TUNE SPREAD STUDIES AT INJECTION ENERGIES FOR THE CERN PROTON SYNCHROTRON BOOSTER

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Abstract

In the near future, a new H^- injector, Linac4, will replace the current proton-injector of the CERN Proton Synchrotron Booster (PSB), Linac2. The new charge-exchange injection at 160 MeV will yield higher brightness beams compared to the conventional 50 MeV multi-turn injection of Linac2. To make full use of the higher injection energy, space-charge effects will need to be understood and mitigated to optimize the intensity versus transverse emittance reach. This includes an optimization of longitudinal acceptance and distribution with a two-harmonic rf system, careful selection of the working point to accommodate the large Laslett tune-shift of ≈-0.5 and compensation of resonances within their stopbands. This paper will present calculations of the tune spread, based on measurements of longitudinal parameters and transverse emittances, for energies up to 160 MeV, different bunch densities and varying beam intensities. This should provide valuable information on the expected tune spread after the connection of Linac4 with the PSB and input for the study of resonance compensation techniques.

INTRODUCTION

The Proton Synchrotron Booster (PSB) located at CERN, Geneva, Switzerland, is currently boosting protons injected by Linac2 from 50 MeV to 1.4 GeV. It is the second accelerator of the LHC injector chain and consists of four superposed rings. Projected LHC beam requirements for the phase after the second long LHC stop currently planned for 2018 identified the PSB injection as first bottleneck many years ago. This led to the design of Linac4, a H^- linear accelerator already being under construction, which will increase $\beta\gamma^2$ by a factor of 2 by increasing the PSB injection energy from 50 to 160 MeV. Moreover transverse phase space painting possible thanks to the H^- charge exchange injection will allow a tailoring of transverse emittances. Space charge effects will on one hand decrease due to the higher energy, but on the other hand much higher beam brightness will be requested by the LHC and other clients. Even longitudinal phase space painting is foreseen to alleviate space charge effects.

This work presents measurements close to the current injection energy and at future Linac4 injection energy, from which the tune spread can be deduced.

CALCULATION OF THE TUNE SPREAD

The tune spread calculation is based on transverse and longitudinal beam measurements. The horizontal tune spread can be derived from Equation 1 [1].

$$\Delta Q_x = \frac{\lambda_{max} r_p}{2\pi\beta^2\gamma^3} \oint \frac{\beta_x(s)}{\sigma_x(s)[\sigma_x(s)+\sigma_y(s)]} ds \qquad (1)$$

with $\sigma_x(s) = \sqrt{\beta_x(s)\epsilon_x + D_x^2(s)(\frac{\Delta p}{p})^2}$ being one standard deviation of the horizontal beam size and $\sigma_y(s) = \sqrt{\beta_y(s)\epsilon_y}$ one standard deviation of the vertical beam size, as the vertical dispersion is approximately zero in the ring.

λ_{max} corresponds to the maximum line density [number of protons/m], r_p to the proton radius, β and γ to the relativistic factors, $\beta_{x,y}(s)$ to the horizontal/vertical beta functions, $\epsilon_{x,y}$ to the horizontal/vertical physical emittances, $D_x(s)$ to the horizontal dispersion function and $\frac{\Delta p}{p}$ to the rms momentum spread.

For the vertical plane Equation 1 changes as follows:

$$\Delta Q_y = \frac{\lambda_{max} r_p}{2\pi\beta^2\gamma^3} \sqrt{\frac{1}{\epsilon_y}} \oint \frac{\sqrt{\beta_y(s)}}{\sigma_x(s)+\sigma_y(s)} ds \qquad (2)$$

BEAM PREPARATION

Three different beams have been prepared on PSB ring 2 for the purpose of these measurements with identical magnetic cycle. After injection at 50 MeV the magnetic field is adiabatically ramped up to a 163 MeV flat top and then decelerated back to 50 MeV (see Fig. 1), where the beam is subsequently lost in the machine (the PSB has no internal dump).

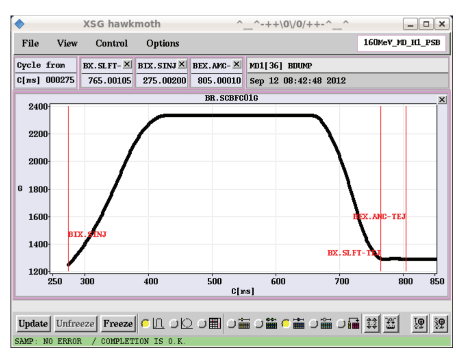

Figure 1: Shown is the B-field of the flat 163 MeV cycle. Injection into the PSB happens at c=275 ms (50 MeV), and usually the beam gets extracted at c=805 ms.

