

IMPROVED RECOMBINATION OF THE 20 PSB BUNCHES AND MERGING INTO 5 DENSE BUNCHES IN THE CERN PROTON SYNCHROTRON

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Introduction and Summary

Different combinations of the beams from the 4 CERN Proton Synchrotron Booster (PSB) rings allow several PS injection schemes. Up to now, the 20-bunch-to-bucket transfer which brings sequentially to the PS level the beams from the 4 superposed PSB rings (Fig. 1a) has been used in operation. This transfer mode has recently been adapted to the higher intensity beam delivered by the new Linac. Last year two new modes of combining the 4 PSB beams were achieved to provide a high line density for \bar{p} production on a cycle-to-cycle change basis: i) beams from two PSB rings are simultaneously ejected and vertically added in the transfer line and similarly for the other two rings leading to the so-called 10 bunch mode (Fig. 1b); ii) a further gain in line density is obtained by the 5 bunch mode (Fig. 1c): each of the two double beam batches is ejected from the PSB at a slightly different energy, trapped in five PS buckets after azimuthal shift and accelerated up to high energy.

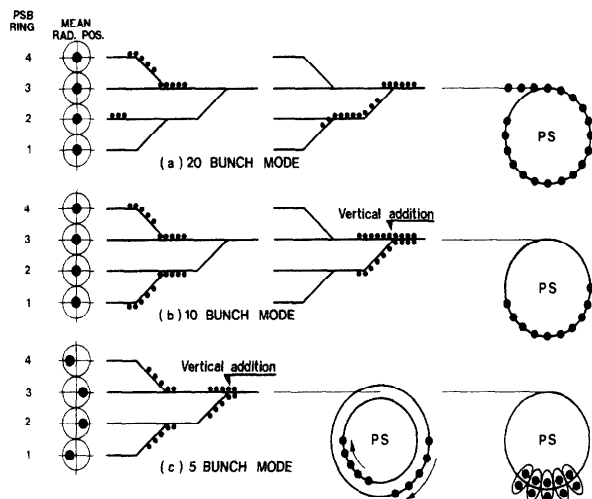


Fig. 1 Recombination principle

The phase space problems associated with the various beam combinations are analysed and the corresponding modifications to the 800 MeV recombination, transfer, and measurement lines are indicated. Matched injection through the PS magnet fringe field was achieved and checked by means of monitors in the PS. The behaviour of the different beams influenced at low energy by strong space-charge and stopbands is described. Beam characteristics obtained in the different transfer modes are summarized in the Conclusions.

Operational PSB to PS transfer (20 bunch mode)

The 20 bunch mode¹ was improved mainly as regards transfer efficiency and beam blow-up, PS injection and matching, as well as the related instrumentation.

Recombination and transfer improvements² (Fig. 2) Doubling of the emittances and intensity with respect to the design values made it necessary:

- i) to increase the acceptances to $A_H = 50 \mu\text{rad m}$, $A_V = 20 \mu\text{rad m}$, $A_L = 12 \text{ mrad}$ (limited respectively by vacuum chamber geometry, kicker strength and kicker rise-time). This was achieved mainly by decentring quadrupoles, tuning the kickers and minimizing beam envelopes. The transfer efficiency was thus brought up to 95% for highest intensity beams, despite the passage through 5 septum magnets.

- ii) to reduce the transverse beam blow-up for 95% of particles to 15% in the horizontal plane and to 20% in the vertical one. For this the influence of the mis-steering of beams from different rings or from one bunch to the next was minimized by placing a narrow vertical waist inside the kickers, optimizing kicker field rise and using 9 position monitors. The effect of the horizontal mismatch between rings due to the different vertical deflections was reduced by matching to the PS acceptance the whole recombined beam around a mean value determined in the measurement line.

