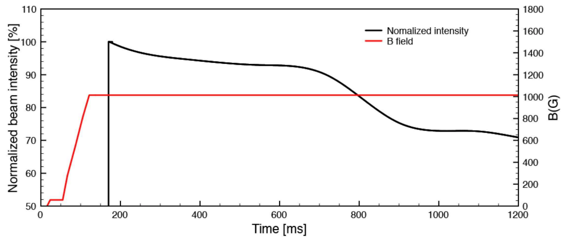

Figure 1: Magnetic cycle used for the 1.4 GeV measurements with the signal from the beam current transformer normalized to the injected intensity.

An example of a BCT acquisition is shown in Fig. 1: every reduction of the beam intensity corresponds to the crossing of a given resonance. An automatic measurement system, described in the next section, was also implemented to quickly and systematically measure with a very dense grid the working points and the losses, either fixing the vertical tune and scanning the horizontal tune and vice-versa. An example of the tune scan for one of the 2 GeV cases is shown in Fig. 2, where the black dots indicate the points at which the tune and losses were measured. The plot of the resonances is then obtained by interpolating the tune and the losses between the measured points. The losses are quoted in terms of the derivative of the BCT signal dN/N.

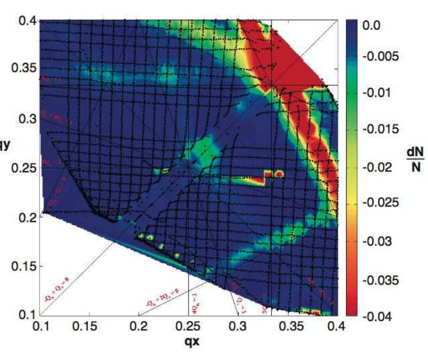

Figure 2: Tune diagram resulting from the loss measurement at 2 GeV. The color scale indicates the derivative of the BCT signal, i.e., the red lines indicate the larger losses. The measurement points are indicated by the black dots.

Automatic Measurement System

An automatic Labview© application was implemented to speed-up the acquisition work. The application, via a dedicated GUI, executes the following steps: a) the tune intervals to scan are specified in the GUI by the user; b) the application programs the currents of the elements; c) the acquisition of the BCT is saved to evaluate the losses; d) the tune is measured to validate the programmed working point; e) the tune data are saved. The process is iterated until the selected tune interval is scanned.

MEASUREMENTS AT 1.4 GEV

The 1.4 GeV tune scan results are shown in Fig. 3, with the case of the bunched beam (left) and debunched beam (right). A difference can be noticed for all the resonances identified: the synchroton motion, together with the large chromaticity in both planes at about -1.0, pushes the particles periodically through the resonances, in trapping-detrapping phenomena very similar to the one described in [6]. In particular, the resonance $2Q_h$+Q_v=1 is qualitatively different in the two cases: losses appear after crossing the resonance for the bunched beam, probably due to the betatronic amplitudes modulated by the coupling with the longitudinal motion. These measurements also confirm that

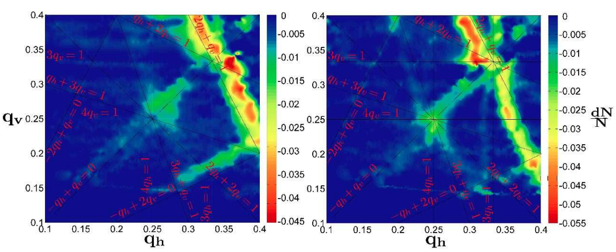

Figure 3: Tune scan results at 1.4 GeV, for a bunched beam (left), and a debunched one (right). The color scale indicates the derivative of the BCT signal, i.e., the red lines indicate the larger losses.

the choice of the working point for the LHC-type beams of about Q_h=0.23 and Q_v=0.24, with a maximum Laslett tune shift of -0.21, is far away from any important resonance.

