SHAPING OF PROTON DISTRIBUTION FOR RAISING THE SPACE-CHARGE OF THE CERN PS BOOSTER

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ABSTRACT

The intensity of the PS Booster is limited by space-charge defocusing forces which create a spread in the betatron tunes of up to $\Delta Q \simeq 0.5$. Shaping of the transverse and longitudinal distributions was used for accommodating more particles in a given working area and enabled the Booster to accelerate 2×10^{13} protons per pulse, twice the design intensity. Modifying the RF potential well by an experimental second-harmonic cavity yields beam intensities and densities well beyond the present performance. The corresponding PSB experiments and improvements are described and an outlook on future developments is given.

1. SUMMARY AND INTRODUCTION

Reaching the space-charge limited PSB design intensity of 10^{13} ppp within the design emittances had mainly meant moving the working area in the Q-diagram to a region with stop-band and stability characteristics more favourable than those of the region chosen initially, and developing and putting into operation a (novel) longitudinal active damping system[1,2].

To increase the intensity to twice the design value and possibly beyond, a working area with a height of $\Delta Q_V \sim 0.5$ has now been provided by simultaneous stopband corrections and introduction of an improved dynamic (zero particle) working point. Table 1 summarizes the computed maximum space-charge detuning (Q-spreads) of beams at different stages of PSB performance. Because of the strong dependence on the particle distribution in geometrical space, as uniform a distribution as feasible is aimed at.

Table 1 - PSB beam emittances at injection (50 MeV) and calculated Q-spreads after capture for uniform and parabolic transverse particle distribution.

Stage of performance	ε_V determined by	B_f (mean/peak intensity)	ε_H ($\pi\ 10^{-6}$ rad m) 95% of N	ε_V	Nacc (10^{12} p ring 3)	ΔQ_H uniform (G = 1)	ΔQ_V	ΔQ_H parabolic (G = 1.55)	ΔQ_V
Design value	Specification	0.41	130	40	2.5	0.13	0.23	0.20	0.35
1975 [1]	PSB-PS transfer		150	50	3.5	0.16	0.26	0.24	0.40
1978	PSB vertical acceptance		150	70	4.5	0.19	0.27	0.29	0.41
1980		0.44			6.0	0.23	0.33	0.36	0.51
Recent test		0.58			7.2	0.21	0.30	0.33	0.47

Basically the beam profiles can be shaped in either of two ways (Table 2), or a combination thereof. On the one hand, one can modify directly the distribution. On the other hand, one can modify the shape of the potential wells confining the particles in the accelerator. Experiments and improvements are described and an outlook on future developments is given.

Table 2 - Methods explored for reducing space-charge detuning.

Phase plane(s)	Modification of distribution	Change of potential well
Transverse	i) Vertical mis-steering at injection &/or ii) Enhanced linear coupling at injection	Different ratio of horizontal to vertical focusing
Longitudinal	i) Manipulation of linac beam with 2nd harmonic debuncher, or ii) Deposition of empty buckets in beam coasting in the PSB	Change of longitudinal focusing by additional cavity working at twice the accelerating frequency

2. MIS-STEERING OF VERTICAL INJECTION TRAJECTORY AND ENHANCED LINEAR COUPLING AT INJECTION

The evolution of the area of betatron tunes covered by a bunched high-intensity beam is shown in Fig. 1. The installation of a stopband correction system for the simultaneous time-varying compensation of $2Q_H + Q_V = 14$, $Q_H + 2Q_V = 15$, and the structural stopband $3Q_V = 16$ (= number of PSB lattice cells) opened up the possibility of using the (t = 0) working point $Q_H = 4.30$, $Q_V = 5.45$ [3]. (This point is programmed so as to leave the third order stopband region within 100 ms.) The ratio intensity/emittance then increased by about 15%.

