BEAM QUALITY PRESERVATION IN THE CERN PS-SPS COMPLEX

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Abstract

The LHC will require beams of unprecedented transverse and longitudinal brightness. Their production imposes tight constraints on the emittance growth in each element of the LHC injector chain, namely the PS-SPS Accelerator Complex. The problems encountered at the different stages of the acceleration in the complex span a wide range of topics, such as injection matching, RF gymnastics, space charge, transverse and longitudinal single- and coupled-bunch instabilities, and electron cloud effects. The measurement techniques developed and applied to identify and study the various sources of emittance dilution to the high precision required for the LHC beams and the solutions found to control such phenomena are illustrated.

THE LHC INJECTOR CHAIN AND THE LHC BEAM

The proton beams for CERN's Large Hadron Collider (LHC) will be supplied by the PS-SPS Accelerator Complex consisting of:

- Linac 2
- Proton Synchrotron Booster (PSB)
- Proton Synchrotron (PS)
- Super Proton Synchrotron (SPS).

The main target parameters of the nominal proton LHC beam with 25 ns bunch spacing in the Injector Complex are summarized in Table 1. The bunch populations are calculated assuming negligible losses.

Table 1: The LHC beams in the Injector Chain

	PSB@inj.	PSB@extr.	PS@inj.	PS@extr.	SPS@inj.	SPS@extr
Momentum [GeV/c]	0.31	2.14	2.14	26	26	450
Kinetic energy [GeV]	0.050	1.4	1.4	25.08	25.08	449.06
Revolution period [μs]	1.67	0.572	2.29	2.1	23.07	23.05
Tunes (H/V)	4.3/5.45	4.2/5.2	6.22/6.25		26.185/26.13	
Gamma transition	4.15		6.11		22.83	
n. bunches/ring	1	1	6	72 *(24)*	2-4 × 72 *(2-4 × 24)*	2-4 × 72 *(24 × 24)*
Nominal N_b [10^{11} p]	13.8 **(20.4)**	13.8 **(20.4)**	13.8 **(20.4)**	1.15 **(1.7)**	1.15 **(1.7)**	1.15 **(1.7)**
Bunch spacing [ns]	-	-	326.88	24.97 *(74.91)*	24.97 *(74.91)*	24.95 *(74.85)*
Full bunch length τ_b [ns]	571	190	190	4	4	<2
$\varepsilon^*_{H,V}$ [μm] (1 σ)	-	<2.5	-	<3	-	<3.5
ε_L [eV s] (2 σ)	~0.7	1.4 *(0.9)*	1.4 *(0.9)*	0.35	0.35	<0.8

A beam with 75 ns spacing (parameters in italics, wherever different from those of the nominal 25 ns spacing LHC beam) will be also delivered to the LHC with bunch population up to the nominal during the early physics runs. The 25 ns ultimate beam parameters are indicated in bold wherever different from those of the nominal beam.

THE LHC BEAM CHALLENGE IN THE INJECTORS [1-2]

The nominal LHC proton beam longitudinal and transverse brightness (i.e. the ratio between the bunch population and its longitudinal and transverse emittance) largely surpasses that of the other multi-bunch beams produced so far by the accelerators of the LHC injector chain. In the SPS, only the bunches during the $p\bar{p}$ period had similar transverse and longitudinal brightness but the total charge of this beam was smaller than that of the nominal LHC beam by almost two orders of magnitude [3][4].

The target values of the transverse and longitudinal brightness can be achieved only by a strict control of the longitudinal and transverse emittances throughout the whole injector complex. This task is even more arduous because of the high total intensity and implies understanding and controlling a wide spectrum of phenomena that could lead to emittance growth and that can be schematically grouped in three main categories:

- single-particle phenomena,
- single-bunch phenomena,
- multi-bunch phenomena.

High energy colliders require short bunches and a tight bunch spacing in order to maximize luminosity. High harmonic numbers (i.e. high RF frequency acceleration systems) are also needed for the high energy injectors to provide the RF voltage required for the acceleration. On the other hand low harmonic numbers (i.e. low RF frequencies) are better suited for the lower energy injectors to: (i) minimize space-charge effects, (ii) avoid longitudinal or transverse coupled-bunch modes, (iii) provide the large frequency range required for the acceleration in the non-relativistic regime, (iv) maximize the longitudinal acceptance. The complicated longitudinal gymnastics required to match the two conflicting requirements is an additional challenge for the production of the LHC beam [5].

