INVESTIGATION OF SPACE CHARGE EFFECTS IN THE SPS

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Abstract

Space charge effects generally play a rather minor role in high energy machines like the SPS. Rather high space charge tune shifts may however become unavoidable in the SPS for the heavy ion beams required by the LHC. We describe recent measurements performed with intense proton beams in the SPS. The space charge effects were enhanced by a reduction of the injection energy from 26 to 14 GeV.

1 INTRODUCTION

Space charge effects are strongly energy dependent ($\sim 1/\gamma^3$). High space charge tune shifts in access of 0.5 have have been observed in smaller machines [1–3]. Such high space charge tune shifts are typically accompanied by blow-up and short lifetimes, well below a second.

In larger, high energy machines like the SPS, space charge effects usually play a rather minor role. Space charge tune shifts in the SPS generally remain well below 0.1 and do not cause any lifetime problems or blow-up [4, 5]. For the LHC heavy ion program, it is planned to inject lead ions into the SPS at $\gamma \approx 5.5 - 7.3$ [6, 7]. Space charge tune shifts above 0.1 may become unavoidable. In addition, good lifetimes and little blow-up during the about 40 seconds long injection plateau will be important. The required heavy ion beams will only become available in several years from now after an upgrade of the injector chain.

We describe here an investigation performed with high intensity proton beams. To enhance space charge effects, the injection energy in the SPS was lowered from 26 GeV to 14 GeV.

2 SPACE CHARGE TUNE SHIFT

We used the maximum single bunch intensity currently available from the PS for low emittance single bunch operation of $N = 1.2 \times 10^{11}$ protons. The relevant beam parameters are summarized in Table 1. Beam dimensions and the momentum spread are given in terms of single σ r.m.s values.

Table 1: Measured beam parameters.

Proton momentum	$14\,\mathrm{GeV/c}$
Initial proton intensity	$N = 1.2 \times 10^{11}$
Relative momentum spread	$\sigma_{\Delta p/p} = 1.9 \times 10^{-3}$
Normalized emittances	$\epsilon_{x,N} = 3.43\,\mu\mathrm{m}$
	$\epsilon_{y,N} = 3.75\,\mu\mathrm{m}$
Bunch length	$\sigma_t = 0.75\,\mathrm{ns}$

The emittances were obtained from transverse profile measurements using a wire scanner (`WS51995` in the SPS in a place without dispersion). The measurements generally showed approximately Gaussian beams and no significant blow-up over time scales of about a second. Bunch lengths were measured using a longitudinal pickup and a digital oscilloscope.

The beam dimensions in x, y around the ring were calculated from

$$\sigma_{x,y} = \sqrt{\epsilon_{x,y}\ \beta_{x,y} + (D_{x,y}\ \sigma_{\Delta p/p})^2}\,. \qquad (1)$$

where $\beta_{x,y}$ and $D_{x,y}$ are the beta-functions and dispersions. Geometrical emittances $\epsilon_{x,y}$ and normalized emittances are related by

$$\epsilon = \epsilon_N \,/\, (\beta\gamma)\ .$$

The incoherent space charge tune shift parameters $\Delta Q_{x,y}$ are calculated according to

$$\begin{aligned} \Delta Q_x &= -\frac{r_c}{2\pi\,\beta^2\gamma^3}\ \frac{N}{\sqrt{2\pi}\,\sigma_z}\int_0^L \frac{\beta_x}{\sigma_x(\sigma_x+\sigma_y)}\,ds \\ \Delta Q_y &= -\frac{r_c}{2\pi\,\beta^2\gamma^3}\ \frac{N}{\sqrt{2\pi}\,\sigma_z}\int_0^L \frac{\beta_y}{\sigma_y(\sigma_x+\sigma_y)}\,ds \end{aligned} \qquad (2)$$

by numerical integration around the ring using nominal values of the β functions and dispersion (here on average $\beta_x = 41.5\,\mathrm{m}$, $\beta_y = 41.6\,\mathrm{m}$, $\sigma_x = 3.48\,\mathrm{mm}$, $\sigma_y = 1.9\,\mathrm{mm}$). r_c is the classical proton radius and σ_z the bunch length.

With the (measured) beam parameters of Table 1, we obtain for the conditions of the experiments described here the rather substantial space charge tune shifts of

$$\begin{aligned} \Delta Q_x &= -0.14 \\ \Delta Q_y &= -0.18 \quad . \end{aligned}$$

It is likely that the beam sizes obtained from the wire scanner were overestimated by 30% (due to a problem in the low level software of the instrument). This would imply even 30% larger tune shifts.

3 LIFETIME DEPENDENCE ON TUNE

We performed scans in the vertical and horizontal tune and observed the decay of the proton intensity over times of up to 10 seconds from injection. For the vertical tune scan, the horizontal tune was kept at a fixed value of $Q_x = 0.2^{\dagger}$. For the horizontal scan, the vertical tune was kept at $Q_y = 0.234$. Chromaticities were set to small negative values in both planes (14 GeV is below the transition, $\gamma_{\mathrm{tr}} \approx 23.2$).