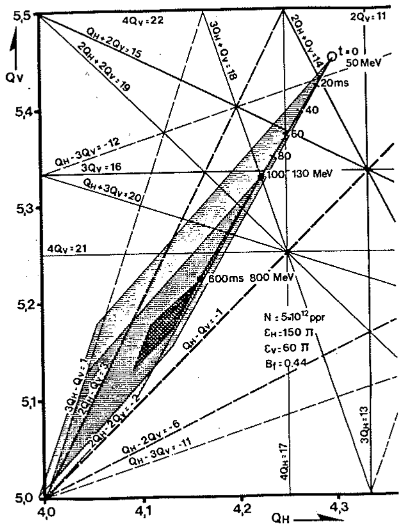


Fig. 1 - Space-charge detuning in the PSB.

As a result of normal multiturn injection, the centre of the horizontal phase plane is almost uniformly filled, whereas in the vertical plane the Gaussian linac distribution is essentially maintained. Any controlled redistribution must be made right at injection because the fast initial blow-up and loss on the integer stopbands, RF capture and residual losses on third order stopbands all take place within a few milliseconds. Both the misadjustment of the vertical injection trajectory ("mis-steering") and the enhancement of the linear coupling resonance $Q_H - Q_V = -1$ by skew quadrupoles ("skew" injection[4]) shift particles from the vertical phase-plane centre to larger amplitudes, i.e. decrease the form factor G (Equ. 1), and reduce the space-charge detuning (Table 3). (The reason for their observed beneficial effect on residual losses due to the stopband $3Q_V = 16$ is less clear.) The greater efficiency of linear coupling for filling the vertical phase space is apparent from Fig. 2 (i.e. the shift of the barycentre of $n(a_x,a_z)$ towards larger vertical amplitudes). Cases b) & c) yield maximum intensity within the somewhat reduced vertical emittance required for $\bar{p}$-production in the ten-bunch mode[5].

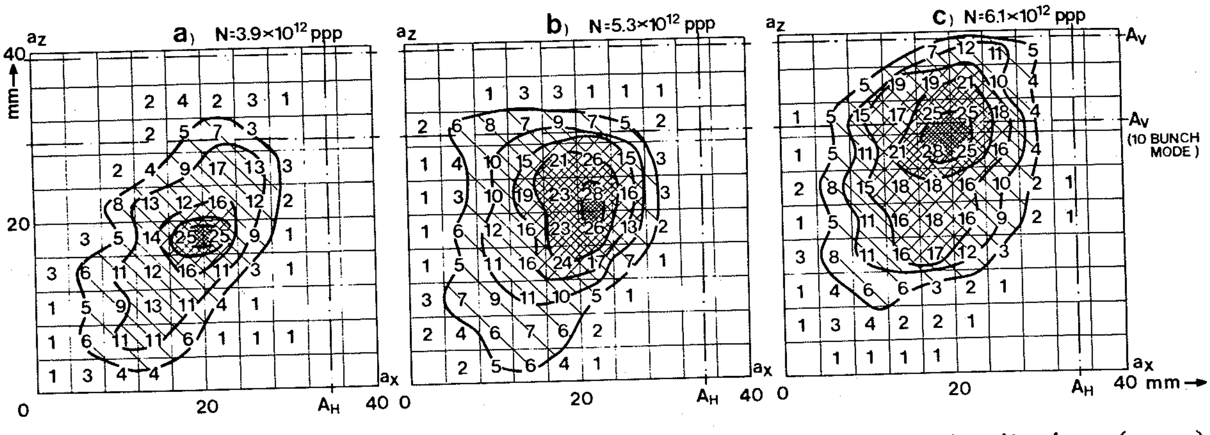


Fig. 2 - Influence of mis-steering and linear coupling on the amplitude distribution $n(a_x,a_z)$ of the PSB beam, 7 ms after injection. Beam height reduced stepwise by target, horizontal profiles measured with Beamscope[7]. Intensities in units of 10^{10} pp square division. Acceptances $A_{H,V}$ and total intensities N are also indicated; for a) to c) see Table 3.

Table 3 - Intensities N in ring 3 (after initial loss) when filling the vertical acceptance by mis-steering and enhanced linear coupling at injection. Cases a) to c) correspond to those of Fig. 3; the maximum space-charge detuning $\Delta Q_{H,V}$ has been computed, square division by division, for the distributions shown there. Case a) suffers particularly from initial loss.

