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PROGRESS IN SPACE-CHARGE LIMITED MACHINES: FOUR TIMES THE DESIGN INTENSITY IN THE CERN PROTON SYNCHROTRON BOOSTER

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Abstract

Starting from rather modest performances, the CERN Proton Synchrotron Booster has now reached its sum-of-four-rings design intensity of 10^{13} protons per pulse in each ring, featuring the outstanding maximum space-charge tune shift of 0.6 units. The latter requires dynamic compensation of half and (even systematic) third integer stopbands. More measures were introduced to push the intensity ceiling higher: careful choice of working area, controlled linear coupling to enhance injection efficiency and to fill the full aperture with a better-suited transverse charge distribution; bunch shaping by addition of a second-harmonic RF system, beam loading compensated by fast feedback; RF feedforward in the fundamental cavities; feedback systems taming longitudinal coupled-bunch instabilities, and transverse wide-band dampers replacing octupoles previously used. The article reviews these techniques as well as some of the Booster's unique beam diagnostics, crucial to the achievement of these performances.

Increasing the Space-Charge Limit

Space charge remains the ultimate limit to intensity in all machines accelerating ions injected at energies below, say, 1 GeV. In this sense the expression for space-charge detuning, essentially due to Laslett [1] but cast in a more appropriate form, is fundamental to all attempts to push the intensity of such a machine:

$$\Delta Q_y = (N r_p / \pi B_f \epsilon_y \beta^2 \gamma^3)\, F_y G H_y\,, \qquad (1)$$

where

- B_f is the bunching factor < 1, average/peak density,
- ϵ_y is the physical emittance in the y-plane,
- F_y corrects for image forces, ≈ 1 [1, 2],
- G is the form factor > 1 accounting for transverse density distribution; $G = 1$ for uniform density in the x-y plane;
- $H_y = \langle [1 + \sqrt{[\epsilon_x\beta_x + D(\Delta p/p)]/\sqrt{(\epsilon_y\beta_y)}}]^{-1}\rangle < 1$ represents the aspect ratio of the beam averaged ($\langle\ \rangle$) over a superperiod.

In smooth approximation and with $\Delta p/p = 0$,

$$\bar{H}_y = [1 + \sqrt{(\epsilon_x/\epsilon_y)}\sqrt{(Q_y/Q_x)}]^{-1} \quad \text{and} \quad \bar{H}_x + \bar{H}_y = 1.$$

In order to maximize the number N of protons per pulse, one may 'work' on almost all factors. This is exactly what has been done in the CERN Proton Synchrotron Booster (PSB): only β,γ (the injection energy of 50 MeV) and $F_{x,y}$ (vacuum chamber and magnet poles) have remained unchanged since the PSB came into operation in 1972. Figure 1 displays the various improvements and the resulting intensity gain. One may notice that, in general, measures affecting the space-charge limit alternate with the introduction of some stabilizing feedback system, reflecting the well-known fact that after every breakthrough in intensity, more instabilities crop up and wait to be tamed.

Improvements Directly Raising the Space-Charge limit

Measures taken are presented in chronological order; the factors of Eq. (1) which are specifically influenced are quoted in parenthesis.

Working region (ΔQ, $H_{x,y}$): Under the influence of space charge the beam occupies a 'necktie'-shaped area (Fig. 2) in the Q_x,Q_y plane [3]. Consequently, less stopbands intersect with this shape in the lower left-hand corner of a quadrant than around the design working point in the upper right-hand quadrant ($Q_{x,y} \approx 4.8, 4.8$). As was found in a later study [4] the particular quadrant chosen ($Q_{x,y} \approx 4.2, 5.3$) coincides with the minimum of H_y for the PSB lattice, thus reducing the more critical ΔQ_y.

