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PAST AND PRESENT OPERATION OF THE CERN PS BOOSTER

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This paper reviews 40 years of operation of the CERN Proton Synchrotron Booster, from the commissioning in the early 1970s until today's operation as injector for the Large Hadron Collider (LHC) and as one of the backbone accelerators for CERN's fixed-target physics program.

Keywords: Accelerators; cyclic; synchrotrons; charged particle beams in accelerators.

PACS numbers: 29.20.−c, 29.20.D−, 29.20.dk, 29.27.−a

1. Introduction

On 26 May, 1972, the CERN Proton Synchrotron Booster (PSB) accelerated for the first time protons to the design energy of 800 MeV. This marked the beginning of by now 40 years of operation, continuous upgrade and optimization. The machine is today operating in a parameter range which exceeds the design parameters in terms of energy, beam intensity and beam brightness (ratio of number of protons per bunch N_b and normalized average emittance ε^*) by large factors. Moreover, the machine reliability after 40 years of operation is at the 95% level or beyond.

2. A New Injector for CERN's Proton Synchrotron

Prior to construction of the Booster, protons were accelerated up to 50 MeV in a linac (CERN's Linac1 at the time) and injected directly into CERN's Proton Synchrotron (PS) to be accelerated up to 26 GeV. Around 1960 the PS machine had reached an extracted intensity of about 10^{10} protons per pulse (ppp), and by the mid-1960s the extracted intensity had been increased to 10^{12} ppp. However, new and demanding clients — the Intersecting Storage Ring (ISR) and the Super Proton Synchrotron (SPS) — were being discussed, and the requested beam intensities were out of reach of what could be delivered by the PS at the time.

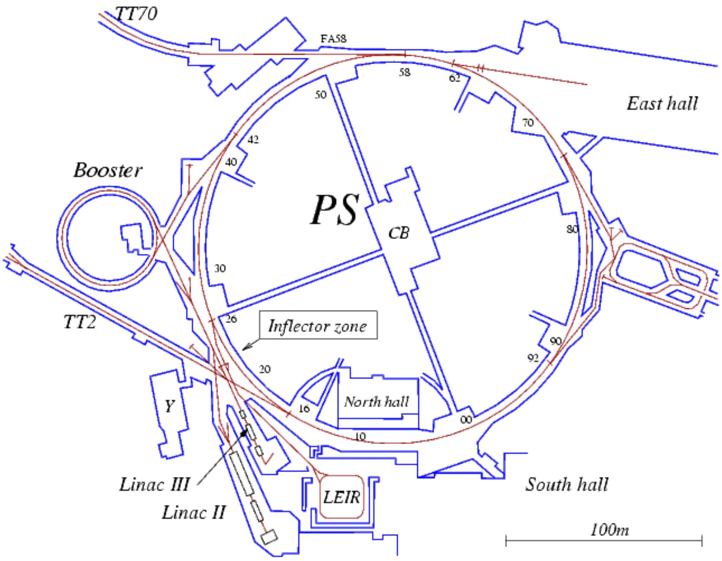

Fig. 1. Implantation of the PSB as pre-injector for the PS.

A way was therefore to be found to further increase the beam intensity out of the PS by one order of magnitude to 10^{13} ppp. Since the main intensity limitation was identified to be the Laslett tune spread (see Subsec. 5.3), proportional to $\beta^{-1}\gamma^{-2}$, an increase of the injection energy into the PS by at least a factor 10 was aimed at. In the years 1966–1967 different scenarios for a new PS injector were studied. Besides a new 200 MeV linac, the option of adding a synchrotron as pre-injector for the PS was on the table. This synchrotron solution could either be a Rapid Cycling Synchrotron (RCS), two interlaced rings at 600 MeV (Twin Accelerator Ring Transfer (TART)) or a system of four superposed rings at 800 MeV. Eventually the choice fell on an 800 MeV, slow-cycling 4-ring Booster synchrotron. Its injection energy would remain 50 MeV, but each of the four rings could be filled up to the same space-charge limit as before the whole PS ring, yielding a factor 4 in intensity. Moreover, the machine design would allow for longer bunches, yielding an additional factor 1.5 in intensity. Construction of the machine took place in the years 1968–1972, with the center of the machine lying exactly on the Swiss–French border (Fig. 1).

3. Machine Design

3.1. *Vertical distribution system*

Design and construction of the PSB posed a number of technological challenges at the time. Injection into and extraction from the four Booster rings requires a complicated system which is touched here only very briefly. Before being injected into the Booster rings via a multi-turn injection process, the 50 MeV proton beam from the linac is split up vertically by a dedicated system consisting of the so-called

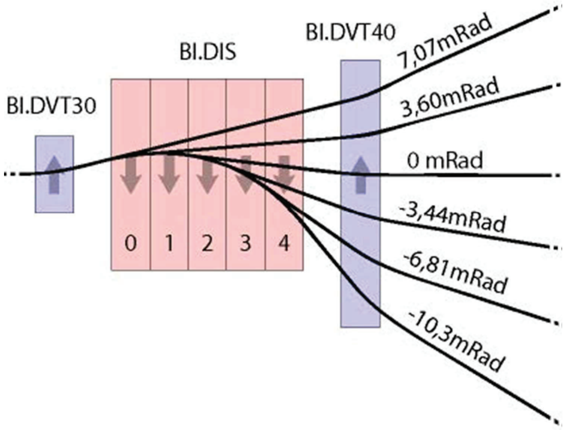

Fig. 2. Schematic representation of the proton distributor splitting the incoming beam into up to four slices. The initial deflection angles are increased by a downstream vertical septum.

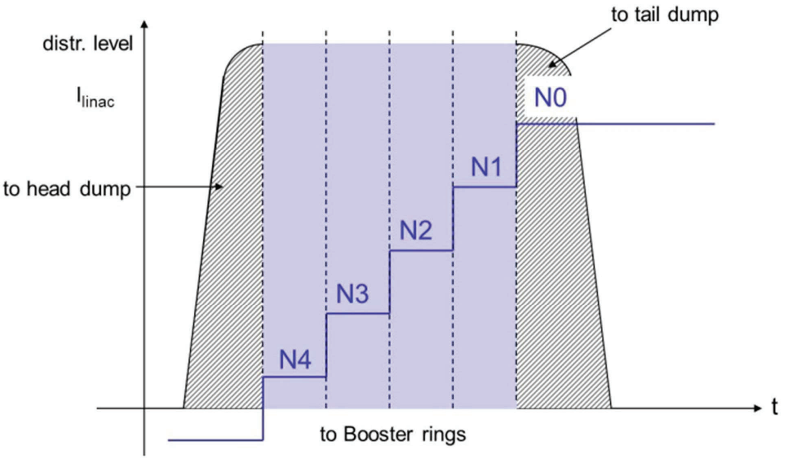

Fig. 3. Beam pulse from the linac split up into slices by the proton distributor.

proton distributor and a vertical septum. The proton distributor is a series of pulsed magnets which give small deflection angles to the incoming beam pulse from the linac. The deflection happens by successively activating the five modules of the distributor which, in conjunction with a downstream vertical corrector dipole, give small angles to the four beamlets (Figs. 2 and 3). The beamlets get further deflected by a vertical septum. The rings are filled from top to bottom (4-3-2-1). The rising and falling edge of the linac beam pulse are dumped in dedicated absorbers (head and tail dump) integrated in the vertical septum. Once the separation of the beam slices has reached that of the Booster rings, they are deflected back into the horizontal plane. Figure 4 shows schematically the vertical septum and the magnets which

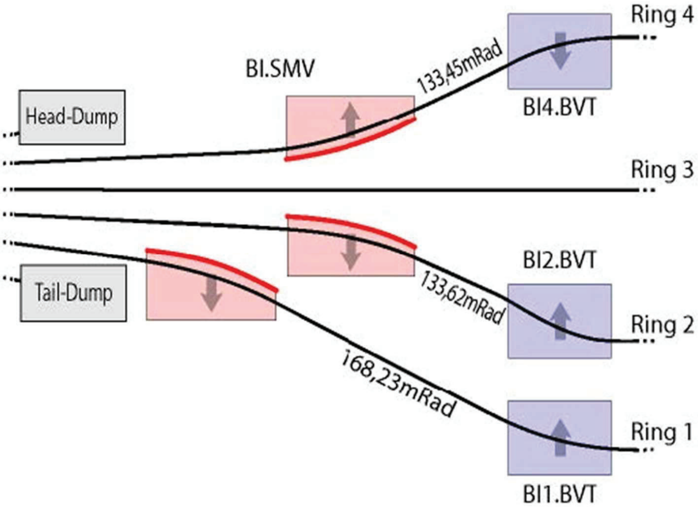

Fig. 4. Schematic representation of the vertical septum, which increases the deflection angles given by the distributor. A stack of dipoles bends back the beams in the plane of the four rings once the final separation is reached. Dedicated absorbers (head and tail dump) are integrated in the septum to absorb the rising and falling edge of the beam pulse coming from the linac.

