INJECTION AND TRAPPING OF THE BEAM AT 800 MeV IN THE CPS

D. Boussard, M. Bouthéon, B. Carpenter, P. Lefèvre, J.P. Potier
CERN, Geneva, Switzerland

Summary

The principles of injection and trapping of the 800 MeV beam from the CERN PS Booster are briefly described. A local deformation produced by a set of four bumpers displaces the closed orbit on the edge of a septum magnet, while the incident beam is made to jump the septum thickness by a full aperture kicker. The PS buckets are matched to the incoming bunches; the normal accelerating conditions are then reached adiabatically. A short review of the equipment needed for inflection, longitudinal trapping, acceleration and beam measurements is made. Results obtained in running-in sessions and operation are summarized.

Introduction

The CPS improvement programme[1] was essentially completed in the second half of 1973 by the successful increase of the accelerated proton intensity using the Booster injector.

This paper describes the injection equipment and operating procedures. Two kinds of system are used, a specific one for the 800 MeV PSB beam inflection, and a general-purpose one adjusted for this usage. This is necessary because the CPS has two modes of operation: one at 50 MeV from the Linac and one from the PSB. The computer has proved to be a great help for these applications.

Injection

Principle

The slow-cycling injector synchrotron (PSB) has been described elsewhere[2,3] as well as its performance [4,5,6]. The beam extracted from the 4 PSB rings is recombined and measured in a transfer line[7,8,9]. Matching is also achieved there by a set of 6 quadrupoles and drift spaces.

The principle of monoturn injection[10] is rather simple. A localized deformation of the CPS closed orbit allows using a fixed septum magnet, lying outside the synchrotron acceptance, as an input point in the machine. Four horizontal dipoles (septum bumpers) produce a forced closed orbit deformation over two magnet periods (1 betatron period = 8 magnet periods). Currents are calculated to produce the desired displacement with no residual deformation outside the inflection region. Local fluctuations of the focusing betatron function (β) were taken into account since a 2 10^{-3} error on one deflection leads to a 1 mm residual deformation. The incoming beam is brought on the closed orbit by a fast deflection at half a wavelength away from the end of orbit deformation.

Initial inflection conditions are achieved horizontally by a dipole in the transfer line and the septum magnet and vertically by two dipoles before the CPS input. Energy adjustment is made by a synchronization between the two machines, based on a very accurate pulse train linked to the magnetic field of the CPS (10 μT resolution with 3 μT jitter)[11].

The aim of the procedure is to achieve the conditions given in Fig. 3. The emittance of the incoming beam, suitably matched, determines the jump to be made at the level of the septum. Synchronization is fixed by the PSB energy; it is only necessary to adjust the local closed orbit deformation so as to avoid any residual betatron oscillation. The usual strong focusing synchrotron matrix calculations show that only the closed orbit angle and position at the septum level have to be adjusted. The use of 4 dipoles gives an additional degree of freedom which is used to cater for some possible future acceptance-limiting conditions (vertical stacking, two-turn radial injection). The hardware specifications allow incoming beam emittances (95% of the particles) of $E_H = 33\ \pi\ 10^{-6}$ rad.m and $E_V = 12\ \pi\ 10^{-6}$ rad.m, on closed orbits which at the input point can vary horizontally between + 15 and - 7.5 mm in position, ± 0.6 mrad in angle, and vertically between ± 5 mm and ± 0.25 mrad.

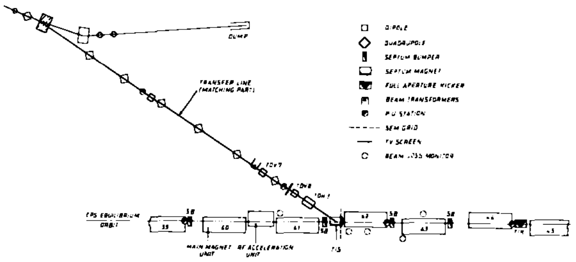


Fig. 1 Layout of inflection region

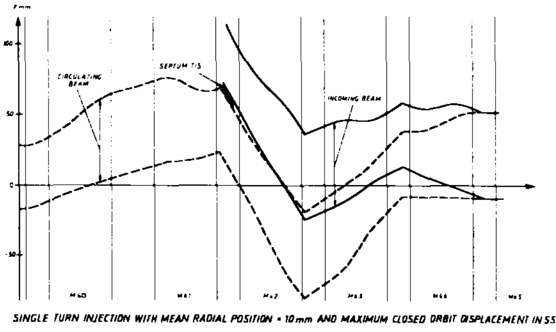


Fig. 2 General optics for 800 MeV injection

Control of magnetic state of the CPS

This system comprises the set of magnetic corrections of up to the 3rd order to control the CPS magnetic state up to about 6 GeV/c for both 50 and 800 MeV injections.