Dynamic working point (ΔQ): In the absence of blow-up, the Laslett tune shift decreases with $(\beta\gamma^2)^{-1}$. This suggests that the bare (zero intensity) working point should be moved so that stopbands that are unavoidable at low energy are no longer crossed once the 'necktie' has sufficiently shrunk with increased energy. Figure 2 illustrates the trajectory of the working point as it is programmed in the PSB.

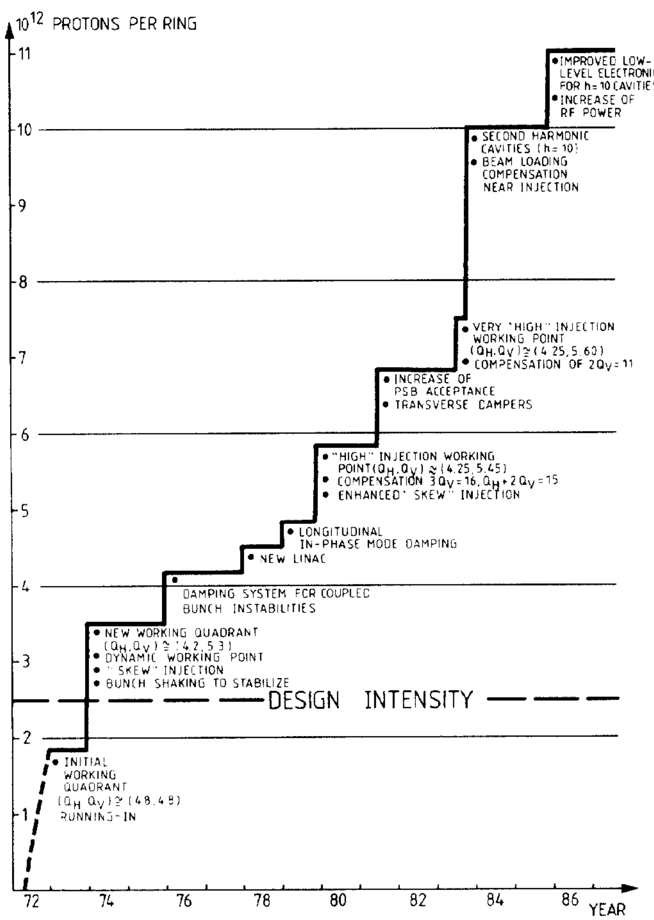

Fig. 1 CERN PS Booster: peak accelerated intensity, best ring.