The 3 beams differ only in the longitudinal plane. The PSB has three cavities at its disposal, the main accelerating 2 MHz cavity (C02), a 4 MHz cavity (C04) used to increase the longitudinal acceptance and for double splitting and a

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16 MHz cavity (C16) for bunch flattening and longitudinal bunch stabilisation. The aim of preparing three different beams for these measurements was to modify space charge conditions through the longitudinal plane and evaluate the effect on the tune spread. The three cases are distinguished as follows:

1. Beam version 1 (**B1**), h1 only: single harmonic case using only the C02 cavity at its maximum voltage (8 kV).

2. Beam version 2 (**B2**), h1+h2 out of phase: C02 and C04 are both at maximum voltage (8 kV), but dephased in order to maximise the longitudinal acceptance. These conditions are usually applied for high-intensity beams in the PSB.

3. Beam version 3 (**B3**), h1+h2 in phase: C02 and C04 at maximum voltage (8 kV); the phase between the cavities approaches zero to achieve the most stringent RF conditions in terms of space charge.

Case B3 exhibits the lowest bunching factor followed by B1. Therefore we expect the largest tune spread values for B3 and the smallest values for B2 for the same transverse beam settings and intensities.

Beam intensities for the three cases were also varied by injecting different number of turns from Linac2, from 1 turn to the maximum of 13 turns, above which there is no more gain in intensity with the current PSB multi-turn injection layout. For each of the 13 measurement points, the injection point on the injection bump was optimised to minimise injection oscillations and the low-energy working point was tuned to achieve good beam brightness.

Measurements were performed at **60 MeV** (c=297 ms), **100 MeV** (c=345 ms) and at the start of the flat top at **163 MeV** (c=427 ms). From Fig. 1 it can be seen that the two measurement series at lower energies are taken during acceleration, whereas for the 163 MeV measurement point the bunch is in a stationary bucket.

EMITTANCE MEASUREMENTS

Precise longitudinal and transverse measurements are the basis of a valid determination of the tune spread. Special care was taken to minimise errors.

Longitudinal Measurements

In the PSB, the measurement of the longitudinal beam parameters relies on phase space tomography using the tomoscope application [2]. Multiple profiles of the same bunch are measured by a longitudinal pickup and acquired by the application, each separated by a few machine turns. A two-dimensional density distribution of the bunch is then iteratively reconstructed, whose projections converge towards the measured bunch profiles.

For the purpose of the calculation of the tune spread, the following parameters were deduced from an average of 3 tomograms per measurement point: the full bunch length and maximum bunch height to calculate λ_{max} in Equations 1 and 2. In addition, for the horizontal emittance measurement the value of $\frac{\Delta p}{p}$ is needed to correct for the horizontal dispersion at the location of the wire scanner.

Usually the application converges nicely, but for the h1+h2 cases with different phase settings (B2 and B3) and for lower energies with accelerating buckets, the convergence could sometimes slightly be improved by manually tuning the fix point and the phase difference before tomography.

Examples for longitudinal phase space plots are shown in Figs. 2 and 3.

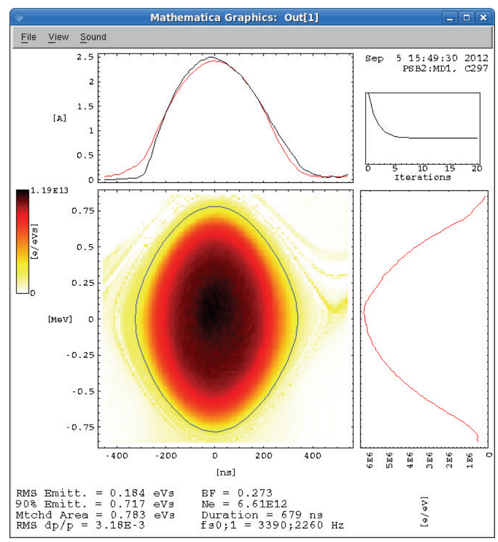

Figure 2: Tomogram of one bunch at 163 MeV for the B3 case with 13 turns injected. The bunch fills the full h1 acceptance indicated by the blue line in the 3-dimensional plot and exhibits minor bunch oscillations. It can be seen that some particles escape the acceptance. From the projected profiles of this particular measurement point, a bunch length of 679 ns and a bunching factor of 0.273 for a bunch intensity of 661E10 particles were deduced.