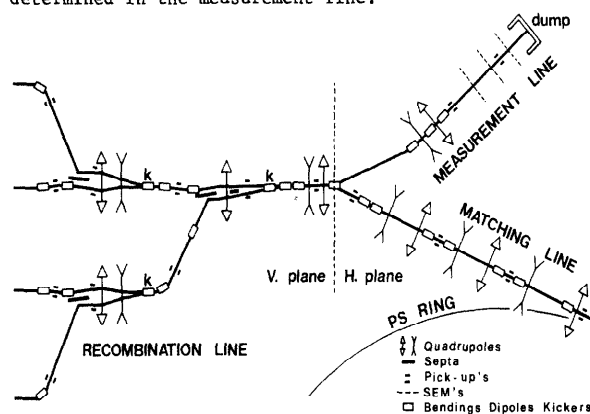


Fig. 2 Booster to PS transfer line

Instrumentation To enable a better setting and measurement of beam quality, the recombination line is being fitted with extra position monitors; the measurement line³ was brought to a state of reliable and precise operation and an on-line treatment program for the Secondary Emission Monitors (SEM) installed in the PS ring and in the measurement line was developed. This program automatically corrects the profile signal for noise and erroneous data, determines the beam tails, then calculates for each individual beam and for the total recombined beam the main transverse characteristics: steering, matching as well as the partial emittances and densities (by integration of the amplitude distribution in phase space deduced⁴ from the projected measured profile). With the help of this program and of special displays (Fig. 3), the 800 MeV measurement line is used in operation daily for routine monitoring of beam quality on pulses not needed for PS injection. Data obtained have been carefully checked: the matching by systematic variations of quadrupole strength and the emittances by comparison with target measurements (agreement to $\pm 5\%$ up to 90% of particles).

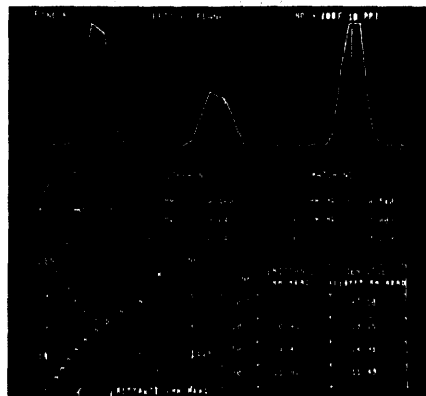


Fig. 3 Main PSB transverse characteristics deduced from SEMs signals in the measurement line

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Injection into the PS The injection principle as already described⁵ has not been changed. A stronger injection kicker of modular design is at present being installed for reasons of flexibility, reliability, and easier maintenance. Moreover the matching of an injected beam into the PS was improved by i) the knowledge of the precise beam parameters deduced from the measurement line; ii) the evaluation of the injection fringe field transfer matrix from correlations between controlled mis-steering of the injected beam and trajectory oscillations around PS closed orbit; iii) the checking of the six matching quadrupole setting by means of the SEMs in the PS ring. A beam of up to 1.65×10^{13} p could then be injected.

Vertical addition (10 bunch mode)

Addition After the corresponding synchronized ejection, the ten equally spaced bunches coming from rings 3 and 4 travel simultaneously in the recombination line with those coming from rings 2 and 1. They follow the usual 20 bunch mode trajectories up to a point where they are vertically added, above and below the 1 mm symmetrical double septum TSMV30, installed for this purpose. At this point, the distance between the two 10 bunch beams is adjusted in order to bring each of them tangent to the septum (Fig. 4). In vertical phase space, the beam resulting from addition is represented by the smallest ellipse circumscribing the two initial beam ellipses. To minimize the vertical emittance of the resulting beam, the respective angles of the two initial beams are adjusted so as to align the axes of their representative ellipses (Fig. 5). Thus the vertical emittance of the beam after addition becomes only 2.65 times that of each initial beam.

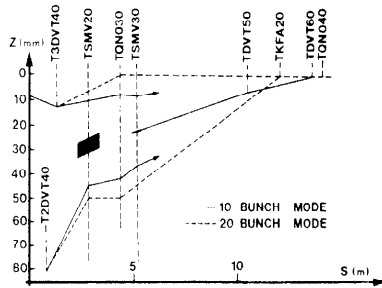


Fig. 4 Vertical addition beam trajectories

Matching The matching parameters of the resulting beam were first deduced theoretically from geometrical addition of the primary ellipses. A new setting of the matching quadrupoles could then be worked out to match this new beam to the PS acceptance in the two planes. With this setting, the horizontal matching of each individual beam remains unchanged, while the vertical one suffers a 66% mismatch. The corresponding values have been measured in the PS by means of the 3 SEMs.

PS acceptance, addition loss trade-off The addition of individual beams with vertical emittances $E_v = 12 \mu\text{rad m}$ at 800 MeV gives rise to a beam with $E_v = 35 \mu\text{rad m}$, which reaches the PS vertical acceptance limit. For larger PSB beams a trade-off between losses on the addition septum (12%) and losses during the first turns in the PS (17%) had to be made in order to keep the beam core unaffected and to provide the best PSB to PS transmission. Thus the addition of the highest intensity PSB beams has been set as if they only had a 10 $\mu\text{rad m}$ vertical emittance. Injection settings in the PS are kept identical to the 20 bunch mode. No change in horizontal trajectories is observed. In the vertical plane, each individual beam, before dilution, oscillates with opposite phase around the vertical closed orbit with a peak-to-peak excursion of 25 mm. The resulting beam is consequently centred on this closed orbit and 1.25×10^{13} p could then be accepted at injection in the PS.

