Measurement and Reduction of Transverse Emittance Blow-up Induced by Space Charge Effects

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Abstract

The CERN PS, as part of the LHC injector chain, will have to keep a high intensity, high brilliance beam for 1.2 s at the injection energy. The transverse particle density will exceed, by a factor of three, the highest currently attained. Careful experimental studies have recently been carried out in the PS to investigate transverse emittance blow-up in such a severe space charge regime. In addition, a new controlled longitudinal blow-up technique has been developed to produce bunches with flat-topped density profiles and, accordingly, reduced peak current. The results achieved so far are presented and discussed.

I. INTRODUCTION

Transverse emittance conservation is a major concern in the LHC injector chain of LINAC, PS Booster (PSB), PS and SPS [1, 2]. In the PS, for example, the total transverse emittance blow-up must be less than 20%.

One of the peculiarities of the beam for the LHC is that the PSB cannot deliver sufficient intensity to the PS within the required transverse emittances in a single cycle. Consequently, the PS beam will be made up of two PSB batches (each of four bunches) separated by the 1.2 s PSB cycle time. The first batch transferred to the PS will have to circulate at the injection energy of 1 GeV during this time in a strongly space charge dominated regime, leading to an incoherent tune shift, $|\Delta Q_{x,z}| > 0.4$.

For bunches with Gaussian transverse distributions, the space charge detuning at the centre of the bunch may be written

$$\Delta Q_{x,z} = -\frac{r_0}{ec}\,\frac{I_\mathrm{p} R^2}{Q_{x,z}\beta^3\gamma^3}\,\frac{1}{\sigma_{x,z}(\sigma_x+\sigma_z)} \tag{1}$$

where $Q_{x,z}$ are the horizontal and vertical tunes, r_0 is the classical proton radius and e its charge, c is the speed of light, R is the machine radius, and β and γ are the usual relativistic factors; I_p is the peak bunch current which, for a parabolic line charge density, is equal to $3N_\mathrm{b}e/2\tau_\mathrm{b}$, with N_b the number of particles in the bunch and τ_b the full bunch duration. The rms transverse betatron beam sizes are

$$\sigma_{x,z} = \sqrt{\beta_{x,z}\mathcal{E}_{x,z} + \left(D_{x,z}\frac{\sigma_p}{p}\right)^2} \tag{2}$$

where $\mathcal{E}_{x,z}$ are the rms transverse emittances, $\beta_{x,z}$ and $D_{x,z}$ are the average beta and dispersion functions, and σ_p/p is the relative rms momentum spread.

Large $|\Delta Q_{x,z}|$ leads to the beam crossing betatron resonances and can cause transverse emittance blow-up. For a given beam intensity and transverse emittance, Eqn.1 shows that $|\Delta Q_{x,z}|$ can only be reduced by increasing the energy of the beam and/or by decreasing I_p. How much the PS injection energy should be raised and what can be done to reduce the peak bunch current are the two points addressed here.

II. SPACE CHARGE INDUCED TRANSVERSE BLOW-UP

A. *Blow-up Evaluation Method*

Refined tracking programs exist [3, 4] to evaluate beam blow-up, but simulation of the PS beam during 1.2 s would require excessive computing time. Instead, several experiments simulating LHC beam conditions have been conducted in the PS [5]. These tests were performed at the present injection energy of 1 GeV and the space charge tune shift was modified by varying the bunch length by means of the RF voltage. After injection in the PS, the RF voltage was raised and maintained at an elevated value for 800 ms, then returned to its original value as shown in Fig.1. Beam emittances before and after the voltage

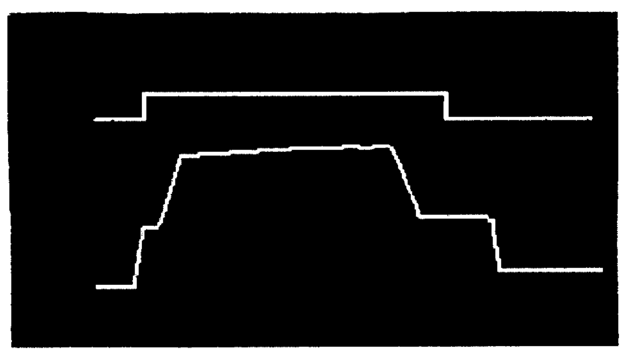

Figure 1: Beam current (2×10^{12} protons/div.) and RF voltage (50 kV/div.) versus time (200 ms/div.).

increase were measured by flying-wire scanner and compared. The experiment was performed at two different working points. As expected, slightly raising Q_z improves the situation as the beam moves away from the integer resonance $Q_z = 6$. However, in order to avoid the third-order resonance $Q_z = 6.33$, Q_z was not set above 6.28.

B. *Experimental Results*

The results shown in Fig.2 are plotted as a function of the detuning calculated from the measured beam dimensions. The detuning expected from Eqn.1 for the LHC beam at 1 GeV in the PS is $|\Delta Q_{x,z}| > 0.4$, so that Fig.2 can be used to estimate that the resultant transverse emittance blow-up would exceed 30%. An acceptable emittance increase requires $|\Delta Q_{x,z}| < 0.3$ which, from Eqn.1, implies that the PS injection energy must be raised to 1.4 GeV.