Transverse Emittances

The most delicate measurement turned out to be the transverse emittance measurement. In the PSB, rotational wire scanners are installed in each ring, one per plane. The wire flies through the beam at a speed of 15 m/s. The resulting secondary particle shower is detected by a photomultiplier (PM) after passing through a selectable filter. For each energy, intensity and particle distribution, a suitable combination of filter and PM voltage has to be chosen to avoid saturation and to maximise the signal-to-noise ratio. The resulting measured emittance is very sensitive to the correct working regime, therefore saturation curves have

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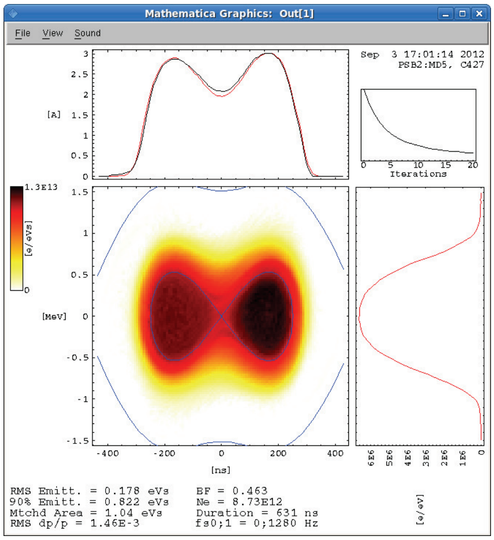

Figure 3: Tomogram of one bunch at 163 MeV for the B2 case with 13 turns injected. The projection plot on the top shows the measured and reconstructed bunch profile. The h2 contribution to the pure h1 case can clearly be seen. This yields an increased bunching factor of 0.463 for a reconstructed bunch intensity of 873E10 particles. There is no visible beam loss out of the longitudinal acceptance.

been made for the three beams and different energies and intensities.

In addition, care has been taken to choose correct optics parameters. For this purpose, the tune has been measured for each point and the corresponding horizontal and vertical beta functions and the horizontal dispersion calculated at the location of the wire scanners. These parameters have been used as input in the wire scanner application together with the measured $\frac{\Delta p}{p}$. An average of 5 measurements per point was used to determine the beam size from a 5-parameter Gaussian fit to the measured profiles, from which the transverse normalised 1σ emittance is deduced. The beam intensity is measured at the same time with the ring transformer at the corresponding cycle time.

In the PSB, the emittance in the horizontal plane is mainly determined by the multi-turn injection process. The vertical emittance, instead, should depend principally on injection errors (mis-steering and mismatch), coupling between transverse planes at injection, as well as potentially on the space charge blow-up. Actually, as the dependence of the vertical emittance on the injected intensity does not change significantly between the three types of beams analysed in this paper, we might be led to believe that the longitudinal distribution does not play a major role on space charge within the possibilities of our current RF systems (although it has a clear impact on maximum intensities and losses through the acceptance).

The average transverse emittances as a function of the beam intensity are shown in Fig. 4 for the three cases. The curves at the three energies are basically overlapping, suggesting that our beams do not exhibit any significant effect of emittance growth in spite of the high values of tune spreads at injection (see next section).

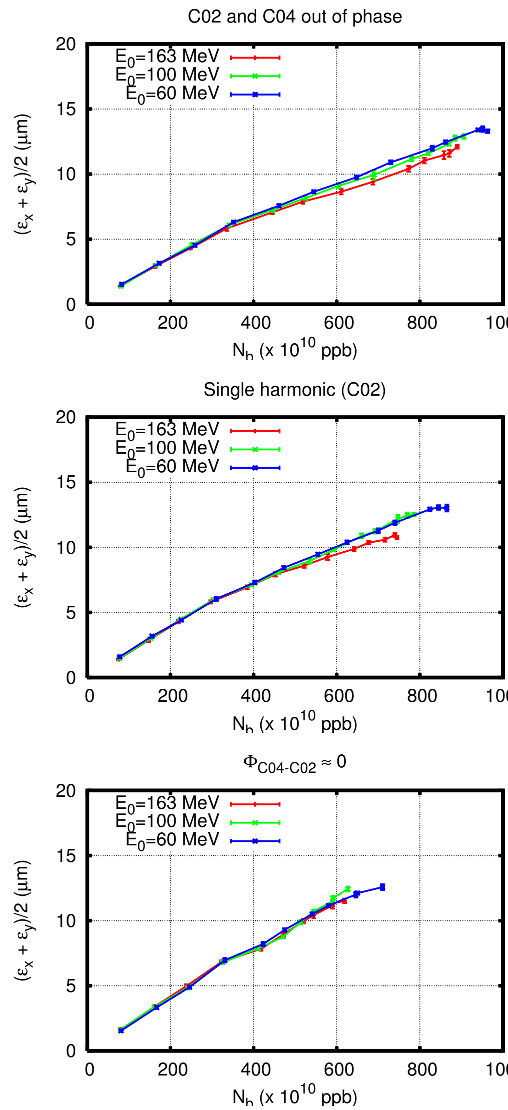

Figure 4: Measured 1σ normalised average transverse emittance as a function of bunch intensity and for 60, 100 and 163 MeV. Top: B2, middle: B1 and bottom: B3.