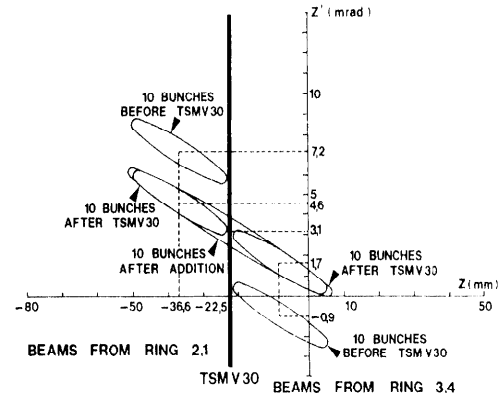
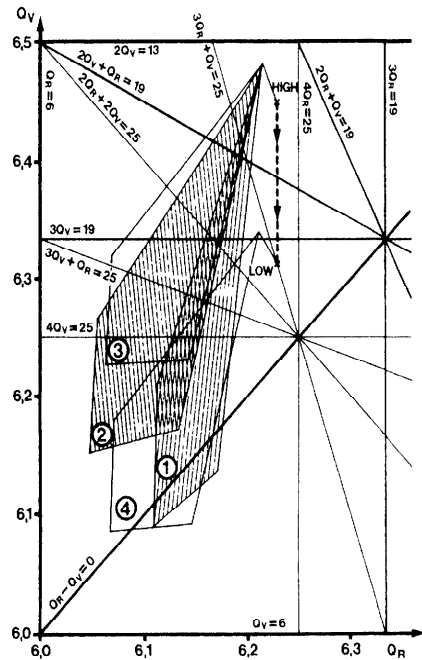


Fig. 5 Vertical phase space at addition septum

Space-charge effects and working point

During betatron oscillations in the PS and before smear-out, the space-charge Q shift = 0.3 suffered by the beam in normal operation, exceeds 0.4 in the 10 bunch mode, due to beam mismatch (Fig. 6). Consequently, the intermediate working point of the 20 bunch mode ($Q_R = 6.23$; $Q_V = 6.35$) fitting the beam between the strong integer $Q_V = 6.0$ and the sextupolar $3Q_V = 19$ stopbands, has to be moved up to a higher Q_V value ($Q_R = 6.23$; $Q_V = 6.45$). Part of the beam then lies on the sextupolar stopbands ($3Q_V = 19$ and $2Q_V + Q_R = 19$), strongly excited by coupling between closed orbit and octupoles powered to damp transverse instabilities. In the future these instabilities will be cured by means of a transverse feedback avoiding the use of octupoles, leaving sextupolar stopbands with their natural strength and making their dynamic compensation easier. Moreover dilution is fast enough to reduce vertical density and allow shifting within 20 ms to a low working point. In fact the incoherent space-charge detuning is strongly affected by the longitudinal and transverse distribution and their evolution with time.



Low-energy longitudinal addition (5 bunch mode)⁶

PSB ejection and PS injection The 4 PSB beams are recombined into two 5-bunch groups as previously described for the 10 bunch mode. As these 2 groups will be trapped in the PS with the phase loop switched off, the revolution frequency in the PS is first tuned to exactly one quarter of the PS one. Then the ejection energy of rings 3 and 2 is increased (+2.5 MeV) by adjusting the synchronized acceleration frequency and the mean radial position. After vertical addition, the beams from these 2 rings constitute the first 5 bunch batch. Similarly the beams from rings 4 and 1 with a slightly decreased energy (-2.5 MeV) are recombined to form the second batch. Transfer of these batches requires phasing of the kickers to the correct frequency, and correction of the horizontal recombination trajectories to inject the beam with the nominal steering. The more energetic batch is injected on its external orbit by slight changes in the injection septum and kicker settings. The resulting oscillation of the less energetic batch around its internal orbit is reduced by means of an ejection kicker used at injection for this purpose. With the new modular injection kicker, different deflection strength can be applied to the 2 batches, allowing for injection without residual oscillation (Fig. 7).

