PRESENT PERFORMANCE OF THE CERN 800 MeV PS BOOSTER (PSB)

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Summary

The CERN 800 MeV PSB consists of four synchrotrons stacked one on top of the other. The injector is the present 50 MeV CERN Proton Synchrotron (CPS) linac. Its beam is injected sequentially into the four rings via a vertical distribution system. Monoturn or multiturn injection of up to fifteen turns is available. After acceleration to 800 MeV, the four beams are ejected sequentially and brought to a common level by a recombination system. All twenty bunches are then transferred to the CPS, thus potentially increasing its intensity to 10^{13} p/p. Construction started in 1968, running-in on 1 May, 1972. Experiments on injection, acceleration, and transfer to the CPS were carried out whilst completing the installation of beam observation systems, debugging the interface to the IBM 1800 control computer, and bringing the software to operational standard. Closed orbit deviations are less than anticipated (only a few mm). Linear coupling and sum resonances were studied with a beam coasting at injection energy: they can be compensated with a small fraction of the available correction strength. Multiturn injection, RF trapping efficiency, acceleration, synchronization, ejection, and transfer to the CPS are described in their latest stage. At the end of the year the design intensity of 2.5×10^{12} p/p was reached in one ring.

Introduction

The PSB and its main systems have already been described elsewhere.[1] A parameter list is also available,[2] so that we will not give general information here. Though five months have elapsed since the last accelerator conference in Moscow, not much more progress has been made in the PSB running-in owing to poor linac performance in November, and to the CPS shutdown which started at Christmas. We will try to make this report both a comprehensive description of the present status, and a complement of the review given earlier.[3]

Injection

PSB studies are made in parallel with normal CPS operation. Every second pulse from the linac is sent to an injection line where the beam either: i) passes through a debuncher and is sent to the PSB, or ii) is switched into an emittance measuring line, or iii) into a spectrometer. The latter is vital for recognizing suitable beam quality, and its analogue signal is consistently used to tune the linac. Spectrometric measurements integrating separately over the time of injection into each of the four rings will soon be available and should be of great help since many pending questions are related to the energy spread. A zoom in the energy scale will be provided by rotation of the wire array out of the focal plane.

Transporting the beam from the linac to the PSB and steering the pulse to the four levels has eventually been a success although the operation of this transfer line suffers from a lack of instrumentation.

Monoturn injection

Monoturn injection is used when low intensity beams are wanted. Injection is made with a septum magnet (septum 1 mm thick), steering and matching being helped by observation of retractable screens. The beam is bent onto the closed orbit by a kicker magnet (fall time ∿ 40 nsec). For careful orbit measurements with the pick-up electrode system[4] the linac beam is chopped at the PSB RF frequency (3 MHz). An orbit

acquisition on two consecutive revolutions enables the computer to display frequency, amplitude, and phase of the coherent trajectory. Although monoturn injection is straight-forward, reducing coherent oscillations down to 1 mm manually by checking the analogue signals from pick-up electrodes is time consuming when eight orbits are to be aligned (4 rings × 2 planes).

A coasting beam at injection field level has been extensively used for the study of beam dynamics and instabilities.

The magnet quality was born out not only by field measurements,[5] but also by the beam behaviour. At the beginning of the running-in, distortions of the uncorrected closed orbit did not exceed 3 mm peak-to-peak. A more recent and precise measurement is shown in Fig. 1, where the analogy between the four orbits speaks for itself. Most of these distortions are due to small displacements of the triplets since the first alignment in May 1972. A realignment was made during this shutdown.
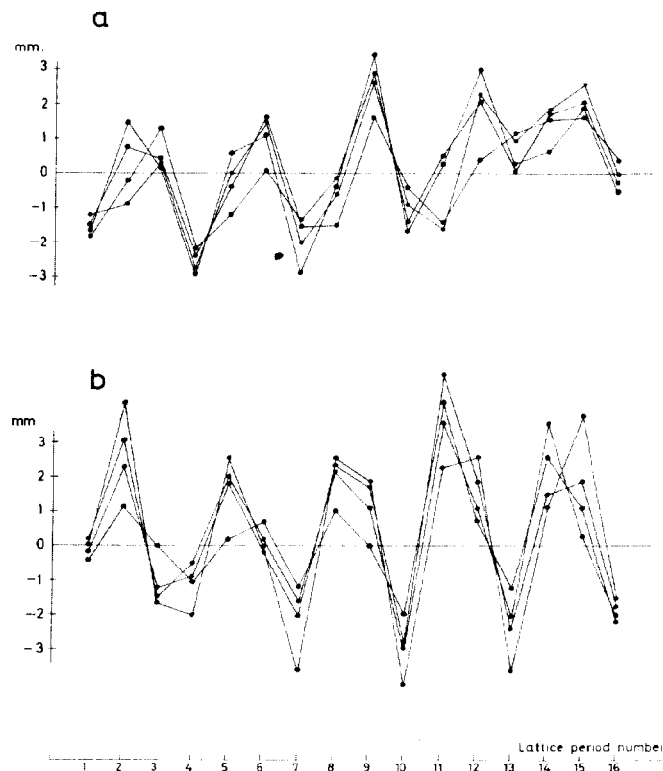

