

The PSB Staff (reported by K.H. Reich)

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Summary and Introduction

At the 6th International Conference (1967), higher energy linacs and booster synchrotrons, cycling fast or slow, were discussed as a means for raising the intensity of the main proton synchrotron. Today one machine of each of these types is in operation: the 200 MeV AGS Linac; the 8 GeV NAL Booster; and the 800 MeV slow-cycling four-ring CERN PS Booster (PSB). It is still too early to assess the full PSB capabilities, but at present the design expectations seem, on the whole, to be realizable, as far as intensity (10^{13} ppp), machine systems performance, and reliability are concerned. Not unexpectedly, obtaining and preserving beam density has been more difficult, and we are almost a factor of 2 below the design values.

This report consists of two parts. First, the major design options are assessed in the light of the experience gained over the last two years. Secondly, the efforts to obtain and to preserve beam density are reported; in particular, optimization of multiturn injection, choice of the working point in the Q_H, Q_V diagram, compensation of stopbands, adiabatic RF trapping, and avoidance or damping of various instabilities. The concluding remarks contain data on the latest performance as a CPS injector, and an outlook into the future.

Assessment of Some Major Design Choices

For 50 MeV injection, the CPS intensity is space-charge limited to about 2×10^{12} ppp. The purpose of the new CPS injector is to raise the intensity to about 10^{13} ppp with only moderate increase in transverse and longitudinal emittances. Major choices concerning this injector (Fig. 1) and their assessment are listed in Table 1. While good progress was made during the last two years^{21,8}, resulting in successful runs for neutrino physics, the original performance aims have not yet been reached completely. (Because of the reduction in resources available, it was decided to operate the PSB for part of the CPS time only, and at an intermediate intensity level of about 5×10^{12} ppp, until higher intensity is required by the SPS.) Thus some of these assessments may need to be updated and/or eventually completed.

Multiturn Injection^{8,21}

Extensive computational studies²² showed that horizontal multiturn injection with stacking in transverse phase space is a promising method for obtaining beams of high transverse density in the PSB. With a stable Linac beam of good quality it was found that the measured efficiency values, typically in the region of 30 to 50% (depending on such parameters as number of turns, Linac beam emittance, acceptable PSB beam emittance, value of Q_H , etc.) agree remarkably well (to within 5%) with the predicted figures. Unfortunately, lack of usable observation equipment for the trajectory at injection led to rather lengthy setting-up procedures by trial and error. With a Linac beam of 50 mA (half the design intensity), 8 to 9×10^{12} p (total of the four rings) are now routinely injected into the nominal horizontal emittance ($\epsilon_H = 130\pi \cdot 10^{-6}$ rad m at 50 MeV). Recent experimental and theoretical studies²³ demonstrated that for small values of $|Q_H - Q_V|$ a substantial improvement of the efficiency (up to 60%) can be achieved by means of a linear coupling introduced by zero-harmonic skew quadrupoles. After reinventing²⁴ this technique for the PSB, we used it in operation for

some time. Although leading to an unwanted vertical emittance increase (due to $\epsilon_V < \epsilon_H$) it is nevertheless considered an interesting way of obtaining higher beam intensities for making machine experiment, for instance on beam loading.

Choice of Working Point, Stopbands

At the design stage it was unclear whether the working point should be above 4.5 or below. On the one hand, transverse resistive wall instabilities are more serious above. (Ionic instabilities are more serious below, but because of the low pressure of $< 10^{-7}$ Torr, they were not expected to occur.) On the other hand, for a Q -value below 4.5, there is not much working room available for accommodating larger (incoherent) Q -shifts. Furthermore, the space-charge driven fourth-order difference resonance $2Q_H - 2Q_V = 0$ was expected to lead to beam blow-up for $|Q_H - Q_V| < 0.2$ ²⁵.

The final choice was $Q_H = Q_V = 4.5$ for zero quadrupole trim currents and to rate the trim supplies such that the entire area $4.0 < Q_{H,V} < 5.0$ and some outside regions could be reached. On account of the high current, high proton density goal, slightly more weight was, however, given to providing room for the Q -shifts. Hence, the first lenses for stopband narrowing were planned with $4.5 < Q_{H,V} < 5.0$ in mind and the running-in started with working points in that area.

