# Providing the Longitudinal Beam Parameters of the LHC Beam

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*Abstract*

The luminosity foreseen for the Large Hadron Collider (LHC), at present being built at CERN, places stringent requirements on the longitudinal beam parameters of the high intensity proton beam. Critical points in the production of this beam occur both in the injector chain and at transfer and capture in the LHC itself. The consequent design of the superconducting RF system as well as the proposed damping and higher harmonic RF systems is discussed. Emphasis is also placed on some areas in the SPS machine, injector for the LHC, where transient beam loading and both single and multi-bunch instabilities must be carefully controlled to attain the high beam quality required.

## 1 Introduction

The two proton beams in the LHC are accelerated independently, each LHC ring having its own RF system. Each system consists of eight single cell superconducting cavities at 400 MHz (each 2 MV). Superconducting cavities have been chosen for high stored energy to minimise beam-loading effects at the revolution frequency harmonics during collisions (up to a factor 10 better than warm cavities), and power requirements (a factor 2 better) [3].

The beams accelerated in the SPS (LHC injector) are composed of 243 bunches (intensity $1.05 \times 10^{11}$) spaced at 25 ns intervals [1], [2]. The beam occupies only 3/11 of the circumference (1 turn = $23.1 \mu s$). This beam is accelerated to 450 GeV and injected into the LHC on twelve consecutive SPS cycles for each LHC ring. The resulting total intensity in the SPS is about twice smaller than the maximum that has been accelerated in the SPS in fixed target mode (FT) (where the ring is completely filled), but the intensity in the occupied 3/11 of the ring will be about twice higher. It is this high "batch" intensity that can lead to beam loading and instability problems.

At injection in the LHC, dynamic aperture restrictions imply a beam with a low energy spread, and both injection errors and transient beam loading effects require short bunches to avoid losses at transfer. These two together, in conjunction with the maximum RF voltage available at 200 MHz in the SPS, 8 MV, give a range of acceptable longitudinal emittance from 0.5 eVs to 0.7 eVs, the lower value being preferred. Providing this emittance at 450 GeV in the SPS is particularly difficult. The bunch injected into the SPS will have an emittance approaching 0.5 eVs after its injection transient. Even an emittance of 0.7 eVs at 450 GeV allows little blow-up.

## 2 Errors at injection into the LHC

Energy and phase errors at injection into the LHC come from the injector, the LHC itself and the inevitable synchronisation errors. In the SPS, the existing four 200 MHz travelling wave (TW) cavities will be used for acceleration. There are also two TW cavities available for Landau damping, operating at the 4th RF harmonic [2]. The 200 MHz TW RF cavities are broadband with a transient response of $\sim$ 600 ns. An additional feature is that the transfer function relating beam induced voltage $V_b$ to beam current $I_b$ is not the same as that relating the generator induced voltage $V_g$ to the generator current $I_g$ [4]. This complicates both the feedback and feedforward which are essential for reducing periodic transient beam-loading. In particular the minimum beam induced voltage that can be obtained by optimum use of feedforward techniques in the first 600 ns of the beam pulse is $\sim V_b/4$. The result is a minimum peak phase modulation over the first bunches $\sim \pm$ 15 degs measured at 400 MHz. From experience in the SPS it is expected that synchronisation errors can be limited to $\pm$ 10 degs. The installed power in the LHC will be sufficient to compensate the beam induced voltage in the superconducting cavities. With the strong RF feedback, essential to reduce the impedance and maintain beam stability, there will be almost complete cancellation of phase errors due to periodic beam loading along the batch [3]. The total phase error at injection will therefore be $\sim \pm 25$ degs.

In the superconducting LHC magnets the persistent current effects will cause the dipole field to drift by up to $\sim 3 \times 10^{-4}$ during the injection procedure. This effect will be compensated by the closed orbit dipoles. By measuring the energy error between injections, using the synchrotron oscillation or the first turn orbit, it should be possible to reduce the effective error to $\leq \pm 10^{-4}$.