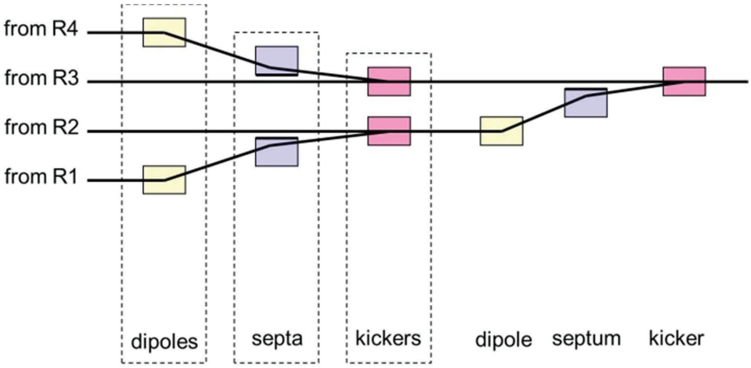

Fig. 5. Recombination of the four Booster rings with a system of vertical septa and kickers.

bend the beams back into the plane of the PSB. Each beam slice is then injected into its corresponding ring by means of multi-turn injection (see Subsec. 5.1).

3.2. *Recombination system*

At the end of the acceleration cycle, the bunches in the four Booster rings are first synchronized and then extracted by a system of slow bumpers (extraction bump), fast extraction kicker and a horizontal extraction septum (see Subsec. 5.2). The beams from the four rings are then recombined by a system of vertical kickers and septa in the order 3-4-2-1 (Fig. 5).

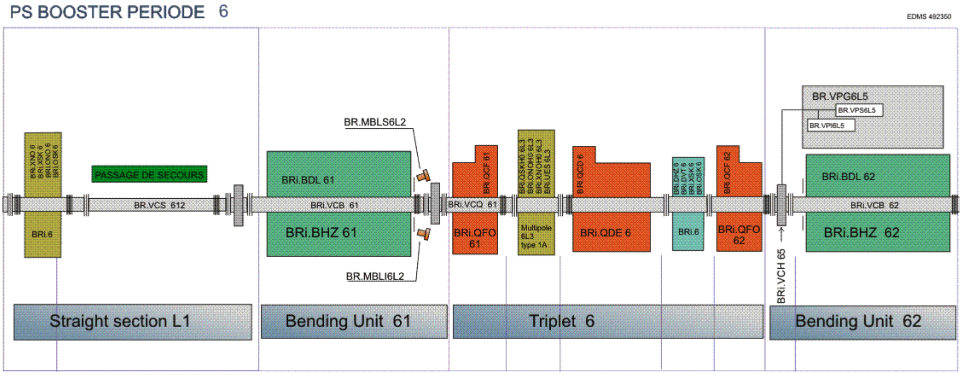

Fig. 6. Period of the PSB with two main dipoles, quadrupole triplet and straight sections.

3.3. *Booster rings*

The Booster rings have a radius of 25 m (1/4 the radius of the PS). They consist of a total of 32 dipoles and 48 quadrupoles (separated function magnets, unlike the combined function magnets of the PS). Each of the dipoles and quadrupoles consists of a stack of four magnets with a common yoke, allowing them to be powered in series by a single main power supply. Additional coils and trim power supplies allow individual adjustment of the rings. The main technological challenges at the time of construction were the field quality and equality between rings, kickers with fast rise and fall times, power supplies operating directly from the electrical network and the then innovative computer controls. The design aimed at flexibility and reliability, and good safety margins were applied which would prove to be very useful in the years to come.

The Booster has a periodicity of 16, where the same sequence of main magnetic elements is repeated. Each of the periods contains two main dipoles and a triplet of quadrupoles. Five straight subsections leave place for diagnostics, correctors and other equipment. Figure 6 shows schematically a period of the PSB.

4. Commissioning

Running-in of the PSB took place from May 1972 to December 1973, where in a first phase an intermediate intensity of 5×10^{12} ppp could be accelerated. In a second commissioning phase, the design intensity of 1×10^{13} was reached in 1974. Between these two milestones there was a period where the further commissioning was put on hold and even questioned. First of all, the PS had already reached an extracted intensity of 1.7×10^{12} ppp, essentially sufficient for the ISR, which had by then started up. Before start-up of the SPS, planned for 1975, there was no real need to further increase the intensity. Therefore, the compromise was found to stay temporarily with the intermediate intensity. The further commissioning was hampered by a number of constraints and problems. First of all, pulsing of the PSB was not allowed while the ISR was in coast (electrical perturbations). Furthermore, a power limitation imposed a flat top of well below 800 MeV. In addition there were a number of equipment failures, water intrusion and stability problems with the linac beam. The key dates during the first commissioning phase were in chronological order (see Ref. 1):

- 1 May 1972: first beam in ring 3, one single turn.
- 5 May 1972: circulating beam in ring 3.
- 17 May 1972: circulating beam in all rings.
- 25 May 1972: first RF capture and acceleration to 130 MeV.
- 26 May 1972: acceleration to 800 MeV.
- 30 June 1972: 2×10^{11} protons extracted from ring 3 at 800 MeV.
- 24 August 1972: first beam injected into the PS.
- 1 September 1972: 5 bunches circulating in the PS at 800 MeV.
- 21 December 1972: 6×10^{12} ppp, 800 MeV, sum of all rings.
- 22 December 1972: 2.55×10^{12} ppp, 800 MeV, ring 3.
- 19 October 1973: 5.2×10^{12} ppp in the PS at 26 GeV, intermediate intensity goal reached.
- 14 November 1973: 5.4×10^{12} ppp in the PS at 26 GeV, delivered to Gargamelle.

Throughout the first half of 1974 the Booster operated at the intermediate intensity, and there was only limited time available for machine studies. The beam behavior beyond the operational intensity of 5×10^{12} was known to be space-charge dominated. However efforts continued, and eventually two main novelties paved the way to nominal intensity and emittance: a new, high working point and the stabilization of longitudinal instabilities via “Magnani Shaking” (see Subsec. 5.4). A first test of the Magnani Shaking was performed on 14 June 1974, and on 18 June 1974 the PS could extract 1.02×10^{13} at 10 GeV. The commissioning of the Booster to its design intensity was fully completed.

5. Accelerator Physics Challenges

5.1. *Multi-turn injection*

Beams are injected into the single Booster rings via multi-turn injection. For this, a horizontal injection bump is generated using four bumper magnets. The incoming beam from the linac is deflected by the injection septum and performs oscillations around the deformed Booster orbit (Fig. 7).