Case	Mis-steering	Linear coupling	$N(10^{12}$ ppr)	Bunchg.factor (mean/peak)	ε_H (10^{-6} rad m)	ε_V	ΔQ_H (maximum)	ΔQ_V	G(Equ.1) Hor.	Vert.
a)	OFF	OFF	3.9	0.40	144	58	0.24	0.46	1.41	1.77
b)	ON	OFF	5.3	0.44	156	62	0.29	0.49	1.50	1.64
c)	ON	ON	6.1	0.44	158	75	0.29	0.37	1.37	1.23

3. DIFFERENT RATIO OF HORIZONTAL TO VERTICAL FOCUSING

For negligible image forces, in the smooth approximation, and for $\Delta p/p = 0$, the space-charge detuning[6)] is given by

$$\Delta Q_{H,V} = [(N\, r_p\, G)/(\pi\, B_f \beta^2 \gamma^3)]\, [\varepsilon_{H,V} + \sqrt{\varepsilon_H \varepsilon_V} \times \sqrt{Q_{H,V}/Q_{V,H}}]^{-1} \qquad (1)$$

where r_p is the proton radius, G is a form factor accounting for the transverse particle distribution (see Tables 1 & 3), and the other symbols have their usual meanings. Hence, for $\varepsilon_H >> \varepsilon_V$, ΔQ_V can be decreased markedly by increasing the ratio Q_V/Q_H and vice versa (Fig. 3); this has been verified experimentally. After a systematic exploration of the stopband widths in the various possible working regions a new working point $Q_H = 3.30$, $Q_V = 5.40$ is under study. Part of the gain having already been made when leaving the main diagonal, the further potential intensity gain is ∿ 10%. Taking into account the influence of the emittance and Q-ratios (Fig. 3) at the machine design stage may result in higher gains.

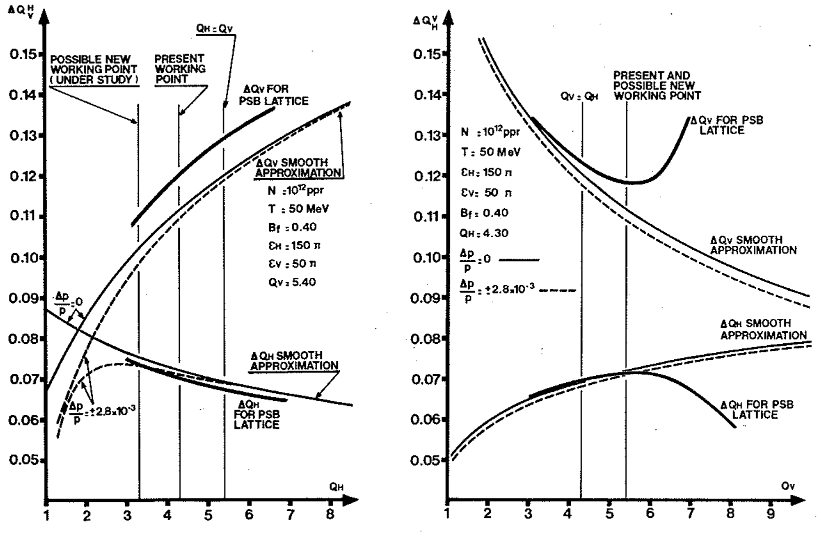


Fig. 3
Space-charge induced tune spread as a function of Q_H (left) and Q_V (right).

4. MANIPULATION OF ENERGY DISTRIBUTION BY SECOND-HARMONIC DEBUNCHER OR EMPTY BUCKET DEPOSITION

Calculations[8)] show that "hollow" phase-space distributions exist, which give bunch shapes in the PSB with long flat tops and therefore higher bunching factors. A bunching factor 35% higher than usual requires an injected beam with a central density equal to only 40% of the peak density. - Three debunchers are available in the Linac-PSB injection line: two at the fundamental frequency (200 MHz, V_1), and one at the second harmonic (400 MHz, V_2). By proper choice of linac bunch length as well as V_1 and V_2, an S-shaped bunch form can be created in the phase plane, which after debunching produces the desired distribution (Fig. 4). Measurements of the energy spectrum in the PSB show that this desired distribution is adversely influenced by longitudinal space-charge forces during debunching9) (lasting from the debuncher action to RF capture in the PSB) and by the multiturn injection process. These effects can, however, be compensated partly by optimized debuncher settings.