† we refer to the non-integer part; integer tunes are 26 in both planes

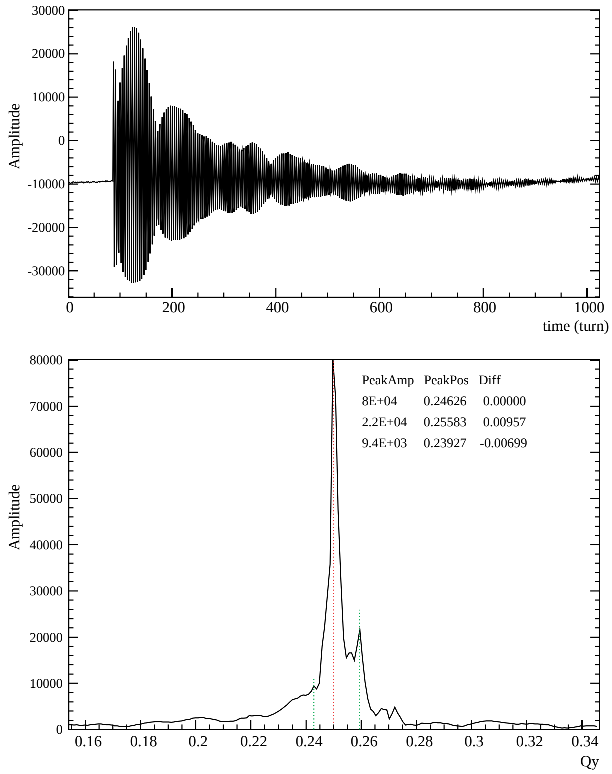

Figure 1: Example of a tune measurement, here $Q_y = 0.2462$, which gave a good lifetime. The beam was kicked 3 s after injection at an intensity of 1.1×10^{11} protons. Vertical centre of gravity oscillations recorded by the tune meter are shown on top and the spectrum after fast Fourier transform (FFT) on the bottom.

An example of a tune measurement is shown in Fig. 1. The tune meter records the coherent (centre of gravity) motion of the bunch. To first order, the central tune value obtained is not effected by the substantial internal space charge tune spread.

Intensities as function of time over the first 10 s from injection are shown in Figures 2 and 3 for various tunes. Losses of less than 10% over 10 s corresponding to over 100 s lifetime were observed for "good" tune settings. The observed decay however, particularly for the "poor" tune settings, is not always exponential. Transitions between slow decay and rapid losses and nearly linear decay were also observed.

Rather than using lifetime, we are now going to present the same data in terms of transmission (ratio of final over initial intensity) over 10 s as a measure of stability. The results as function of tune are shown in Figures 4 and 5. Stability is poor for low (< 0.2) and very high (> 0.4) vertical tunes. There is more freedom in the choice of the horizontal tunes (as expected due to the lower space charge tune spread in this plane). Poor stability in the horizontal plane was observed for very low (< 0.1) tunes.

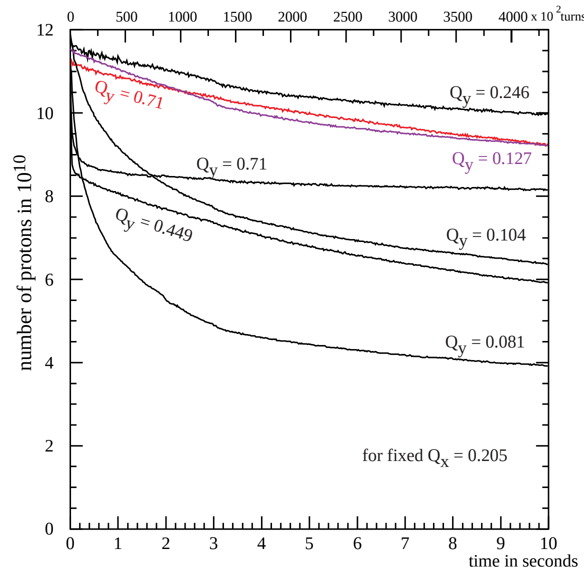

Figure 2: Single bunch intensities in the SPS over 10 s from injection for various vertical tunes Q_y and a fixed $Q_x = 0.2$.