Fig. 1   Closed orbit distortions measured in mid-October 1972 at 50 MeV for the four rings: a) horizontal plane, b) vertical plane.

Skew quadrupolar field imperfections in the machine have been carefully compensated after observation of coupled oscillations excited in one plane with the Q-measurement kicker (see Fig. 2).
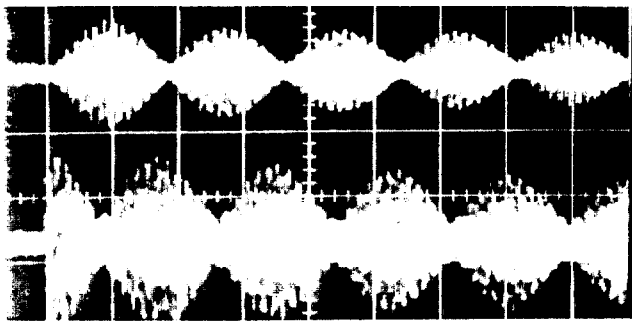
Fig. 2 Coupled oscillations excited by Q-measurement kicker with $Q_H - Q_V \sim 0.003$. Signals from pick-up electrodes, upper trace: $\Delta H(0.02 \text{ V/div})$, lower trace: $\Delta V(0.01 \text{ V/div})$, horizontal scale: 0.1 msec/div.

To demonstrate the magnet quality[5] and accuracy of measurements we give the following example:

Ring	Compensation deduced from magnetic measurement (A)	Compensation from beam observation (A)	Available compensation strength (A)
1	-0.88	-1.0	
2	-0.47	-0.5	20
3	-0.82	-0.8	
4	+0.21	+0.45	

Stop-bands are scarcely felt by the beam. To give an example, for the half integral resonance $2Q_V = 9$ the stop-band width was measured to be $\delta Q < 0.01$ and it was reduced to no visible effect on beam traversal, when compensated with only 0.62 A (0.63 A was deduced from field measurements). Magnetic differences between inner (2,3) and outer (1,4) rings are negligible as far as dipole and quadrupole fields are concerned; this fact eases the operation since rings can be considered equal, as far energy and Q-tune are considered.

Multiturn Injection

For normal operation, multiturn injection is performed up to fifteen turns. A higher number of turns, up to thirty, can be tried for machine study simultaneously in two rings.

For multiturn injection[6] the closed orbit is deformed locally by four programmable kicker magnets whose time dependence is adjustable in order to modify the phase-plane density distribution. In first approximation the system works as foreseen, even better than anticipated in the sense that a higher efficiency results from the increased acceptance due to the small orbit distortions.

Up to 7×10^{12} protons have been injected in one ring; the beam is generally coasting without drastic losses until it reaches the vacuum chamber wall (see Figs. 3 and 4). The multiturn process was often upset by linac energy variations, both within the burst and jitter from pulse to pulse. Even when the process was deliberately limited to eight turns per ring, we could rarely count on equal filling of the rings. The maximum total number of protons we managed to inject in the four rings is 2×10^{13}, but the emittance occupied by

the beam then is too large. For 3×10^{12} protons in ring 4 we measured the following emittances (area/π of ellipse including 95% of all particles):

$$\varepsilon_H = 180 \text{ mm mrad}, \qquad \varepsilon_V = 40 \text{ mm mrad},$$

to be compared with the nominal values of 130 and 40, respectively.

