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Measurements of Emittance and Tune Spread at Linac2 and Linac4 Injection Energies for the Proton Synchrotron Booster (PSB)

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Abstract

The effect of space charge on the proton beam as a function of energy has been studied in the PSB. This work is part of the preparations for the connection of Linac4 to the PSB involving H^- charge-exchange injection compared to the current Linac2 multi-turn injection. In the current injection process, an important fraction of the injected beam is lost after injection, and this study should help in understanding the part that is due to space charge effects, and thus give indications on the expected improvement with the new Linac4 injection. In this note, measurements of emittance and calculations of tune spread at a range of energies on a specially prepared magnetic cycle are presented. The effect of crossing the half-integer resonance is also discussed.

1. Introduction

Linac2 is currently injecting 50 MeV protons into the PSB using a classical multi-turn injection with a horizontal injection septum. A maximum of 13 turns per PSB ring (the PSB comprises four vertically stacked rings) can be injected; with ~165 mA Linac2 current and an injection efficiency of around 65% this yields <1.5E13 p injected. The injection takes place on a magnetic ramp, followed by beam capture and bunching with a two-harmonic system (h=1 plus h=2) to minimise space charge effects through maximisation of longitudinal acceptance. Due to large Laslett tune shifts at injection energies (ΔQ_0~-0.5) [1], tune spread and coherent tune shift[1], additional losses occur at low energies during the first tens of ms of the ramp. To compensate for the important space-charge induced tune shifts, the PSB needs to use a dynamic working point along the cycle, and in particular in the vertical plane, where no active phase-space stacking except for a vertical injection offset can be performed, the injection working point (Q_v~4.60) lies above the half-integer resonance for high-intensity beams, which it crosses during acceleration.

In a few years, the current injection scheme will be replaced with a charge-exchange injection scheme of 160 MeV H^- ions supplied from Linac4. Measurements in this paper are used to evaluate the changes with respect to space charge effects between the two injection energies.

[1] The vertical tune shift has been measured and amounts to ~-0.07 at 160 MeV [2].

2. The Magnetic Cycle

A special magnetic cycle was prepared in the PSB for Linac4 space charge studies, where beam is injected in ring 2 at 50 MeV and ramped up to 160 MeV. After a flat top of about 270 ms duration the beam is decelerated and then lost in the machine[2] (Figure **1**). Measurements were taken at four points along the cycle: 297 ms, 334 ms, 550 ms and 665 ms, which correspond to proton kinetic energies of 60 MeV, 88 MeV, and twice 163 MeV, respectively. The Linac2 injection timing corresponds to 275 ms after the cycle start (c=0).