RESULTS

With the input of the longitudinal and transverse measured beam parameters, the tune spread can now be calculated using Equations 1 and 2. As expected the tune spread is smallest for the h1+h2 out of phase beam (B2; see Fig. 5), followed by the pure h1 beam (B1; see Fig. 6). The largest tune spread values occur for the beam with the smallest bunching factor (B3, h1+h2 in phase; see Fig. 7), exceeding $\Delta Q_x = -0.5$ (blue curve) and $\Delta Q_y = -0.8$ (green curve) for intensities of 700E10 ppb at 60 MeV. Nevertheless it has to be mentioned that this is associated with

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relative losses around 23% with respect to the measured intensity at the centre of the 163 MeV flat top, represented by the red bars at the bottom of each plot. At 163 MeV, the corresponding tune spread values reach -0.3/-0.45 for 630E10 ppb, correspondingly.

For B2 (largest longitudinal acceptance) on the other hand higher bunch intensities can be achieved with vertical tune spread values reaching $\Delta Q_y = -0.77$ for almost 1000E10 ppb (relative losses around 14%). At 163 MeV one approaches $\Delta Q_x = -0.22$ and $\Delta Q_y = -0.35$ for 900E10 ppb.

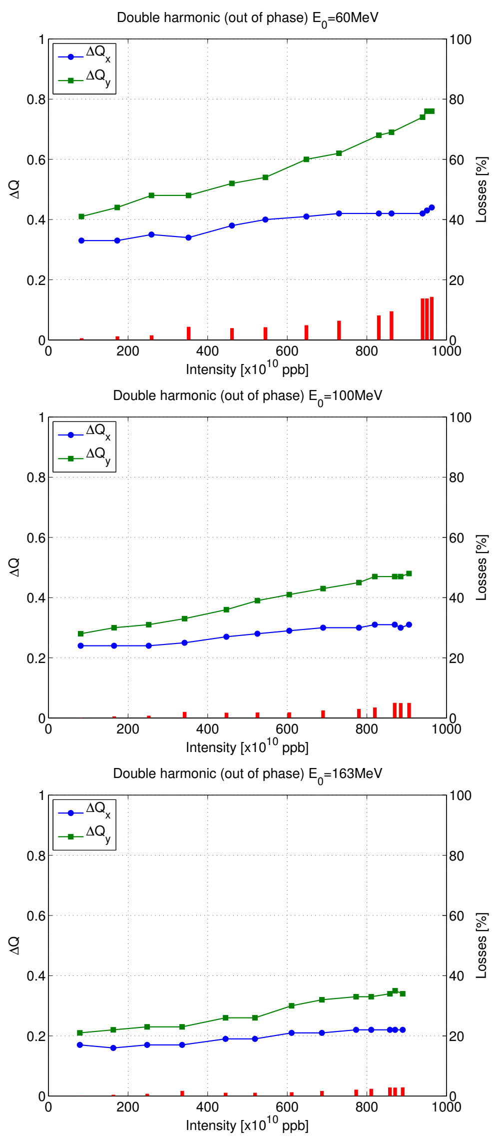

Figure 5: Horizontal (ΔQ_x) and vertical (ΔQ_y) tune spread at 60 (top), 100 (middle) and 163 MeV (bottom) as a function of intensity for B2. The losses at each measurement point are indicated as red bars.

