THE CERN PS BOOSTER, A FLEXIBLE AND RELIABLE INJECTOR

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Summary and introduction
Working point, injection, closed orbit, transverse instabilities
Synchronisation, ejection, recombination, transfer
Operation statistics, reliability
Conclusions and outlook
Acknowledgements
References
Figures

*) A condensed version of this report is to be presented at the V All-Union National Conference on Particle Accelerators, Dubna, 5-7 October '76.
Summary and introduction

In 1976 the PS Booster (PSB), a slow-cycling four-ring 800 MeV synchrotron, operates full-time and reliably as injector for the CERN proton synchrotron (CPS). Running in had started in mid 1972 but, due to restricted resources, full service was delayed. In 1975, 4'500 h of injector operation were logged, with a peak operational intensity of $1.3 \times 10^{13}$ ppp, and an average down time of about 1.5%. A wide-ranging programme of modifications and improvements meets increased and new needs of the CPS users.

As the earlier developments are well documented\textsuperscript{1) this report describes the most recent work in the areas of transverse and longitudinal phase space as well as in PSB operation, and outlines some possible future developments.

Working point, injection, closed orbit, transverse instabilities

Good experience continues to be made with separating $Q_H$ and $Q_V$ by an integer, thus avoiding the strong 4th order coupling resonance $2Q_H - 2Q_V = 0$. Operating just above an integer\textsuperscript{2) reduces the e-folding rate of transverse instabilities.

Powering extra windings on the main PSB quadrupoles allows since 1975 to reach the shaded area of Fig. 1, previously inaccessible because of the current threshold of the main $Q$-tuning supplies. Starting the cycle with the working point at B, (i) skew (coupled) injection is possible, giving some 15% increase in beam intensity, and (ii) the horizontal emittance at highest intensities does not suffer the substantial increase observed with the working point at A, which is caused by repeated entering into the $Q_H = 4$ stopband due to a combination of Laslett $Q$-shifts and synchrotron motion. Moving the working point to C during acceleration gives the smallest subsequent blow-up (about equal distances from the various stopbands, taking into account the diminishing Laslett $Q$-shifts).
A further ninety-six normal and skew correcting sextupoles and octupoles (Fig. 4) are now operational\(^3\). Attempts to compensate the systematic resonance \(3Q_V = 16\) gave already encouraging results\(^4\). This may open up the possibility of putting the working point well above this line (just below \(Q_V = 5.5\)) and so to reach the highest intensities within acceptable emittances\(^5\), once the new 50 MeV linac is operational (in 1978).

The beam distributor in the injection line (which distributes the linac beam in sequence to the four PSB levels) was replaced by a faster version (rise time 80 ns, present pulse duration 100 \(\mu\)s, flatness \(\pm 0.5\%\)) which is also easier to service\(^6\). By varying the trigger time, one can inject from one half to fifteen turns (and potentially more with the new linac) into each PSB ring, the (fractional) number being changeable from pulse to pulse. Half-turn injection is designed for orbit measurements at injection, two to fifteen turns for operation with the intensity desired. To enable one to steer the beam more precisely into the PSB, and possibly to go to closed-loop drift control, magnetic beam position monitors are being installed in the injection line\(^7\).

As multturn-injection is (i) the main cause of proton loss (Fig. 2), (ii) the standard mechanism for intensity modulation and (iii) rather sensitive to variation of parameters and jitter of the linac beam, its understanding was further refined both theoretically and experimentally\(^8\). In particular, the mechanism of injecting with increased efficiency onto the line \(Q_V - Q_H = 1\) and its dependence on injection parameters, \(Q\)-values, strength and phase of the first harmonic quadrupoles have become clear\(^9\).

Closed orbit distortions were initially quite small: 1.5 mm peak in the horizontal and 2.5 mm in the vertical plane. Over the years, and despite several realignments, the peak values increased to 6 and 3 mm, respectively. Although such distortions are quite tolerable from the acceptance point of view, there was interest to reduce them because of their interaction with the multipole fields. The closed orbits were carefully analysed\(^10\) and some
quadrupole stacks displaced accordingly. As a consequence the distortions diminished in quantitative agreement with the predictions. Peak values are now 3 and 2 mm, respectively.

