CHAPTER 9

TRANSVERSE EMITTANCE CONSERVATION AND MEASUREMENT

9.1 EMITTANCE CONSERVATION ISSUES

The conservation of the transverse emittance for the LHC beam throughout the injection chain is an important for reasons which are explained below. The performance of a collider is measured by the luminosity,

$$L = \frac{k_b N_b^2 f_{rev} \gamma}{4\pi\varepsilon_n \beta},$$

which is proportional to the number of events per second and thus has to be maximised. This favours a large particle number per bunch N_b and a small normalised emittance ε_n. However, space charge effects at low energies work against this by limiting the beam brightness, N_b/ε_n, achievable. The strategy is therefore to produce the highest possible brightness beam at low energy and then to transport it through the injector chain by carefully avoiding any performance loss due to emittance blow-up. More detailed considerations can be found in Cha. 2.

The proton injection chain for the LHC consists of the Linac2, the PSB, the PS and the SPS. The 50 MeV beam coming from the linac is injected into the PSB using a multi-turn injection. At 1.4 GeV, four bunches of the four PSB rings are consecutively ejected towards the PS, filling 4/7 of the PS circumference. After injection of a second batch (two rings only) from the PSB, the beam is accelerated to 25 GeV in the PS and ejected towards the SPS. The beam intensities and emittance budgets along the injection chain for nominal and ultimate LHC beams are summarised in Tab. 9.1, no beam losses are taken into account.

Table 9.1: LHC nominal and ultimate proton beam intensities and emittances.

	Linac	**PSB**	**PS**	**SPS**
Nominal				
p/LHC bunch			1.15×10^{11}	1.15×10^{11}
p/pulse	180 mA	1.38×10^{12}/ring	8.28×10^{12}	3.31×10^{13}
		(1 bunch/ring)	(6 PSB bunches)	(4 PS batches)
ε_n	1.0 μm	2.5 μm	3.0 μm	3.5 μm
Ultimate				
p/LHC bunch			1.7×10^{11}	1.7×10^{11}
p/pulse	180 mA	2.04×10^{12}/ring(	1.22×10^{13}	4.90×10^{13}
		(1 bunch/ring)	(6 PSB bunches)	(4 PS batches)
ε_n	1.0 μm	2.5 μm	3.0 μm	3.5 μm

The multi-turn injection into the PSB and strong space charge effects naturally lead to the largest emittance blow-up in the injection chain. Therefore special care has to be taken at injection to achieve a beam with the required high brightness (small emittance). This emittance should then be conserved throughout the injection chain. Therefore, besides the control of resonances and instabilities, the beam-transfers between PSB, PS and SPS are the major concerns. When transferring a beam between two machines, there are three main sources for rms emittance blow-up:

- injection mis-steering: $$\frac{\Delta\varepsilon}{\varepsilon} = \frac{1}{2\varepsilon}\left|\begin{pmatrix} \Delta x/\sqrt{\beta} \\ \sqrt{\beta}\Delta x' + \alpha\Delta x/\sqrt{\beta} \end{pmatrix}\right|^2,$$

- betatron mismatch $$\frac{\Delta\varepsilon}{\varepsilon} = \frac{1}{2}\frac{\beta}{\beta+\Delta\beta}\left|\begin{pmatrix} \Delta\beta/\beta \\ \Delta\alpha + \alpha\Delta\beta/\beta \end{pmatrix}\right|^2,$$

- dispersion mismatch $$\frac{\Delta\varepsilon}{\varepsilon} = \frac{\sigma_p^2}{2\varepsilon}\left|\begin{pmatrix} \Delta D/\sqrt{\beta} \\ \sqrt{\beta}\Delta D' + \alpha\Delta D/\sqrt{\beta} \end{pmatrix}\right|^2 .$$

In the formulae above, α and β are the Twiss-functions in the matched case and $\Delta\alpha$ and $\Delta\beta$ are the deviations due to the mismatch, the same applies for the dispersion function D and D'; $\sigma_p = (\Delta p/p)_{rms}$ is the standard deviation of the relative momentum spread. It should be noted that the emittance blow-up due to mis-steering and dispersion mismatch is inversely proportional to the initial emittance. Thus, these two error sources are particularly important for the LHC beam due to its small design emittance.