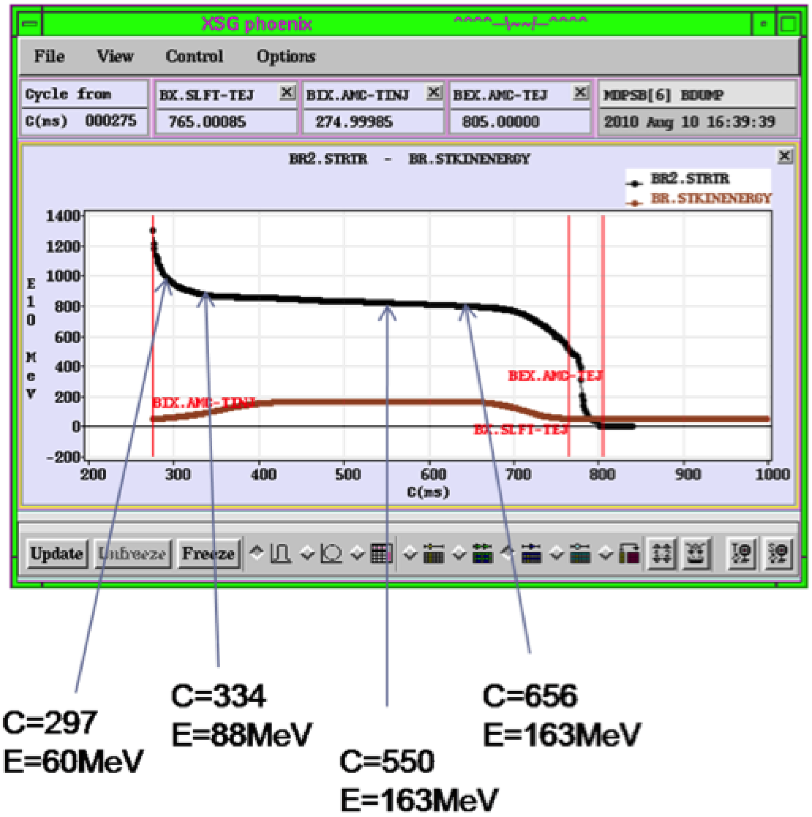

Figure 1: The kinetic energy (brown bottom curve) and the beam intensity (black top curve) are shown as a function of cycle-timing for the 160 MeV flat top cycle. The four measurement points are labelled.

3. Measuring Emittance

3.1 Longitudinal Emittance and Momentum Spread – The Tomoscope

The tomoscope [3] was used to measure momentum distribution and bunch length. The momentum distribution is needed to correct for dispersion in the horizontal emittance measurement presented in the following paragraph. For 297 ms, 334 ms and 656 ms the beam was prepared to contain an important second harmonic contribution, showing up in the tomogram as an inner separatrix within the main bucket (Figure **2**). The 550 ms data shows the single-harmonic case (Figure **3**).

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[2] This is done in order to minimise machine activation (there is no internal dump in the PSB).

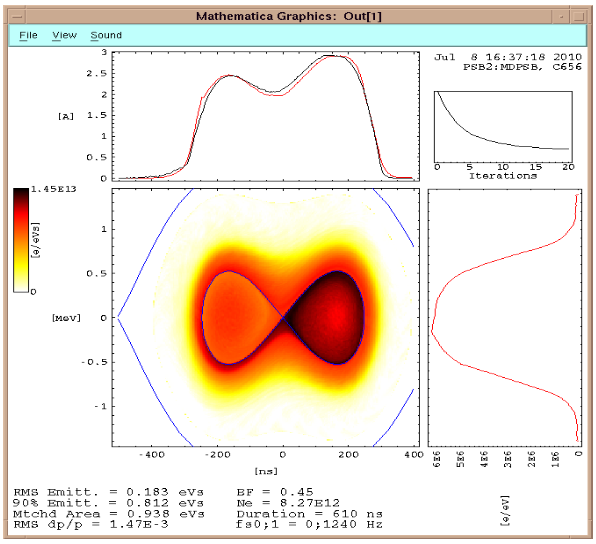

Figure 2: Tomogram taken at c=656 ms with 12 turns injected into the PSB ring. Shown are measured (red line) and reconstructed (black line) bunch profiles as well as the reconstructed longitudinal parameters. The two harmonics can clearly be seen in the 2D reconstruction.

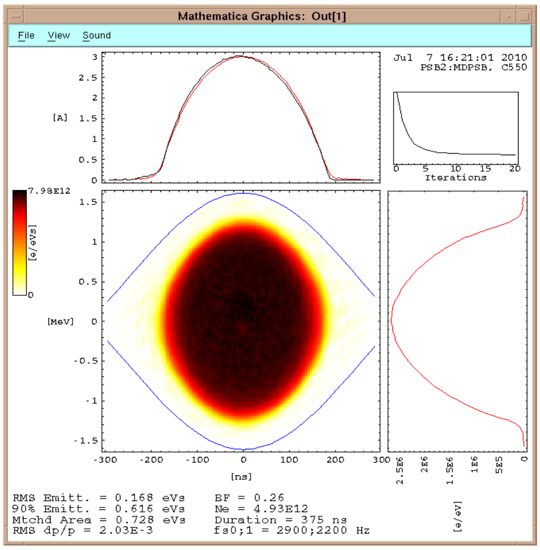

Figure 3: Tomogram taken at c=550 ms with 8 turns injected into the PSB ring. For this measurement point, only the first harmonic was used, leading to a denser beam distribution.