The general policy adopted for the upgrading of this system[12] was to provide independence by using one supply for each lens. The various compensating circuits (in particular harmonics) are achieved by computer programming.

The location of the various elements in the machine is such as to ease some compensation by avoiding dangerous harmonics and minimizing bothersome secondary effects. The corrections enable adjustment of the working point and to act on all stopbands up to the 3rd order in the given energy range. This is necessary because of the working point chosen and the space charge effects observed[13,14]. The effect of octupolar resonance has not yet been demonstrated at these low energies but has been studied above transition[15]. The low-energy magnetic corrections are summarized in the following table.

Lens type	No	Description	Maximum strength per lens	Power supply	Use and performance (at 800 MeV)
Horizontal dipoles	20	2-turn windings on the main magnet yoke	10^{-3} Tm (4 mm)	± 10 A 50 V	local + 6th, 7th harmonics radial closed orbit < 8 mm ptp
Vertical dipoles	20	air core on araldite frame *	2.6 10^{-5} Tm	± 10 A 30 V	local + 6th, 7th harmonics vertical closed orbit < 5 mm ptp
Normal quadrupoles	40	air core (L = 15 cm) * 20 at β_{Hmax} locations 20 at β_{Vmax} locations	5.6 10^{-2} T	± 10 A 40 V	zero harmonic: ΔQ_{max} = 0.35 13th harmonic, horizontal and vertical (stopbands $2Q_i = 13$)
Skew quadrupoles	40	idem * on the same frame as the vertical dipoles	3.5 10^{-2} T	± 10 A	zero harmonic ($Q_R = Q_V$) and 13th harmonic ($Q_R + Q_V = 13$)
Normal sextupoles	16	air core, in the straight sections 8 at β_{Hmax} locations 8 at β_{Vmax} locations	2 T.m^{-1}	± 20 A 60 V (± 40 A for enlarged lenses)	zero harmonic (chromaticity variation ± 0.5) 19th harmonic (stopbands $3Q_R = 19$, $2Q_V + Q_R = 19$)
Skew sextupoles	16	idem on the same frame and concentric with the normal sextupoles	2 T.m^{-1}	idem (± 60 A for enlarged lenses)	zero harmonic, 19th harmonic (stopbands $3Q_V = 19$, $2Q_R + Q_V = 19$)

* located between the main magnet coil head

These lenses are excited by medium-power amplifiers steered by programmed voltages which can be time-dependent functions or linked to the magnetic field. These voltages are produced by computer-driven function generators[16]. All the parameters are digitized and acquired by the computer.

Inflection system

This whole set of elements[17,18,19,20,21] was specifically designed for the injection of the beam coming from the Booster and is also entirely computer-controlled. The name and location of the various elements can be found on Fig. 1. Their characteristics are summarized below.

Type of element	Main characteristics	Power supply	Performance	Use and remarks
Transfer dipole (TDH3, TDV7, TDV8)	± 8 mrad	dc ± 20 A	stability: ≤ 10^{-2}	determination of initial conditions
Septum magnet (TIS)	gap height: 60 mm gap width: 100 mm septum thickness: 6 mm 66 mrad	dc 1960 A	field homogeneity: ± 2.10^{-3} stability: ≤ 10^{-4}	located in a β_{Hmin} straight section, adjustable in radial and vertical positions and in angle
Septum bumpers (SB)	gap height: 90 mm gap width: 212 mm on metallized ceramic chamber 23.2 mrad	condenser discharge half sine wave current (f = 240 Hz) 4000 A	accuracy: ≤ 10^{-7} stability: 3.10^{-4}	4 in CPS straight sections; the discharges are balanced to limit the residual closed orbit to a few 1/10 mm during the pulse
Fast kicker (TIK)	delay line kicker gap height: 54 mm gap width: 150 mm 3.7 mrad	60 kV delay line 2.5 µs pulse length	stability: 2.10^{-3} ripple: 2.10^{-2} fall time: 50 ns	the discharge instant is stabilized by feedback

The general synchronization of the injection is derived from a master pulse linked to the main CPS magnetic field. This master pulse defines the injection timing. Pre or post pulses synchronize the PSB ejection transfer and the CPS injection. To synchronize the bunches, pulses linked to the PSB accelerating voltage are used (fine tuning of recombinations, TIK, etc.). Most of the adjustments are made via a computer.