During the injection process, the amplitude of the injection bump decreases linearly. As this process takes place, subsequent linac beam “slices” are injected, with increasing oscillation amplitude around the instantaneous closed orbit (“horizontal stacking”) (Fig. 8). Since not only the incoming beam slices are cut by the septum at injection, but they touch again the septum during their first few turns in the machine, the remaining beamlets are polygons which have lost a substantial part of their initial intensity (Fig. 9). As the amplitude of the injection

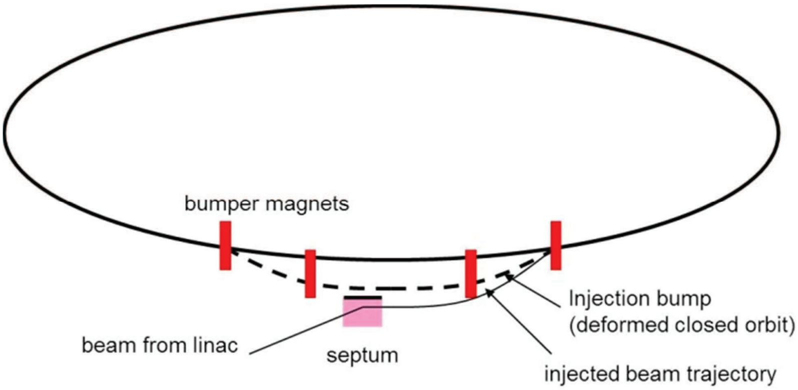

Fig. 7. Injection process. The amplitude of the injection bump decreases linearly with time, filling the phase space by horizontal stacking.

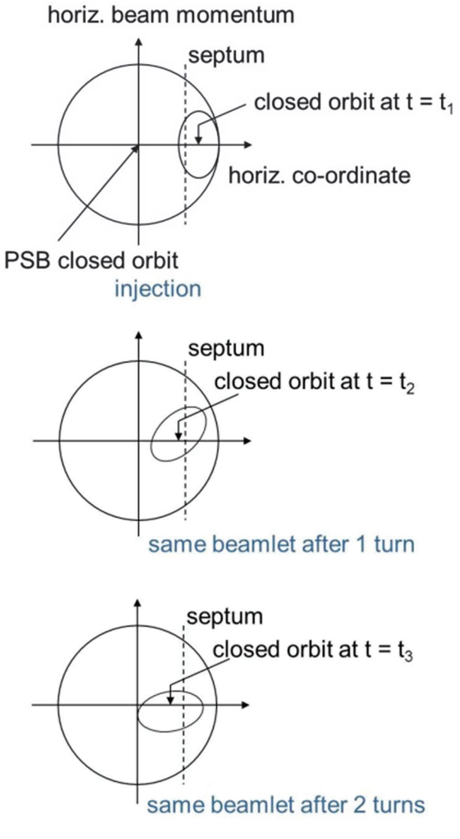

Fig. 8. Multi-turn injection. At $t = t_1$ the incoming beam hits the septum for the first time. Once circulating in the machine, the same beamlet touches the injectum septum several times losing a significant fraction of its initial intensity.

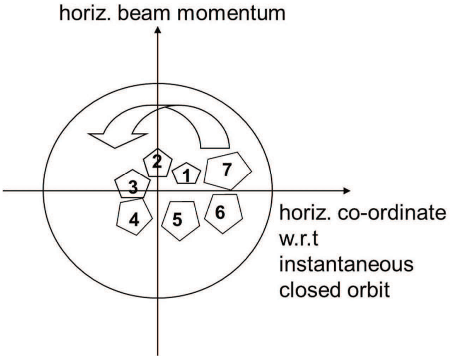

Fig. 9. Process of horizontal stacking. Subsequent linac beam slices are injected with increasing oscillation amplitude around the instantaneous closed orbit. The beamlets are polygons, as they have undergone several cuts at the injection septum. They spiral up around the (moving) closed orbit, leading to an intensity distribution which is dense in the core and less dense in the outer part.

bump decreases, the phase space is subsequently filled up with beam slices which spiral up around the (moving) closed orbit, leading to a density distribution which is dense in the core and less dense in the outer part. The beam size is given by the overall envelope of the injected beamlets (today between 2 and 3 turns for LHC-type beams and up to about 13 turns for high-intensity beams). The number of injected turns per ring can be chosen by the operator and determines the length of the beam pulse sent by the linac. The beam size (and hence the transverse emittance) is a linear function of the injected number of turns.

5.2. *Fast extraction*

Before extraction from the Booster rings, the bunches are synchronized on the flat top of the cycle and in the example below they are physically superposed (Fig. 10). The phase and hence spacing of the extracted bunches is controlled by the operator according to the needs of the beam user.

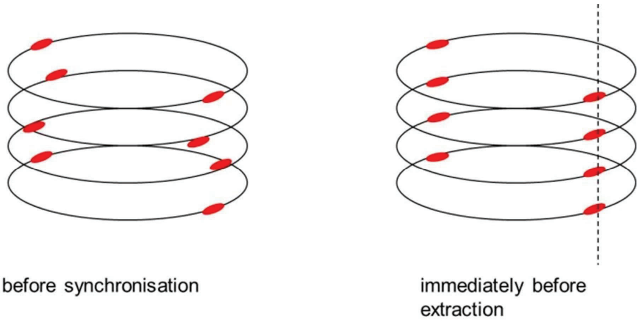

Fig. 10. Immediately before extraction the beams of the four rings are synchronized such that the bunches are physically superposed. The example shows a second harmonic beam.

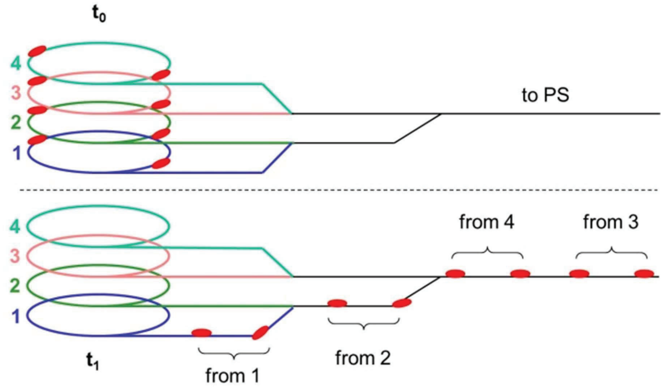

Fig. 11. The extraction is performed in the order 3-4-2-1. This order is imposed by the time constants of the recombination kickers. The example shows a second harmonic beam used to fill the PS at harmonic 8.

The extraction process takes place in the order ring 3–ring 4–ring 2–ring 1 (Fig. 11). This order is imposed by the recombination kicker time constants. The ejection mode is a fast extraction, i.e. the bunch or bunches from one ring are extracted in one turn. In the above example, a complete extraction from the machine takes therefore four times the revolution period of 572.8 ns (at 1.4 GeV), i.e. 2291 ns. In the case of a single harmonic beam, the timing between bunches can be reduced (the limitation being the recombination kickers in the transfer line) typically giving four bunches extracted within 910 ns.

5.3. *Space-charge and tune spread*

Accumulating a high charge at injection energy (50 MeV) in the PSB leads to space-charge effects due to Coulomb force repulsion of the particles. The strong space-charge results in a large tune spread at injection energy, which covers several stop bands leading to beam loss (Fig. 12). With increasing energy space-charge effects are reduced ($\beta^{-1}\gamma^{-2}$ dependence) and so is the tune spread.

During the early days of operation, the working point, originally set to ($Q_H = 4.8, Q_V = 4.8$), was moved to ($Q_H = 4.2, Q_V = 5.3$) to avoid repeated stop band crossing and hence beam blow-up and losses. In addition, a fast move of the working point (Q_H, Q_V) during acceleration to an area clear of stop bands proved to be beneficial. The remaining stop band crossings during the acceleration process are compensated by multipole correctors.