3.2 Transverse Emittance Measurement – The Fast Wire Scanners

The fast wire scanners [4] were used to measure the normalised emittance in both the horizontal and vertical plane (see Figure **4** and Figure **5**). The beam intensity was varied with the number of turns injected into the PSB from Linac2. The number of turns was changed from 0.5 to 2 in half-integer steps, and then up to 13 in integer steps. The wire scanner parameters were optimised and a set of up to 10 measurements were taken per intensity step for improved statistics.

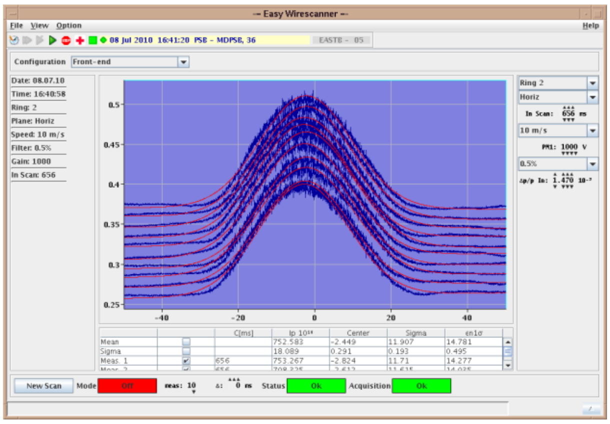

Figure 4: Wire scanner display of 1-sigma normalised emittance and intensity measurements in the horizontal plane for c=656 ms; 12 turns injected into the PSB.

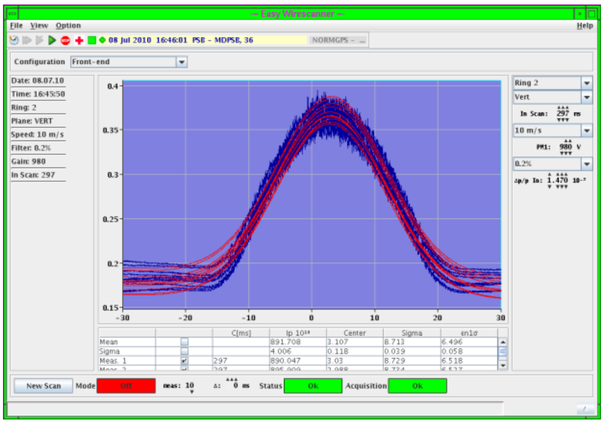

Figure 5: Wire scanner display of 1-sigma normalised emittance and intensity measurements in the vertical plane for c=656 ms; 12 turns injected into the PSB.

4. Evolution of Transverse Emittance with Intensity

The normalised emittance in the horizontal (Figure **6**) and vertical plane (Figure **7**) as measured by the wire scanner is shown below as a function of beam intensity for the four different measurement series. Except for the measurement series at c=334 ms (see following paragraph) the emittance increase follows approximately linearly the intensity increase.
Due to the large intensity range that has been covered with these measurements, different filters attenuating the particle flow reaching the photomultipliers had to be used. This might also result in some measurement systematics. For example the large fluctuations in measured horizontal emittance for the five highest intensity points for c=297 ms and the four highest intensity points for c=334 ms can be attributed to a wrong filter/gain combination that led to a too low signal.

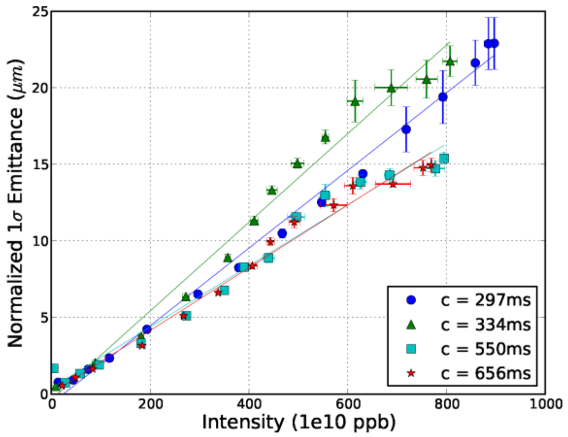

Figure 6: Normalised horizontal 1-sigma emittance vs. intensity for all four measurement series with linear fit and 1-sigma errors.