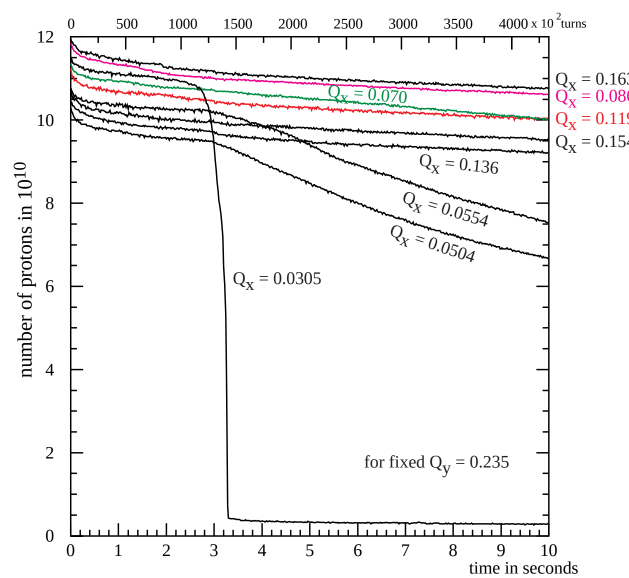

Figure 3: Single bunch intensities in the SPS over 10 s from injection for various horizontal tunes Q_x and a fixed $Q_y = 0.234$.

4 TESTS WITH OCTUPOLES

The measurements reported so far were obtained for a rather linear machine. This was verified by measurements of detuning with kick amplitude.

It is known that octupoles improve the stability under certain conditions [8]. The last hour of available beam time was used for a first quick test on the effect of the two octupole families ("vertical and radial") on the stability in the presence of space charge. Losses increased whenever the octupoles were run at strong negative excitation which

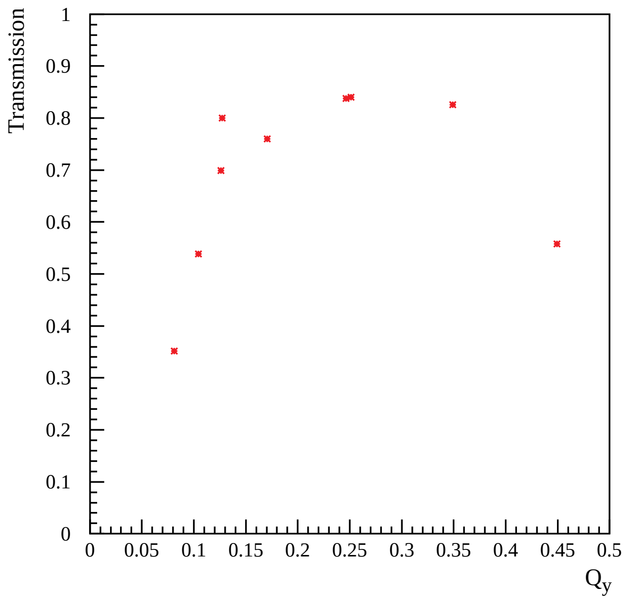

Figure 4: Results of the vertical tune scan in terms of transmission over 10 s.

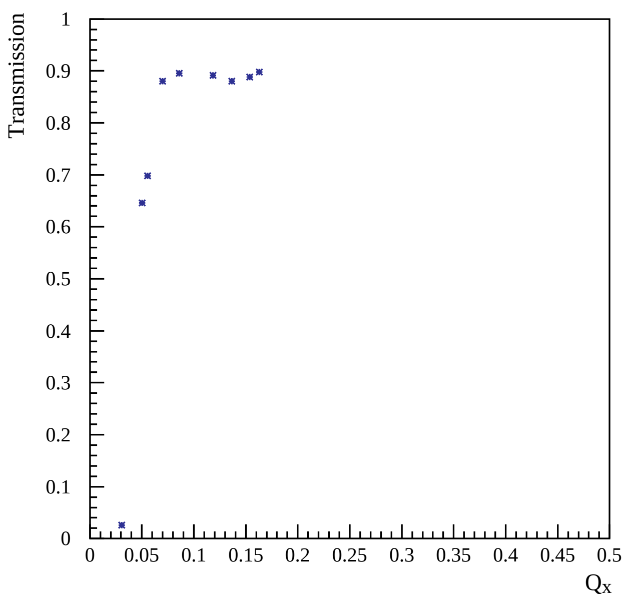

Figure 5: Results of the horizontal tune scan in terms of transmission over 10 s.

corresponds to positive detuning with amplitude. Positive radial settings had no visible effect. Strong positive vertical octupole excitation ("settings of +6 or better +11") appeared to improve the stability. Using these settings, we were able to reduce the bunch length (by an increase of the rf-voltage from 1.5 to 5 MV) without major losses.

5 SUMMARY AND OUTLOOK

Studies with high intensity single bunch proton beams injected at 14 GeV allowed a first investigation in the SPS of the behaviour of beams at space charge tune shifts of 0.14 to 0.18. Good stability with lifetimes of over 100 s were observed over a rather broad range of tunes. This is encouraging and leaves some margin for an overall optimization of beam parameters in the injector chain for heavy ion operation of the LHC. Further measurements including systematic studies with octupoles are foreseen.

6 REFERENCES

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