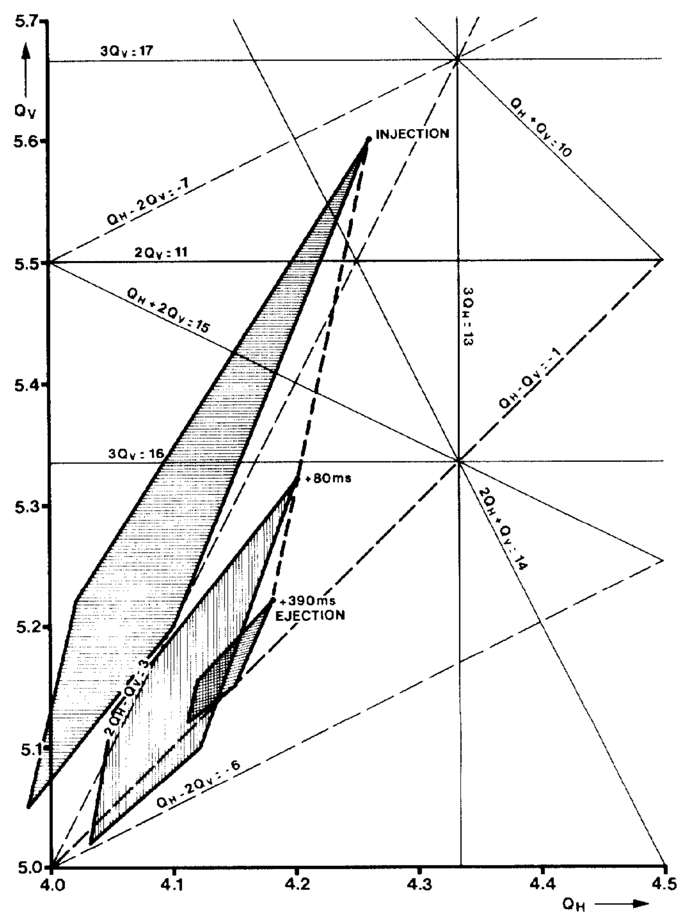

Fig. 2 Dynamic working point and occupied tune areas in the PSB (1×10^{13} protons per ring).

unstable owing to local loss of Landau damping at the maximum of the hollow distribution mentioned. Some concepts of the beam control system had to be modified, e.g. the control of relative phase of the h = 10 cavity proved to be more effective when beam-derived from a pick-up rather than from the fundamental gap. Nevertheless a *modus operandi* has been developed and the system is now indispensable for the highest intensities per ring required for antiproton production.

Instabilities and their Cures

Longitudinal instabilities were the first to prove troublesome once the PSB had its intensity boost due to the new working region. In retrospect it may be interesting to note that in the beginning they were not clearly identified [9] as the *coupled-bunch modes* they actually were. Careful studies eventually led to the development of a feedback system [10, 11], operating on the sidebands of the sixth and seventh harmonic of the revolution frequency. Given five bunches, this covers all but the in-phase modes (the phase loop takes care of the dipole in-phase mode, whereas a loop to damp the *quadrupole in-phase mode* had to be added later). Although the bandwidth of 15 kHz covers all up to octupole modes, only dipole and quadrupole modes are efficiently damped, as higher ones have insufficient spectral power at the revolution harmonics 6 and 7. Growth and occurrence of these modes suggest impedance peaks of a couple of hundred ohms around 9 MHz and 14 MHz, respectively. Ejection kickers plus their cables can well exhibit these impedance peaks, but calculations predict values of less than 100 Ω [12]. The damper is indispensable for acceleration of more than 2.5×10^{12} protons per ring and has stimulated the development of a number of similar systems in other machines.

Beam-loading instabilities. No provisions for any feedback were made for the fundamental RF system, which inevitably led to problems at capture of beams containing more than 6×10^{12} protons per ring. A fairly simple fixed-frequency feedforward device that is active only during capture and at the ejection flat top [13] greatly improved the stability. A fast feedback around the final stage of the amplifiers integrated in the design of the second-harmonic cavities [8] prevented any visible beam-loading effect in them.

Transverse instabilities have never constituted a major problem. With increasing intensity the same octupole excitation programme provided sufficient Landau damping to keep the beam stable, as any intensity gain is accompanied by emittance increase and more (space-charge and external) tune spread. Nevertheless (mainly to get rid of octupoles) a Transverse Feedback System has been built. After an unsatisfactory attempt with a simple resistive-wall damper, a conventional wide-band feedback with switched delay [14], filters with a 3 dB bandwidth of 13 MHz, and closed-orbit signal suppressor eventually replaced the octupoles. Surprisingly enough, intensity increased by 2–3% and the vertical emittance at the end of the cycle diminished by 10–15% with beneficial effect for PS injection. Detailed study with BEAMSCOPE revealed a short burst of horizontal instability in the middle of the cycle emitting only weak coherent signals. The horizontally grown amplitudes were apparently transferred to the vertical plane by coupling. In normal operation, only horizontal feedback is needed—space-charge non-linearity suffices to Landau-damp the vertical head-tail instability. However, on a working point approaching an integer from below, such as $Q_V = 4.9$, full power is required to beat the high resistive-wall impedance of the lowest-frequency line. Resistive-wall impedance normalized to 1 MHz is 21 kΩ/m (horizontal) and 74 kΩ/m (vertical), scaling 1/f below 2.4 MHz. In the horizontal plane, one has to add the kicker impedance—irregularly distributed peaks between 5 and 20 MHz and up to 100 kΩ/m high.