With a slower, i.e. more adiabatic trapping than usual, bunch shapes close to the desired ones were finally obtained (Fig. 5). This beneficial bunch shape does unfortunately not yet survive very long especially if the coupled-mode damping system2) is switched on. Local instabilities develop in the centre of the bunches and result in a redistributed stable bunch with the maximum phase space density in the centre, decreasing towards the edge (Fig. 5c). This instability is explained by the sign change in the bunched beam transfer function caused by the sign change in the slope of the radial density function in the longitudinal phase plane, which enters in the dispersion integral for this transfer function10).
- Deposition of an empty bucket in the centre of the injected beam prior to trapping was also tried. Although this worked at low intensity the method was not pursued because of its complexity and several intensity-related problems.

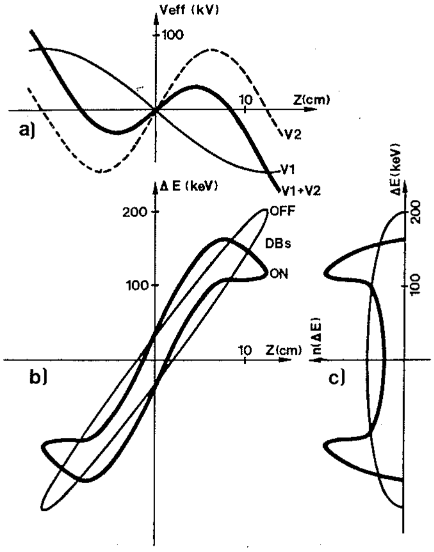
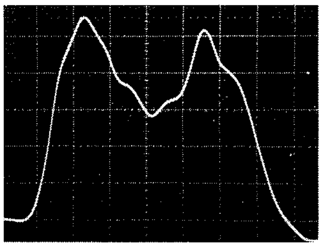
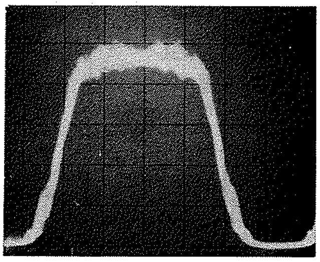


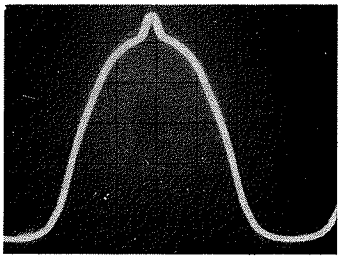
Fig. 4 - a) Effective debuncher voltage of fundamental (V1) and second harmonic (V2) debunchers, b) corresponding linac bunch shapes without (OFF) and with debunchers (ON), c) resulting energy distribution.



a) Energy distribution in PSB measured by the beam transfer function11); 62 keV/Div.



b) Bunch shape 5 ms after trapping; 50 ns/Div.



c) Bunch shape 500 ms after trapping; 50 ns/Div.

Fig. 5 - Tailored linac energy distribution and bunches at 50 MeV (N ∿ 5 × 10^{11} p).

5. SECOND-HARMONIC CAVITY

The potential well for various ratios of fundamental (V_5) and second-harmonic (V_{10}) gap voltages are shown in Fig. 6. If the corresponding buckets can be filled with an elliptic distribution8), then the bunches will have the same shape as the potential well resulting in an improvement of the bunching factor of up to 33%. Other benefits one can reasonably expect are (i) some increase in bucket area (∿ 15% for $V_{10}/V_5 = 0.5$) and (ii) a larger spread of synchrotron frequencies, which should improve stability at high intensities. In order to verify experimentally at least some of the above expectations, a test cavity was assembled by modifying an existing spare, and the necessary ancillaries put together from such equipment as was available (usable up to 200 MeV). It has been found possible to form and accelerate high-intensity bunches with shapes and change of bunching factors in good agreement with theoretical predictions (Fig. 7). An intensity increase of the trapped beam of some twenty percent was obtained (Table 4), attributed mainly to the decreased space-charge detuning.

