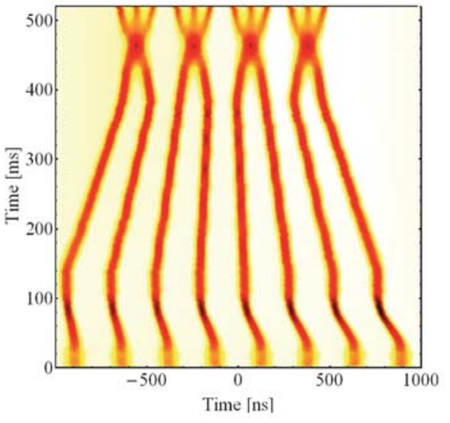

Fig. 3.12. Evolution of the bunch train between injection and at 2.5 GeV showing bunch train compression, combination of bunch pairs and triple splitting. Ordinate: time during the cycle; abscissa: longitudinal position of bunches along the orbit in terms of time [21].

3.4 Boosting PS Beam Intensity

Karlheinz Schindl

By the mid-1960s, CERN's 26 GeV Proton Synchrotron accelerated routinely ~ 10^{12} protons per pulse, a performance largely exceeding its design. However, at this level there were signs of saturation, in particular at injection energy (50 MeV) where a phenomenon called "space charge" appeared to limit the intensity. With new potential clients — the ISR and the SPS — on the horizon, a study on how to increase the output beam intensity of the PS to ~ 10^{13} protons per pulse (ppp) was launched. The space charge limit is brought about by the Coulomb force between the protons in a beam repelling each other and, therefore, working against the external focusing. The limit is strongly dependent on beam energy, and, during acceleration, the repulsive force gets weaker while the beam becomes stiffer. Hence, the limit is lowest at PS injection and it was overcome by raising the injection energy from 50 MeV to 800 MeV (kinetic) moving the limit up by a factor eight with an expected similar increase in intensity. A study of several alternatives led to the adoption of a very compact, slow-cycling 800 MeV synchrotron with four superimposed rings, the PS Booster (PSB) [22, 23], and re-use of the existing 50 MeV Linac. Operating each of the four rings (radius 25m, 1/4 of the PS) with five bunches at their individual space charge limit and transferring these four bunch trains sequentially to the PS would potentially deliver the desired 10^{13} protons to the PS.

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The PSB was constructed between 1968 and 1972 after a very significant stumbling block was removed by diplomatic rather than technical skills: the PSB is the first accelerator ever built straddling an international border (Switzerland and France), paving the way for the much bigger accelerators also stretching across the border later. It was integrated in the PS injector chain in 1973, right away raising the PS output to 5×10^{12} ppp, just in time for the neutrino physics experiments with Gargamelle (Chapter 3.1).

It was the first particle accelerator with synchrotron rings stacked on top of each other. The four superimposed rings feature separate dipole (32) and quadrupole (48) magnets (as opposed to the PS where guide fields and gradients are generated by "combined-function" magnets) [24]. Each of them is a vertical stack of four magnets with a common yoke (Fig. 3.13). Their coils are connected in series and energized by one big power converter, while correction loops operating with rather small currents enable the guide and focusing fields to be adjusted for each ring. The stringent requirements on field quality and equality between rings gave rise to extensive studies of the prototype magnet stacks. The cross-section of both the magnet yokes and the coils were chosen large: the former mainly for better field quality, resulting in a relatively low magnetic field of ~ 0.6 T at 800 MeV, and the latter for minimizing integrated cost (construction + 10 years of operation). These latter features proved invaluable for later raising the PS Booster ejection energy to 1 GeV and 1.4 GeV. A further step to 2 GeV is planned.

A novel scheme [25] was also introduced to power the main magnets from a static power supply, rather than from a motor-generator set with a flywheel for energy storage, which draws constant active power from the mains as in the PS. Since the direct current varied between 200 and 3000 A during the acceleration cycle, this implied a power variation of about 7 MW. In order not to perturb the mains (voltage variation < ± 0.25%), the reactive power had to be compensated by a passive filter. A second passive filter was installed to ensure that the sinusoidal shape of the CERN mains voltage is maintained without parasitic oscillations at other points of the network (distortion < 0.5%). This system works satisfactorily for repetition times as low as 1.2 s, lower repetition times showed resonance effects in the generators of the main Geneva hydro-electric power plant (Verbois).