We count on significant improvements of these two figures, in the course of a careful optimization. Steps for this improvement are: i) a better linac stability, ii) when necessary a beam chopped for orbit measurement, iii) beam size measurement on each cycle by the ionization beam scanner.
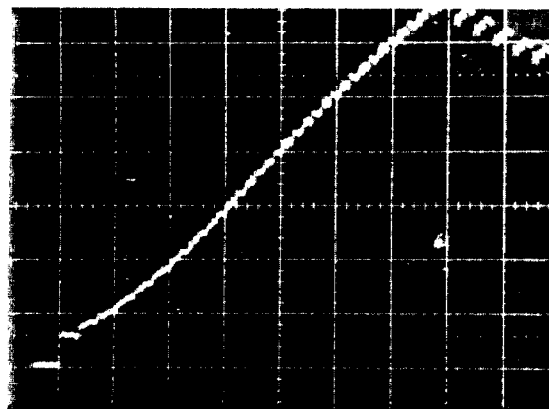

Fig. 3 Build-up of current in multiturn injection (twenty turns). Signal from fast beam transformer. Hor. scale: 5 μsec/div. Vert. scale: 80 mA/div.
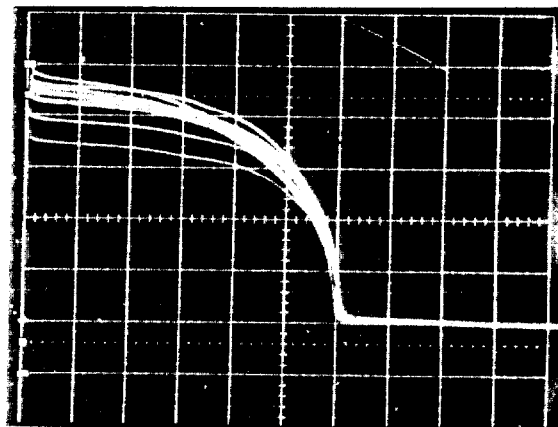

Fig. 4 Decay of a coasting multiturn injected beam due to rising magnetic field. Signal from slow beam transformer. Hor. scale: 1 msec/div. Vert. scale: 50 mA/div.

Acceleration

The systems for RF acceleration and beam control are described in detail elsewhere.[7,8]

By proper shaping of the voltage increase from 0.6 kV to 10 kV in the first 500 μsec after injection, so-called "adiabatic" trapping was achieved with an efficiency of up to 96% in low-intensity monoturn injection. With multiturn injection, trapping efficiency is smaller and further losses appear, more or less uniformly distributed over the whole cycle. Typical figures are listed below.

	Injected current (mA)	Trapping efficiency (%)	Acceleration losses (%)	800 MeV p/p
Monoturn	50	96	0	0.5×10^{12}
Multiturn	400	65	15	2.2×10^{12}

For high-intensity beams, the trapping efficiency could not be improved beyond the present figures despite of systematic optimization of phase lock and radial control loops. When the trapping efficiency is high, it is sensitive to the correct RF frequency; when it is low the optimum is less pronounced and sometimes two optima have been observed. It is not yet clear to what extent this comes from excessive energy spread or possibly even from longitudinal instabilities in the beam.
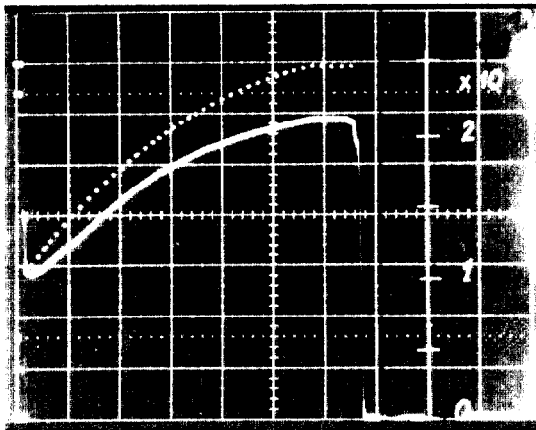

Fig. 5   Beam current during high intensity acceleration. Trapping efficiency 70%, acceleration losses 15%. Dotted line: ideal (lossless) acceleration. Hor. scale: 100 msec/div.

