INVESTIGATION OF SPACE CHARGE EFFECTS AND INTRABEAM SCATTERING FOR LEAD IONS IN THE SPS

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Abstract

Space charge effects and intrabeam scattering usually play a minor role in high energy machines like the SPS. They can potentially become a limitation for the heavy ion beams needed for the LHC at the injection plateau in the SPS. Experimental studies on space charge limitations performed on low energy proton beams in the SPS will be described. Theoretical studies have been performed to predict emittance growth times due to intrabeam scattering using several different codes.

INTRODUCTION

Space charge and intrabeam scattering (IBS) are strongly energy dependent ($\Delta Q \div 1/(\beta\gamma^2)$). High space charge tune shifts in excess of 0.5 have been observed in smaller machines [1, 2, 3]. Such high space charge tune shifts are typically accompanied by blow-up and short lifetimes, well below a second.

For LHC operation, protons will be injected into the SPS at p = 26GeV/c corresponding to γ= 27.73, and the space charge tune shifts will remain well below 0.1 and are not expected to cause any noticeable blowup or losses. For the LHC heavy ion program, it is planned to inject lead ions into the SPS at γ=7.3 [4]. The length of the injection plateau will be 43.2 s, or about four times longer than for proton injection. Space charge tune shifts of 0.08 at injection into the SPS will have to be handled in routine heavy ion operation, and there has been some concern that this could not be feasible without major hardware modifications like adding a lower frequency rf-system to lengthen the bunches and reduce space-charge and intrabeam effects.

First experimental studies performed with protons injected at 14GeV/c already indicated that it should be possible to handle space charge tune shifts in the SPS in excess of 0.1 with lifetimes of the order of 100 s [5]. Further studies, both theoretical and experimental are described here.

SPACE CHARGE TUNE SHIFT

We used the maximum single bunch intensity currently available from the PS for low emittance single bunch operation of N = 1.2×10^{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. The emittances were obtained from transverse profile measurements using a wire scanner in the SPS in a dispersion free region). 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.

Table 1: Proton beam parameters

Proton momentum	14 GeV/c
Initial proton intensity	$N = 1.2 \times 10^{11}$
Relative momentum spread	$\sigma_{\Delta p/p} = 2 \times 10^{-3}$
Normalized emittances	$\varepsilon_{x,y,N} = 2.5$ µm
Bunch length (at 2 MV)	$\sigma_t = 0.8$ ns

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

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

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

$$\varepsilon = \varepsilon_N / \beta\gamma$$

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

$$\Delta Q_{x,y} = -\frac{r_c}{2\pi\beta^2\gamma^3}\frac{N}{\sqrt{2\pi}\,\sigma_z}\int_0^L \frac{\beta_{x,y}}{\sigma_{x,y}\left(\sigma_x + \sigma_y\right)} ds \qquad (2)$$

by numerical integration around the ring using nominal values of the functions and dispersion (where on average β_x = 42.2m, β_y = 42.4m). r_c is the classical proton radius and σ_z the bunch length.

MEASUREMENTS IN THE SPS

Experimental studies on space charge performed in the year 2003 in the SPS aimed mainly at getting the highest possible space charge tune shift. Protons were injected at 14 GeV/c and bunches further shortened by ramping the RF voltage from 2 to 7 MV in the first 0.1 s following injection. Bunch length measurements in the SPS showed a reduction from σ_t = 0.8 to 0.6 ns. To allow to measure longer lifetimes, the SPS was run in a special mode which allowed to stop the regular magnetic cycling of 19.2 s period and to remain at the injection momentum of 14 GeV/c over several cycles. Fig. 1 shows the proton intensity recorded over 1.6 s following injection as well as 19.2 s and 2 × 19.2 s later, under conditions of very high space charge tune shifts. For the data shown in Fig.1, we expect from the beam parameters of the injected beam, that initial tune shifts reached about $\Delta Q_y = -0.3$. We see however from the same Fig.1 that the intensity rapidly decreased to about 0.8×10^{10} protons. Using the measured intensity and beam sizes 1 s after injection, we find space charge tune shifts of $\Delta Q_x = -0.14$ and $\Delta Q_y = -0.24$ with lifetimes of over 50 s.