5.4. *Instabilities*

From the early days the Booster suffered from longitudinal and transverse instabilities. Longitudinal instabilities were first fought by "Magnani Shaking," where the RF phase was modulated by ∼4 kHz after RF trapping. This novel technique

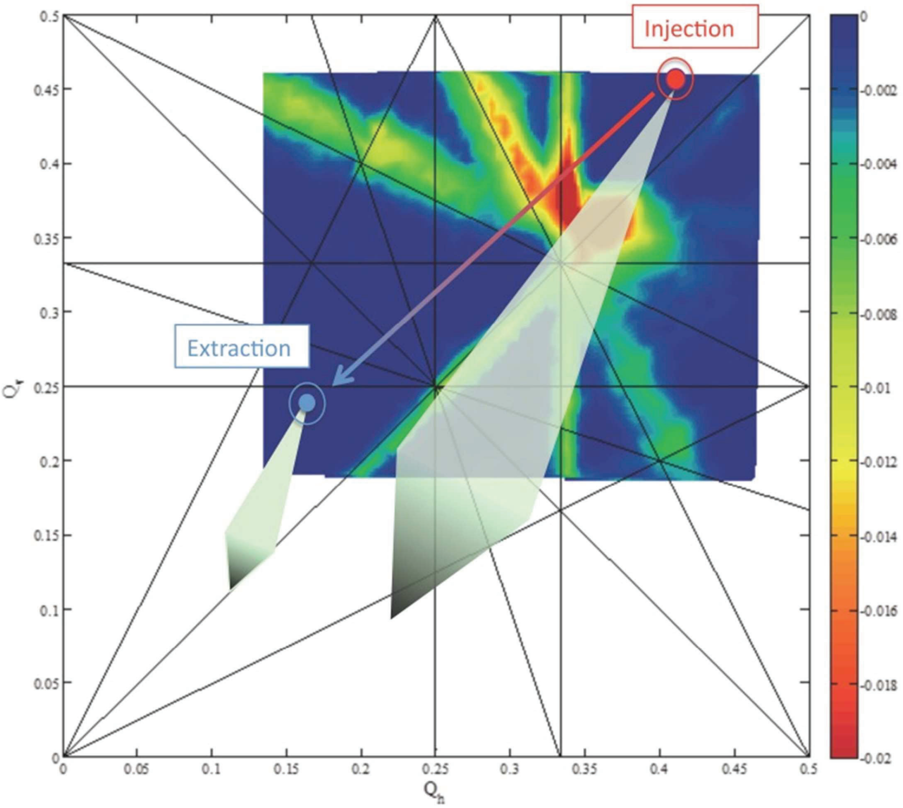

Fig. 12. Tune diagram of the PSB with dynamic working point. The example shows the shrinking of the space-charge tune spread for LHC beams plotted on a partly measured tune diagram for the bare machine. This illustrates the need for a dynamic working point along the cycle and for resonance compensation.

was decisive to reach the design intensity. An analytical study of transverse and longitudinal instabilities by the late Sacherer resulted in a more general understanding of coherent instabilities in particle accelerators, and a longitudinal feedback system based on these theories was developed for the PSB. In 1980 also a transverse feedback system was added.

6. Performance Improvement and Evolution over the Years

Throughout the years accelerator physicists continued to optimize the beam performance and to push intensity and brightness limits of the PSB. Today the Booster accelerates up to 4×10^{13} ppp to 1.4 GeV and reaches unprecedented brightness values for the LHC beams. The fact that today the performance exceeds by large factors the design parameters is the consequence of a number of upgrades and improvements which were implemented over the years and which are recapitulated here briefly.

6.1. *Linac2*

A new injector linac for the PSB (Linac2) was put into operation in 1978. It was equipped with a then novel Radio-Frequency Quadrupole (RFQ). While the injection energy remained at 50 MeV, the injected beam current was increased to 150 mA. It took a number of years and required a few modifications for the Booster to fully exploit this intensity increase. The installation of multipole correctors allowed elimination of stop bands, and the addition of higher harmonic cavities ("bunch-flattening cavities") lowered the peak intensity, thus reducing space-charge effects and hence the tune spread and allowing for increased bunch intensity. By 1985 a peak intensity of 3×10^{13} ppp could be reached.

6.2. *Energy upgrades*

The increased intensity in the PSB made the next bottleneck appear, namely the injection into the PS. The PS was unable to digest the high bunch charge at 800 MeV, and the PSB was upgraded to a top energy of 1.0 GeV, which was possible with only minor hardware modifications. The safety factors built in the machine design proved to be worthwhile.

A second energy upgrade to 1.4 GeV, required for the production of low-emittance beams for the LHC, was completed by early 2000. This second energy upgrade required significant hardware modifications, e.g. a new main power supply, increased water cooling and modifications in the transfer line to the PS (see Subsec. 6.7).

6.3. *Working point*

The original working point of the Booster ($Q_H = 4.8, Q_V = 4.8$) had been moved to ($Q_H = 4.2, Q_V = 5.3$) during the early years of commissioning in order to avoid crossing stop bands. This high working point was in use for many years until 2003, when the working point was lowered again to ($Q_H = 4.17, Q_V = 4.23$) (Ref. 2) at extraction. The lower working point turned out to be favorable for high-intensity beams, since only the $2Q_V = 9$, $3Q_V = 13$, $2Q_V + Q_H = 13$ and $Q_V + 2Q_H = 13$ lines are crossed.

6.4. *Dispersion-free injection line optics*

The optics of the transfer line from Linac2 to the Booster was subject to intense studies in the early 2000s. The aim was to match simultaneously Twiss parameters, dispersion and dispersion derivative at injection. While a solution on paper could be rapidly found, a large number of cross checks and tedious bug fixing was required before the new, achromatic optics could be put in operation in 2005.[3] The advantage of an optics featuring $D = D' = 0$ at injection was to reduce the beam size thus reducing losses at the injection septum and increasing the injected intensity for a given number of turns. This was beneficial for high intensity beams, but even more important for high-brightness beams for the LHC. Since the overall emittance of a beam in the PSB is determined by the ensemble of injected beamlets (see Subsec. 5.1), injecting a given intensity with less turns results in an increased brightness.

6.5. *Ions in the PS Booster*

In the early 1980's a physics program using light ions started, for which the old Linac1 was converted into an ion injector for the PSB. Ion species involved oxygen, sulphur, deuterons and alphas. The low intensities (by three orders of magnitude below the one of the proton beams) proved to be a challenge for the beam instrumentation as well as for the RF. When a dedicated ion linac (Linac3) was put into operation, also heavier ion species like lead and indium were accelerated in the PSB. With the conversion of LEAR to an ion accumulator, LEIR, ions are today injected from Linac3 into LEIR and then into the PS, and the Booster is today no longer part of the ion injector chain.

6.6. *ISOLDE at the PS Booster*

In 1989 a proposal was made by Billinge *et al.* to attach CERN's isotope separator ISOLDE to the PSB. Until then the facility had been fed by its own, dedicated proton driver, the Synchro-Cyclotron (SC). The machine had however reached the end of its lifetime, and the Booster was by then able to deliver pulses of 3×10^{13} p. Moreover, the Booster delivered pulses at 1.2 s intervals only about half of which were used by the downstream synchrotrons. The project was completed during the years 1989–1992, including the construction of a new ISOLDE facility close to the PSB and a transfer line from the PSB to the ISOLDE targets. Initially ISOLDE received protons at an energy of 1.0 GeV, later optionally at 1.0 GeV or 1.4 GeV. Figure 13 shows the ISOLDE facility at the PS Booster.

6.7. *Intensity evolution*

The different optimization processes quoted in the previous sections have resulted in an impressive intensity evolution over the past 40 years of operation. Figure 14 shows the maximum achieved intensity over time.