9.1.1 Transfer PSB to PS:

The expected maximum emittance blow-up between PSB ejection and PS ejection is 0.5 μm (Tab. 9.1). Assuming that 0.2 μm are assigned to effects during acceleration in the PS, the remaining 0.3 μm can be split into three equal parts for the blow-up sources mentioned above and one can quote typical values for maximum tolerable steering and matching errors between the two machines. The centre of the straight section 45 in the PS (location of the fast injection kicker) was chosen as reference point for the calculations[1]. The Twiss-parameters are $\beta_x = 20.3$ m, $\beta_z = 11.9$ m, $\alpha_x = \alpha_z = 0$, $D_x = 3$ m, $D'_x = 0$. It was assumed that the errors are only in position, beta-function and dispersion and are zero for the derivatives.

The maximum tolerable mis-steering or mis-matches are quoted in Tab. 9.2. Each effect alone accounts for an emittance increase in ε_n of 0.1 μm.

Table 9.2:Maximum tolerable steering/matching errors for the transfer PSB to PS.

PS-section 45 centre	**horizontal**	**vertical**
Beta-function	20.3 m	11.9 m
Dispersion	3.0 m	-
Injection mis-steering	$\Delta x = 0.9$ mm	$\Delta z = 0.7$ mm
Betatron mismatch	$\Delta\beta = 5.7$ m	$\Delta\beta = 3.4$ m
Dispersion mismatch	$\Delta D = 0.7$ m	–

The optics presently in use for the transfer between PSB and PS is not well matched in terms of dispersion. Up to now, this fact was not too important but for the LHC beam, with a small transverse emittance and a large momentum spread ($\sigma_p = 1.25 \times 10^{-3}$), it becomes relevant. To improve in this area, modified optics [1, 2] which significantly reduce the dispersion mismatch (while preserving the betatron matching) was being tested and verified.

In the case of the PSB the fact that there are four rings which need to be recombined imposes additional difficulties. To minimise the injection oscillations in the PS it is required to individually correct the trajectories of the four bunches. The number of independent correction elements is in theory sufficient, but in practice it is not straightforward to equalise the trajectories from different rings to better than ± 1 mm. Furthermore, the reproducibility of the trajectories is not guaranteed and therefore an injection damper will be installed in the PS to provide bunch-by-bunch correction of these residual injection errors.

As far as betatron matching is concerned, the vertical dipoles in the recombination section create optical differences between the rings which cannot be corrected with the present hardware. The effect is small but if required it can be reduced by installing a correction quadrupole [3].

9.1.2 PS Injection Damper

A mis-steering of less than 1 mm at PS injection leads to a significant emittance increase of LHC-type beams (see Tab. 9.2). The four beams from the PSB, recombined to one and sent in two batches to the PS,

[1] It should be noted that for the calculation of the emittance blow-up due to mis-steering and dispersion mismatch the unnormalised emittances have to be used.

undergo some unavoidable mis-steering because (i) small time-dependent variations of elements such as power converters or RF feedback loops lead to degrading beam orbits and (ii) the eight horizontal and vertical kicker magnets in the PSB-PS beam transport suffer from overshoot and flat-top ripple with frequencies of up to ~15 MHz (this latter effect cannot be corrected with steering dipoles). For these reasons, two injection oscillation dampers, one for each plane, are being built for the PS. They feature travelling-wave kicker magnets of 12.5 Ω characteristic impedance with a bandwidth of ~ 20 MHz. One 3 kW power amplifier will drive each kicker, which would then be capable of reducing a 1.5 mm initial injection oscillation to less than 0.5 mm within 50 μs (20 turns), to be compared to the 400 μs filamentation time constant. Recent beam observations suggest that these systems would be quite suitable also to tackle transverse head-tail instabilities during the PS cycle, even at lower power (200 W available). As the prototype kickers and power amplifiers are not yet finalised and further machine experiments are required to fully understand all aspects of the instabilities, the parameters given here are preliminary.

New pickup electronics have been developed and a prototype was installed in 2003. The frequency range is 20 kHz to 40 MHz, enough to cover the requested bandwidth with some margin. It will also permit the damper to function over the full intensity range from 10^9 to 10^{13} protons per bunch, again somewhat exceeding the required range.

