UPGRADING THE CERN PS BOOSTER TO 1 GeV FOR IMPROVED ANTIPROTON PRODUCTION

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Abstract

For efficient antiproton production, a maximum number of protons has to be concentrated within one quarter of the CERN Proton Synchrotron (PS) ring before sending the beam to the production target. Now, with the Antiproton Collector (AC) added to the Antiproton Accumulator (AA), the bunch length has to be shorter (about 20 ns) than before in order to allow bunch rotation in the AC. Whilst a more ambitious scheme providing such a beam is being implemented, a funnelling method—where beams of two rings out of the four-ring Proton Synchrotron Booster (PSB) are recombined in pairs by means of an RF dipole that permits longitudinal interleaving of successive bunches—is in operation since the start-up of the AC. Preliminary experiments had shown that the PS space-charge limit had to be overcome in order to make the scheme feasible. Indeed, after raising the PSB output energy from 815 MeV to 1 GeV—with a rather modest effort—beams of > 10^{13} protons squeezed into one quarter of the PS ring were achieved. As a spin-off of this development, a new record proton beam for fixed-target physics was accelerated in the Super Proton Synchrotron (SPS), while beam losses in the PSB–PS line were reduced. Here we deal with this upgrading, give a short summary of past, present, and future $\bar{p}$ production beams in CERN, and discuss some trickier beam dynamics aspects of the very particular one obtained by funnelling.

1. Introduction

Antiprotons are produced by an intense beam of protons focused onto a copper target at 26 GeV/c. In order to match the circumference of the AC [1], the production beam must occupy, prior to ejection, one quarter of the PS. Contrary to the requirement of the 'pre-AC' production beam, the proton bunches have to be short (~ 15 ns) so as to profit fully from the AC debuncher cavities, which turn the short, fat (large momentum spread) $\bar{p}$ bunches emerging from the target, into long, thin bunches. Three ways of achieving such production beams have been used: i) five bunches, from one PSB ring, fill five PS buckets; ii) ten bunches, from two PSB rings, are accommodated, in pairs, in five PS buckets after funnelling them by means of a vertical RF dipole [2]; iii) ten bunches, from two PSB rings, are accelerated in the PS and squeezed into five buckets by quasi-adiabatic RF manipulations at 3.5 GeV/c (merging) and 26 GeV/c (compression) [3]. Raising the PSB output energy [4, 5] proves beneficial for all schemes, in particular for the funnelling method (ii) on which this paper focuses.

2. Why Increase the PSB Energy to 1 GeV?

Raising the beam kinetic energy at injection leads to a reduction of the transverse incoherent tune shifts by a factor proportional to $1/\beta\gamma^2$, and to a reduction of the beam transverse dimensions by a factor proportional to $1/\beta\gamma$, where β and γ are the usual relativistic parameters. From 815 MeV to 1 GeV these two reduction factors are 1.27 and 1.15, respectively.

Figure 1 shows the area occupied by the beam in a ΔQ_h, ΔQ_v diagram for both energies. A smaller area allows the machine to be tuned away from strong resonances and results in reduced beam losses. In addition, smaller transverse beam dimensions provide more clearance in transfer lines and machine acceptance.

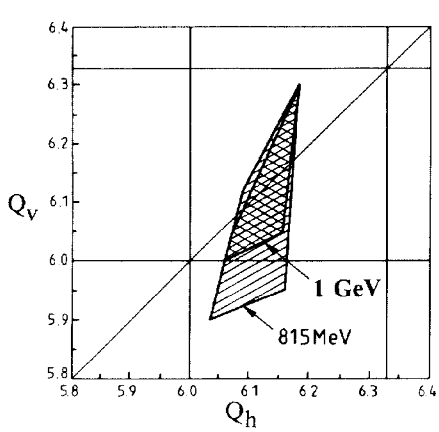

Fig. 1: Incoherent tune shifts of a beam of 2 × 10^{12} p per bunch at 815 MeV and 1 GeV. The area shown includes the effects of space-charge self-fields and images, of betatron amplitudes, and of synchrotron motion.

3. Hardware

No modifications in the beam-control and cavity-tuning equipment were needed to increase the maximum acceleration RF by 3.5%.