While the PSB could then be made to accelerate beams of good intensity, their vertical emittance was up to two or three times larger than the design value ($\epsilon_V = 9\pi \cdot 10^{-6}$ rad m at 800 MeV). The most likely explanation is that a combination of the Laslett Q -shifts with the synchrotron oscillations causes repeated crossing of several stopbands. When a working point was found in this area that avoids stopbands, denser beams could be accelerated but then the beam became unstable transversely. Head-tail modes 1, 2, and 3 were observed for the first time²⁶. Moderate to strong octupole fields cured this instability, but widened some stopbands as expected⁷.

Most of these problems were overcome by moving the working point to the region $Q_H \approx 4.18, Q_V \approx 5.24$ for the following reasons²⁷: i) both Q -values are above integers, hence resistive-wall instability growth rates are slower; ii) the difference line $2Q_H - 2Q_V = -2$ was expected to be narrower than the $2Q_H - 2Q_V = 0$ line since both space-charge forces and Landau damping octupoles [which can anyway be weaker because of (i)] are essentially zero harmonic; iii) because of (ii), more room for Laslett shifts should be available even without narrowing of stopbands. These points were confirmed by experiments, and for the time being this is the usual working point leading to the transverse densities reported in Table 1.

The measured widths of the stopbands agree remarkably well (to within 20% in many cases)²⁸ with those computed from the actual azimuthal distribution of the measured magnet errors.

Though exploring and narrowing stopbands is tedious (and needs more correction lenses than we have at present) we may have to come back to the area $4.5 < Q_{H,V} < 5.0$ for accommodating larger Q -shifts. (At present it is only used to produce high intensity beams when a vertical blow-up can be accepted exceptionally.)

RF Trapping and Acceleration

For the adiabatic voltage rise used¹⁴, trapping efficiencies above 90% are expected theoretically^{29,30}.

Experimental results³¹ are shown in Fig. 2. The values obtained for a beam of 1.2×10^{12} p/ring thus agree with the estimates. Corresponding figures (lower efficiencies for larger Linac beam energy spreads) apply to 2.5×10^{12} p/ring, as long as no instabilities occur (see below). Acceleration and synchronous transfer into the CPS buckets³² are almost lossless, i.e. total loss about 5%, since the time that the beam control and synchronization system³³ became fully operational³⁴. Under normal conditions the bunch area of a 6×10^{12} ppp beam is 9 mrad in units of $(\Delta p/m_0 c) \times RF$ radians.

Instabilities and their Cure

At the present level of operational beam intensity, instabilities, both transverse and longitudinal, are not harmful with either working point, provided the Linac beam energy spread is $\Delta E \approx \pm 150$ keV (design value) and that appropriate zero-harmonic octupole fields are applied. In machine experiments where different working points, other magnet cycles, and/or smaller energy spreads are used, various types of instabilities were studied. An example of a horizontal instability occurring with a 50 MeV coasting beam is shown in Fig. 3. Note the presence of a longitudinal structure, as yet unexplained. Bunched beam instabilities have already been referred to when discussing the working point; they are reported elsewhere in this Conference²⁶. These instabilities appear to be driven by the long-range resistive-wall forces³⁵. In general, the growth rates are as expected from theory, but the threshold intensities tend to be higher than those calculated, possibly because of neutralization (for coasting beams) or the additional frequency spreads introduced by the strong non-linear space-charge forces³⁶.

For large intensities and Linac beam energy spreads $\pm < 150$ keV, bunch position and bunch shape oscillations⁸ occur soon after injection; so far, studies have brought out neither pure modes nor exponential growth. Instrumentation for more detailed observation is being developed³¹.

Conclusions and Outlook

During the two neutrino physics runs in 1973 with the PSB-CPS beam³⁷, the average number of protons delivered to the external target was about 5×10^{12} ppp, thus fully meeting the intermediate intensity goal. The beam was remarkably stable (Fig. 4) and operation reliable. All studies made so far have not disclosed any difficulties of a basic nature which would prevent us from attaining the original performance aims. Hence the major design options chosen appear to have been sound.

Besides the completion of the beam observation apparatus and the expansion of the computer control system²¹ already mentioned, we list among the necessary improvements: i) more protons from the Linac (a new 50 MeV accelerator is under construction³⁸); ii) extra multipoles¹² for stopband compensation (being ordered); iii) refined RF voltage amplitude control¹² (under way); and iv) a faster Linac beam distributor to facilitate trajectory studies at injection and equal filling of the four rings (being built).

The anticipated capacity for accommodating new requirements has already shown up in two ways: i) the planned use of the PSB as pulse-to-pulse intensity modulator when the CPS will supply sequentially various users (25 GeV physics, ISR, SPS) with intensities differing by a substantial factor; and ii) simultaneous and independent use of each of the four rings for machine experiments, operator training, and hardware and software tests.