9.1.3 Transfer PS to SPS:

The beam optics of the TT2/TT10 transfer lines, linking PS and SPS has been reviewed and as a result the dispersion and the betatron matching was improved [4]. In addition to that, orthogonal tuning knobs to minimise the unavoidable residual mismatch were developed [5]. To minimise the blow-up due to injection mis-steering, the SPS damping system was re-engineered [6]. More details can be found in Chaps. 14 and 15.

9.2 BEAM DIAGNOSTIC UPGRADES IN VIEW OF LHC BEAMS

The high brightness LHC beams require close observation of possible emittance blow-up during acceleration in Linac2, PSB and PS and during transfers from one machine to the next. In view of these low-emittance beams, several diagnostics instruments have been substantially upgraded while a few new ones have been built in order to cope with new diagnostic requirements.

Two new Secondary Emission Monitor grids (SEM-grids) were installed in the PSB close to the injection septum and the SEM-grids in the PSB measurement line were upgraded. Eight new wire scanners for profile measurements in the 4 rings were installed in the PSB.

In the PS, the measurement targets have been upgraded and new electronics have been developed for their remote control. In addition, tests have been made for the development of a non-destructive profile measurement to measure beam profiles during the entire PS acceleration cycle. Unfortunately the results are high corrupted by background due to losses in the machine and further development in this direction has been abandoned.

9.2.1 Injection Matching Studies in the PS

In the PS ring, three SEM-grids are installed. In normal operation they are used to determine the emittance of the beam injected from the Booster. Very fast electronics has been built for one of these SEM-grids, allowing the measurement of beam profiles turn by turn (the revolution period at injection is 2.2 μs for a 1.4 GeV beam). The electronics consists of fast amplifiers with a rise time of 100 ns and 40 MHz flash ADCs. With this modified SEM-grid the transverse matching between the four PSB rings and the PS was measured by recording the beam size oscillations during the first turns in the PS (Fig. 9.1). The beam was ejected after 30 turns in order to make sure that the SEM-grid did not overheat due to multiple beam passages.

The turn by turn profiles were fitted with a Gaussian and the evolution of the mean position as well as the profile width were calculated. From the position oscillations the dispersion parameters were extracted as well as the machine tune while the width oscillations were determined by betatron and dispersion mismatch [7]. These measurements can only be done during dedicated MDs because the presence of high intensity beams in the machine would destroy the detectors.