With the present working point, transverse resistive-wall instabilities occur only sporadically. To ensure operational stability, a zero harmonic octupole field, increasing from 95 T/m\(^2\) at 50 MeV to 450 T/m\(^2\) at 800 MeV, is applied. Octupoles, even of this rather modest strength, may perturb the planned stopband compensation and one would prefer to avoid them. An active damping system is therefore being developed. A relatively straightforward arrangement, with a beam position detector and a deflector located a quarter betatron wavelength apart, should cope with head-tail modes \(m < 3\) \(^{11}\) throughout the cycle. The closed-loop transfer function is designed to model the natural resistive wall impedance in a frequency range from 30 kHz to 8 MHz and to fall off steeply beyond \(^{12}\). The value of 8 MHz corresponds to the maximum distance between two spectral lines of a mode, i.e. the feedback loop acts strongly on at least two lines.

**RF trapping, acceleration, longitudinal instabilities**

The evolution of the beam intensity from the linac to the CPS is shown in Fig. 2. In operation, adiabatic trapping efficiency at high intensity is so far limited to about 80%. Higher efficiencies require a smaller linac beam energy spread than the ± 150 keV used at present. This is readily available but leads to unacceptable bunch-shape oscillations and potential instabilities \(^{2}\).

Longitudinal instabilities are at present cured by modulating the RF frequency with a fixed frequency signal (near 4.2 kHz). As the synchrotron frequency (5 to 2 kHz) sweeps through the "shaking" frequency, particles are rearranged within the bunch, and the peak density lowered by about one third. Settings are rather critical at high intensity and the "shaking" may result in five to ten percent losses along the cycle.
After many theoretical and experimental studies, a feedback damping system is therefore being brought into operation\textsuperscript{13}). Bunch signals are analyzed\textsuperscript{14}), the troublesome dipole, quadrupole and sextupole modes selected, and the amplified damping signals applied to the RF accelerating system on the respective sidebands of the sixth and seventh harmonics of the revolution frequency. (The RF cavity is tuned to $h = 5$, but has still sufficient impedance at $h = 6$ and even $h = 7$.) From successful tests of the prototype one expects that use of this system will (i) permit to work with lower linac beam energy spreads and hence to obtain higher trapping efficiencies, (ii) reduce losses during acceleration, and (iii) make the RF settings independent of the beam intensity\textsuperscript{*}.

\textbf{Synchronization, ejection, recombination, transfer}

The most critical operations occur on the "flat top" of the magnet cycle where the field is stable and reproducible to $\pm 10^{-4}$. The steps involved in synchronization and ejection are the following (i) equalization of the mean radial beam position in each ring to $< 0.2 \text{ mm}$, as observed by the orbit observation system, by means of the trim-windings ($\phi_{Bd1}$) in the main bending magnets, (ii) individual position and angle correction of the closed orbit at the ejection septum magnet in each ring (the four ejection magnets are positioned as a unit and powered in series, without individual trim supplies), (iii) frequency and phase synchronization of the four accelerating systems to a crystal-controlled generator and transfer of its frequency with the proper phase to the CPS accelerating system, (iv) local deformation of the closed orbits to bring the beam close to the ejection septum magnets, (v) successive triggering of the PSB fast ejection kickers by the PSB RF frequency gated by a signal from the rising CPS magnetic guide field.

\textsuperscript{*}) The well-known technique of spreading the synchrotron frequencies by modulating the accelerating voltage at the revolution frequency was recently experimented with\textsuperscript{19}). Despite the relatively high modulation speed required, first tests lead to a stable record intensity of $1.55 \times 10^{13}$ ppp, with a somewhat more intense linac beam.
The complex 800 MeV recombination, transfer and measurement lines have been improved by adding four steering dipoles and two beam position monitors, replacing certain vacuum chambers by enlarged ones, and repositioning some quadrupole lenses. Eliminating the major stray signals (mainly from the recombination kickers) and improving the data treatment (Fig. 5) has rendered the measurement line operational. For pulse-to-pulse use the magnet switching the beam from the transfer into the measurement line is being replaced by a pulsed version.