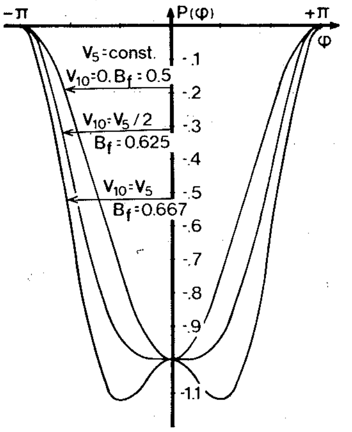


Fig. 6 - RF potential well and bunching factors B_f. 14)

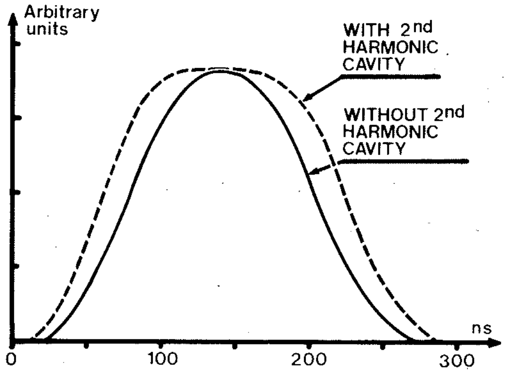


Fig. 7 - Observed bunch shapes

Table 4 - Typical intensities per pulse accelerated in ring 3 (in units of 10^{12} p).

RF voltage	Injection (50 MeV)	After capture	At 200 MeV
Fundamental (V_5) only	9.6	6.3	5.9
2nd-harmonic (V_{10}) added ($V_{10} = 0.5\ V_5$)	9.8	7.8	7.2

6. CONTROLLED INCREASE OF THE LONGITUDINAL EMITTANCE ε_L BEFORE TRANSFER TO THE PS

The following method for increasing ε_L from the nominal value of 8 mrad (in units of $\Delta(\beta\gamma)$ - rad) to about 15 mrad was explored. Towards the end of the acceleration the stable phase (∿ 5^o) is modulated by about ± 2^o at twice the central synchrotron frequency, thereby exciting selectively the coherent quadrupole mode ($n = 0$, $m = 2$). To increase the synchrotron frequency spread the RF voltage is lowered. Above 1.3×10^{13} ppp an octupole mode ($n = 0$, $m = 4$) develops which leads to about 10% of beam loss and a deformation of the bunch shape which makes efficient capture in the PS more difficult.

7. OUTLOOK ON FUTURE DEVELOPMENTS

Higher linac currents, tailoring of the linac beam energy distribution and a change of the working point (if decided) are planned for increasing further PSB intensity and improving emittance control. To exploit the full PSB potential a second-harmonic cavity system is planned and an increase of the transverse acceptance is being considered. The development of the beam observation equipment (Table 5) for use in normal operation is progressing. Within this perspective beams with an intensity of 3×10^{13} ppp or alternately present beams with adjustable density and lesser machine irradiation appear on the horizon.

Table 5 - Techniques used for the measurement of distributions in geometrical and phase space.

	Geometrical space (1)	Phase space (2)	Remarks
Transverse phase space	Secondary emission strip detectors in 800 MeV line	Measurement targets and Beamscope7)	(1) can be calculated from (2)
Longitudinal phase space, unbunched		50 MeV spectrometer Empty bucket scans12) Schottky scans + FFT13 Beam transfer function11)	Distrib. changed until PSB Strongly perturbed by space charge
Long. bunched	Wide-band pick-up station		Connected to fast digitizer

ACKNOWLEDGEMENTS

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DISCUSSION

I.A. SHUKEILO (Leningrad): I would like to mention that the idea of adding the second harmonic in an RF accelerating field for increasing the longitudinal acceptance and the intensity of a proton synchrotron was proposed earlier by L.Z. Barabash, L. Goldin et al. in ITEP (Moscow). The theory and experimental results have been published in the Proceedings of All Union Conference on charged particle accelerators held in Moscow in 1968 [added *a posteriori* to list of references of the above paper by the authors].