6.8. *Preparation for the LHC era*

With CERN's Large Hadron Collider (LHC) at the horizon, a program was launched to upgrade the proton accelerators as LHC injectors. The luminosity in the LHC is given by

$$L \sim k_b (N_b)^2 / \varepsilon^* \,,$$

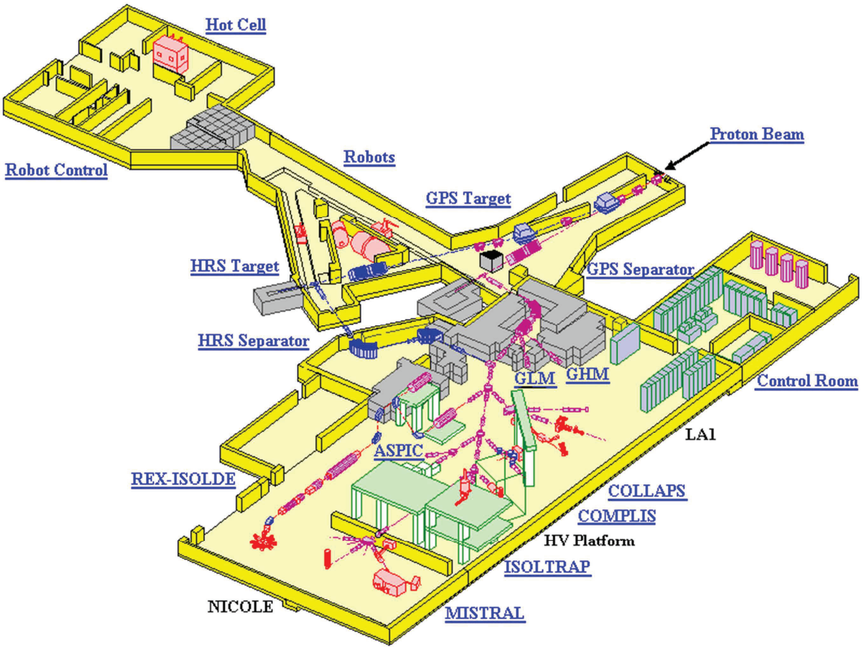

Fig. 13. The ISOLDE facility at the PSB as in 2012. Further upgrades and extensions are planned within the HIE (high intensity and energy) ISOLDE project.

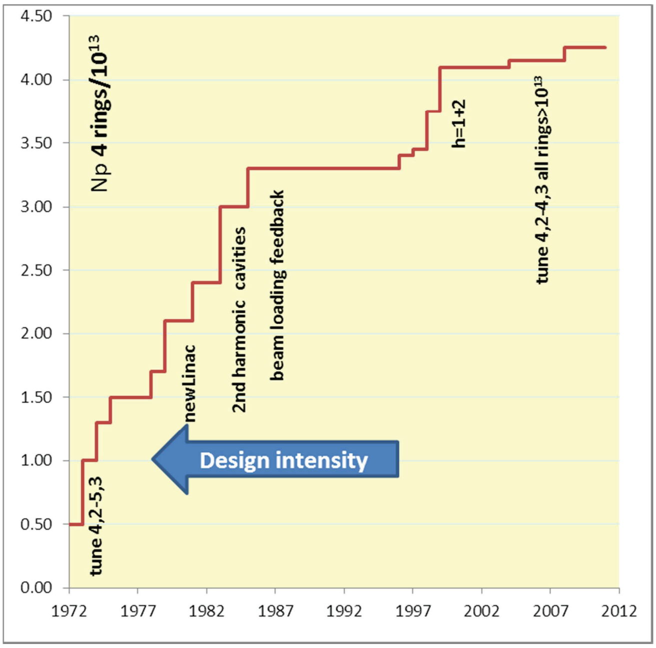

Fig. 14. Evolution of the accelerated beam intensity over the years.

where k_b is the number of bunches per LHC ring, N_b the number of protons per bunch and ε^* the normalized rms emittance. While the Booster was easily able to produce beam intensities well beyond of what the LHC requested, the beam brightness N_b/ε^* was the challenge, as it would lead to space-charge detuning up to unacceptable values. Two measures were implemented to reduce the space-charge tune spread in the PSB. The first one was the concept of double batch filling of the PS, allowing a reduction of the injected intensity per PSB ring. In order to do so, four (one per ring) LHC bunches are extracted from a Booster cycle, followed by two bunches from the next cycle. In this scheme, the first batch has to wait for the second extraction at low energy in the PS, where it is vulnerable to space-charge effects. The second important measure to conserve the beam brightness was the increase of the transfer energy to the PS from 1.0 GeV to 1.4 GeV. The second energy upgrade of the Booster was more challenging than the first one from 800 MeV to 1.0 GeV, since it exceeded the design margins of a number of equipment which had to be replaced. Moreover new low level and high level RF systems were installed with $h = 1$ (2 MHz), $h = 2$ (4 MHz) and variable harmonic C16 (16 MHz) cavities. The new hardware was installed and commissioned by early 2000, and setting up of the LHC-type beams in the PSB started.

In the context of standardizing and streamlining operational procedures, the former control rooms of PS complex, SPS, technical infrastructure and LHC and its cryogenics were merged to a common control center (CERN Control Center, CCC) in 2006.

7. Today's Operation

7.1. *Cycling and ppm operation*

Owing to the unique four-ring geometry and the fast cycling, the Booster is an extremely versatile machine and can deliver a wide range of intensities, energy and time structures depending on the user request. Within a 1.2 s time slot ("basic period"), injection starts at 275 ms and beams are extracted at 805 ms. Figure 15 shows the magnetic field as a function of time.

Different beams can be produced in cycles following each other at intervals of 1.2 s. The underlying concept is known as pulse-by-pulse modulation (ppm). This means that the destination of the beam and essentially all beam parameters can be independently set for a given cycle, including e.g. RF settings, injected intensity, optics etc. For example, during one cycle a high-intensity beam with a large number of injected turns can be produced, while in the next cycle a low-intensity high brightness beam for the LHC is generated. The different cycles are completely independent. They follow each other in a predefined sequence (supercycle), which is repeated in an endless loop. Figure 16 shows a typical Booster supercycle as displayed in the control room.

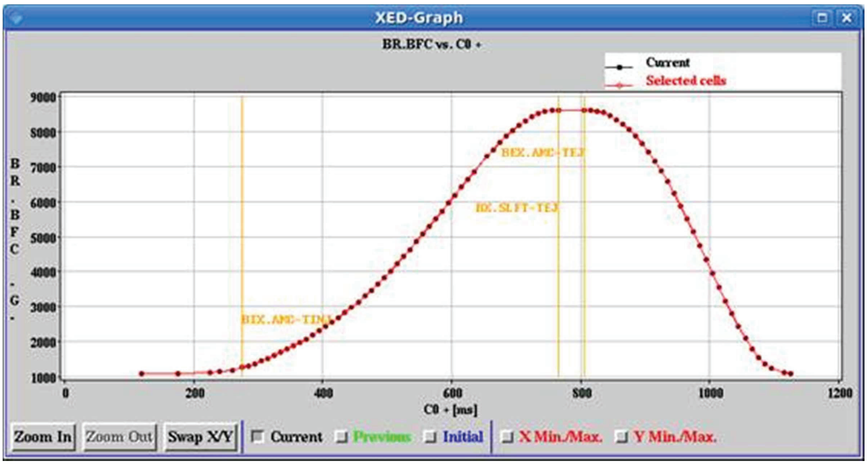

Fig. 15. Magnetic cycle of the Booster.

PSB Fixdisplay – W 49 04–Dec–2012 10:42:53

Comments (29–Nov–2012 17:59:22)

Supervisor : K.Hanke 164465
CCC Tel. : 76671

BP	User	Pls	Inj.	Acc.	b.Ej.E10	Ej.E10	Dest.
11	STAG_ISOHRS	19	○●●●	○●●●	976	313	BDUMP
12	TOF	18	○●○○	○●○○	722	714	TOF_
13	---zero---	24	○○○○	○○○○	0.05	0.00	BDUMP
14	---zero---	24	○○○○	○○○○	0.05	0.00	BDUMP
15	TOF	18	○●○○	○●○○	713	702	TOF_
16	---zero---	24	○○○○	○○○○	0.00	0.00	BDUMP
17	Orbit_Studies	20	●●●●	●●●●	51.20	38.00	BDUMP
18	EASTA	5	○●●○	○●●○	341	344	EASTA_
19	---zero---	24	○○○○	○○○○	0.02	0.00	BDUMP
20	TOF	18	○●○○	○●○○	714	701	TOF_
21	EASTC	13	○●●○	○●●○	267	267	EASTC_1x1cm
23	LHC_Nom_El_H9_A	9	○○○○	○○○○	0.04	0.00	BDUMP
	LHC_Nom_El_H9_B						PS

23/29 No Message

Fig. 16. Sequence of Booster cycles in a "supercycle". The supercycle is composed of so-called basic periods of 1.2 s length. During each slot a beam for a given destination is injected, accelerated and extracted. Presently, most of the machine hardware and software can work in pulse-by-pulse modulation (ppm) mode, i.e. the single cycles are fully independent.