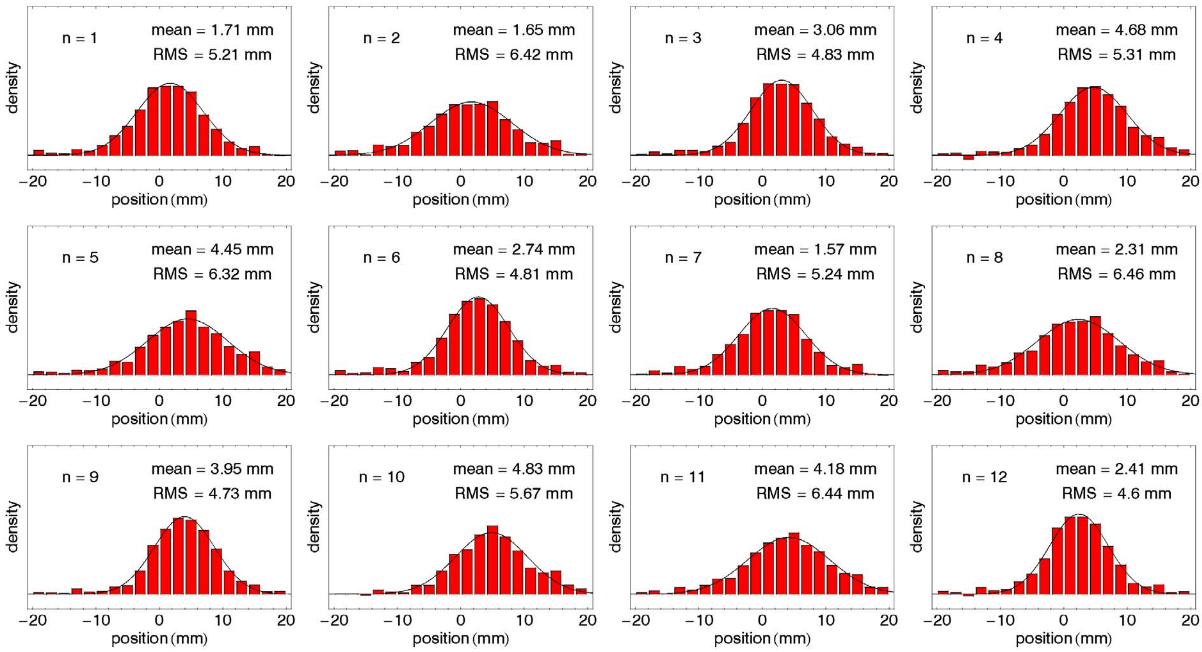

Figure 9.1: Turn by turn horizontal beam profiles measured at PS injection (first 12 turns).

9.2.2 The PSB Fast Wire Scanners

Since 1993, fast wire scanners are used in the PS to measure transverse beam profiles to very high precision and it was natural also to install these devices in the PSB in order to get consistent measurements in both machines. It was known that wire scanners could be used for 1 GeV proton beams, but their performance at lower energies, especially at 50 MeV injection energy, was doubtful. Before investing in ten new wire scanners (1 horizontal and 1 vertical for each of the 4 PSB rings + 2 spares) the spare PS wire scanner was mounted in ring 1 of the PSB for investigation. During machine studies in 1997/1998 its performance was tested and results compared to other already available measurements (BeamScope in the PSB, PSB measurement line and SEM-grids in TT2).

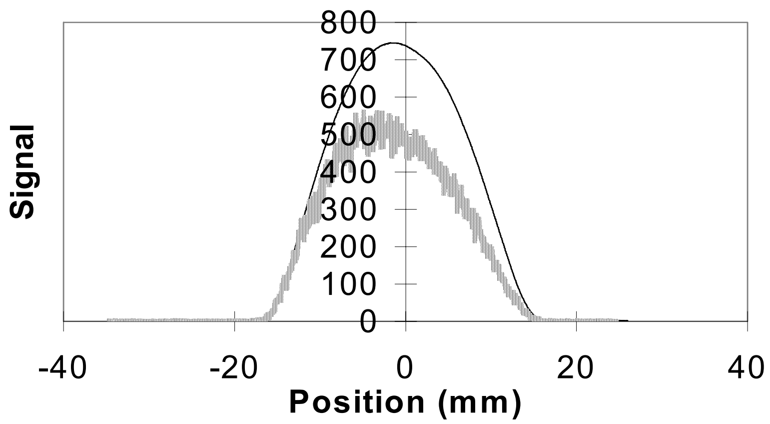

Figure 9.2: Profiles taken with photomultiplier (grey) and secondary emission at 50MeV.

The PS wire scanner uses a scintillator and photomultiplier system in order to detect secondary particles created by the interaction of the circulating beam with the passing wire. This method works fine down to proton energies of a few hundred MeV but fails at very low energies (below the pion creation threshold). In order to cover the full PSB energy range, measurement of the secondary emission current from the wire instead of detecting secondary particles on the scintillator (Fig. 9.2) was attempted.

Very clean profiles were obtained even at 50 MeV proton energy. Comparison between profiles taken with the two detection methods at higher energies showed no difference. Since the test measurements with the spare wire scanner yielded convincing results, the TRIUMF laboratory (Vancouver) has been contracted to build 10 such devices. For these new PSB wire scanners the control and readout electronics has seen a major overhaul and each scanner unit is now equipped with its own dedicated motor controller. These controllers consist of autonomous microprocessors with ADC and DAC for speed control thus taking away the burden of the very time critical movement control from the main VME processor. This processor is now used exclusively for the acquisition of wire position and profile signals from the photomultiplier and the secondary emission current from the wire. The application program for the PS wire scanners has been upgraded so that it is capable of driving the PS as well as the PSB version of the wire scanners.