SINGLE-PARTICLE PHENOMENA

Mismatch, i.e. any deviation of the optics seen by the beam with respect to the model (steering errors, dispersion and betatron mismatch), induce transverse emittance growth at the transfer between accelerators.

While static steering errors can be easily corrected by means of an adequate monitoring and correction system, cycle-by-cycle trajectory variations can be suppressed by transverse feedbacks. The relative normalised emittance growth after filamentation $\Delta\varepsilon^*_{af}/\varepsilon^*$ due to injection errors is given by (β and γ are the relativistic factors):

$$\frac{\Delta\varepsilon^*{}_{af}}{\varepsilon^*} = \frac{\Delta X_n^2 + \Delta X_n'^2}{2\varepsilon^*}\beta\gamma \qquad (1)$$

where ΔX_n and $\Delta X'_n$ are the errors in the normalized position and angle at injection, respectively. The effect of the injection errors is larger the higher is the energy of the beam. The SPS is equipped with a damper to minimize the blow-up due to injection errors.

Uncertainties in the values of optical parameters at the beginning of the transfer line translate into betatron and dispersion mismatch. The relative normalised emittance growth for betatron and dispersion mismatch after filamentation is:

$$\frac{\Delta\varepsilon^*{}_{af}}{\varepsilon^*} = \frac{1}{2}\left[\frac{\beta_0}{\beta_m} + \frac{\beta_m}{\beta_0} + \left(\alpha_0\sqrt{\frac{\beta_m}{\beta_0}} - \alpha_m\sqrt{\frac{\beta_0}{\beta_m}}\right)^2\right] \qquad (2)$$

$$\frac{\Delta\varepsilon^*{}_{af}}{\varepsilon^*} = 1 + \frac{\left(\Delta D_n^2 + \Delta D_n'^2\right)\left(\frac{\Delta p}{p}\right)^2}{2\,\varepsilon^*}\beta\gamma \qquad (3)$$

respectively, where β_m, α_m are the measured Twiss parameters at injection β_0, α_0 are the corresponding expected values, ΔD_n and $\Delta D'_n$ are the errors in the dispersion and its derivative in normalised coordinates and $\Delta p/p$ is the rms momentum spread of the injected beam.

Dispersion mismatch is particularly critical for the LHC beam because of its small transverse emittance and large momentum spread, furthermore its impact is larger the higher is the injection energy.

The estimation of the optical parameters at extraction from the PS machine is particularly difficult because the extracted beam is passing through the lateral fringe-field of the PS combined-function magnets [6]. The Twiss parameters the dispersion and its derivative at extraction from the PS and their dependence on the extraction momentum have been measured [7-8].

The dependence of the emittance blow-up factor after filamentation on the momentum offset has been estimated from the measurement of the dispersion in the TT2-TT10 transfer line performed in 2001 after a first campaign of measurement of the PS extraction parameters and of matching of the transfer line optics. In the horizontal plane a dependence on momentum offset is still observed although in the range of momenta covered by the LHC beam the expected blow-up is acceptable and a new optics is being studied to further reduce such effect.

In order to verify the quality of the matching and of the control of injection oscillations a beam with very small transverse emittance ($\varepsilon^* < 1$ μm) and momentum spread comparable to the LHC beam has been transferred through the whole injector chain. The results of the comparative emittance measurements performed in all the accelerators are shown in Fig. 1 (horizontal plane). Less than 10 % blow-up is observed in these extreme conditions indicating that this source of emittance growth is under control.

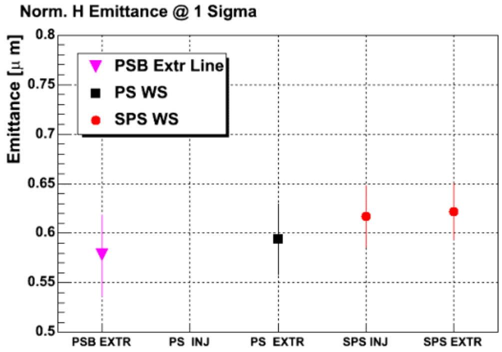

Figure 1. Horizontal normalised emittance evolution along the injector chain (WS=wire scanner, PSB Extr. Line=line at PSB extraction, equipped with SEM grids).