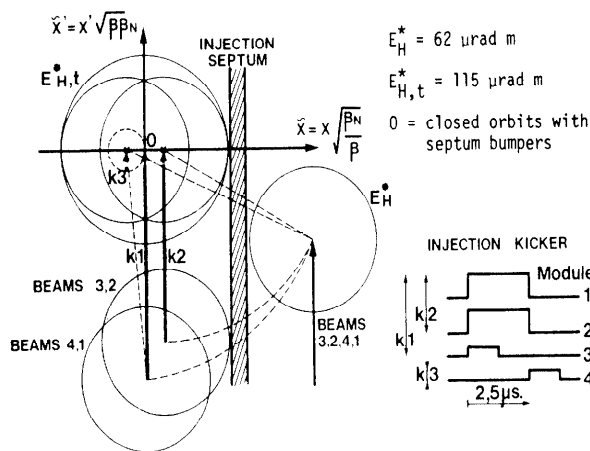


Fig. 7 5 bunch mode injection scheme

Trapping and beam behaviour The PS accelerating cavities are split into two groups, each of them driven by one fixed PSB synchronization frequency. It has been verified that the frequency difference must be at least equal to 4 times the synchrotron frequency to avoid perturbations between buckets⁷. As a result, each of the double beam batches is independently trapped in 16 mrad PS buckets⁸. Owing to the energy difference, the second group overtakes the first one. After about 800 μs, when the 5 first bunches are phased with the 5 others, all accelerating cavities are switched to one of the 2 frequencies and provide their maximum 50 mrad buckets; the phase loop then locked moves this frequency to the superbucket central value. After a few synchrotron oscillations (Fig. 8), filamentation of the 10 initial bunches leads to five 40 mrad superbunches. In the transverse plane, before the 2 batches overlap, smear-out reduces vertical density to a lower value than the one reached in the 10 bunch mode. During the shifting, when 2 bunches are at the same azimuthal position, the corresponding space charge Q_v shift is of the same order as the one suffered in the 10 bunch mode, and the same high working point (Fig. 6) can be used with identical stopband compensations. Nevertheless the evolution of line densities during shifting and synchrotron oscillations, brings some particles to cross the sextupolar stopbands several times and requires a good compensation of these resonances.

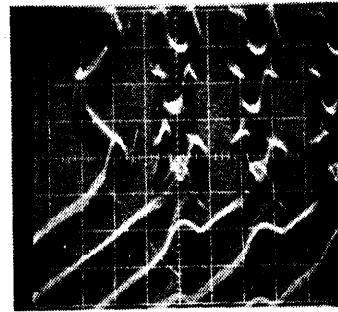


Fig. 8 Oscillations in PS superbuckets after shifting and trapping in the 5 bunch mode

Results A beam of 1.15×10^{13} protons was injected with 5% more losses than in the 10 bunch mode. In fact PS vertical and horizontal acceptances (respectively 35 and 100 μrad m) are filled up -- the former due to vertical addition, the latter due to the injection scheme (Fig. 7). Radio frequency trapping in the 2 buckets of different frequency, and azimuthal shift, are performed with high efficiency. Nevertheless, after trapping in the 5 superbuckets substantial losses (20-30%) occur, which disappear when the injected intensity is reduced by a factor of 2. It was found that only dilution of dense-enough bunches leads to losses (even if only one vertically-added bunch is trapped in a superbucket) and that the beam does not suffer any radial or vertical instabilities. Therefore, losses seem not to be due to transverse space charge effects but could be related to other mechanisms such as microwave instabilities.

Conclusions

The table below sums up the main characteristics of the beams obtained at high energy with the 3 different transfer modes.

Transfer bunch mode	Total No. of part. (10^{12} p/pulse)	No. of part./bunch (10^{16} p/bunch)	Normalized emittance $E^* = 8\gamma E$		Long. emittance (mrad)
			Hor. (μ rad m)	Vert. (μ rad m)	
20	15	75	62	28	8
10	11	110	62	47	8
5	7	140	110	47	40

It appears that: i) the 10 bunch mode provides a 50% increase of longitudinal density, with respect to the 20 bunch mode, without significant prejudice for vertical density; ii) the 5 bunch mode, in spite of its inherent losses leads to twice as many particles per bunch as in normal operation. Improved figures could be obtained with the future PSB beams, of higher vertical density⁹. From these 3 transfer modes, already used for the Initial Cooling Experiment, the 10 bunch mode is retained as part of densification for \bar{p} production¹⁰.

Acknowledgements

We are grateful to D. Boussard and R. Cappi for their precious collaboration, particularly in experiments concerning longitudinal behaviour.

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