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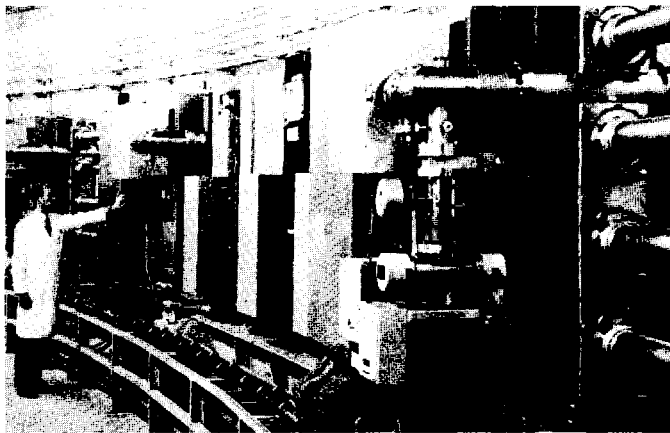


Fig. 1 View into PSB tunnel showing (from right to left) long straight section, bending magnet (with vacuum pumps), triplet, bending magnet, long SS.

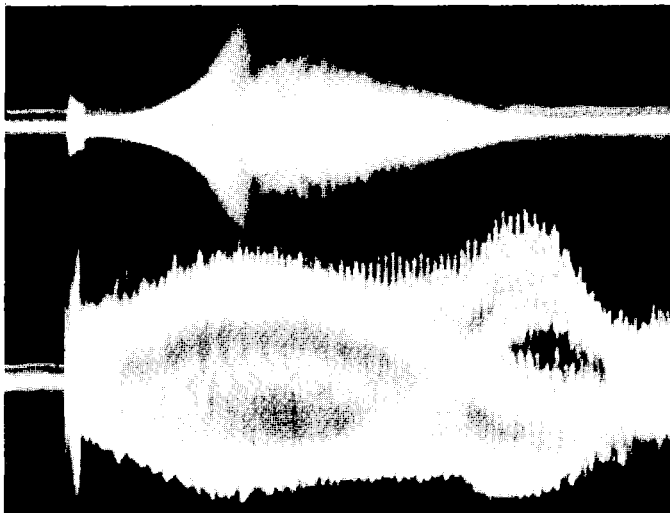


Fig. 3 Horizontal instability observed with a 10^{12} p per ring beam coasting at 50 MeV.
 $\Delta E_{\text{Linac}} = \pm 60 \text{ keV}$; $Q_H = 4.18$, $Q_V = 5.24$;
 time scale 20 msec per division.
 Upper trace: difference signal from electrostatic pick-up electrode.
 Lower trace: sum signal.

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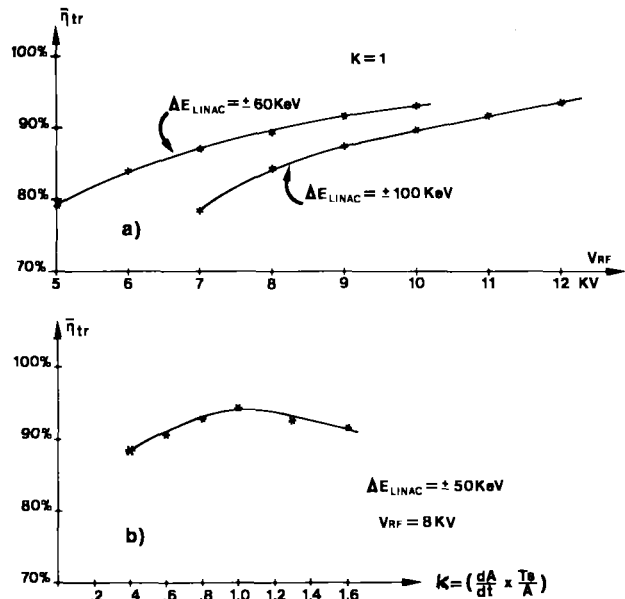


Fig 2 Measured efficiency of RF trapping η_{tr} of a 1.2×10^{12} p/ring beam using an adiabatic voltage rise from 1 kV to final RF voltage indicated ($K = 1$ means rise-time equal to synchrotron oscillation period T_s), a) as a function of RF voltage (for two Linac beam energy spreads); b) as a function of K .