MEASUREMENTS AT 2 GEV

The measurements on the 2 GeV flat bottom showed different results compared to the 1.4 GeV case. This is because the working point is adjusted using the PFWs and the F8L in order to be able to access the same tune interval as at lower energy. In this case, the magnetic errors introduced by the PFWs are different than the ones introduced by the quadrupoles. On top of this, it is possible to generate the same linear working point with completely different non-linear components, virtually with the possibility of exciting very different resonances. An example of this is shown in Fig. 4. The pragmatic approach chosen for these measurements is to reduce at maximum the non-linear chromaticity for one set of data, and to scan the working point from the integer to the half integer stop-band in both planes. The reason is to be able to scan the maximum phase space available for the upgraded LHC beams. The results of a first scan with a bunched beam are shown in Fig. 2, with resonances very similar to the ones of the 1.4 GeV case of Fig. 3. An attempt was made to reach the integer resonance and determine the width of the stop-band (see Fig. 5). Unfortunately, once the stop-band is approached, the beam is quickly lost, leaving only few measurement points available for the interpola-

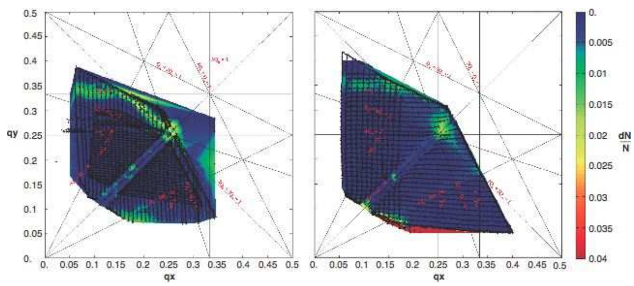

Figure 4: Tune scan results at 2 GeV, for two different settings of non-linearities introduced by the PFW. The resonance $2Q_h+2Q_v=1$ appears to be different.

tion. Losses appear already at Q_h=0.05 and Q_v=0.03, with a no-satisfactory agreement with the recent PTC-ORBIT [7] simulations that tends to indicate a width of about 0.01 in both planes. The agreement between measurements and simulation is still difficult due to the missing information on the magnetic errors of the main dipoles. There are, in fact, no reliable error tables yet for the magnets, which were built in the late 1950s.

SPACE-CHARGE DOMINATED BEAM MEASUREMENTS

A first attempt was made to measure the transverse emittance increase for space-charge dominated beams. A single-bunch beam with a transverse emittance of $\approx$2.5 μm mrad (1σ normalised), an initial bunch length of 130 ns (4σ), an intensity of 180 10^{10} protons, is accelerated up to 2 GeV. The bunch length is then reduced adiabatically to about 80 ns by a bunch rotation to increase the space-charge tune-shift, as described in [8]: the Laslett tune shift goes from an initial ΔQ_h = 0.16 and ΔQ_v = 0.197 to a final ΔQ_h = 0.19 and ΔQ_v = 0.27. Three different working points were studied, with a preliminary analysis done as follow: a) Q_h =0.196, Q_v=0.15. An emittance increase of the vertical plane is observed, corresponding to a horizontal emittance reduction, with the sum of the two approximatively constant. No losses were observed. A large fraction of the beam is below the integer resonance; b) Q_h =0.17, Q_v=0.23. Only emittance increase of the vertical plane is observed, but practically without any horizontal emittance variation. A fraction of the beam is touching the integer resonance; c) Q_h =0.17, Q_v=0.3. Beam losses are observed and thick tails appear in the vertical transverse profiles, corresponding also to a change of the bunch shape with a depletion of the center of the bunch. Most probably, particles are periodically traversing the integer and the ⅓ stop bands and lost.

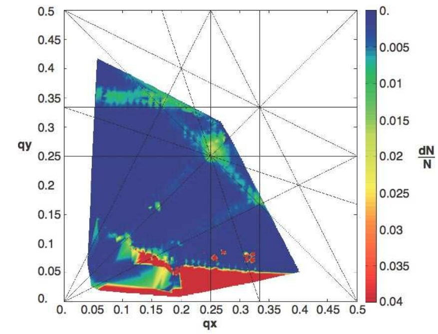

Figure 5: Tune scan results at 2 GeV to approach the integer resonance.

CONCLUSIONS

A scan of the tune diagram was done to identify, via beam losses, the most dangerous resonances which could be traversed by a space-charge dominated beam due to a large Laslett tune-shift at injection energy. This proved that the working point chosen for the PS LHC-beams is already optimised. In the case where the working point is adjusted by using the Pole-Face Windings, different resonances appears. A preliminary study of the space-charge dominated beam showed different regimes of emittance increase, which might lead to beam losses depending on the chosen working point.

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