The 8 MV at 200 MHz available in the SPS will give a total bunch length of 1.7 ns for 0.7 eVs. This is the maximum tolerable bunch length for the expected phase and energy errors combined to avoid uncaptured particles in the LHC. To avoid significant blow-up in the LHC damping systems at 200 MHz for better kick linearity across the bunch, will be installed in the LHC rings. The system is designed to damp phase and energy errors affecting the whole batch in 2 to 3 synchrotron periods and with slightly longer times for the fastest changing phase errors [1]. With the expected errors and bunch lengths at transfer, the bunch edges will be near the separatrix. The nonlinearity of the 400 MHz RF waveform at these amplitudes reduces the efficiency of the damping system and emittance blow-up may be large. To improve the situation the voltage waveform can be partially linearised by the addition of voltage at 800 MHz. Studies have shown [5] that the emittance increase of a 0.63 eVs bunch injected with both the maximum phase and energy errors can be reduced from $\sim$ 25% to $\leq$ 10% by the addition of 2MV at 800 MHz. A preliminary design of a suitable cavity, superconducting and sitting in the same cryostat as the 400 MHz cavities is underway.

If the emittance at extraction from the SPS is higher than 0.7 eVs then an extra RF system is needed in the SPS to produce the short bunches and an 800 MHz system in the LHC becomes mandatory. A study has been made of a 400 MHz superconducting system based on the LHC design which could be used in the SPS to provide extra voltage. A prototype cavity installed in the SPS produced 1 MV in the presence of a high intensity proton beam during tests [6].

From all these critical issues low emittance in the SPS is desirable.

## 3 Low emittance beams in the SPS

To prevent longitudinal emittance blow-up of the initial parts of the batches at injection into the SPS (26 GeV) due to beam loading RF feedback and feedforward must be used on the TW cavities.

The main cause of emittance blow-up is expected to be due to instabilities. LHC type beams (25 ns bunch spacing) have not been available up until now in the SPS, upgrades in the pre-injector chain to produce this beam are nearing completion. However strong instabilities are observed on the high intensity fixed target proton beams which have comparable total intensity but a different bunch spacing of 5 ns and which occupy the full ring. A comparison between FT and LHC beams is given in Table 1. We used this FT beam and single bunches of varying emittance, length and intensity, to study possible single and multi-bunch instabilities.

### *3.1 Single bunch instabilities*

The microwave instability is at present a source of emittance increase at injection into the SPS [7]. A few possible solutions to raise the instability threshold were examined.

Increasing the momentum spread by additional voltage in the injector would require significant hardware - the PS is already very short of space.

Another possibility is to lower the transition energy in the SPS. This idea which has been tested in the SPS [9] requires the installation of two new families of quadrupoles (24 in total).

With the help of a method to measure the impedance of elements in the machine having high R/Q and low Q, R being the shunt impedance and Q the quality factor, [8], the main impedance sources causing the instability have been identified. They are the magnetic septa, and the approximately 800 inter magnet pumping ports and will be shielded [2]. The shield for the magnetic septa is designed and a prototype already installed. The design for the vacuum ports is being finalised. It is complicated by the need for a sliding RF contact to allow disconnection and removal of magnets in case of failure. To install these shields in the pumping ports it is necessary to displace one machine magnet in two (400), a huge task. All magnetic septa shields will be installed during the 1998-99 shutdown. The shielding of the pumping ports will be a heavy effort occupying three two month periods over the next three years.

Shielding has an additional advantage in reducing the low-frequency inductive impedance which lowers the coherent frequency shift and can help stabilise other instabilities.

### *3.2 Multi-bunch instabilities*

Our main effort at the moment is aimed at understanding multi-bunch instabilities which are observed on the high intensity FT beam. The beam on the FT cycle suffers

Table 1: Fixed target and LHC beam characteristics in the SPS

| | FT Beam | LHC beam |
|---|---|---|
| Bunch intensity | $10^{10}$ | $10^{11}$ |
| Bunch spacing | 5 ns | 25 ns |
| Total intensity | $4.7 \times 10^{13}$ | $2.43 \times 10^{13}$ |
| Filling pattern | 10/11 | 3/11 |

an emittance increase from 0.5 eVs at 26 GeV (1.5 s) to greater than 2 eVs at 450 GeV (4.54 s) , Fig.1, for the voltage programme (constant at 6 MV), used in normal FT operation. The beam continually blows up to fill the available bucket space. By reducing the voltage to the point of particle loss the emittance can be kept lower up to 400 GeV (4.1 s) but from then on it is impossible to hold the beam at constant emittance. The final emittance is significantly lower but still large, (V2 curve Fig.1). Any increase in voltage leads to higher emittances. Note that before transfer to LHC the voltage must be raised to the highest values to minimise bunch length.