SINGLE-BUNCH PHENOMENA

The high longitudinal and transverse brightness of the LHC beam is at the origin of single bunch phenomena like:

- Longitudinal instabilities (e.g. μ-wave instability)
- Space charge
- Transverse instabilities

Microwave Instability in the SPS

The ultimate LHC beam in the SPS has unprecedented space charge tune spread at injection but even more the nominal bunch population was well above the threshold for the onset of the microwave instability before the upgrade of the SPS as LHC Injector (Fig. 2).

The threshold for the microwave instability has been estimated with the Keil-Schnell-Boussard criterion [11-12] from the values of the longitudinal impedance measured (|Z|/n=10-40Ω in the SPS for a broadband resonator model [13]) before the upgrade of the SPS as LHC Injector. This estimation is strictly valid for a pure broad-band impedance and it is only qualitative in the presence of narrow-band components.

A continuous decay of the peak detected signal, accompanied by beam loss, was observed along the flat bottom, as a consequence of the microwave instability, when the first injection tests with the LHC beam were performed in the SPS in 1999.

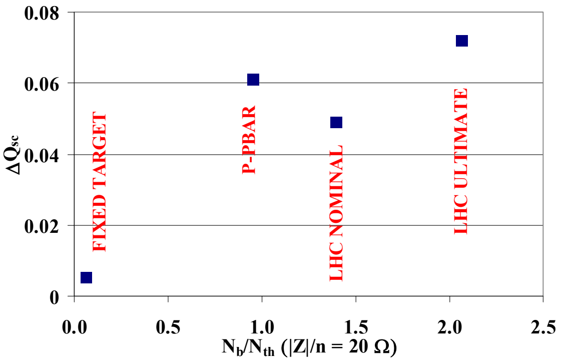

Figure 2. Space charge tune spread ΔQ_{sc} and bunch population N_b normalised to the threshold N_{th} for the microwave instability at the SPS injection energy for the LHC beams and for some of the proton beams accelerated so far [9-10].

A campaign of measurements was started in 1995 to determine the SPS longitudinal impedance spectrum and to identify the sources among the machine elements. The spectrum of unstable modes of high intensity proton bunches injected in the SPS with RF off was measured. In order to resolve the fine structure of the narrow-band impedances long bunches ($\tau_b \sim 25$ ns) were used [14].

The main source of microwave instability was found to be the impedance (at frequencies >1.4 GHz) of almost 1000 pumping ports installed in the SPS. Additional contributions were identified with the impedance of the main RF system around the fundamental frequency (200 MHz) and with the impedance introduced by some extraction magnetic septa and kickers (400 MHz).

Among the possible solutions to increase the threshold for the microwave instability:

- increase of the momentum spread of the beam,
- increase of the transition energy,
- stronger damping of the pumping port cavities,
- reduction of the machine impedance.

the latter was retained because of the positive implications for other high intensity beams. The impedance reduction program in the SPS was almost totally completed during the shutdown 2000/2001 [15].

Measurements with a single bunch done in 2001 [16] demonstrated a significantly improved bunch stability. A decrease of the bunch lengthening with intensity by a factor 7 and of the longitudinal quadrupole frequency detuning with intensity by a factor 2.5 were measured. No high frequency signal was visible up to the nominal bunch intensity. Measurements with LHC beam on the flat bottom showed a clear increase in beam lifetime and absence of losses.

Space Charge

Direct space charge tune spread ΔQ_{sc} is one of the primary issues in the production of high brightness beams, in particular in low energy machines, as it can be inferred from expression 4 (where R is the machine radius):

$$\Delta Q_{sc} \div \frac{N_b}{\tau\,\varepsilon^*}\,\frac{R}{\beta\gamma^2} \qquad (4)$$

As a result of the tune spread the beam overlaps several resonances and it is subject to emittance growth and losses. The intensity of these two effects depend on the choice of the working point, on the strength of the resonances close to the working point and on the amount of time spent in these conditions. The shorter is the time spent at low energy and the smaller is the tolerable tune spread for a given emittance preservation budget. In particular in the PSB and PS tune spreads larger than 0.5 and 0.3, respectively are not tolerable, for that reason the following upgrades have been implemented [17]:

- Double batch injection into the PS, resulting in a reduction of the bunch intensity by a factor two in the PSB. This has implied the installation of a new RF system operating at h=1 (the previous system was operated at h=5 and has been transformed in an h=2 RF system for bunch flattening to further reduce ΔQ_{SC}).
- Increase of the extraction energy in the PSB from 1 to 1.4 GeV to reduce the tune spread at injection in the PS (by a factor 1.5).

