Experiments to Test Beam Behaviour Under Extreme Space Charge Conditions

R. Cappi, R. Garoby, D. Möhl, J.L. Vallet, E. Wildner
CERN-PS
CH - 1211 Geneva 23

Abstract

For special applications (e.g. in "bunch compression rings" for heavy ion fusion drivers [1] or for spallation neutron sources) it is desirable to work at an intensity and beam bunching level where space charge induces a very large tune depression. The final bunching prior to extraction is very fast and hence the dwelling time in the extreme space charge regime short. Thus incoherent Laslett tune shifts $|\Delta Q|$ of one or several units, much larger than the limiting $|\Delta Q|$ of 0.3-0.5 in conventional synchrotrons, have been contemplated. We have undertaken experiments at 1 GeV injection energy into the PS to test the beam blow-up under such conditions. The emittances are measured before and after the bunch compression using the "scanning wire method". Attempts have been made to compensate half-integer stop bands crossed due to the tune-shift. So far we have been able to obtain peak tune-shifts of almost 1. The emittance blow-up during the complete up and down variation of the tune was at worst 50% in the horizontal and less than 30% in the vertical plane depending on the beam conditions.

1. INTRODUCTION

We define the tune shift as the betatron frequency variation $\Delta Q_{x,y}$, due to space charge effects, of the particle located in the centre of the bunch with respect to its value for vanishing current [2]. It is also sometimes called tune spread, incoherent tune spread or shift. Moreover we shall consider the coherent tune shift as negligible.

For bunches with Gaussian transverse distributions, an approximate formula for the tune shift is given by

$$\Delta Q_{x,y} \cong -\frac{r_0}{ec}\frac{I_p R^2}{Q_{x,y}(\beta\gamma)^3}\frac{1}{\sigma_{x,y}(\sigma_x+\sigma_y)}\frac{q}{A} \qquad (1)$$

Where r_0 is the classical proton radius, e the proton charge, c the speed of light, R the machine radius, $Q_{x,y}$ the horizontal and vertical tunes, β and γ are the usual relativistic factors, q and A are respectively the charge state and the mass number of the ions (both equal to 1 for protons). I_p is the bunch peak current which, for a parabolic line density, is given by

$$I_p = \frac{3eqN_b}{2\tau_b} \qquad (2)$$

where N_b is the number of particles (or ions) in the bunch and τ_b is the total bunch duration. The rms transverse beam sizes are

$$\sigma_{x,y} = \sqrt{\beta_{x,y}\varepsilon_{x,y} + \left(D_{x,y}\sigma_p/p\right)^2} \qquad (3)$$

where $\varepsilon_{x,y}$ are the rms transverse emittances, $\beta_{x,y}$ and $D_{x,y}$ are the average beta and dispersion functions of the ring and σ_p/p is the relative rms momentum spread. Note that in the PS, $D_y \approx 0$ and hence $|\Delta Q_y| > |\Delta Q_x|$ if $\varepsilon_x \approx \varepsilon_y$.

The behaviour of a dense beam in a space charge regime with $|\Delta Q| \approx$ 0.3-0.4 for a time longer than one second has been recently studied in the PS in relation with the LHC project [3]. Taking these beams as a starting point, we used two different RF techniques of bunch compression in order to increase the tune shift by more than a factor of two.

2. EXPERIMENTS

2.1. *General*

The experiments were performed with protons at the present PS injection energy of 1 GeV. The magnetic cycle was modified in order to have a long flat bottom (one second instead of 20 ms in normal operation) at this energy . To avoid coupled bunch collective effects only one bunch was injected. Careful chromaticity and transverse feedback adjustements were done to prevent any single bunch instability. The bunch compression gymnastics took place about 200 ms after injection. The transverse beam emittances were measured, 20 ms before and after bunch compression, by means of the scanning wire method [4]. Two horizontal and two vertical wire scanners were used.

2.2. *Bunch compression by "RF phase jump"*

To obtain a bunch compression the RF voltage at harmonic number h=20 was slowly (~100 ms) increased to its maximum value of 200 kV. Then a fast (180 degrees in ~20 μs) RF phase jump put the beam on the unstable phase point, where it was "stretched" by a factor ~1.5 in 27 μs. A second phase jump brought the bunch back to the stable fixed point where it started a rotation inside the RF bucket, reaching minimum length (i.e. maximum compression) after ~1/3 of the synchrotron period (~1/3 x 253 μs in our case). Starting again ~1/3 of synchrotron period later, a phase jump gymnastic (perfectly symmetric to the first one) brought the beam back to its original stable longitudinal position and shape (see Figures 1 and 2).