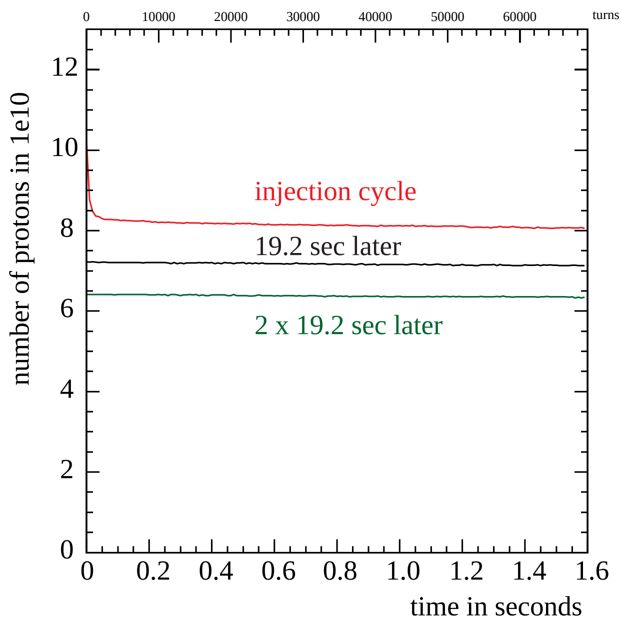

Figure 1: Single bunch intensity measured in the SPS after injection, 19.2 s later, and 2 × 19.2 s later.

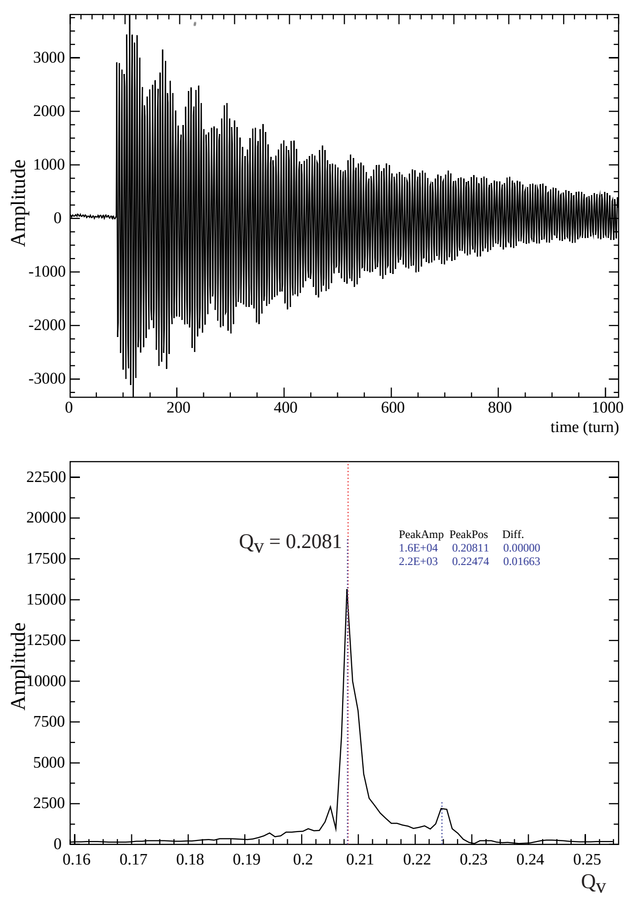

Figure 2: Vertical tune measured before the lifetime measurement of Fig.1. Vertical centre of gravity oscillations recorded by the tune meter are shown on top and the spectrum after fast Fourier transform (FFT) on the bottom.

It was also observed, that our current working point for proton injection at 26 GeV/c of Q_x = 26.184 and Q_y = 26.13 is not optimal at 14GeV/c in the presence of high space charge tune shifts, and that better conditions were obtained when the vertical tune was increased to about Q_y = 26.2. Fig. 2 shows the vertical tune measurement for the conditions of Fig.1. The beam was kicked 1 s after injection at an intensity of 1.04×10^{11} protons. The tune meter records the coherent (centre of gravity) motion of the bunch. To first order, the central tune value obtained is not affected by the substantial internal space charge tune spread.

We also investigated the effect on other parameters like chromaticity and octupole settings. We saw clear changes using octupoles and some improvements for non-optimal tune settings, but found typically no further improvement, after optimisation of the tune working point.

INTRA BEAM SCATTERING

Transverse and longitudinal emittance growth times due to intra beam scattering on the SPS injection plateau have been computed using three different codes, *MAD8* [6], the standard *IBS* routine in *BeamOptics* [7], both using the Bjorken-Mtingwa formalism [8], and the *IBSCATT* code [9-10]. Two situations have been considered: the "nominal" and the "bunchlet" lead ion injection scheme [4]. Intrabeam scattering estimations for the "nominal" scheme are reported in Table 2. The *MAD8* and *BeamOptics* intrabeam scattering routines yield rather different results, while the MAD8 and Piwinski computations agree rather well. Yet, the lower bound for the longitudinal growth time is given by the *BeamOptics* calculation.