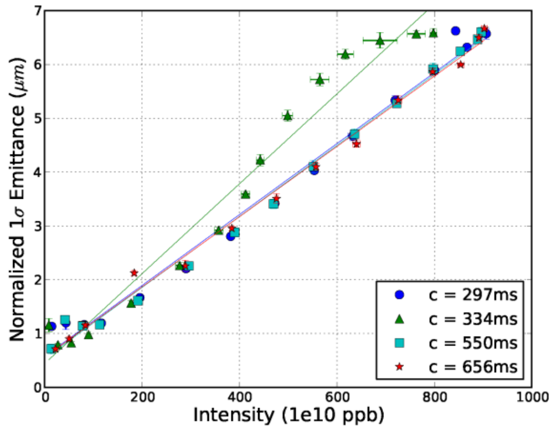

Figure 7: Normalised vertical 1-sigma emittance vs. intensity for all four measurement series with linear fit and 1-sigma errors.

4.1 Resonance Effects

As can be seen in Figures 6 and 7, the normalised emittance at c=334 ms (88 MeV) exhibits a different trend compared to the emittance at other points in the cycle. In particular, the (normalised) emittance appears larger at this point in the cycle than it is even found later in the cycle at higher energies. We believe that this effect can be either instrumental, as the emittance measurement is performed during the ramp, or can be explained by looking at the tune diagram. Since the 334 ms measurement point sits exactly on a half-integer resonance (vertical plane), the measured emittance growth could probably be directly caused by the measurement itself. By flying the wire through the beam while it is crossing a strong resonance, we might be creating a localized perturbation that excites the half-integer resonance, which could result in a blow-up of the transverse beam emittances. It can be noted that the relative emittance increase is larger in the vertical than in the horizontal plane, but also present in the horizontal plane probably due to coupling (see 4.3). The results of this measurement series at 88 MeV should therefore be taken with caution.

In summary, to obtain perfectly consistent and more precise results, these emittance measurements should be repeated; the half-integer measurement series should be avoided and filter/gain combinations used for the wire scanners that have been optimised in the meanwhile.

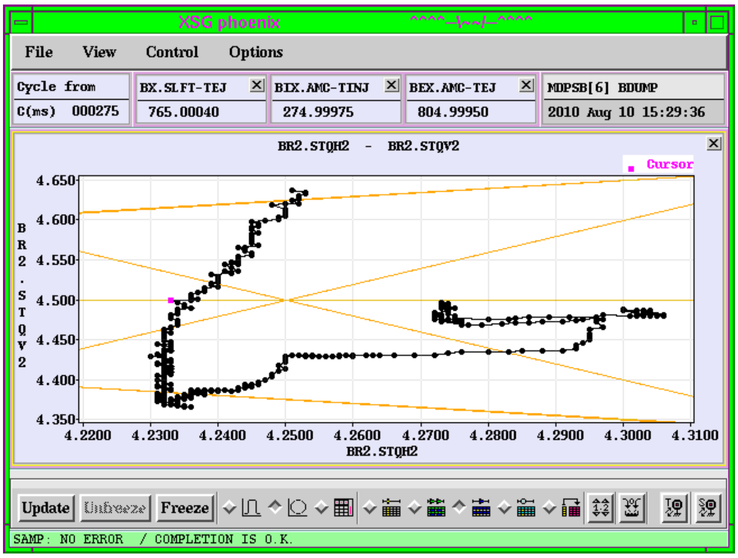

Figure 8: Tune diagram showing the programmed vertical vs. horizontal tune along the cycle as well as the resonance lines. A high vertical tune is programmed at injection due to the large tune spread. The cursor (in pink) corresponds to the values at c=334 ms, sitting exactly on the half-integer resonance line.

4.2 Comparison of Calculated Tune and Measured Tune

To determine the machine tune, the fractional tune was measured at three different beam intensities (100E10, 470E10 and 825E10 ppb) for each of the four measurement points[3]. This was done using the BBQ application (see Figure **9**), which excites the beam and measures the fractional tune value from the induced oscillation [5]. The measured tune values can be found in Table **1**.

Table 1: Measured tune values for the four measurement points as a function of beam intensity.