9.2.3 The PSB Measurement Line

The PSB measurement was equipped with 3 SEM-grids per plane, to measure the emittance of the beam sent to the PS. Their mechanisms were more than 20 years old and needed replacement. It was decided that instead of replacing these mechanisms it would be better to have new, higher resolution grids installed permanently in the beam. The new grids consist of a series of wires instead of ribbons to minimise the interaction with the beam. The number of wires per plane has been increased to 32 and the wire distance decreased to 1 mm for the outer SEM-grids and 0.5 mm for the central one.

The analogue electronics chain was replaced and the digital electronics now uses VME ADCs instead of the old CAMAC scanning ADCs. The installation has been done during the 1999/2000 shutdown.

9.2.4 The PS Measurement Targets

In addition to the wire scanners, the measurement targets can be used in the PS to measure beam sizes. The target consists of a fork with 2 fingers whose distance can be adjusted. The fork flips into the beam and beam losses are observed on the DCBCT. The measurement targets, which can also be used for limiting the aperture, scraping the beam halo away, were only used manually up to now. In order to remotely control the devices, the motors adjusting the distance of the fork fingers had to be replaced. New electronics had to be developed giving remote access to internal parameters (fork finger distance, retention magnet, flip timing etc.). In addition, an application program controlling the devices, reading the beam loss from the DCBCT and displaying the results in a user-friendly way was developed.

9.3 OTHER BEAM DIAGNOSTICS

Not only the emittance and profile measurement devices, but many other beam measurement and diagnostics systems in the LHC pre-injector chain (Linac2, PSB rings and PS) underwent a close scrutiny to highlight the problems and to propose solutions for the essential elements of the LHC filling scheme. While the changes required in the linacs were minimal, close attention had to be paid to the existing systems in the PSB rings, PS and the beam transfer tunnel TT2. Many systems had to be improved and modified, essentially to cater for the new RF harmonics in both the PSB and the PS.

One of the limiting factors for high brightness beams are low order resonances. For this reason the resonance compensation scheme in the PSB has been revisited and resonance driving term measurements were carried out in 2002 using the existing PSB half-turn pickup. However, more precise results can be obtained from turn-by-turn beam position measurements in two consecutive PSB sections (separated by roughly 90º betatron phase advance). For this, two closed orbit pick-ups were modified and four new head amplifiers, with a bandwidth of up to 55 MHz, were implemented during the 2003/2003 shutdown. Extensive measurements with this system were carried out during the run 2003.

In 1993, the successful testing of the ideas behind the LHC filling scheme had shown that the existing PSB closed orbit measurement system was able to handle the new RF beam structures, though perhaps not perfectly. No major changes have been carried out in this system. It is however envisaged that the PSB closed orbit system will undergo a hardware upgrade in the LHC era to perfectly match the beam characteristics in the PSB.

A new tune measurement system [8, 9] based on the existing "*Q*-kickers" [10] for each of the four PSB rings , using synchronised beam excitation with a small-amplitude, one-turn kick and obtaining fast Fourier transform spectra using a DSP Board was developed. The kicker pulser length is gated to the varying revolution period (1670 ns at injection to 570 ns at extraction) and similarly, the ADC is synchronised to sample the signals at four times the revolution frequency. The system is fully integrated into the standard VME based control system. Tune measurements may be performed every 10 ms in both planes for each of the 4 rings through the full acceleration ramp (50 MeV – 1.4 GeV) in the nominal 1.2 s PSB cycle (Fig. 9.3). Measurements have shown that the amplitudes of the transverse oscillations, generated by a small-amplitude kick, are sufficiently small not to affect the beam emittance. Hence, tune measurements may be carried out all the time without affecting the beam. However, to improve the measurements near 1.4 GeV, the automatic control of the kicker amplitude is foreseen for implementation in the near future.