Table 1. Overview of the different RF systems of the PSB and their functions.

Cavity	Frequency range [MHz]	Maximum voltage [kV]	Function
C02	0.6–2.0	8	acceleration on $h = 1$ adjustment of bunch spacing ($h = 2 + 1$)
C04	1.2–3.9	8	acceleration on $h = 2$ bunch flattening or shortening ($h = 1 + 2$) bunch splitting ($h = 1 \rightarrow 2$)
C16	6–16	6	controlled longitudinal blow-up

7.2. *Beams*

The Booster produces today harmonic 2 (one or two bunches per ring, total maximum 8 bunches) and harmonic 1 beams (one bunch per ring, total maximum 4 bunches). Beams produced today by the PSB comprise high and intermediate intensities for the PS and SPS fixed-target physics (notably for the — now stopped — CNGS facility), high intensity beams for the ISOLDE facility and high-brightness beams for the LHC. Intensities range from single bunch beams for the LHC with 5×10^9 particles per bunch to bunch charges of up to 10^{13} (harmonic 1 beam for ISOLDE, total extracted from all four rings up to 4×10^{13} ppp). Only for the LHC a variety of about 10 different beam flavors is available. These beams are readily prepared and archived, and can be mapped on time slots upon request.

7.3. *RF gymnastics*

Originally designed and equipped for harmonic numbers $h = 5$ and $h = 10$ (5 bunches per ring, i.e. 20 bunches extracted toward the PS), today the Booster is equipped with an $h = 1$ and an $h = 2$ RF system per ring. In addition, a higher frequency cavity is installed in each ring for controlled longitudinal emittance blow-up. Table 1 lists the RF systems presently installed in the PSB.

Harmonic 2 beams are the type used for the SPS fixed-target physics program as well as the beam delivered to the — now stopped — CERN Neutrino Gran Sasso (CNGS) facility. The LHC-type beams are generally harmonic 1 beams (some studies with $h = 2$ beams were done in Ref. 4). Some beams, in particular the high-intensity beams for ISOLDE, make use of all three RF systems by dual-harmonic capture and acceleration. Applying both $h = 1$ and $h = 2$ systems, bunch flattening provides the maximum longitudinal acceptance needed for these beams and lowers the peak intensity, which is beneficial to mitigate space-charge effects. Figure 17 shows the effect of the three RF systems of the PSB on the intensity distribution in a bunch.

The voltage of the various RF systems, as well as the relative phase between them, along the cycle can be entered by the operator via a function editor and tailored individually according to beam specifications.

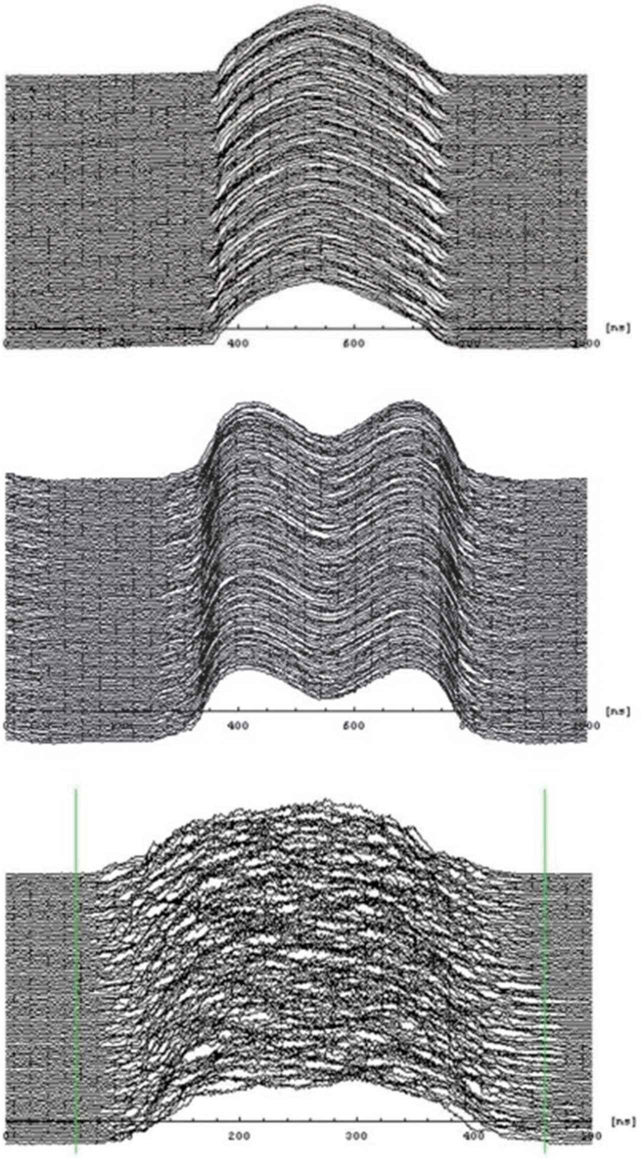

Fig. 17. Intensity distribution with (from top to bottom) harmonic 1 only, harmonic 1 plus 2, harmonic 1 plus 2 plus higher harmonics for bunch flattening.

7.3.1. *Longitudinal shaving*

Certain beams, notably low-emittance LHC-type beams, require their intensity to be adjusted without changing their transverse emittance. In order for this to be accomplished, a scheme has been developed where the bunch intensity is adjusted

Table 2. Beams for fixed-target physics in the PSB as of 2012.

Beam	Harmonics at extraction	Rings	Intensity per ring [protons]	Transv. emittance (norm., rms) [π mm mrad]	Long. emittance [eVs]
Beam for ISOLDE	1	all	2^{10}–800^{10}	up to 12.5	2.3
Beam for PS fixed target physics	1	single or up to 4	5×10^9–5.5×10^{10}	< 1.0	0.3–1.3
Beam for SPS fixed target physics	2	all	$450-600 \times 10^{10}$	5–8	1.55
Beam for CNGS	2	all	650×10^{10}	~ 9	1.6
Beam for AD facility	1	all	450×10^{10}	6.5	1.3
Beam for nTOF facility	1	ring 2	$600-900 \times 10^{10}$	10	2.0

purely by manipulating the voltage function of the RF system. In order to longitudinally "shave" intensity, the rising edge of the RF voltage is either steepened (more particles captured) or flattened (more particles lost) hence varying the bucket size at capture.

A recently proposed scheme leaves the voltage function of the first harmonic RF system constant while adjusting the bunch intensity only by means of the amplitude of the higher harmonic cavity.

7.4. *Fixed-target program*

CERN's fixed-target physics program comprises ISOLDE, the PS East Area, the SPS North Area, as well as the Antiproton Decelerator (AD) and Neutron Time-of-Flight (nTOF) facilities. The CERN Neutrino Grand Sasso (CNGS) facility has come to an end in 2012. Beams range from high-intensity, large emittance (e.g. ISOLDE) to low intensity ($\sim 10^{11}$ ppp) beams as for example for the PS East Area. The availability of these beams is in the 96% level. Table 2 lists the fixed-target physics beams presently delivered by the PSB with their main parameters.

7.5. *The Booster as LHC injector*

Beams for the LHC comprise those beams used to produce luminosity as well as so-called pilot beams which are used to probe the machine. A total of about 10 different beam flavors for the LHC are today available in the injector complex. This comprises single bunch beams as well as multi-bunch beams for luminosity runs.

Table 3. LHC-type beam specifications in the PSB as of 2012.