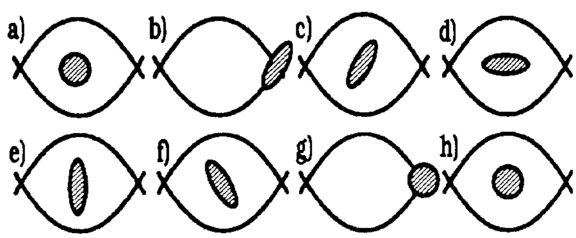

Figure 1. Illustration of RF phase jump gymnastic. The picture represents the following steps: a) the original matched bunch; b) the bunch after stretching on the unstable fixed point; c) jump back on the stable fixed point; d) ~ 1/8 of a synchrotron period later (the bunch length goes through a maximum); e) ~ 1/4 of a synchrotron period later (the bunch length is minimum); f) ~ 5/8 of a synchtrotron period later (the bunch has gone through another maximum and fits on the trajectories near the unstable point); g) the bunch restores its original shape on the unstable point; h) the matched bunch after the jump back to the stable point.

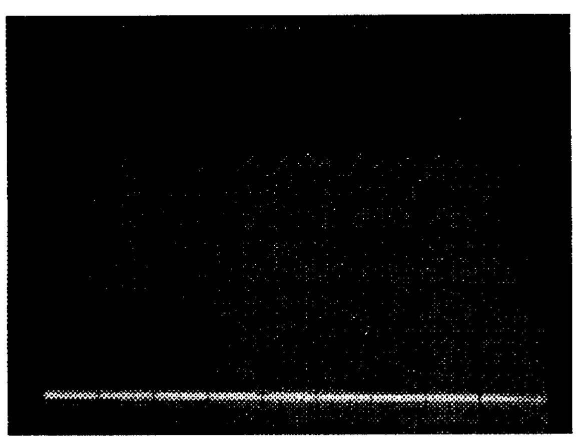

Figure 2. Signal from a wide band longitudinal pick up showing a bunch compression by "RF phase jump" followed by small residual bunch shape oscillations (time scale: 100 μs/div).

Ideally the bunch recovers exactly its original longitudinal shape. Then any change in the transverse dimensions, measured by the wire scanner, will be exclusively related to the betatron blow-up, even if it is located in a dispersive region, as it is in our case.

Some results are shown on Table 1, where $\varepsilon^*_{x,y}$ are the normalized rms transverse emittances, ε_l is the longitudinal emittance and "blow-up" is the ratio between the final and the initial transverse emittances after a full up and down modulation of $|\Delta Q|$ i.e. after a full bunch compression - decompression cycle. One notes that a peak vertical tuneshift of about 0.5 is associated with 10% blow-up whereas in the horizontal plane with a comparable tune shift, no significant emittance increase was measured.

The bunch can be considered "compressed" during ~40 μs, which corresponds to about 20 machine turns, see Figure2.

Table 1
Machine and beam parameters during "RF phase jump" bunch compression experiments

	τ_b[ns]	$-\Delta Q_{x,y}$	$\varepsilon^*_{x,y}$ [μm]
before b.c.	35	0.40 , 0.41	3.01 , 3.62
during b.c.	24	$\boxed{0.49 , 0.57}$	-
after b.c.	35	0.39 , 0.38	3.09 , 4.02
		transverse blow-up	$\boxed{1.03 , 1.11}$

T=1GeV, V_{RF}=200kV, h=20, ε_l=0.16 eVs, N_b=4.5$10^{11}$ p/b

2.3 Bunch compression by "RF voltage jump"

In this experiment another RF bunch compression technique was tested: a fast (compared to the synchrotron period) rise of the RF voltage induced a bunch rotation in longitudinal phase space. A voltage jump back to the original value one half of a synchrotron period (~400 μs) later, recovered the initial longitudinally stable bunch shape.