The necessary increase (14.5%) of the magnetic rigidity of the ring and the transfer line was acceptable for most of the magnets and their supplies. The peak field level of the main dipoles in the PSB was increased from 0.59 to 0.69 T—still a very comfortable figure far below magnet saturation, and readily attainable by the static main power converter. Upgrading was, however, needed for the following:

i) Septum magnets, involving upgrading of the water-cooling system now supplied with desoxygenized water at elevated pressure to avoid sedimentation in the coils.
ii) Kicker magnets, whose pulse generators had to be modified for higher voltage output, including new coaxially mounted thyratron switch units, HT feedthroughs and coaxial cable connectors; adaptation of the spark gaps terminating the pulse-forming network line, and new ceramic vacuum feedthroughs for the magnets.
iii) Reduction of the pole gap, from 140 to 110 mm, of a big steering magnet, approaching saturation in the emittance measurement and dump line.

Finally, a fair amount of improvements were made and consolidation work was carried out for the low-level electronics equipment of various supplies and of beam observation instrumentation.

4. PS Beam Behaviour and Performance in Standard (20-bunch) Operation

With the new injection energy, and for the standard 20-bunch operation for fixed-target physics, the previous record high-intensity beam of 2.2 × 10^{13} protons has been regularly produced and a peak value of 2.34 × 10^{13} has been achieved.

5. Beam Behaviour and Performances in 'Funnelling' (RF Dipole) Operation

5.1 Funnelling

As each PSB bunch is slightly less than 180° long, two of them fit into a stationary PS bucket. A square-wave vertical deflector, operating at the common PSB-PS RF frequency (~ 8 MHz), would be required to steer each bunch vertically on an ideal orbit. The actual resonant sine-wave deflector leads to unavoidable over- and under-deflection, which results in vertical mis-steering as illustrated in Fig. 2

Fig. 2: Sum (left) and vertical (right) difference signals of a beam position monitor of the recombined beam. On the sum signal, bunches 1, 3, 5, 7, 9 stem from PSB ring 3, bunches 2, 4, 6, 8, and 10 from ring 2. A mis-steering of ~ 5 mm, inherent to sine-wave deflection, is seen on the difference signal.

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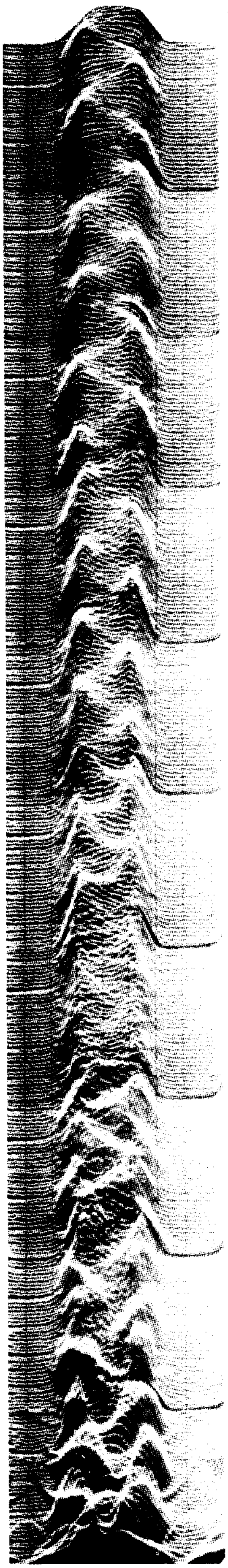

Fig. 3: Mountain-range display of the first 10 ms of merging in the PS of two bunches from the PSB. Horizontal sweep, 20 ns/division. Only every tenth turn is displayed. The time goes from bottom to top.