Intensity [1E10 ppb] vs. **c-timing** [ms]	825	470	100	825	470	100
	Horizontal measured tune			**Vertical measured tune**		
297	4.227	4.244	4.255	4.464	4.469	4.53
334	4.228	4.239	4.237	4.42	4.443	4.488
550	4.231	4.24	4.244	4.309	4.338	4.345
656	4.254	4.256	4.249	4.329	4.344	4.367

We can expect that the programmed tune values will be systematically higher than the measured ones, especially with high intensity, because due to image charges and impedance effects, the beam feels an extra-defocusing effect and the tune moves downwards [2].

[3] Actually at c=295 ms, 335 ms, 550 ms and 655 ms since the application could only set c-timings in multiples of 5ms.

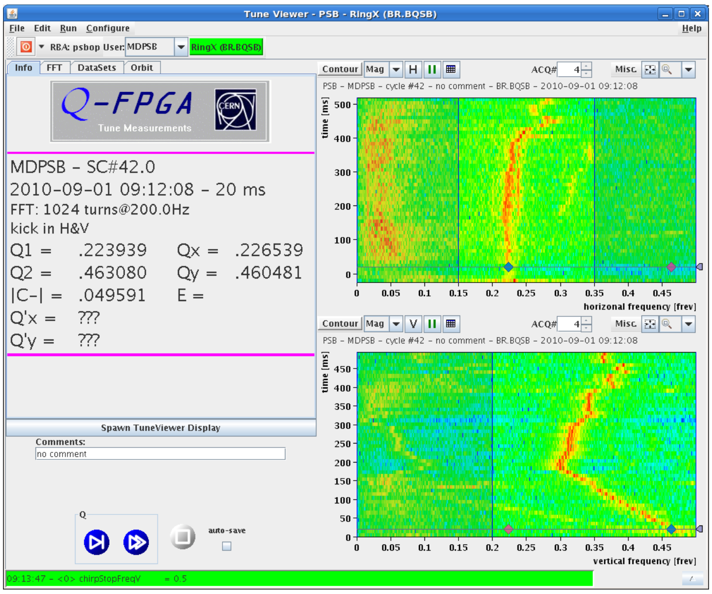

Figure 9: Screenshot of the tune viewer application that visualises the measured fractional horizontal and vertical tune along the cycle.

4.3 Coupling

The half-integer resonance is crossed only in the vertical plane, but the emittance blow-up at 334 ms (observed when measuring the emittance) occurs in both the vertical and horizontal plane. This is strong evidence of coupling between the two planes. We believe this is mainly due to alignment errors in the quadrupole magnets. Over the years, a few alignment campaigns to reduce the orbit took place, as the installed orbit correctors were not operational. In this context, to equalise the performance of the four Booster rings, some of the main quadrupoles have also been tilted [6].

5. Tune spread

The tune spreads were calculated using the following formulae (1)

$$\begin{cases} \Delta Q_x = \dfrac{N_b r_p}{(2\pi)^{3/2}\gamma^3\beta^2\sigma_z} \oint \dfrac{\beta_x(s)}{\sqrt{\beta_x(s)\varepsilon_x + D_x^2(s)\sigma_\delta^2}\left(\sqrt{\beta_y(s)\varepsilon_y} + \sqrt{\beta_x(s)\varepsilon_x + D_x^2(s)\sigma_\delta^2}\right)} ds \\ \Delta Q_y = \dfrac{N_b r_p}{(2\pi)^{3/2}\gamma^3\beta^2\sigma_z} \dfrac{1}{\sqrt{\varepsilon_y}} \oint \dfrac{\sqrt{\beta_y(s)}}{\sqrt{\beta_y(s)\varepsilon_y} + \sqrt{\beta_x(s)\varepsilon_x + D_x^2(s)\sigma_\delta^2}} ds \end{cases} \quad (1) \quad [7]$$

with N_b= bunch population, r_p= classical proton radius, β,γ= relativistic factors, σ_z= rms bunch length, $\beta_{x,y}(s)$= horizontal/vertical beta function around the ring, $\varepsilon_{x,y}$= horizontal/vertical physical beam emittance, D_x= dispersion function and σ_δ= rms momentum spread.