For these experiments we took advantage of the Booster (PSB) and PS modifications for the LHC project, to increase the beam density [5,6]. A single bunch was accelerated in the PSB on h=1 and injected into the PS at h=8. Results for two runs with different beam densities are given in Table 2a and 2b. In the first case the maximum tune shift is 0.35, 0.6 (horizontal and vertical), comparable to the situation obtained with the RF phase jump method. The concurrent blow-ups of 22% and 5% respectively, are higher in horizontal and lower in the vertical plane than with the phase jump gymnastics. In the second run, tuneshifts of 0.54, 0.95 were obtained with a blow-up of 50% and 30%.

One notes that the "phase jump" and the "voltage jump" experiments are not in very good agreement, at least as far as the horizontal blow-up is concerned. It should be mentioned that they were done six months apart. No time was available during the second experiments to repeat the "phase jump" measurements.

Table 2a
Machine and beam parameters during "RF voltage jump" bunch compression experiments

	V_{RF} [kV]	τ_b [ns]	$-\Delta Q_{x,y}$	$\varepsilon^*_{x,y}$ [μm]
before b.c.	22	200	0.26 , 0.27	2.69 , 3.24
during b.c.	200	67	0.35 , 0.60	-
after b.c.	22	200	0.23 , 0.25	3.42 , 3.54

transverse blow-up 1.27 , 1.09

T=1 GeV, h=8, ε_l=0.9 eVs, N_b=1.5 10^{12} p/b

Table 2b
Parameters during "RF voltage jump" bunch compression experiments with a higher density beam

	V_{RF} [kV]	τ_b [ns]	$-\Delta Q_{x,y}$	$\varepsilon^*_{x,y}$ [μm]
before b.c.	15.6	200	0.34 , 0.38	2.88 , 2.85
during b.c.	200	60	0.54 , 0.95	-
after b.c.	15.6	200	0.23 , 0.27	4.32 , 3.67

transverse blow-up 1.50 , 1.29

T=1 GeV, h=8, ε_l=0.75 eVs, N_b=1.9 10^{12} p/b

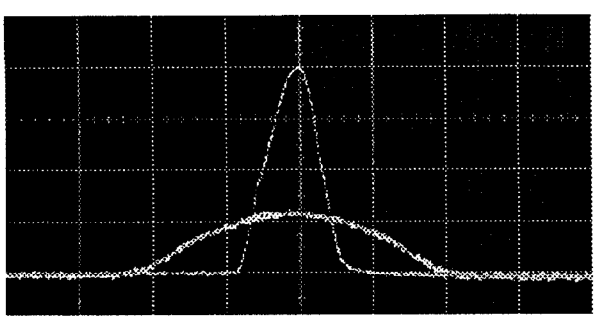

Figure 3. Bunch shape before (long), during (short) and after (long and superposed) bunch compression (time scale: 50 ns/div).

2.4 $2Q_{x,y}$=12 harmonic compensations

With a working point Q_x=6.23 , Q_y=6.28 and a $|\Delta Q|$>>0.3 one expects the beam to cross the $2Q_y$=12 and $2Q_x$=12 resonances. An attempt to compensate these resonances by modulating, with a 12th harmonic, the current of the low energy trimming quadrupoles, was tried during two of the bunch compression experiments. In some cases, after optimisation of the amplitude and the phase of the $2Q_y$=12 correction, the resulting vertical blow-up was reduced from ~20% to ~10% , while the effects for $2Q_x$=12 were not conclusive. We plan to continue these experiments.

3. SUMMARY AND CONCLUSIONS

By compressing the bunch it was possible to "modulate" the space charge tune shift from -0.3 to ~ -1 and back to -0.3 during a time of about 20 machine turns (~40 μs).

The resulting transverse blow-up as a function of the tune shift, was measured to be between ~5% and ~50%. Most measurents showed much stronger blow up in the horizontal plane where, presumably, gradient errors are larger. In the vertical plane, a tune shift of almost 1 could be reached with only 30% emittance increase during the full modulation cycle.

By compensating the $2Q_y$=12 resonance it was possible, most of the time, to reduce the vertical blow-up by ~10%. The horizontal compensation produced no conclusive effects. All the figures in Tables 1 and 2 are without compensation.

No other harmful effects (e.g. beam losses and instabilities) were observed.

The good results, especially for the vertical plane, give hope that in a well designed compression ring large tune shifts can be obtained with a tolerable blow-up.

Due to the present PS limitations in accelerating voltage, beam density and dynamic aperture, it will not be possible to produce tune shifts much larger than 1.

4. REFERENCES

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