Beam	Harmonics	Rings	Intensity per ring [protons]	Transv. emittance (norm., rms) [π mm mrad]	Long. emittance [eVs]
Individual bunch physics beam	1	single or up to 4	2×10^{10}–12×10^{10}	< 2.0	0.3
"Probe" beam	1	ring 3	5×10^9–2×10^{10}	< 1.0	0.2
100 ns beam	2	$2, 3, 4$	10^{10}	0.3	0.9
25 ns beam	1	$1, 2, 3, 4 + 3, 4$	160×10^{10}	2.5	1.3
50 ns beam	1	$1, 2, 3, 4 + 3, 4$	80×10^{10}	1.25	1.2

Intensities for the LHC-type beams in the Booster range from 5×10^9 particles per bunch for the single bunch "Probe" beam up to about 160×10^{10} particles per bunch (with a total of 6 bunches extracted to the PS) for the 25 ns spacing in the LHC physics beam. Other multi-bunch beams have bunch spacings of 50 ns or 75 ns in the LHC (the 75 ns variant is presently not in use), respectively 100 ns for proton–ion physics in the LHC. The minimum transverse emittance, and hence the brightness of these beams is determined in the Booster via the multi-turn injection process. The longitudinal parameters of the multi-bunch beams are generated in the PS by means of bunch splitting, while for the single-bunch beams also the longitudinal parameters are already determined in the PSB.

Table 3 lists the beams today available for the LHC in the PSB. Here listed are only the beams which were used in standard operation during 2012. Other beams have been set up and archived which could potentially be used if needed in the future (e.g. single batch transfer of the 50 ns and 75 ns variants). In addition, new beams have been set up which could potentially become operational in the future (Batch Compression, Merging and Splitting BCMS).

7.5.1. *Double-batch transfer*

The 25 ns and 50 ns variants quoted in Table 3 make use of a double-batch transfer to the PS. This means that during a first Booster cycle all rings accelerate one bunch per ring and extract the four bunches to the PS, followed by a second Booster cycle during which only two rings accelerate and extract bunches. This results in six bunches being sent to the PS with a time delay of 1.2 s. The bunches then undergo splitting in the PS and are progressively transformed into the 36 (50 ns) or 72 (25 ns) bunches that are then injected into the SPS and eventually into the LHC. The advantage of this scheme is that the Booster is able to generate bunches with maximum brightness, filled up to the space-charge limit. However, the first batch injected into the PS has to remain at injection energy waiting for the second injection, where it is vulnerable to space-charge effects. Presently double batch

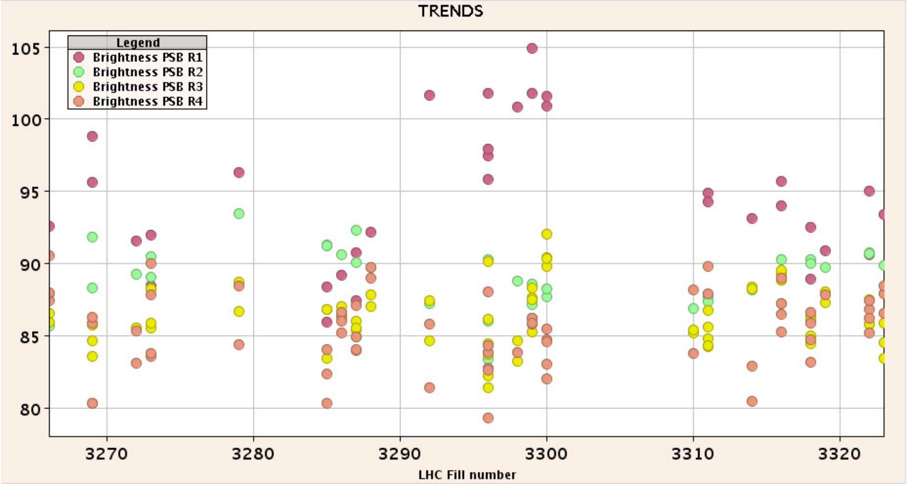

Fig. 18. Brightness for the 50 ns LHC beam for the four Booster rings versus LHC fill number.

transfer is employed for the 25 ns and 50 ns variants. However, also a single batch transfer has been set up and tested (Ref. 4). This scheme has been set up for the 50 ns and 75 ns variants. In this scheme the required six bunches are generated by filling only three Booster rings at $h = 2$, at higher charge per ring (and larger transverse emittances).

7.5.2. *Operational experience*

Operation as LHC injector has added another, demanding client to the number of users that receive beams from the PSB. Beam brightness — and hence the transverse beam emittance generated in the PSB — is critical and requires constant monitoring and adjustment. Emittance measurements are done with wire scanners. Two wire scanners, one horizontal and one vertical, are installed in each ring. During 2012 a system has been put in place to record the emittance data throughout the LHC injector chain thus identifying rapidly any source of emittance blow-up. The overall experience is that the beams from the Booster meet or exceed the requirements, and that the stability and availability of the beams is excellent. Figure 18 shows the recorded brightness for the different PSB rings versus LHC fill number.

Constant optimization and gaining operational experience has led to an improvement of the LHC beam parameters beyond the original specifications. In addition, new and promising production schemes have been developed in view of further increasing the beam brightness.[5] Table 4 shows the optimized beam parameters for the operational multi-bunch beams as achieved during 2012. As can be seen the transverse emittances have been reduced by careful optimization (injection matching, adjustment of tunes) and the intensities pushed further.

Table 4. Achieved beam parameters for the LHC multi-bunch beams in the PSB in 2012.

Beam	Harmonics	Rings	Intensity per ring [protons]	Transv. emittance (norm., rms) [π mm mrad]	Long. emittance [eVs]
25 ns beam	1	$1, 2, 3, 4 + 3, 4$	160×10^{10}	2.0	1.3
50 ns beam	1	$1, 2, 3, 4 + 3, 4$	120×10^{10}	1.35	1.2

Table 5. Beam parameters for the LHC multi-bunch beams in the PSB for the proposed BCMS scheme. Two batches using all four Booster rings are extracted toward the PS, where they undergo a newly developed RF scheme which results in bunches with unprecedented brightness for the LHC.

Beam	Harmonics	Rings	Intensity per ring [protons]	Transv. emittance (norm., rms) [π mm mrad]	Long. emittance [eVs]
25 ns beam	1	$1, 2, 3, 4 + 1, 2, 3, 4$	75×10^{10}	1.0	1.3
50 ns beam	1	$1, 2, 3, 4 + 1, 2, 3, 4$	60×10^{10}	0.9	1.2

The beam parameters are shown in Table 4 represent the limit of what can be achieved with the traditional production schemes. However new, innovative schemes have been developed and may be put in operation when restarting the PSB after the first long LHC shutdown in 2014. A very promising scheme is the so-called Batch Compression, bunch Merging and Splitting (BCMS) scheme. In this scheme, the Booster provides two batches using all four rings at $h = 1$ to the PS. The intensity per ring is lower than for the classical 25 ns and 50 ns production schemes, and hence the transverse emittances are also smaller. The two batches injected into the PS undergo a newly developed RF gymnastics which eventually results in bunches with increased brightness in the LHC (however, at the expense of a reduced number of bunches per train injected into the SPS). The presently achieved beam parameters for the BCMS scheme in the PSB are reported in Table 5.

On the operational side the LHC has imposed a new rhythm in the sequence of operation and shutdown periods. Due to the long time constants required for warming up and cooling down the machine, the LHC cannot take advantage of a shutdown period of a few months as it was practice in the pre-LHC era. Instead, the LHC imposes long operation periods which stretch over typically 3–4 years without any significant stops, followed by long shutdowns (of the order of one year).