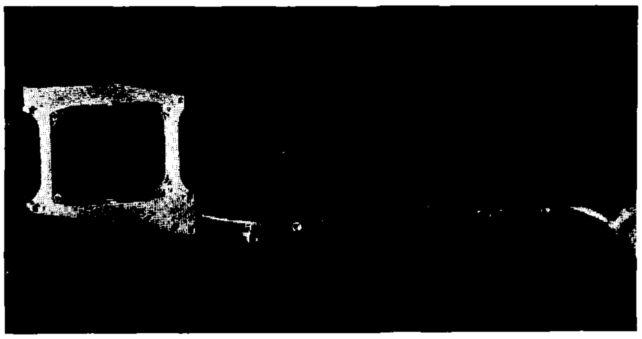
Transverse beam observation and measurements[22]

Beam position is checked by a few TV screens but mainly by electrostatic PU electrodes (two at the end of the transfer). The usual CPS trajectory measurement system[23] is the main tool for fine tuning of the inflection, thanks to the 1st turn synchronization in a given bunch.

Independently of the data given by the PSB instrumentation[24], a set of current transformers[25], located at the end of the transfer line and in the CPS, measure the beam intensity. The signals are used for analog observation and are afterwards integrated and digitized (for elaborate numerical display. The frequency range of interest is covered by passive (60 MHz) or active transformers with various integration ranges (with the possibility of independent digitizing of the first 6 turns).

Signals of 6 beam loss monitors with ACEM-type photo-multipliers[26] are used to detect the likely cause of an inflection loss: analog observation and integration digitization, gated to choose the timing of the measurement (n turns after hth).

The most sophisticated apparatus is for emittance and matching measurements. A set of 10 secondary emission wire monitors (SEM grids[27]) is used with a double monitor on the incoming and circulating beam at the septum exit, and 3 monitors at 3 λ/8, 5 λ/8 and 6 λ/8 from the inflection point in both transverse planes. The measuring grid is made of 32 0.1 mm Cu-Be wires, spaced by 2 mm. The charge on each wire is integrated over one CPS turn and digitized. The data are processed by computer to reconstruct the beam profile and with 3 profiles the injected beam emittance can be computed and its matching checked. The double monitor is also used to check whether the injection is correct.



SEM grid and its mechanical positioning device

Measured beam profiles. Left: circulating beam. Right: both incident/circulating beams

Longitudinal Trapping

Principle

The PSB bunches have to be matched to the CPS RF buckets by modifying the main magnet Ḃ and the RF voltage, and normal conditions are then reached rapidly but adiabatically. Several methods were possible, depending upon the dilation allowed. The following was chosen as the best compromise between various requirements (accuracy of synchronization from magnetic field

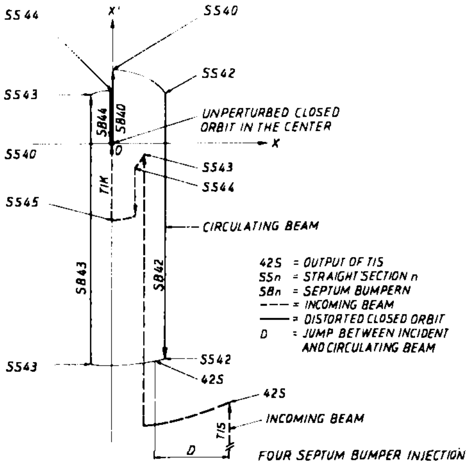
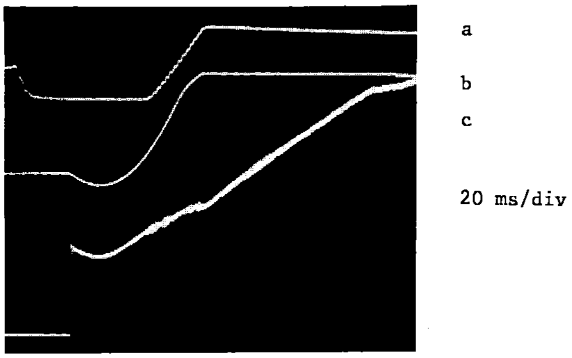