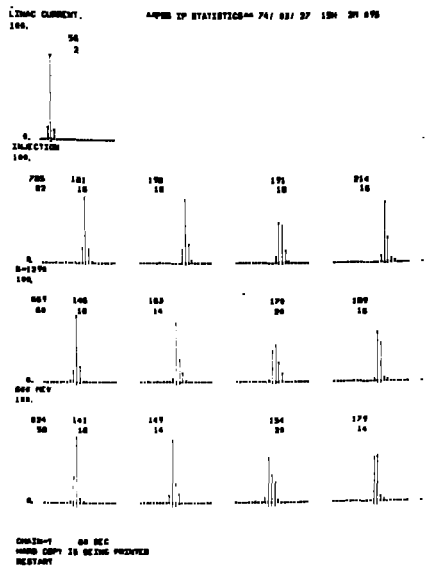


Fig. 4 Histogram (for 100 acceleration cycles) of Linac current and PSB intensities. (At injection 100 mA circulating correspond to $\sim 10^{12}$ p). From top to bottom: Linac current, intensities accepted by PSB before trapping (rings one to four from left to right), intensities trapped, and intensities accelerated to 800 MeV and synchronized. The figures indicate mean values and standard deviations, respectively. The left-hand column gives the average of the total intensities (of the four rings). The PSB was not optimized when this photograph was taken; during the neutrino runs the intensities were about 20% higher (with the same distribution).

Table 1

Assessment of some major PSB design choices

Aim	Choice, including reasons given in 1966-1969	Consequences of choice	Particular actions taken	Assessment in March 1974
10 ¹³ ppp	800 MeV slow-cycling circular injector: for about the same cost as a 200 MeV Linac, higher beam quality; spare capacity for contingencies and improvements ^{1,2} ($\beta\gamma_{800 \text{ MeV}}/\beta\gamma_{200 \text{ MeV}} \approx 3.5$)	Need to study, select, and design the first slow-cycling "Booster" synchrotron ³ , a fairly complex machine in which collective effects were expected to be significant, particularly in longitudinal phase space.	Taking into account beam intensity effects from the start ⁴ ; emphasis on simple design and easy, reliable operation.	Final cost indeed very comparable to that of a 200 MeV Linac; too early for comparing performance limits; with a 50 mA Linac beam $\sim 8 \times 10^{12}$ ppp were accelerated to 800 MeV ($\sim 5 \times 10^{12}$ ppp within design emittances).
High phase-space density, adjustable within some range	a) Four rings: comparatively modest extrapolation of transverse phase-space density beyond the 1966 state of the art; favourable numerology including the possibility of combining two beams for better ISR performance ^{2,5} .	Need to compare horizontally interlaced version with vertically stacked version; higher complexity and probably cost than with two or three rings; need to distribute the Linac beam and to recombine the four beams prior to transfer into the CPS.	Vertical stacking whenever possible; use of combining (magnet yokes, pumping of vacuum systems, etc.) and multiplexing (beam observation, data treatment, and display, etc.); emphasis on simple and reliable design for beam distribution and recombination.	Distribution of the beam to the four PSB levels and precision recombination present no particular problems <i>per se</i> , but the load of running in and setting up four almost independent rings was underestimated; vertical stacking is definitely beneficial.
	b) Lattice with 16 periods and no super-periods; separate function magnet: no systematic resonances for $4.0 < Q_{H,V} < 5.3$; ease of moving the working point; good probability of providing a magnet system of high quality, notably through the use of a computer simulation program ⁷ .	Larger number of magnet units than in the case of a combined function magnet; occupation of a larger fraction of the machine circumference in the present case of relatively low peak magnet fields.	No remedy possible or needed in view of the relatively small total number of magnet units and the relatively large PSB circumference, determined independently as $4R_{\text{PSB}} = R_{\text{CPS}}$.	Performance aims achieved; distortions of the uncorrected closed orbit do not exceed a few millimetres peak to peak; half integer stopband widths were measured as $\delta Q \approx 0.01$, and the four rings were found ⁸ to be within the narrow tolerances specified ⁷ .
	c) Provision of a number of correction lenses from the beginning: faster running in; improved final lens order.	Need to anticipate most wanted types of lenses and their strength without much quantitative experience available on which to base oneself.	Extensive calculations and machine measurements; provision of two extra lenses of a different type for experiments.	On the whole successful approach (see text); the need for skew sextupole corrections was underestimated.
	d) Decision to design equipment from the start with a low beam-coupling impedance: faster running in; better final phase-space density.	Need to specify acceptable impedance values without much quantitative experience for judging beforehand the effect on beam; this led in some cases to awkward decisions whether or not to change a given prototype design.	Calculations ⁹⁻¹¹ and measurements ¹² on prototypes and final equipment (RF cavities, fast kicker and septum magnets, quick-connect vacuum couplings, beam detectors, etc.); assessment and modifications to the best of one's knowledge.	Since so far no beam interaction with a fixed-frequency parasitic resonator has been observed, and the impedances cannot be adjusted, assessment is not easy; in view of the difficulty of later changes the course of action adopted appears justified.