Diagnostic Equipment particular to the PS Booster

Two rather unique computerized devices proved to be highly useful both in routine operation and in the machine development leading to today's performance. BEAMSCOPE [15] is the instrument for (partially destructive) fast-emittance measurement as well as for the display of betatron amplitude distributions at any moment in the acceleration cycle. Its advantage over profile detectors is that it immediately produces an amplitude distribution as opposed to the projected density (which necessitates an Abel transform). Figure 4 is an example of a display option.

Longitudinal phase-space information is provided by the other instrument [16]. A fast digitizer records the bunch shape, and all parameters required to reconstruct and display bucket and bunch (see Fig. 5) in phase space are acquired. A sophisticated computer code includes space-charge forces and computes bunch and bucket areas, bunch length, bunching factor, peak current, etc.

Performance and Losses

Top intensities in one ring together with integrated losses are displayed in the following table.

Distribution of losses in high-intensity operation

Process	One ring	Total for four rings			
	Surviving p's per pulse and ring in 10^{13} protons	Incoming protons per year ($\times 10^{20}$)	Fraction lost		
			No. of protons (%)	At energy (MeV)	Energy deposit (%)
Injection line	2.39				
Multiturn injection	1.46	2.6	42	50	37
RF trapping	1.23	1.5	17	50	9
Transverse losses		1.2	12	70	7
Acceleration	1.1				
Ejection	1.0	1.1	8	815	47
		Total	61		100

The number of protons is to be compared with the design figure: 2.5×10^{12} protons per ring at the PS entrance.

Despite the large fraction of particles lost at low energies, this accounts for only half the energy deposited. In principle, all particles lost below 70 MeV should be stopped in the injection septum or in the BEAMSCOPE aperture, the 'loss concentrator'. This renders these losses acceptable.

Problems and Potential Improvements

A challenging problem arises in Ring 4 (only!): Beyond a threshold around 6×10^{12} protons per pulse, an instability occurs fairly regularly when the frequency of the main RF system reaches 7.7 MHz (at 600 MeV). Suddenly all bunches develop tails that undergo in-phase dipole motion at the local synchrotron frequency of the bunch edge. Eventually these tails produce a bunch with pedestals, and a few percent of the particles are spilled out of the bucket and lost. The bulk of the bunch is virtually unaffected. When the tails appear, revolution harmonics around 1 GHz appear and persist for a few milliseconds. The underlying mechanism of this instability is still unknown.

Improvements envisaged consist in increasing the top energy to 1 GeV in order to raise the space-charge limit of the PS and to make full use of the recombination (of beams from a pair of PSB rings) by an RF dipole [17], inefficient at 815 MeV. Acceleration to 1 GeV in the PSB and transfer of all four rings implies raising some kicker voltages, a development that is under way.

Implementation of a fast RF feedback around the power stage of the main RF is being studied. Developments towards very low intensities (acceleration of ions) are reported elsewhere in these Proceedings [18].

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Stopband compensation to accommodate $\Delta Q_y \approx 0.6$: The working area chosen (Fig. 2), with the advantages mentioned above, also suffers from a serious drawback: it is crossed by the structural third-order resonance $3Q_y = 16$ (16 = number of lattice cells). In fact, three third-order stopbands have to be compensated until the working point can be moved below $Q_y = 5.33$. A 'universal' stopband-correction scheme of multipole stacks [5] was installed, but finding the optimum correction programmes for the (all different) four rings proved labourious. In fact, the finally achieved 'dynamic compensation chart' (Fig. 3) appears to be valid only for a beam with large amplitudes and became effective after systematic 'aperture filling', eventually opening the Q-space up to 5.5. All these difficulties—not yet completely understood—seem to be peculiar to a structural resonance and have not been observed on, say, $3Q_y = 14$.