Nevertheless, in the last minutes of the last run before the shutdown, nominal intensity was accelerated in ring 3 as 2.5×10^{12} protons reached 800 MeV. Figure 5 is typical of such high intensity acceleration. Bunch shape and position oscillations can be seen in Fig. 6. They probably come from imperfect beam control; another cause could be beam equipment interaction.[9]
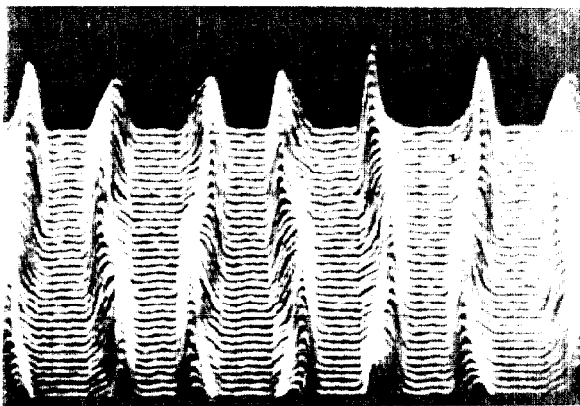

Fig. 6   Bunch oscillations at 800 MeV.   Hor. scale: 100 nsec/div. Vert. scale: one sweep every twenty revolutions (12 nsec).

In order to avoid dilution of the bunches in the twenty buckets of the CPS, synchronization of the PSB rings must be accurate to a few RF degrees. This is done on the flat top prior to ejection in three steps: i) frequency synchronization to an external oscillator, ii) coarse, iii) fine phase adjustment, the whole process lasting about 30 msec. Synchronization is now working in four rings, but the process shakes the bunches thus inducing bunch displacements. Improvements are under way.

Ejection and transfer to CPS

Prior to ejection, three dipoles in each ring deform the closed orbit locally in order to bring the beam close to the ejection septum. A fast kicker then jumps the beam over the septum. Beams are ejected in the sequence 3-4-2-1 and are all recombined on level 3 with the help of three additional kicker magnets. Ejected beams which are not brought to the CPS can be deflected from the transfer line through a measurement line into a dump. Setting up the beam in the transfer line is done with the aid of retractable scintillator screens, and monitoring can be made via pick-up electrodes, whereas ejection and transfer efficiencies are computed from beam transformer measurements. All this equipment has been working satisfactorily.

Refined matching of trajectories, of transverse phase-plane ellipses, and of mean energy is to be checked, after recombination, in the measurement line.[16] Beams ejected from the four rings have already been sent to the dump through the measurement line, but the complex equipment there was not yet operating.

A beam has been sent to the CPS on several occasions. Injection and acceleration of five bunches with low intensity was successful, while transfer, injection, and acceleration of five bunches of high intensity (2.0×10^{12}) was accompanied by important losses due to the large transverse emittances (see "Injection"). Nevertheless, during the last run 8.5×10^{11} protons have been accelerated to transition,[11] which represents the highest intensity ever accelerated in five CPS bunches.

Collective effects

No transverse instabilities of the bunched beam have been of any significance up to the nominal intensity of 2.5×10^{12} p/ring. Longitudinal bunch-shape and bunch-centre oscillations are already partly cured, and one hopes that they will disappear with the improvement of the beam control and synchronization system.

Some interesting behaviour of the coasting beam could be observed[12] near injection.

For beams of 2 to $4 \cdot 10^{12}$ p, transverse instabilities occur erratically both in the vertical and horizontal planes. These coherent oscillations begin in one or the other plane during the first milliseconds after injection (see Figs. 7a and 7b). Thresholds and e-folding times for vertical oscillations fit with theoretical predictions;[13] for the horizontal plane it is not yet agreed whether the growth rate can be explained or not. These instabilities are accompanied by strong beam losses, and at the same time there sometimes occurs a longitudinal structure which can be seen from the wide band pick-up station (Figs. 7a and 7b).

Even more exotic is the appearance of numerous narrow (< 10 nsec) depressions in the azimuthal beam density.[12] These first occur some milliseconds after injection, and the higher the intensity the sooner they occur. As time passes, the depth of the spikes increases (to about 20% modulation) and their number decreases to stay at two to four (see Fig. 8). No convincing explanation for the mechanisms has yet been given.

a) vertical oscillations
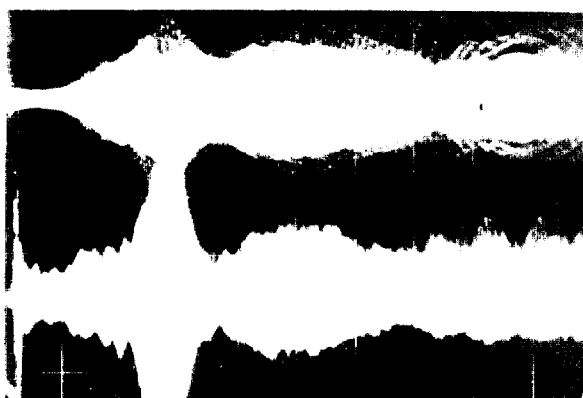
b) horizontal oscillations.