Transverse Instabilities

The double batch injection scheme into the PS implies that the first PSB batch has to circulate in the PS at injection energy for 1.2 s and it is subject to single-bunch transverse instabilities. Horizontal single-bunch instabilities with high head-tail mode number have been observed in the PS at 1 GeV, as expected from the classical Sacherer's head-tail instability theory if the resistive wall impedance is considered [18]. A low negative chromaticity ($0<\xi_H<0.05$) could damp the instability but this kind of operation is impractical given the narrow region of stability. Even at the higher injection energy, stabilization for the single- and coupled-bunch instabilities by linear coupling proved to be determinant for the achievement of the nominal LHC beam parameters in the PS [19].

LONGITUDINAL GYMNASTICS

Adiabatic de-bunching and recapture is the straightforward solution to the problem of transforming the bunch structure of the beam to match the conflicting requirements of low harmonic RF systems for low energy machines and high harmonic RF systems for high-energy accelerators. In the initial scheme for the production of the LHC beam the 25 ns bunch spacing was produced in the PS at extraction energy by adiabatic de-bunching on h=16 (7.6 MHz) and re-bunching on h=84 (40 MHz). This solution presented two major drawbacks [5]:

- Microwave instabilities arise during the de-bunching process and they can only be cured with a longitudinal emittance blow-up which produces 5 ns long bunches filling completely the SPS 200 MHz bucket.
- The beam fills the PS circumference and no gap is left for the extraction kicker rise-time, hence 3 bunches are lost in the extraction process and 2-3 are extracted with large errors.

In order to eliminate the above two problems a new scheme has been developed: 6 bunches delivered by the PSB in 2 batches are captured on h=7 in the PS. Immediately after the injection of the second batch a triple splitting is started and the beam, now consisting of 18 bunches, is accelerated on h=21 up to 26 GeV/c where each bunch undergoes two double-splitting processes in cascade to give a total of 72 bunches on h=84 with a gap of 320 ns in the bunch train.

This new scheme (implemented in the year 2000) has the additional flexibility of producing different bunch patterns, namely beams with 50 or 75 ns spacing or even more exotic patterns [20-21].

The splitting process is sensitive to longitudinal coupled-bunch instabilities, which can originate asymmetric intensities if they occur during the splitting, for that reason a controlled longitudinal blow-up is applied and a longitudinal damper has been implemented during the last shut-down to fight coupled-bunch instabilities up to high energy [22].

MULTI-BUNCH PHENOMENA

The high bunch population, the large number of bunches, concentrated in about one third of the machine circumference with a tight bunch and batch spacing, make the LHC beam in the SPS more prone to multi-bunch phenomena in the longitudinal plane (beam loading, longitudinal coupled bunch instabilities) and in the transverse plane (resistive-wall instability and electron cloud instability). These phenomena could result in emittance growth if not suppressed or at least controlled.

Transverse plane

The resistive wall instability manifests in the SPS as a coupled-bunch instability (of low order). The SPS transverse feedback has been designed to provide enough strength and bandwidth (up to 20 MHz) to fight such instability.

From the first tests performed with the LHC beam in 1999 it became evident that electron multipacting was occurring in the SPS vacuum chambers in the presence of this beam [23] as a consequence of the high bunch population and of the bunch spacing. The electrons accelerated from a bunch might gain enough energy to traverse the vacuum chamber before the next bunch passage and to extract secondary electrons from the chamber walls, in which case the following bunch accelerates in turn the secondary electrons. An exponential growth of the number of electrons occurs if the Secondary Electron Yield (SEY) of the vacuum chamber surface is larger than 1 at the energy of the impinging electrons. The energy gained by the electrons depends on the bunch population, bunch length, bunch spacing and on the chamber dimensions. These parameters determine the multipacting threshold.

Above the threshold for the onset of electron multipacting transverse instabilities develop along the batch, starting from the tail and progressing to the head of the batch, and resulting in strong emittance blow-up and in beam losses, mainly affecting the tail of the batch. Cures exist to suppress or at least reduce multipacting:

- increase of the bunch spacing (e.g. 75 ns spacing)
- reduction of SEY by electron bombardment induced by the beam.

The latter process has been thoroughly studied at CERN [24] and it has been observed in the SPS [25-26]. The thresholds for the onset of the beam-induced multipacting have correspondingly increased from 0.3×10^{11} p/bunch to 1.0×10^{11} p/bunch in the arcs which are covering approximately 70% of the SPS circumference.