8. Upgrade Plans

While the Booster delivers routinely beams to the LHC within — or in excess of — today's specifications, there is a request for increased luminosity in the coming years. In the frame of the High-Luminosity LHC (HL-LHC) project, ultimate

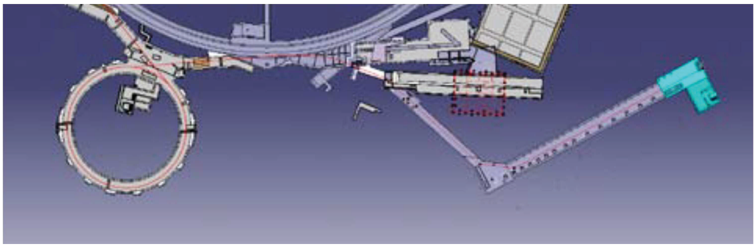

Fig. 19. Lay-out of the PSB (left) with CERN's new Linac4 (right).

beams for the LHC are being proposed which are out of reach of what the injector complex can deliver today. Following the Chamonix 2010 workshop,[6] a massive upgrade program for the entire injector complex was launched which aims at enabling the injectors to provide beams with ultimate specifications and in a reliable way throughout the lifetime of the LHC. The Booster is particularly concerned by the injector upgrade, as both its injection will be modified with a new injector linac, and another (the third) energy upgrade will be put in place.

8.1. *New injection scheme*

A new injector linac (Linac4) is presently under construction at CERN.[7] Unlike its predecessor, Linac2, it will accelerate H^- ions rather than protons. Furthermore, its energy will be at 160 MeV as compared to today's 50 MeV. Figure 19 shows the implementation of Linac4 as new injector for the PSB. The advantage of Linac4 for the PSB will be twofold:

(1) The increased injection energy will reduce the space-charge tune spread at injection as it will increase the $\beta\gamma^2$ factor by 2.
(2) The change of the injection scheme from multi-turn stacking to charge-exchange injection will drastically reduce beam loss at injection and at the same time allow tailoring the beam transversely according to specifications.

8.1.1. *Increasing the injection energy*

Increasing the injection energy from 50 MeV to 160 MeV will increase the relativistic $\beta\gamma^2$ by a factor of 2 and reduce the space-charge induced detuning detailed in Subsec. 5.3. Since the present beam distribution system (proton distributor and vertical septum) is not able to handle a beam energy of 160 MeV, they need to be replaced, along with a number of magnets and the pick-ups in the Booster injection line.

8.1.2. *Charge-exchange injection*

The injection of H^- ions into the PSB will be done by means of charge-exchange injection. For this, the horizontal injection septum, main bottleneck and source of beam loss at injection, will be replaced by a stripping foil. When passing through the stripping foil, the incoming H^- ions will strip off their electrons and be transformed into protons which will follow the closed orbit of the machine. This injection scheme avoids the losses at the septum (almost 50% of the initial intensity, see Subsec. 5.1). Only about 1–3% of the incoming beam remains unstripped, or is stripped only partially. These remaining H^0 and H^- ions will be dumped in dedicated absorbers. One of the great advantage of charge-exchange injection is that it allows over-injecting in the horizontal phase space and should therefore provide lower emittances for the same injected intensities than in a multi-turn injection process. During the injection process an injection bump ("chicane") is generated by dedicated dipole magnets. The amplitude of the chicane bump is reduced during the injection process to remove the beam from the foil. The number of injected turns can be adjusted from 1 to 100. The painting process, performed by dedicated horizontal painting kickers situated outside the actual injection period, allows tailoring emittances according to the request of the end user. This allows generating high intensity, large emittance beams as well as extremely brilliant beams. Figure 20 shows schematically the principle of charge-exchange injection and phase space painting.

8.2. *Energy upgrade to* 2.0 *GeV*

The intensities accumulated in a small phase space volume with Linac4 will move the bottleneck in the LHC injector chain to the PS injection. This will be overcome by upgrading the PSB top energy from 1.4 GeV to 2.0 GeV thus reducing space-charge effects at PS injection. The ratio of the $\beta\gamma^2$ factors at 1.4 GeV and 2.0 GeV is

$$(\beta\gamma^2)_{2\,\mathrm{GeV}}\big/(\beta\gamma^2)_{1.4\,\mathrm{GeV}} \approx 1.63\,,$$

i.e. about 63% more intensity can be injected into the PS keeping the same space-charge tune spread as present. The implications on the Booster hardware have been evaluated in Ref. 9. The main magnets can operate at the required field levels. Some modifications to their cooling circuits, to the shimming and to the retaining plates are unavoidable. A number of equipment needs either to be modified or exchanged. These are in particular the Main Power Supply (MPS), numerous extraction and recombination elements, transfer line elements in the transfer line to the PS, cooling system and many others. Also the PS injection will be completely modified. Work is constrained by the long LHC shutdowns and is presently planned to be completed during the second long shutdown.

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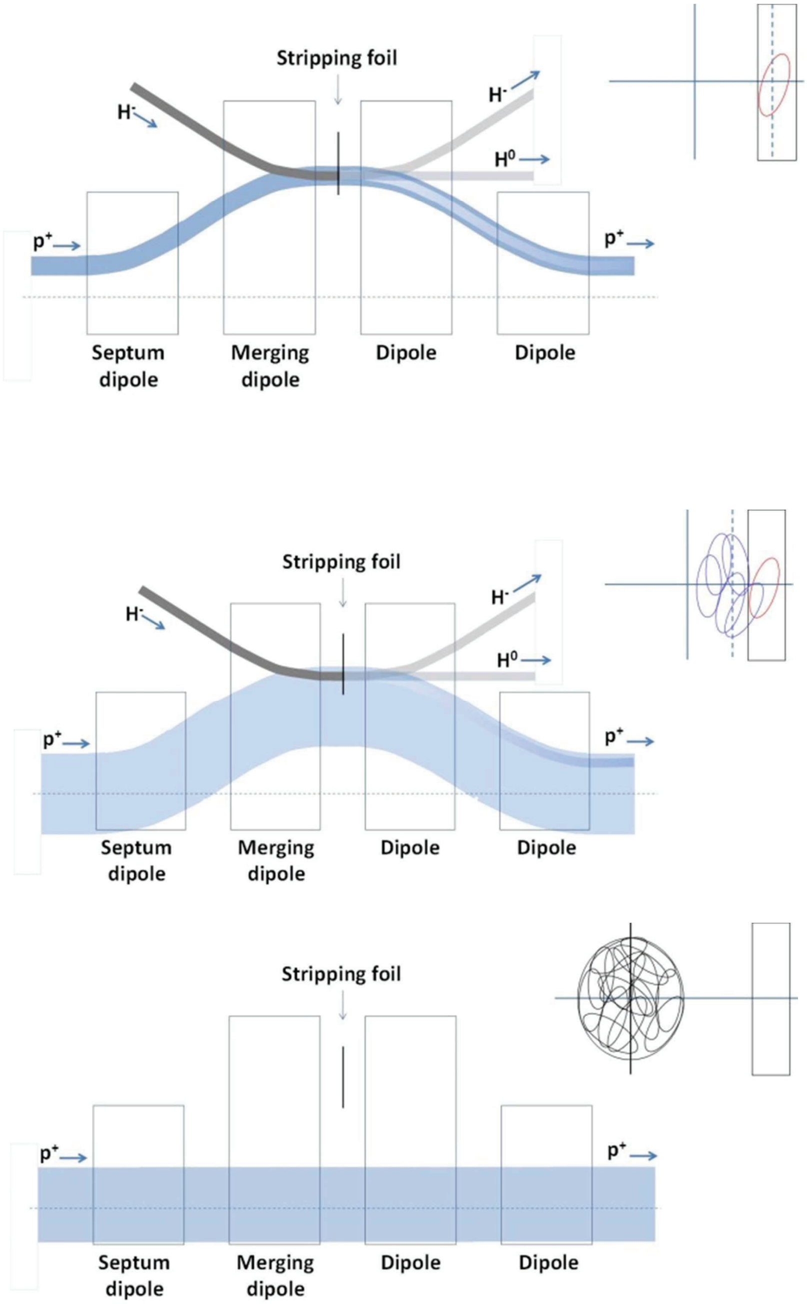

Fig. 20. Principle of charge-exchange injection. Top: The incoming H^- beam loses its electrons when passing through the stripping foil. The proton beam follows the machine orbit, while H^- ions continue to be injected and merge almost loss-free with the circulating proton beam. Middle: Dedicated painting kickers move the beam across the foil and fill the machine aperture with beam. Bottom: The chicane switches off to zero amplitude after injection (from Ref. 8).

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