The β and γ factors were calculated directly from the energy at each measurement point. The lattice used to obtain the optics parameters can be found at the CERN accelerator optics website [8].

The tune spreads in the horizontal and vertical plane as a function of intensity are represented in Figure 10 and Figure 11, correspondingly. As could be expected, the estimated tune spreads are maximal for the highest intensities soon after injection and capture (i.e. for the lowest energy, 60 MeV). We can observe that the tune spreads measured at c=550 ms are about 30% lower than those measured after injection/capture (especially visible at the highest intensities), because the factor ~2 gained thanks to the higher energy is partly lost because of the reduced bunch length at this measurement point. It is also interesting to observe that the tune spreads at c=656 ms, which also corresponds to 160 MeV like the measurement series at c=550 ms, are consistently smaller than those measured at the previous points. This is because we add the second RF system (h=2) towards the end of the flat top in order to lengthen the bunch and flatten it in the middle. The reduction of the space charge effect due to this RF manipulation can therefore be seen in the decrease of the tune spread value, which in the vertical plane can amount to almost 30%.

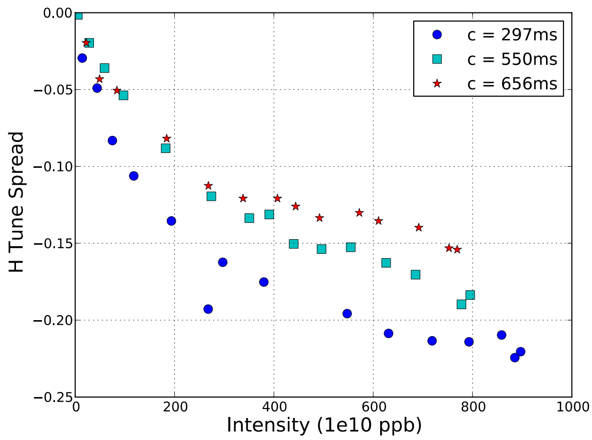

Figure 10: Horizontal tune spread vs. beam intensity.

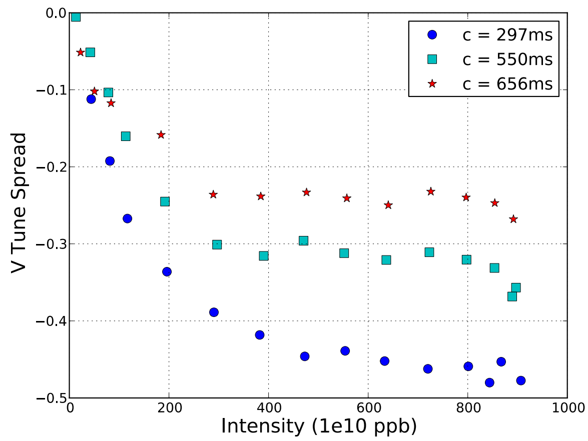

Figure 11: Vertical tune spread vs. beam intensity.

6. Conclusions

Through measurements of bunch length and emittance at different energies (60, 88 and 163 MeV) and intensities, the tune spread could be calculated within this parameter space.

The emittance follows a roughly linear relation with intensity at lower intensities for the entire energy range. The curve flattens off in the horizontal plane at around 700E10 ppb for 160 MeV, which indicates saturation. This is not completely understood, but it could be due to horizontal aperture limitations during the multi-turn injection process. The emittance-intensity relation remains roughly linear for the lower energies in the horizontal and for all energies in the vertical plane within the measured intensity range, which indicates that the saturation point is not reached.

The horizontal/vertical tune spread for a high-intensity beam of ~800E10 ppb and maximal acceptance (h1+h2 at max. voltage) derived from the measured quantities amounts to ~-0.22/-

0.46 for a 60 MeV beam and ~-0.15/-0.23 for 160 MeV, whereas the latter values increase for a pure h1-beam to ~-0.17/-0.32 (31% shorter bunch length).

Due to some problems with the wire scanner measurements, and also to complete the picture with a more complete bunch-length dependence, it is proposed to redo measurements and analysis in 2012.

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