Fig. 3 Inflection trajectories in a normalized phase diagram

derived pulses among others): $\dot{B} = 0.22\ \mathrm{Ts}^{-1}$, initial bunch length 145°; RF voltage: 37.5 kV, stable phase angle 15°, which give a theoretical 5% dilation after matching. $\dot{B}$ is kept constant for 20 ms, then raised linearly to $2.3\ \mathrm{Ts}^{-1}$ in 20 ms, which is compatible with the adiabaticity condition (synchrotron period of 0.4 ms). The RF voltage is simultaneously adjusted to prevent the bunch length decreasing faster than $(\beta\,\gamma^2)^{-1}$ in order not to increase the transverse space charge forces.

Moreover, the accelerating voltage is adjusted so that the buckets are almost filled in order to prevent possible instabilities by Landau damping.



a = main magnet $\dot{B}$, b = RF voltage envelope,
c = wide-band pick-up signal (detected)

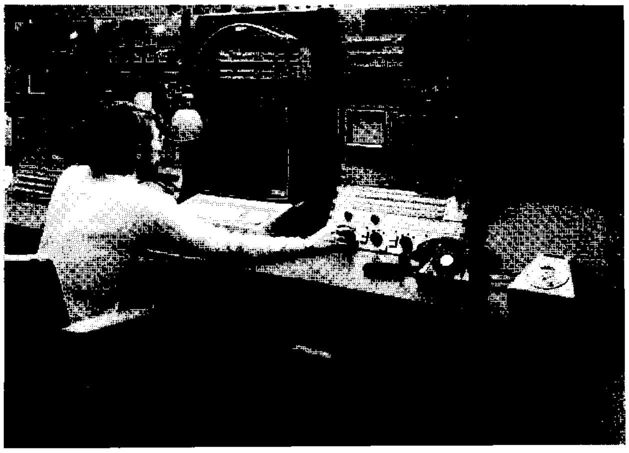
Equipment and measurements

The general phase and radial CPS beam control system[29] has not been modified. The usual adjustments are used and are not described here. The only elements specific to the 800 MeV injection are the initial accelerating voltage programming and the synchronization with the RF of the PSB.

The latter is achieved before injection proper by replacing the PS phase PU signal by one coming from the reference oscillator of the PSB, which is properly phase matched. The usual observations related to the acceleration (radial position error, stable phase, etc.) and to the feedback loops, are used. Beam behaviour is observed with wide-band (1 GHz) electrostatic PU electrodes which enable the evolution of the longitudinal density and its stability during acceleration to be followed. Fast sampling and digitization of these signals is also possible[30].

Operator Interaction

All controls are made using an IBM 1800 computer and its data transmission system[31], with the exception of those for longitudinal capture and acceleration. In consequence all operator access is concentrated at one console[32], which is centred on an alpha-numeric and graphical display. Adjustments and beam observations are made by using the display with the aid of a keyboard and four shaft encoders. The basic software tool is an interpretive syntax, ISAAC (Interpretive System for Automated Accelerator Control[33]). This makes it possible to establish a setting-up procedure employing the calculations mentioned above, and displaying theoretical parameters to the operator in normalized units and in a decoupled form. This has been a significant factor in the success of this injection. For example, the closed orbit is adjusted relative to the injection septum, while keeping the resultant deformation automatically at zero, without the operator having to concern himself with the actual currents in the various dipoles. In addition, it is possible to store reference measurements on the computer's disk store, and by subtracting the present values to display in real time such features as the residual betatronic oscillation at the injection. Since this constitutes the difference between the closed orbit and the actual trajectory, its minimization via the console is, in fact, the fine tuning of the injection.



The injection console

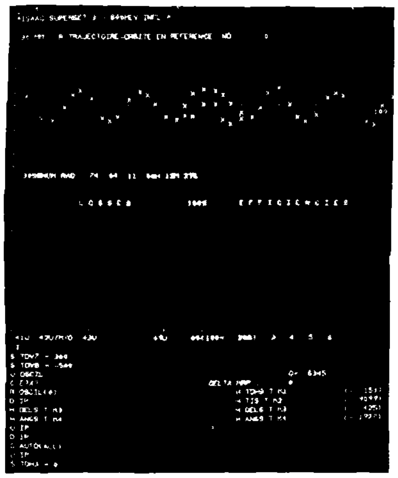
A complete description of the console is outside the scope of this paper. It is however worth noting that all the relevant analog signals are under computer control, providing centralized multiplexing, selection and identification of 225 signals up to 2 MHz and 225 more up to 30 MHz. The simultaneous availability of a large number of analog, numeric and graphical data has been of incomparable help in the understanding, running-in and operation of the injection from the PSB.