At the $1.3 \times 10^{13}$ ppp level (leading to $>10^{13}$ ppp ejected from the CPS) good operational emittances and densities (normalised and for 95% of the particles) of the recombined PSB beams are:

<table>
<thead>
<tr>
<th>Emittance</th>
<th>$\epsilon_H \ [\pi \text{ rad m}]$</th>
<th>$\epsilon_V \ [\pi \text{ rad m}]$</th>
<th>$\epsilon_L \ (\text{per bunch}) [\text{eVs}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$60 \times 10^{-6}$</td>
<td>$25 \times 10^{-6}$</td>
<td>$0.19$</td>
</tr>
<tr>
<td>Density</td>
<td>$\delta_H \ [p/\pi \text{ rad m}]$</td>
<td>$\delta_V \ [p/\pi \text{ rad m}]$</td>
<td>$\delta_L \ [p/\text{eVs}]$</td>
</tr>
<tr>
<td></td>
<td>$2.2 \times 10^{17}$</td>
<td>$5.2 \times 10^{17}$</td>
<td>$3.4 \times 10^{12}$</td>
</tr>
</tbody>
</table>

**Supercycle and pulse-to-pulse modulation**

Supercycles and pulse-to-pulse modulation were introduced to optimize individually the pulses delivered in turn to the various CPS users (SPS, ISR, "25 GeV physics"). Each supercycle may consist of up to thirty-two linac pulses, but at present three or five are usual viz. a sequence comprising one 10 GeV/c accelerating cycle for the SPS followed by one or two 24/26 GeV/c cycles for the ISR and the CPS experimental areas, with an extra linac pulse for beam monitoring within the 24/26 GeV/c cycles. Up to eight different kinds of PSB machine pulses can be provided within a supercycle (four of them being used in current operation), and each pulse is programmed according to the users' intensity and emittance requirements. As the standard CPS cycle is about twice as long as the PSB cycle, intermediate PSB cycles for "parasitic" machine studies are being implemented.
Beam intensity is mainly varied by altering the number of turns injected into the PSB and, occasionally, by working in addition with less than four rings, thereby varying the intensity by factors larger than ten. Beam shaving serves primarily for equalizing beam emittances but may also be used for moderate intensity reduction (radiation problems). Intensity modulation methods being prepared include a sieve in the injection line, modulation of the injection line optics, and "RF gymnastics".

Apart from extending and modifying considerably the whole PSB timing and sequence control network\(^{18}\), much other equipment had to be adapted or rebuilt for working with pulse-to-pulse modulation. The new phase and radial loop electronics of the beam control system covers the entire range foreseen (10\(^{11}\) to 7\(^{10}\)\(^{12}\) ppp per ring at injection) without any need for sensitivity switching\(^{19}\). Similar modifications are being made to part of the beam observation equipment. A special circuit automatically generates the correct amount of radial steering at injection irrespective of the particular injection situation. Some solid-core magnets are being replaced by laminated ones, dc supplies by pulsed supplies, and mechanical polarity switches by solid state ones. The computer control and data acquisition system was modified for working on any one, two, or all kinds of machine pulse. At present, the control values of about fifty variables are refreshed on every cycle by the central computer. A dedicated computer supplies, in a pre-arranged sequence\(^{18}\), one out of three control functions to a given programmed subsystem.

Operation statistics, reliability

The operation statistics to date are summarized in Table 1 and Fig. 3. The good initial reliability and its subsequent improvements can be ascribed to (i) appropriate design and derating of critical electrical components, (ii) careful regular maintenance, (iii) analysis of each "non-routine" breakdown (reported at monthly discussions between all persons involved) and remedial action, (iv) lowering of working temperature, (v) rendering electri-
Table 1: Operation statistics