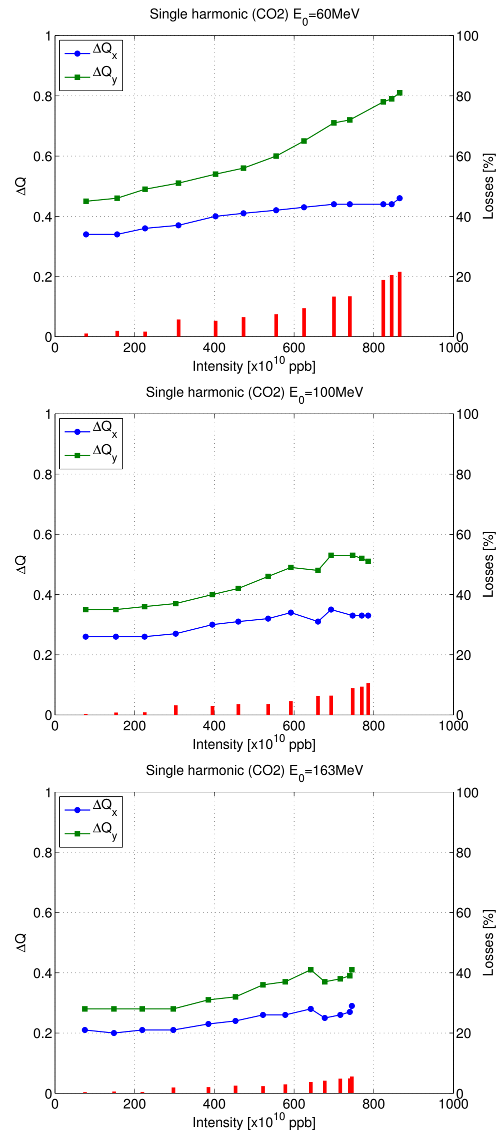

Figure 6: Horizontal (ΔQ_x) and vertical (ΔQ_y) tune spread at 60 (top), 100 (middle) and 163 MeV (bottom) as a function of intensity for B1. The losses at each measurement point are indicated as red bars.

OUTLOOK AND CONCLUSIONS

Presently, by optimising longitudinal acceptance and flattening the longitudinal bunch distribution with the use of a second harmonic cavity, the PSB appears to be able to successfully capture beams with maximum vertical tune spreads in the order of 0.7-0.8 and accelerate them to 160 MeV, where losses are reduced down to few percent and could be further reduced by a careful working point optimisation and resonance compensation. No transverse emittance growth is observed during the process. The future beams requested by the LHC Injector Upgrade and High Luminosity LHC projects rely on the production of beams with maximum tune spreads close to 0.5 in the PSB, which seems in reach given the present performance. One ques-

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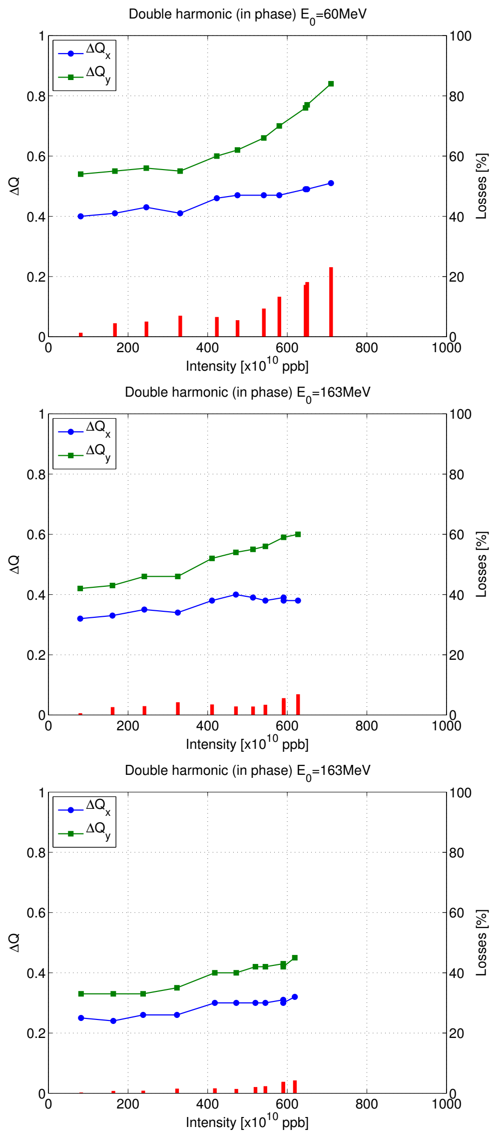

Figure 7: Horizontal (ΔQ_x) and vertical (ΔQ_y) tune spread at 60 (top), 100 (middle) and 163 MeV (bottom) as a function of intensity for B3. The losses at each measurement point are indicated as red bars.

tion that still remains to be addressed is whether the conservation of transverse emittances will still hold when a tune spread of 0.5 is obtained with lower intensities and much lower transverse emittances, too, as required for the future LHC beams (350E10 ppb within average transverse emittances <2 μm). The fact that currently tune spreads around 0.7-0.8 can be accommodated with no emittance growth can lead us to be carefully optimistic. However, simulations of the full H^- injection process and based on an optics model of the PSB fully benchmarked with the data presented in this paper should be set up and used in future to answer this question.

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