Compensating two skew sextupole stopbands simultaneously requires the programming of two families of correction lenses [5, 6].

Compensation of $2Q_y = 11$ proved comparatively straightforward. Static compensation of these stopbands (typical width ≈ 0.003) increases the intensity by about 10%. Figure 4 displays vertical amplitude distributions, measured after resonance crossing is over, and exhibits the depletion due to the uncompensated stopband; only medium and large amplitudes are affected.

Filling the aperture (ϵ_y, G): The obvious way to raise the intensity limit is to increase the beam dimension so that it almost fills the vacuum chamber. In the PSB this is achieved by some mis-steering plus excitation of the linear coupling resonance $Q_x - Q_y = -1$. Thus the energy from the radial plane is transferred to the vertical plane, helping i) to increase the injection efficiency because more particles avoid the injection septum [7], and ii) to create a vertical amplitude distribution wherein large amplitudes dominate. There is evidence that blow-up at the integer resonance $Q_y = 5$ participates in this process, as the vertical emittance of the accelerated beam 'adjusts itself' to the intensity and the available $\Delta Q_y \approx 0.6$. As expected, the intensity ceiling corresponds to a nearly filled machine acceptance.

Yet two beams of equal emittances may have different intensities: the clue lies in the form factor $G > 1$, which describes essentially the ratio of the (two-dimensional) charge density in the beam centre to the average one. Note that its definition is related to that of the emittance in Eq. (1)—only the ratio G/ϵ matters.

With measurable emittances defined as enclosing 95% of the particles, G assumes the values 0.95 and 1.55 (1 and 2 for emittances enclosing 100%) for the uniform and the parabolic beam, respectively. A few years ago, a thorough study was undertaken [4] to measure the form factors G achievable with mis-steering, enhanced linear coupling, and combinations of both. Two-dimensional amplitude distributions after injection and capture were determined by combining BEAMSCOPE*) (see below) measurements and flipping-target interceptions. For optimized injection and filling procedure, G-factors of 1.3 or slightly less are typical. Unoptimized filling results in $G \approx 1.5$–1.7, comparable to that of a parabolic beam. In this context one can give arguments to explain why the PSB is one of the last machines not converted to H^- injection: even with sophisticated filling strategies ('painting'), form factors of 1.1–1.15 are the best one may hope for. Profiting from a sufficiently high linac current ($\approx$ 140 mA) and the low injection energy of 50 MeV, limiting the damage due to multiturn injection losses, there is no immediate justification for the costly replacement of multiturn equipment, which, by the way, is indispensible for the injection of ions other than protons.

In order to use the full chamber aperture the dedicated collimator was opened up. It serves both as loss concentrator at low energies and as precision aperture for BEAMSCOPE emittance measurements. This increase of the vertical acceptance by about 20% (now $\gtrsim 100\pi$ mm•mrad) was complemented by modification of the geometry and optics in the transfer line to the PS. The enlarged aperture yielded about 15% more intensity.

Flat bunches with second-harmonic cavity (B_f): There were two ideas for improving bunching factor B_f already contemplated in 1980 (see Ref. [4]): i) by creating a hollow (double-peaked) momentum distribution of the linac beam which, after adiabatic capture, would end up as a bunch, hollow in RF phase space and with a flat projection onto the time axis. Although the basic reasoning proved correct, insurmountable instability problems with the hollow distribution resulted in this idea being abandoned. ii) The other idea was to add a second-harmonic (h = 10) RF system to the fundamental (h = 5) 3-8 MHz, one. By appropriate control of voltage ratio and relative phase between the two cavities, one can create a flat bottom in the RF potential well, resulting in flattened bucket and bunch shapes. This effect is clearly visible in Fig. 5 representing a high-intensity bunch in its bucket, reconstructed from the measured line density (bunch shape). On top of the increase of the bunching factor B_f of about 30% to reach almost 0.6 after capture, it provides a comparable gain in the longitudinal acceptance—a very welcome effect, as the available 13 kV of the fundamental cavities is somewhat underrated for today's intensities. The impact of the more favourable bunch shape is immediate: the intensity ceiling of a well-optimized beam rises by 25-30% when the h = 10 system is switched on. Its running-in after installation in 1982 [8] turned out to be tricky. One reason put forward is the 'hollow' distribution of synchrotron frequencies (zero for vanishing phase amplitude) which renders the sextupole and decapole in-phase modes