Twelve low-cost kicker magnets for injection and ejection of novel design with short rise or fall times were built using thyratrons instead of the unreliable pressurized spark gaps and introducing ferrite-loaded pulse steepening lines which, depending on the task of the kicker, shortened either the rise or fall time of the deflecting field to less than 50 ns [26]. The design had to be modified later to provide the longer beam pulses required by the new client, ISOLDE, and the higher voltage for the new top energy [27].

Fig. 3.13. One (out of 16) magnet periods showing the four superimposed rings. From right to left: dipole (green); vacuum chambers in straight section (grey); another dipole; a quadrupole triplet (focusing-defocusing-focusing, orange); dipole; RF equipment for beam acceleration (grey).

The path to design performance and beyond

The path to design performance proved arduous. Obstacles were addressed one by one, profiting from a few key developments in accelerator physics and technology.

- The focusing in the accelerator was programmed to quickly reduce, during acceleration, the adverse effects of space charge (unavoidable at injection).
- The five bunches conspired to oscillate in a coherent manner and these coupled bunch oscillations leading to beam loss presented a hard limit. The PS Booster was not the first accelerator to suffer from such instabilities, but it was the one where a deeper understanding of this phenomenon was developed leading to the first electronic feedback system effectively damping these oscillations [28].
- A new Linac 2, still 50 MeV, but with up to 150 mA beam current, was built, replacing in 1978 Linac 1 which proved unable to reach 100 mA as specified; two further measures limited the adverse effects of space charge: new multipole correctors intended to compensate magnetic imperfections and an additional RF system operating at the second harmonic of the main system lowered the peak line density of bunches.

These developments and inventions, together with many other improvements, allowed the PS Booster to reach its design intensity of 10^{13} ppp by 1974, 3×10^{13} by 1985, and eventually 4.2×10^{13} by 2003 (Fig. 3.14).

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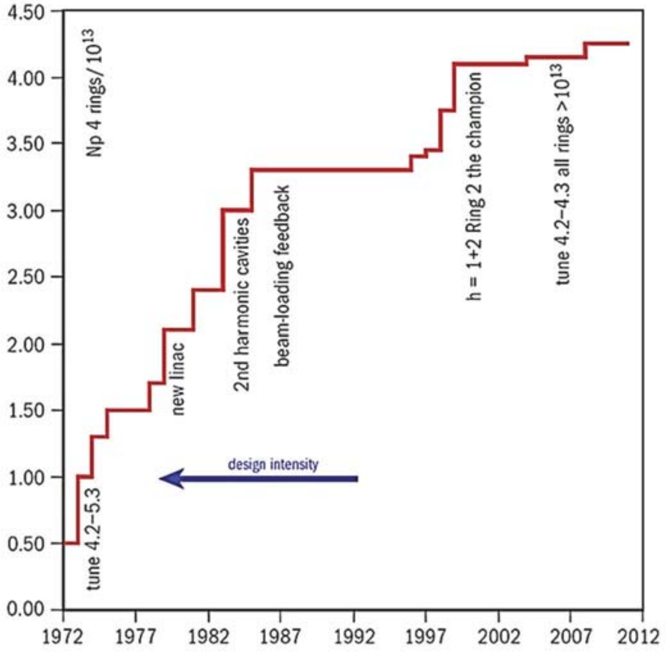

Fig. 3.14. The PSB peak intensity (sum of four rings) over the years. Major hardware additions and improvements are highlighted. (Adapted from [22].)

Also in the 1980s, the PSB got involved in ion acceleration, starting with deuterons and alphas, making its way through the Periodic Table to lead with the advent of Linac 3. This programme gave rise to numerous developments (RF, beam diagnostics) mainly to cope with ion intensities as low as 10^8 ions per pulse — five orders of magnitudes lower than proton beams within the same super-cycle. Since 1991 it replaced the aging CERN synchrocyclotron as proton source for ISOLDE.

In the LHC injector chain

In line with CERN's tradition of using existing accelerators as injectors for new machines, the LHC programme was no exception. It required a further increase of the top energy of PSB to 1.4 GeV and the replacement of the RF systems to deal with one instead of the originally used five bunches per ring [27]. In a further upgrade step the PSB ejection energy will be once more increased to 2 GeV and Linac 2 will be replaced by the new 160 MeV H^- Linac 4 as injector [29]. By this time, the PS Booster will be, in many parts, a new machine, while maintaining in the future its inherent versatility so successfully demonstrated in the past.

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