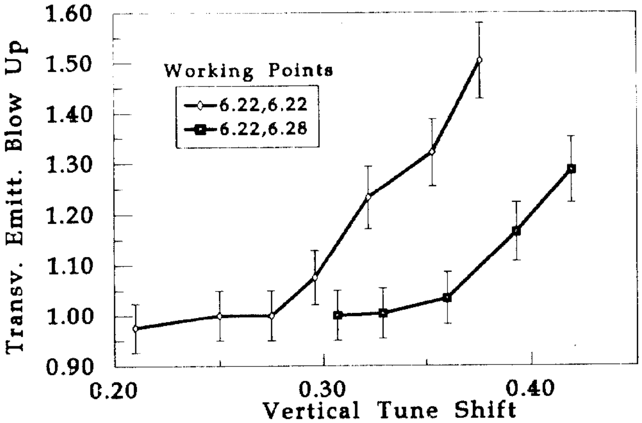

Figure 2: Mean emittance blow-up versus vertical space charge tune shift, ΔQ_z, for two different working points: $Q^{(1)}_{x,z} = 6.22, 6.22$ and $Q^{(2)}_{x,z} = 6.22, 6.28$. The emittance blow-up is evaluated as $1 + \Delta\mathcal{E}/\mathcal{E}$ with $\mathcal{E} = (\mathcal{E}_x + \mathcal{E}_z)/2$. ΔQ_z is calculated from the initial beam dimensions.

Beam blow-up has also been measured as a function of time and this is plotted in Fig.3. No alteration of the shape of the transverse distributions was observed.

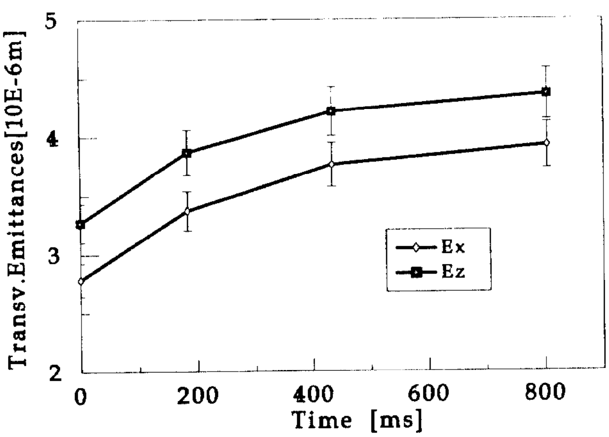

Figure 3: Transverse emittances, $\mathcal{E}_{x,z}$, versus time in a strong space charge regime ($|\Delta Q_{x,z}| = 0.45$) at 1 GeV with $Q_{x,z} = 6.22, 6.28$. Injection is at $t = 0$.

In order to reduce further the harmful effects of space charge, τ_b could be increased to lower I_p. However, there is little margin for this in the PS as the constraints imposed by the injection kicker rise time and by the available RF bucket confine τ_b within a 200 ns bound.

III. FLAT-TOPPED BUNCHES

A. *Principle*

For the same τ_b, proton bunches with flat-topped density profiles have lower I_p than the more usual quasi-parabolic bunches. Reduction of the space charge induced tune shift is then expected (from Eqn.1), for the same transverse particle distributions, and has indeed been obtained using second harmonic cavities [6]. Although effective, the latter technique has the disadvantage of requiring an additional RF system throughout the low-energy stages of acceleration.

However, flat-topped bunches can be matched to a single RF system given a suitable distribution of particles in longitudinal phase space. Experiments performed in the past to capture a LINAC beam with a hollow energy distribution have been inconclusive [6].

B. *Method*

A new method has been developed to transform bunch profiles from quasi-parabolic to flat-topped using two basic ingredients:

- a depopulation of the bunch centre by a dipolar excitation of the bunch within the bucket (peak phase excursion $A_{\rm mod}$ at modulation frequency $f_{\rm mod}$ for $n_{\rm mod}$ periods),
- a "smoothing" of the resulting filamentation by a high frequency RF voltage slightly offset (Δf) from a harmonic of the main RF.

Fig.4 shows the buckets of the two RF components drawn independently in phase space for the parameters in Table 1.

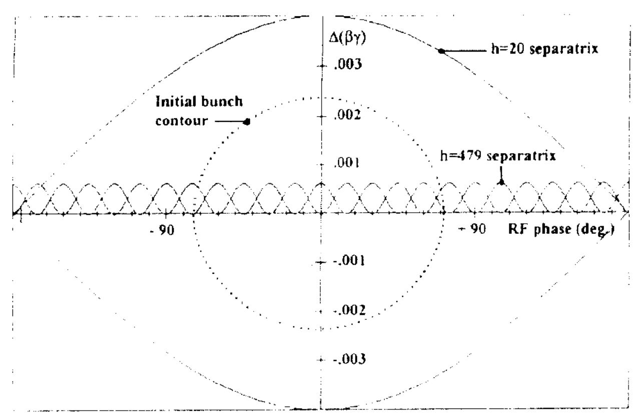

Figure 4: Longitudinal phase space during the production of flat-topped bunches.