Results

After the usual equipment checks for the running-in of a system of this complexity, study sessions (12 hours per month on average) gave the following results in 1973.

"Nominal" beam (from a single PSB ring)

Initial conditions at transfer: intensity $\sim 10^{12}$ p^+/p, $E_H = 21\ 10^{-6}\ \pi$ rad.m, $E_V = 9\ 10^{-6}\ \pi$ rad.m, obtained by target collimation; radial and vertical positions ≤ 2 mm, longitudinal emittance 9 mrad ($\Delta p/m_0$ c, RF rad). Transverse trapping: 97 ± 2%, longitudinal trapping 100%, residual oscillation < 1 mm. Matching: at its best leads to a dilation of about 10% horizontally and 20% vertically (controlled by SEM grid at injection and targets at 10 GeV/c). Loss-less acceleration of $\sim 10^{12}$ p^+/p. Transition crossed without losses or longitudinal blow-up, thanks to the use of the γ-transition jump[34]. Longitudinal instabilities avoided by careful optimization of the accelerating voltage[35]. Longitudinal density twice as large as a 50 MeV injected beam. Transverse instabilities damped by octupoles[36].

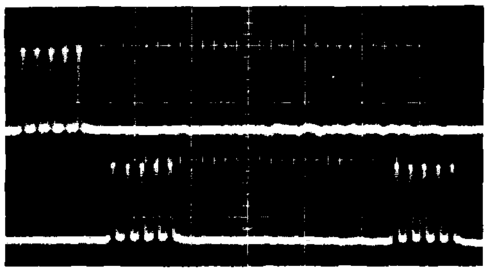


oscillation (first turn)

losses and efficiencies

some instructions of current use

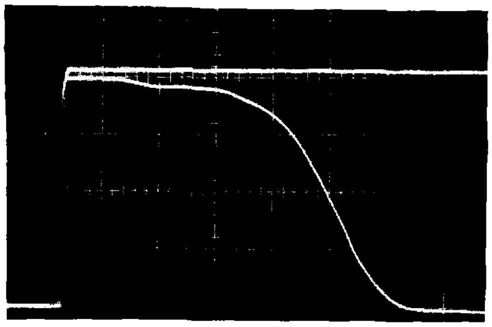
Example of use of alpha-numeric and graphic display



5 bunches (one PSB ring) at end of transfer (a) and two first turns in CPS (b)

"Intermediate intensity" (4 PSB rings)

PSB beams without collimation give: E_H = 24 to 30 $10^{-6}\ \pi$ rad.m; E_V = 14 to 20 $10^{-6}\ \pi$ rad.m; intensity = 1 to 1.5 10^{12} p^+ by ring, depending on the ring. Losses at inflection $\sim 15\%$. Longitudinal trapping 100%. Loss-less acceleration giving about 5 10^{12} p^+/p at 26 GeV/c. In addition to the dilation mentioned above, an initial blow-up occurs due to differences between the rings; after this, no noticeable blow-up appears until 10 GeV/c. However, from 10 to 26 GeV/c, there is an unexplained vertical emittance increase by a factor ≤ 2. Successful tests of fast extraction (26 GeV/c, efficiency $\geq 97\%$) and slow extraction (6 1/3 resonance, 200 ms spill at 24 GeV/c, efficiency $\geq 90\%$) preceded operational use of the system.



"Slow" transformer signals: a = with acceleration
b = coasting beam.

Operation

The "intermediate intensity" has been used several times essentially for the neutrino channel. During these periods the overall PSB - CPS reliability proved to be reasonably good (same failure rate as usual). The peak intensity reached was 6.5 10^{12} p^+/p and 5.58 10^{12} p^+/p was averaged over two weeks.

Near future

Some improvements are planned to achieve reliable operation at 10^{13} p/p:

- to obtain this intensity within the nominal emittances and to refine the matching, avoiding the initial losses at inflection
- to improve the stabilization process of intense beams to maintain high density
- to complete computerization[37,38] providing automatization of procedures and monitoring
- to complete density distribution measurements and studies of their perturbations from injection to medium energies[39].

Acknowledgements

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