For studies, it is possible to inject beam into the SPS so as to fill 1/11, 5/11, or 10/11 (FT) of the ring. We have measured the lowest emittance obtainable with these filling factors as a function of intensity, Fig.2. by lowering the voltage until particle loss results. This was more accurate than measurements using the bunch profile. In Fig.2(a), the results are plotted as a function of total intensity and in Fig.2(b) as a function of single bunch intensity [10]. In the first case the emittance increases with intensity but is dependent on the filling pattern. In the second graph we see that the increase is independent of filling factor if the single bunch intensity is used, except when we have a very low filling factor (1/11). This suggests that short range wake fields covering a few bunches are responsible. We have observed the frequency spectrum of these instabilities and also looked at the sig-

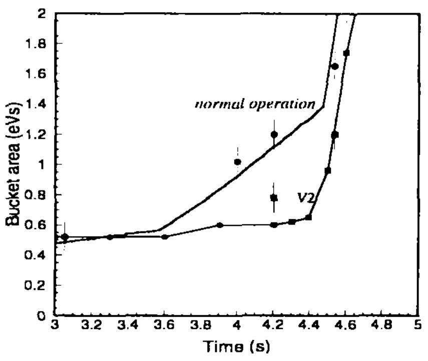


Figure 1: Bucket area for normal FT cycle and minimum no loss voltage cycle V2. Estimated emittances are shown as filled circles and filled squares respectively. Total intensity $4.1 \times 10^{13}$ at 450 GeV

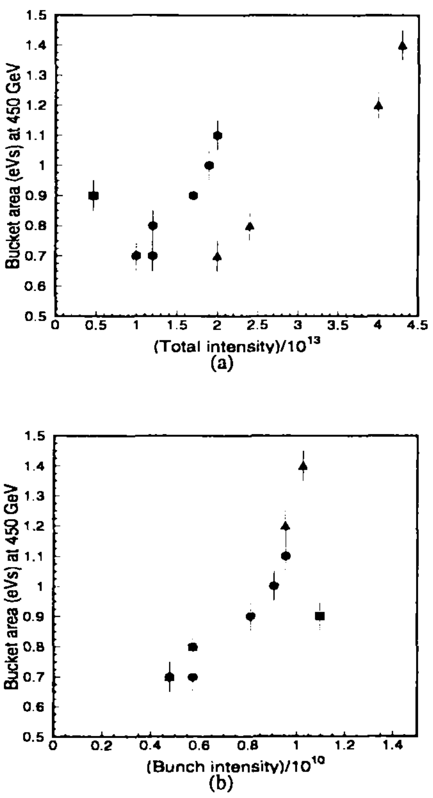


Figure 2: Bunch area at the end of the cycle as a function of total (a) and bunch (b) intensity. Triangles correspond to 10/11 ring filled, circles 5/11 and square 1/11

nals induced in the different cavities. We were unable to identify a single source for this instability and at the moment believe that several sources are involved including the impedance of the vacuum ports. In principle the situation will be improved in 2001 (LEP closure) when shielding is completed and the three lepton acceleration systems are removed from the machine (28 cavities total).

In addition we have been developing tools to try and damp these instabilities.

- The one-turn RF feedback around the 200 MHz cavities is essential. It will be improved by increasing the bandwidth and extending the system from one loop per four cavities to one loop per cavity.
- We have been studying the effect of Landau damping, using an 800 MHz system both in bunch lengthening (BL) and bunch shortening (BS) modes [11]. In BL mode the accuracy of phase programming required for maximum frequency spread precludes the use of this mode operationally. In BS mode we have succeeded in stabilising the fixed target beam up to close to the flat top. We have not been able yet to use both 800 MHz cavities available and hope for better performance with them both in operation.
- We also study a coupled bunch feedback system. This will help with dipole and quadrupole modes but the high order modes that we see in some cases will be difficult to damp. We are preparing the hardware to perform initial tests. The system will be based on the existing 200 MHz standing wave cavities at present used for lepton operation.

## 4 Conclusions

We have two lines of attack in our efforts to keep the emittances in the SPS below 0.7 eVs - removing the sources and damping the instabilities. If these are insufficient then an extra RF system will be needed in the SPS.


This paper describes the work of a team of people in the SL/RF group. I would like to thank both D.Boussard and E.Shaposhnikova for their helpful comments and suggestions.


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