Aim	Choice, including reasons given in 1966-1969	Consequences of choice	Particular actions taken	Assessment in March 1974
Low maintenance; reliable, easy operation (leaving some flexibility)	a) Magnet power supply fed directly from the electricity mains: no rotating machinery (i.e. less wear, no continuous manning of power house); model for SPS.	Lengthy negotiations with the local Electricity Authority including simulated tests with the grid; electrical coupling with other users inside and outside CERN.	Provision of adequate a.c. compensating and filtering networks ¹³ , appropriate regulation of power supply.	Supply gives entire satisfaction from all points of view: stability, reproducibility, ease of control, freedom from creating perturbations (outside tolerances).
	b) Triplet focusing: resulting beam cross-section comparable to that in the CPS in the long straight sections, hence use of some proven existing CPS designs and even equipment; reduced energy storage in PSB magnets.	Sixteen extra lens units (compared to FODO lattice).	(None possible.)	Exact value somewhat difficult to assess; main advantage probably reduction of energy exchange with electricity mains; also appreciated: possibility to install borrowed CPS equipment in PSB.
	c) Air-cooled RF accelerating cavity having only final amplifier stage in machine tunnel: low failure rate.	New development ¹⁴ based on restricted experience; possibility of thermal runaway of ferrites ¹⁵ .	Adoption of sufficiently low working temperature; individual measurement and stacking of ferrite rings according to properties.	So far entirely satisfactory performance from all points of view.
	d) Standardization and modularization: general economy; less spare parts; easier training of operating and maintenance staff.	Unless standardization is based on a full knowledge of all cases to be covered, difficulties arise; standardization may adversely affect individual inventiveness.	Appropriate organization of Project Division, including Parameter and Technical Coordination Committees.	Unqualified success where applied (injection and ejection lines, power supplies, kicker system ¹⁶ , vacuum components ¹⁷ , naming of PSB components from drawings to software, etc.).
	e) No electronics or power supplies in machine tunnel (unless indispensable): no irradiation; spread of maintenance in time.	Degradation of signal quality and power loss due to longer cable transmission.	Construction of auxiliary tunnel and equipment rooms above machine tunnel; appropriate equipment design.	Aims achieved; easy addition of extra equipment appreciated.
	f) Centralized controls, located in the CPS main control room (MCR): easier running-in; faster take over by CPS operating team.	i) Lack of space and specialized facilities during running-in. ii) MCR and PSB systems activities separated by 400 m distance.	i) Basically none, in the future possibly rebuilding of MCR. ii) Intercom and public address, TV and other communication links.	Completion of the centralized controls was clearly a major progress compared to the earlier (temporary) stage of distributed controls; CPS team has not yet taken over PSB operation.
	g) Powerful beam observation apparatus ¹⁸ : faster running-in; better beam quality; easier fault diagnosis.	i) Largish cost item (~ 10% of total). ii) Dilemma of what priority to give: not required before main machine components but much less useful if not ready from the start-up.	i) Multiplexing wherever possible (e.g. one camera for looking at two screens, etc.); cheap solutions where possible (e.g. beam loss monitors). ii) Building by industry (e.g. measurement targets).	Nearly all facilities for the measurement of beam position, beam current, bunch shape, emittance, energy spectrum, closed orbit, and betatron frequency meet expectations and are in use almost continually.
	h) Computer assistance for data acquisition and control: faster measurements; improved beam quality; better reproducibility; easier operation ¹⁹ , hardware tests ²⁰ .	i) Limitations due to existing IBM 1800 (used because of available capacity and time pressure). ii) No manual back-up foreseen (to save cost).	i) Short term: change over to MPX, addition of core memory and a satellite computer for on-line work; long term: new system. ii) Diagnostic means for fault finding.	Data acquisition, treatment and display even more powerful than anticipated; helpful for control after teething troubles ²⁰ were overcome; too early to assess full capability for reducing PSB down time.