Fig. 7   Build-up of coherent oscillations of a coast-
ing beam (2 to 4×10^{12}) protons. Upper trace:
signal from a position pick-up electrode.
Lower trace: signal from a wide-band pick-up
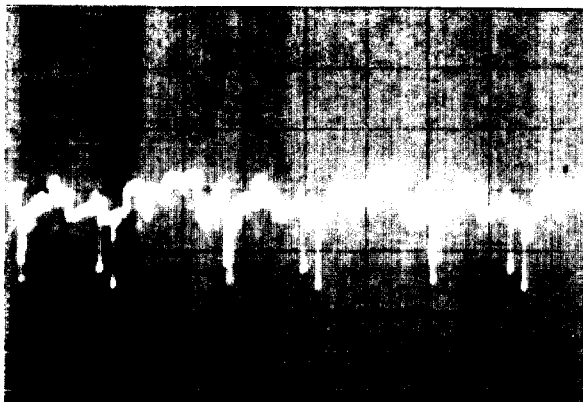station. Hor. scale: 0.5 msec/div:

Fig. 8   Intensity depressions in a coasting beam of
9×10^{11} protons ~ 5 msec after injection.
Signal from a wide-band pick-up station. Hor.
scale: 0.5 μsec/cm. Vert. scale: $\sim 20\%$ modu-
lation.

Machine operation

An appraisal of performances of the different sys-
tems is given in Ref. 3. Let us comment in more detail
on some aspects of the operation.

Difficulties arose from lack of linac stability
and reproducibility. Moreover, we were not aware be-
forehand that any retuning of the linac, to improve our
pulses, would be detrimental to the CPS, which uses the
alternate pulses. For this reason triple pulsing,
which would enable a continuous recording of the linac
beam quality, has not been acceptable so far. Also any
change of the cavity loading which results from creating
at 500 keV: i) long holes to sharpen the edges of the
pulse, ii) short holes to have clean switching over
from ring to ring, or iii) a 3 MHz structure necessary
for accurate orbit measurement, appears now to perturb
the beam properties more than expected.

Experience with the running-in has shown that un-
derstanding the beam behaviour and improving various
systems performances was valid for all rings once
achieved in one of them. But this is not true for the
day-to-day operation, where all refined tuning must be
done four times, more or less independently. This is
of course a very good case for computer assistance, and
the PSB controls had in fact been thought out with this
expectation in mind.[14]

From now on, emittance measurements and spectro-
metry of the linac beam can be required from the PSB
control position on any pulse and the results are dis-
played on TV screens.

Systems (such as the injection line which must be
completely retuned to go from monoturn to multiturn in-
to injection, acceleration, and ejection and transfer,
respectively, allow the operator to change any parame-
ter of the system with the backing of reference values.

Elaborate programs are requested from the PSB maxi-
console to perform orbit measurements via acquisition
of pick-up electrodes,[4] automatic Q_H and Q_V measurements
up to thirty times in a cycle, emittance evolution
measurements, via seven profile acquisitions per cycle
by the ionization beam scanner, emittance measurement
and spectrometry at 800 MeV in the special line,[10]
etc.

Magnet corrections are operated from the maxi-con-
sole via four knobs which may be connected either di-
rectly to the wanted power supplies (through keyboard
designation), or in a coupled way in order to create,
for instance, amplitude and phase of harmonic correc-
tions, etc. Such correcting elements are programmed in
time, as well as several RF parameters, through a digi-
tal function generator. The functions are modified from
the maxi-console in a very efficient way, which made it
possible to create the RF frequency program from scratch
in two hours.

The general display gives on-line information on
many parameters (direct measurement or a maximum of
three acquisitions combined with a simple algorithm),
which can be permanently displayed on twenty Nixie
arrays distributed over the control room. Examples for
displayed parameters are: injection efficiency, trap-
ping efficiency, moving average of the number of pro-
tons transmitted to the CPS, betatron tunes $Q_H(t)$,
$Q_V(t)$, mean radial position $R(t)$, t being any chosen
time during the cycle, etc.

The five underlined items in the preceding descrip-
tion can all work simultaneously except if they imply
control of the same parameter.

In order to centralize the controls of the accele-
rators the PSB is operated from the CPS Main Control
Room. As, however, a lot of maintenance and calibration
of the electronics needs to be done in the PSB building

itself, a remote and movable computer console is now being provided there.

In conclusion, we are pleased to state that the PSB performs as expected. Use of its beam for physics with the CPS is planned for autumn this year.

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