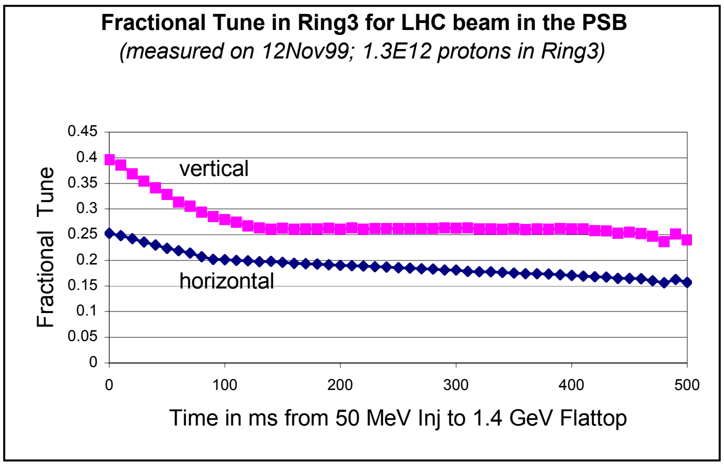

Figure 9.3: PSB tune measurement.

For the PSB to PS transfer channel, the digital system used for the position pickups needed minor changes to cater for the new RF structure of the beam.

In the PS ring, substantial work had to be carried out on the closed orbit and trajectory measurement system. The PS traditionally had a trajectory measurement system, based on the beam position acquisition over two consecutive turns, near injection as well as at any instant in the acceleration cycle. Given the new RF harmonics and gymnastics in the PS required for LHC operation, considerable hardware and software additions and modifications were necessary. This has led to continuity with the traditional trajectory measurements as well as the availability of additional capabilities, required for the double-batch injection, new beam structures and so on up to, but not including, measurements at the extraction of 72 bunches. The new trajectory and closed orbit system is fully integrated in the controls system and is spread over 3 networked VME crates [11-13]. New head electronics for the CODD pick-ups is being designed and a prototype is expected to be ready by early 2004. It should cover the full intensity range of beams in the PS.

Tests are being made using a "normaliser" capable of measuring the beam orbit during the full acceleration cycle. The results will be compared to the current closed orbit system. In the future this system may be made operational or a new combined trajectory and orbit system based on digital techniques will be designed and installed.

For the beam current transformers in the PS ring, the major implication has been the advent of double-batch filling from the PSB. However, most of the changes required are at the level of the timing and specific equipment (ADC channels, triggers and specific software) to provide additional measurement capabilities for this mode of operation. For example, the PS ring DCBCT required an extra facility to permit measurement of the second batch. Similar changes are reflected in other systems like the one used in the PS for measuring beam current in each of the first six turns at injection for protons.

In the beam transfer line TT2 between PS and SPS, two new electrostatic wide-band pick-ups have been developed and installed to observe the particular characteristics of LHC type beams (72 bunches, 4 ns width, 25 ns separation). The pick-ups are judiciously spaced apart in sections 208 and 228 (to determine position and angle of each of the 72 bunches) and have electrodes based on an earlier design for a special 200 kHz - 300 MHz wide-band pick-up in section 98 of the PS ring. With new purpose built electronics the bandwidth of the pick-ups has been extended to a range of 6 kHz to 400 MHz. In addition these pickups were equipped with clearing coils in order to suppress the multiplication of secondary electrons (electron cloud effect). The coil current is controlled from the standard control system. The solenoid field reaches up to ~20 mT in the pick-up centre and no adverse effects were observed on the optics of the line. The signals from the electrodes as well as the sum signals are permanently connected to the analogue observation system and are routinely used for study purposes. The pick-ups also prove useful in observing other types of beams extracted from the PS to the TT2 transfer line, particularly the classical proton 5-turn extraction beam for the SPS. Further experience with this equipment has to be obtained before connecting it to the standard control system.

For beam current measurements in the TT2 transfer line, the LHC beam does not pose any particular problems. However, to supplement measurements from the existing fast beam current transformer TRA203, the lead ion transformers TRA372 and TRA379 have been modified to measure also proton beams. These transformers, built for the lead ion operation from 1994 onwards, measure the stripping efficiency and are installed just at the switching of the beam from the PS controlled TT2 beam line to the SPS controlled TT10 beam line. A new transformer, TRA386, has been installed upstream of the D3 beam dump at the end of TT2 to verify consistency of measurements under all operations. The fast BCT measurements are now completely uniform with automatic switching between the ranges of $\leq 4 \times 10^{10}$, 4×10^{10} - 1×10^{12}, 1×10^{12} - 4×10^{13} electric charges and satisfying all known requirements for SPS and LHC needs.

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