Experience shows that the electron cloud activity cannot be fully suppressed and the final threshold intensities and SEY depend on the operational conditions of the machine. For that reason measures to fight the electron cloud transverse instability have been studied.

The properties of the instability are significantly different in the horizontal and vertical planes. In the horizontal plane it manifests itself as coupled-bunch instability while in the vertical plane a single bunch Transverse Mode Coupling like instability occurs [27].

In the horizontal plane, low order coupled-bunch modes (up to few MHz) are the most unstable. The rise time of the instability is of the order of 40 turns and is only weakly dependent on the bunch population. This instability can be cured by means of the transverse feedback at least up to the nominal intensity.

The vertical electron cloud instability is of single bunch type: a measurement of the bunch-by-bunch position over several turns does not show any phase correlation among subsequent bunches. The instability mainly affects the tail of the batch and the rise time is decreasing with increasing bunch population N_b (the maximum amplitude of oscillation, corresponding to the machine physical aperture, is reached in about 600 turns for $N_b=0.3\times10^{11}$ p and in 300 turns for 0.5×10^{11} p). A vertical motion inside the bunch at frequencies of about 700 MHz has been observed which can be associated with the electron oscillation frequency and possibly with an additional external impedance. The observed single-bunch instability cannot be damped by the transverse feedback that can only detect and correct dipole modes. Running at high chromaticity (ξ_V up to 1.5) is the only cure found so far to fight the electron cloud instability in the vertical plane.

Another possible remedy for the vertical single bunch instability might consist in using linear coupling [28].

Longitudinal plane

The disappearance of uncontrolled longitudinal emittance blow-up due to the microwave instability enhanced other instabilities because of the denser bunches and of the impedance of the main RF system around the fundamental frequency (200 MHz). This was since long considered to be a serious problem both for beam loading and for coupled-bunch instabilities. For the nominal bunch current, the beam induced voltage can rise along the batch, without compensation, to 6 MV within ~ 800 ns (the filling time of the RF Travelling Wave Cavities – TWC), comparable to the maximum RF voltage available.

By the start-up in 2002 each of the four RF Cavities was equipped with [29]:

- feedforward system (providing 10-15 dB impedance reduction in a 1 MHz band on each side of the RF frequency) [30],
- new One-Turn-Delay-Feedback (~20 dB impedance reduction, 2 MHz single-sided bandwidth)

working in parallel to reduce the impedance at the fundamental frequency.

By the start-up 2004 all four TWC have been equipped with new power couplers rated for 1 MW continuous power (to be compared to 700 kW for the previous couplers) and with improved multipactoring control allowing operation at lower voltage without counterphasing and therefore easing operation with high beam loading.

A longitudinal damping system built around two TWC was also installed in 2002 to damp dipole modes up to 3 MHz during the full LHC cycle.

After the upgrades no instability has been observed at low energy, but a coupled-bunch instability occurred at 280 GeV/c and at extraction energy (when the RF voltage is raised to match the LHC 400 MHz bucket) for a single LHC batch and bunch intensities well below the nominal. The origin of such instability is not known, to date.

The coupled-bunch instability at 280 GeV/c can be cured up to nominal intensities and number of batches by increased Landau damping using a fourth harmonic (800 MHz) RF system, the phase shift being programmed in bunch shortening mode. The remaining instability, appearing at extraction energy, was suppressed by a longitudinal emittance blow-up to 0.6 eV.s obtained in two steps:

- at low energy by injecting in a mismatched RF voltage (2 MV instead of 0.75 MV),
- at high energy by phase modulation of the 800 MHz voltage or by pink noise excitation of the 200 MHz amplitude.

SUMMARY AND CONCLUSIONS

The LHC beam presents several challenging aspects in all the injectors. Only a selection of the main issues and of the results of the dedicated work of several colleagues has been presented here.

The beam experiments performed since the early 90’s have provided a precious input to upgrade the LHC injectors which have been built more than 20 years ago.

Nominal longitudinal and transverse parameters have been achieved in the PSB and PS. Longitudinal emittances well below the target have been obtained in the SPS and the transverse emittance is close to the target (within 20 %) for the nominal 25 ns LHC beam and below the nominal values for the 75 ns beam at the extraction energy. Efforts are now directed in further improving the performance (in particular transverse emittance and capture losses in the SPS) and the reproducibility of the beam properties both on a bunch-by-bunch and a cycle-by-cycle basis.

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