$V_{h=20}$ [kV]	$A_{\rm mod}$ [deg]	$f_{\rm mod}$ [kHz]	$n_{\rm mod}$	$V_{h\simeq 479}$ [kV]	Δf [kHz]
44	27	1.65	7	6.5	9.9

Table 1: Parameters to produce flat-topped bunches.

C. Experimental Results

The extent to which flat-topped bunches combat transverse blow-up has been measured in the PS in an experiment very similar to that described above at a working point of $Q_{x,z} = 6.22, 6.22$. By applying the parameters of Table 1 to a quasi-parabolic bunch like that of Fig.5, the flat-topped bunch of Fig.6 was produced. The entire process lasted 10 ms and caused some longitudinal blow-up. The transverse emittances of such a bunch were measured before and after a four-fold increase in RF voltage, as described above. These measurements were repeated with the same voltage programme applied to a quasi-parabolic bunch whose length had been increased by a conventional controlled longitudinal blow-up [7], without modifying its shape, to match that of Fig.6. The overall emittance growth ($\Delta\mathcal{E}/\mathcal{E}$) due to the 800 ms at elevated tune shift was 29% in the case of quasi-parabolic bunches compared with only 17% for the flat-topped ones.

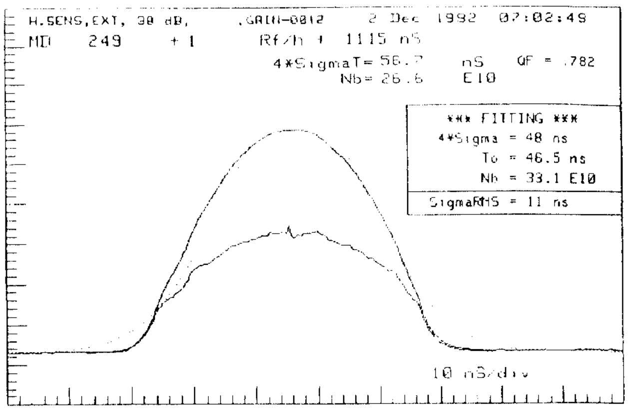

Figure 5: Quasi-parabolic bunch. The dotted curve is a Gaussian fit to the 1-D density profile (upper trace). The lower trace is the 2-D phase space density derived from the profile by an Abel transform [8].

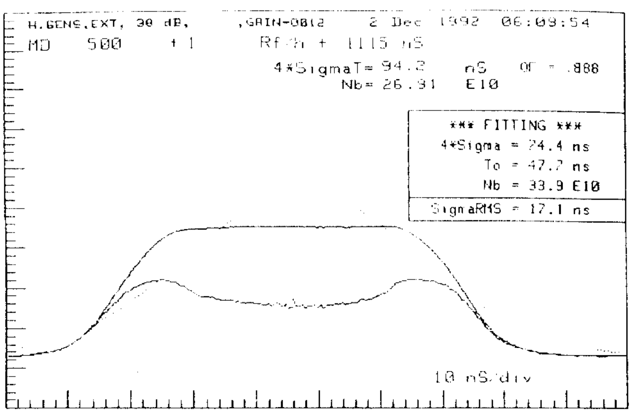

Figure 6: Flat-topped bunch. The Abel transform reveals the depopulation at low synchrotron amplitude.

A "bunch shape quality factor", Q_f, has been devised in analogy with the familiar bunching factor and defined as the ratio of the mean to peak line charge density, where the mean is taken over $\pm\sqrt{3}$ rms standard deviations about the centre of the bunch rather than over the entire bucket length or machine circumference. This makes Q_f largely insensitive to the aspect ratio of the bucket while the factor of $\sqrt{3}$ was chosen so that Q_f is unity for a perfectly rectangular profile. An increase in Q_f from 78% in Fig.5 to 89% in Fig.6 is achieved.

Flat-topped bunches have been produced at 1 GeV and 3.5 GeV/c, at intensities in the range 2–6.5 × 10^{11} protons per bunch, and have proved stable under closed-loop conditions: they have remained flat for $\sim$ 1 s at constant energy and even after acceleration across transition.

IV. CONCLUSIONS

Experiments at 1 GeV in the PS under conditions similar to those that will prevail for the beam for the LHC indicate that the energy of the PSB-to-PS transfer should be raised to 1.4 GeV to preserve the transverse emittance of quasi-parabolic bunches.

A new method for creating flat-topped bunches has been developed and tested. Such bunches are longitudinally stable and are less prone to transverse blow-up due to space charge induced tune shift. The method will be employed in the PSB for the benefit both of the PSB itself and of the downstream PS. It could be of interest in other space charge limited synchrotrons.

V. ACKNOWLEDGEMENTS

The authors wish to thank H. Charmot, C. Hill, F. Nitsch, K. Schindl and H. Schönauer for their various contributions to this work.

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