*) BEtatron AMplitude Scraping by Closed-Orbit PErturbation.

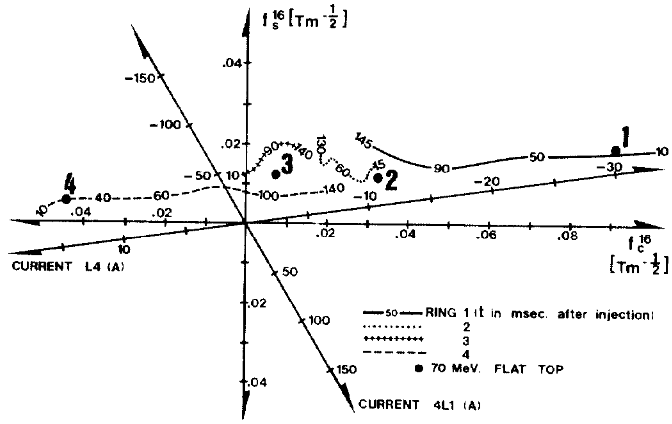

Fig. 3 Strength and phase of $3Q_y = 16$ during the first part of the cycle, derived from compensation settings.

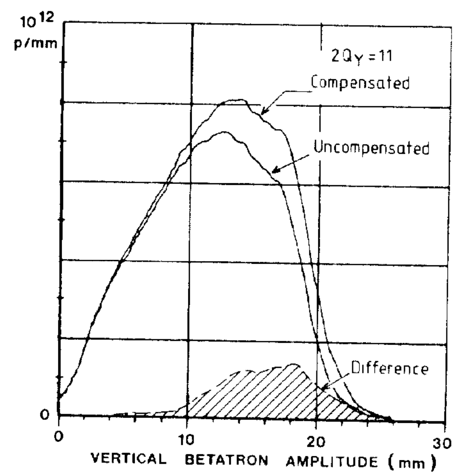

Fig. 4 BEAMSCOPE profiles showing loss of larger vertical amplitudes on $2Q_y = 11$.

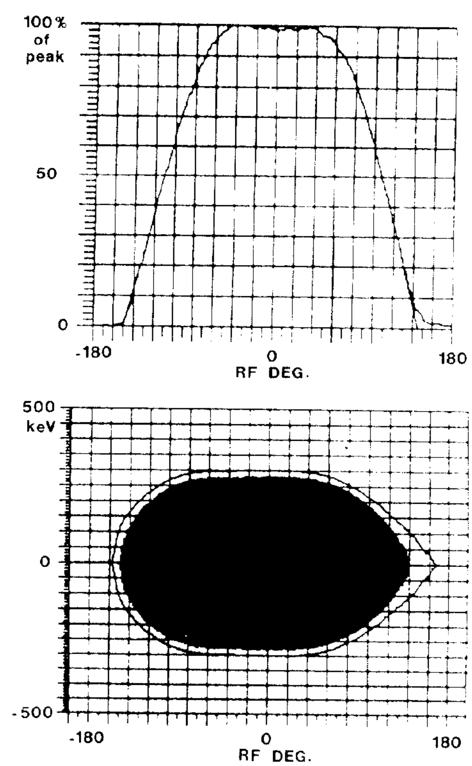

Fig. 5 Flat-topped bunch in RF bucket (below), reconstructed from line density (above), 10^{13} protons per ring, after trapping.