Table 2: IBS calculations for the nominal scheme.

Bunch intensity N_I [ions]			1.2 x 10^8
Relativistic parameter γ			7.31
Longitudinal emittance (2σ) $\varepsilon_{//}$ [eV.s/u]			0.025
RF voltage V_{RF} [MV]			1.0
Bunch length (4 σ) τ_b [ns]			4.0
Relative momentum spread (2σ) $\Delta p/p$			6.5x10^{-4}
Transverse normalised emittance (1σ) $\varepsilon^*_{x,y}$ [μm]			1.0
Initial IBS growth times	*IBS* MAD8	*IBS* Bjorken-Mtingwa	*IBSCATT* Piwinski
Longitudinal $\tau_{//}$ [s]	285	83	271
Horizontal τ_x [s]	725	-5830	838
Vertical τ_y [s]	1130	-1597	950

The time evolution over 2 minutes of the transverse normalised rms emittances and the longitudinal emittance as a result of intrabeam scattering calculations performed using Equ. 3 are displayed in Figs. 3-4.

$$\varepsilon_{x,y,//}(t) = \varepsilon_{x,y,//}(0)\,\mathrm{Exp}\left[\int_0^t \frac{du}{\tau_{x,y,//}(u)}\right] \qquad (3)$$

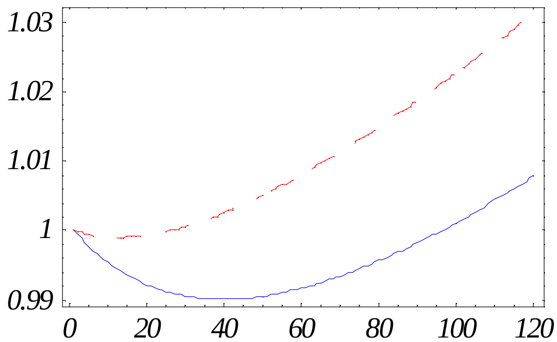

Figure 3: Evolution of the transverse normalised rms emittances [µm] over 2 minutes (horizontal: dotted line, vertical: continuous line, time in seconds) due to intrabeam scattering; most pessimistic computation.

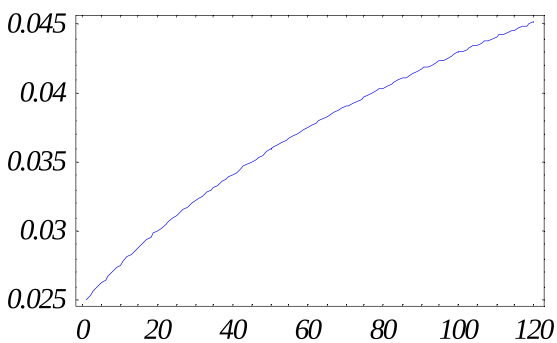

Figure 4: Evolution of the longitudinal (2σ) emittance [eV.s/u] over 2 minutes due to intrabeam scattering; most pessimistic computation.

The worse case calculation forecasted by the *BeamOptics* code (83 s initial longitudinal growth time) has been considered regarding the constraint imposed by the 43.2 s length of the SPS injection plateau.

In the case of the "bunchlets" scheme, the lead ion bunches are first blown-up longitudinally, then split into bunchlet pairs in the PS, before being transferred to the SPS. The resulting bunchlets have half the longitudinal density as the original bunches. This scheme had been originally planned in case the length of the injection flat bottom (43.2 s) would prevent keeping small emittances under a high space charge regime. Since the bunchlets have exactly the same characteristics (emittances, bunch length, etc) as the original bunches but half their intensity, the resulting IBS growth times are simply doubled.

SUMMARY

Recent measurements performed on protons injected at 14 GeV/c allowed to obtain beam charge tune shifts in excess of 0.2 at lifetimes of over 50 s. Estimation of the longitudinal emittance growth due to intrabeam scattering in the most pessimistic computation does not exceed 40% over the full duration of the injection plateau, which is acceptable for the LHC requirements. It should be emphasised that both space charge and intrabeam scattering effects are larger for the first injected bunches than for the later ones. This makes us rather confident, that regular operation at space charge tune shifts of 0.08 as expected for heavy ion injection into the LHC should be realistic without major hardware modifications. The early phase of the project will allow for dedicated measurement periods to estimate if this is really the case or if the bunchlet scheme needs to be implemented.

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