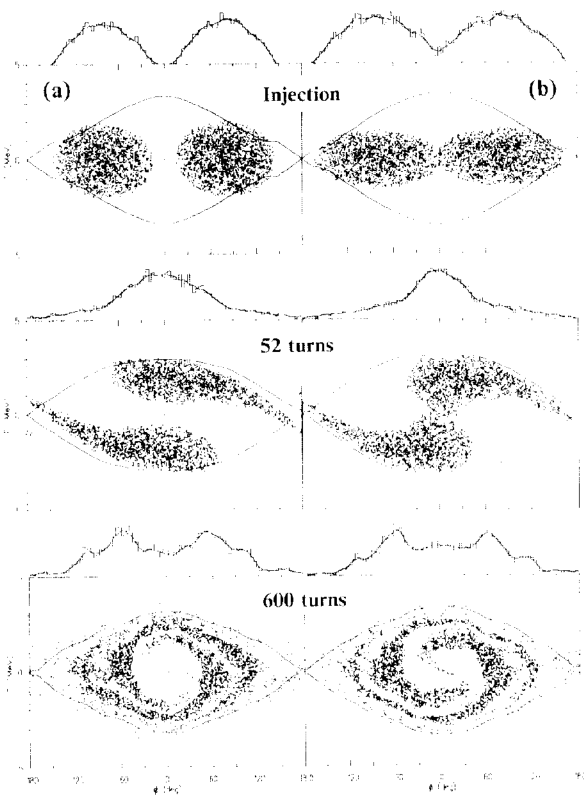

Fig. 4: Longitudinal phase-space plots produced with ACCSIM for optimized (a) and older (b) PSB RF parameters. Although projected line densities are normalized to the same height, the more peaked bunch in (b) can easily be recognized after a quarter synchrotron period (52 turns), causing stronger local space-charge shifts. Filamentation begins at 100 turns and fills buckets a few 100 turns later.

(± 5 mm on a vertical position detector). In this way the vertical emittance (about 15π mm·mrad) is blown up by a factor of > 1.5. The optics has to be changed to cope with the modified aspect ratio. With a vertical PS acceptance of 30π mm·mrad, one would not expect beam losses at injection: the observed beam loss of a few per cent has still to be elucidated.

5.2 Capture in the PS

The 10 bunches coming from the PSB are captured (Fig.3) in 5 out of the 20 PS buckets, leading to the required filling of 1/4 of the PS circumference. Longitudinal matching in such conditions is impossible. As can be seen in the simulation plot (Fig. 4), two bunches end up by filling all the bucket area. The RF voltage is a compromise between a high value required for a good trapping efficiency, and a low value to keep the mismatch and ensuing line density peaks within limits. The best operational performance is obtained by increasing the RF voltage linearly from 49 kV to 85 kV in 5 ms (Fig. 5).

Similarly, a bunch spacing of 160 RF degrees has been found to be the optimum between vertical oscillations and longitudinal trapping efficiency.

Starting from Booster bunches of 0.12 eV emittance, a stable 0.4 eV bunch is obtained, after merging and longitudinally controlled dilution, at the end of the 1 GeV flat bottom (Figs. 6b).

Strong microwave signals are observed about 1 ms after injection (see Fig. 5 and the fine structure in Fig. 6c). These are attributed to microwave instabilities induced by dense filaments developing in the merging process (visible in the simulation, Fig. 4). Such instabilities account for 1% out of the approximately 10% beam losses observed throughout acceleration (Fig. 7).

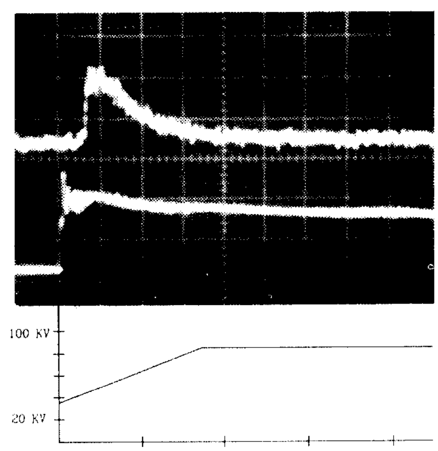

Fig. 5: Top trace: Amplitude of 1.4 GHz component of the longitudinal wide-band PU signal showing the onset of microwave instabilities 1 ms after injection. Bottom trace: Peak-detected signal of the same PU, representing peak line density. The trapping RF voltage program on the same time-scale (2 ms/div.) is plotted below.

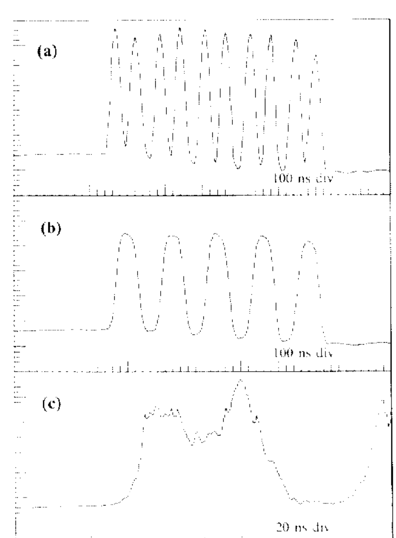

Fig. 6: PS bunches a) right after injection, b) at the end of the 1 GeV flat bottom; c) zoom on one bunch during microwave instability, 1 ms after injection.