<table>
<thead>
<tr>
<th>Year</th>
<th>Operator training</th>
<th>Running in, machine studies &amp; test runs</th>
<th>Injection into the CPS</th>
<th>Total</th>
<th>At least one ring</th>
<th>Four rings during operation as CPS injector</th>
</tr>
</thead>
<tbody>
<tr>
<td>1972</td>
<td>378</td>
<td>532</td>
<td>-</td>
<td>910</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1973</td>
<td>950</td>
<td>691</td>
<td>342</td>
<td>1983</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1974</td>
<td>1648</td>
<td>544</td>
<td>1339</td>
<td>3531</td>
<td>4.4%</td>
<td>2.8%</td>
</tr>
<tr>
<td>1975</td>
<td>32</td>
<td>933</td>
<td>4489</td>
<td>5454</td>
<td>3.6%</td>
<td>1.5%</td>
</tr>
<tr>
<td>1976 (end of August)</td>
<td>18</td>
<td>258</td>
<td>3476</td>
<td>3752</td>
<td>4.4%</td>
<td>1.7%</td>
</tr>
</tbody>
</table>

cal equipment less sensitive to thunderstorms, (vi) fairly powerful fault diagnostics tools, locally and in the main control room, (vii) basic familiarity of the operations staff with the PSB equipment and (viii) immediate intervention of specialists at any time. The offices and laboratories of the PSB maintenance and development staff, and a mobile remote control computer console are located in the accelerator building. This and a video public address system facilitate continuous monitoring and checking of equipment performance. The delay in going to full service permitted fairly early to improve the performance of components or subsystems with relatively short life times. Medium and long term effects like corrosion and radiation are only beginning to make themselves felt. They may force one to go to a policy of periodical replacement of critical subsystems, as started recently for the one RF accelerating cavity per ring.

Conclusions and outlook

Thanks in particular to a large range of beam observation equipment and to the easy control of the working points, the PSB has fairly rapidly reached the design beam intensity and even density. The reliability so far has been above average. An increased effort is required to maintain this reliability despite aging and higher radiation levels. The new tasks of
supercycles and pulse-to-pulse modulation are performed successfully. The new CPS computer control system\textsuperscript{20} should in time facilitate operation and machine experiments.

Theoretical studies on the possibility of increasing the intensity towards $2\times10^{13}$ ppp\textsuperscript{5} so far have not revealed any fundamental barriers and the new linac may well lead to an increase in intensity.

The possibility of reducing the PSB cycle time is being investigated as part of the studies on multi-pulse injection from the CPS into the SPS. Indications are that a reduction to 0.7 s or even 0.6 s (from 1.2 s at present) would be feasible\textsuperscript{21} without undue investments (e.g. no new RF accelerating system\textsuperscript{22}).

In connection with the production of antiproton beams for $\bar{p}-p$ collisions, there arises the problem of maximizing the longitudinal proton density, so that the luminosity is adequate for experiments. As one step towards this aim, experiments are being made to add vertically the beams from two PSB rings ejected simultaneously instead of sequentially. While the vertical density is thus reduced by 35%, the longitudinal (and horizontal) density is doubled\textsuperscript{15}.

Acknowledgements

It is a pleasure to thank our colleagues in the PS Division, notably from the Linac, Operations, Controls and Mechanical groups, as well as from SB Division, for their indispensable contributions to the PSB work, and J. Gareyte for his participation in machine experiments.

Distribution:
PS lists 5 and 6
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Fig. 1: Working point diagram for the PSB (Laslett Q-shifts at 50 MeV after RF-trapping).

Fig. 2: Evolution of proton intensity. (Typical values for high intensity operation in 1975.)

Fig. 3: Partial PSB down-time (at least one ring) in percent of scheduled time (excluding start-up and equipment tests). The 12.9% down time in August 1976 was mainly due to two major breakdowns (corrosion of septum magnet coils). Note that no percentages for mains down-time are available for the first three periods in 1974, and that thunderstorms were frequent and heavy in August 1976.
Fig. 4: One of the eight stacks of the new PSB multipoles, containing each sixteen elements, usually a normal and a skew sextupole, and a normal and a skew octupole per ring.

Fig. 5: Data display of 800 MeV measurement line: beam position, matching and emittances before transfer into the CPS. For small values, the mismatch vector K (shown graphically for each of the four beams) is proportional to the emittance increase. (Beam parameters not optimized.)