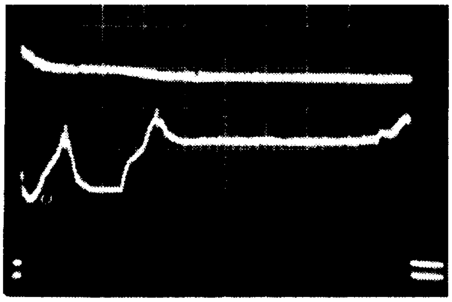

Fig. 7: Beam current (top) and peak-detected wide-band PU for the entire acceleration cycle (100 ms/div.). First loss during and after merging, a few % loss at transition (second peak in bottom trace).

Losses were further reduced when shortening the PSB bunches that were to be recombined (by increasing the RF focusing with $h = 10$ cavities), because i) shorter bunches lead to somewhat less mis-steering with the sine-wave deflection; ii) after a quarter synchrotron period, short bunches turn and become long.

Short bunches are advantageous because the intensity is limited by the amount of space-charge tune-shift fitting between integer and loss-inducing third-order resonances. Consequently, local peak linear density has to be kept as low as possible. The latter is worst when, after a quarter synchrotron period, the two bunches are one on top of the other. The shorter (and taller) the injected bunches, the flatter they will be after the quarter synchotron turn, and consequently their projected density will also be flatter. However, the gain is limited because the unavoidably increased bunch height trespasses on the bucket limits.

5.3 Simulation results

In order to have a better insight into the capture process in the PS, the six-dimensional ACCSIM code [6, 7] was used to simulate various operation modes. The phase-space plots (Fig. 4) for the initial and the improved operation clearly show how shorter PSB bunches (a) lead to a less pronounced projected line density after a quarter synchrotron turn. The Laslett tune shift computed by ACCSIM has indeed improved by 30%. However, the limited resolution of the code does not allow simulation of the microwave instability. Also, the asymmetric bunch shape occurring after about 200 turns is possibly caused by transient beam loading and is thus beyond the scope of the code. For this reason, the simulation was not extended to more than a few hundred turns.

6. Outlook

After about one year of 1 GeV operation, all equipment is still performing reliably, no signs of degradation have been observed and 1 GeV has now become the nominal energy of the PSB.

Schemes for the $\bar{p}$ production beams for the AC/AA, the ways in which they work, and performance figures, are given in the table. At present, method 3 gives the best performance in terms of p on target (50% over method 2), but the gain in $\bar{p}$ for AA is only 10% because of uncomfortably long bunches. Large longitudinal emittances are needed to stabilize the beam against longitudinal instabilities. Its ultimate limit is estimated at 1.7×10^{13} p on the target. Method 4, combining schemes 2 and 3, uses all four PSB rings and may reach 2×10^{13} p. (In this scheme, the RF dipole would recombine bunches from ring 3 with those of ring 2, and bunches of ring 4 with those of ring 1.) It is still not known whether, in this scenario, the PS injection losses can be kept below 2×10^{12} per pulse—a self-imposed limitation intended to keep machine irradiation manageable.

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Antiproton production beams for the Antiproton Accumulator Complex

	Method	Intensity limitation	No. of PSB rings	PSB energy	PSB output intensity	PS accelerated intensity		Comments
						Achieved	Ult. limit	
1	Acceleration of a single PSB ring	PSB at 50 MeV	1	815 MeV 1 GeV	9×10^{12} 9×10^{12}	7.5×10^{12} 8×10^{12}	7.5×10^{12} 8.5×10^{12}	Not used, for comparison only. Used in 1987.
2	Two rings (10 bunches) recombined in the PSB–PS line by an RF dipole (funnelling) into five PS buckets	Losses at PS injection (vert. beam size)	2	815 MeV 1 GeV	9×10^{12} 1.25×10^{13}	7.5×10^{12} 1.05×10^{13}	7.5×10^{12} 1.1×10^{13}	Not used. Used Nov. 1987 to Oct. 1988.
3	Two rings (10 bunches) merged into five buckets by quasi-adiabatic RF manipulations at 3.5 GeV/c (merging of pairs of bunches) at 26 GeV/c (stepwise increase of harmonic number)	Losses at PS injection and transition energy	2	1 GeV	1.75×10^{13}	1.55×10^{13}	1.7×10^{13}	Used since Nov. 1988 and will be used in 1989.
4	Possible future development: Four rings (20 bunches) inserted into ten PS buckets by funnelling, followed by the merging process of method 3	Presumably injection and low-energy losses in the PS	4	1 GeV	2.2×10^{13}	–	2×10^{13}	Would require extensive machine studies, not foreseen before 1990.