ULTIMATE LHC BEAM

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Abstract

The present status of the nominal LHC beam in the LHC injector complex and the limitations towards the achievement of the ultimate brightness are outlined.

INTRODUCTION

The schematic layout of the LHC Hadron Injector Complex with the corresponding kinetic energy range is shown in Fig. 1. In the following only the circular proton injectors will be considered.

The beam parameters for the nominal and ultimate LHC beams are listed in Table 1 for all the circular LHC Injectors at injection and at extraction. The bunch population of the ultimate LHC beam is approximately 50% higher than that of the nominal LHC beam while the transverse and longitudinal emittances are the same. This implies that the longitudinal and transverse brightness of the ultimate LHC beam are 50% higher than those of the nominal beam.

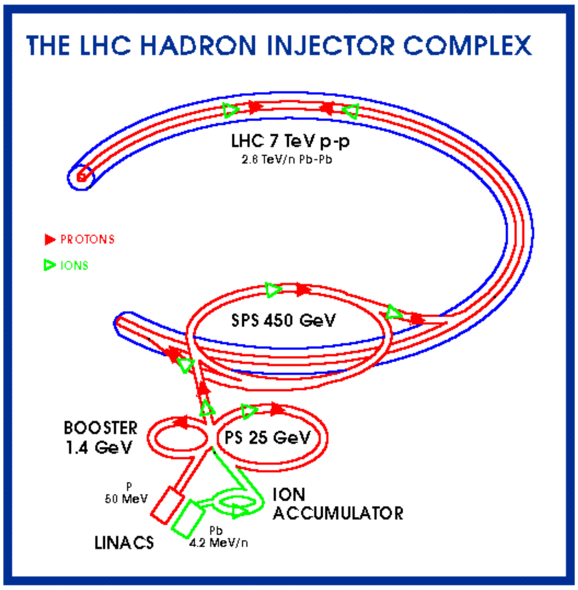

Figure 1. The LHC Hadron Injector Complex. Proton beams are indicated in red while Ion beams are indicated in green.

	PSB@inj	PSB@extr	PS@inj	PS@extr	SPS@inj	SPS@extr
p [GeV/c]	0.31	2.14	2.14	26	26	450
K [GeV]	0.050	1.4	1.4	25.08	25.08	449.06
T_{rev} [μs]	1.67	0.572	2.29	2.1	23.07	23.05
Q (H/V)	4.3/4.45	4.2/4.2	6.22/6.25		26.13/26.18	
γ_{tr}	4.15		6.11		22.83	
bunches/ring	0-1	0-1	6	72	2-4×72	2-4×72
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**
ΔT_{bunch} [ns]	-	-	326.88	24.97	24.97	24.95
τ_b [ns]	571	190	190	4	4	<2
$\varepsilon^*_{H,V}$ [μm]	-	<2.5	-	<3	-	<3.5
ε_L [eV.s]	~0.7	1.4	1.4	0.35	0.35	<0.8

Table 1. Main design parameters of the LHC Nominal and Ultimate (in bold when different from nominal ones) beams [1].

PS BOOSTER

The present performance of the PS Booster for the LHC beam is summarized in Fig. 2 showing the measured normalized vertical and horizontal transverse emittances as a function of the bunch population at extraction. The full green and orange vertical lines indicate the nominal and ultimate bunch populations while the dashed green vertical line indicates the required bunch population in order to achieve the nominal bunch population at the SPS extraction taking into account the losses occurring in the PS and in the SPS. These losses amount to approximately 10-15 %. The blue horizontal line represents the design transverse emittance. The measured data for each of the 4 PSB ring is presented together with the average over the 4 rings. Although the nominal design parameters have been fully achieved the ultimate ones are not within reach at present.

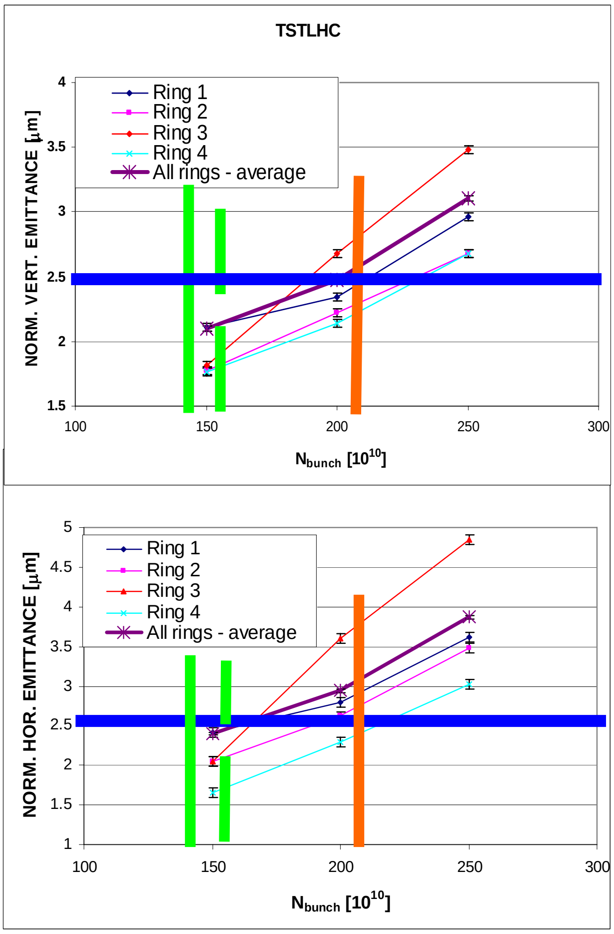

Figure 2. Measured normalized vertical (top) and horizontal (bottom) emittance vs. bunch population for the LHC beam at extraction from the PS Booster. Courtesy of K. Hanke and B. Mikulec.

Space charge is considered to be the main limitation for the achievement of ultimate performance in the PS Booster [2]. The injection at 160 MeV with the LINAC4 should reduce the space charge limit at injection by a factor two [3][4]. A reduction of the losses in the PS and SPS is also mandatory in order to relax the requirements in terms of brightness to the PS Booster.

PS

LHC beams with bunch population close to 1.5×10^{11} p have already been produced in the PS, nevertheless two potential limitations in the road towards ultimate performance have been evidenced [2]:

- space charge;
- electron cloud instability at extraction.

Space Charge

Double-batch injection has been implemented in the PS for the LHC beam (Fig. 3) in order to keep the space charge tune spread at injection in the PSB below 0.5. As a consequence of that the first injected batch remains for 1.2 s at PS injection momentum limiting the maximum acceptable space-charge tune spread in the PS to approximately 0.25.

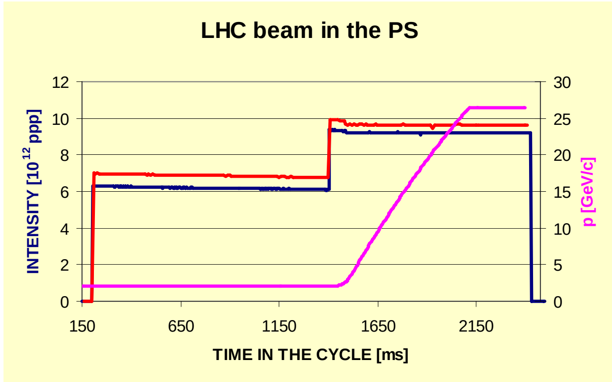

Figure 3. Double batch injection for the LHC beam in the PS. Approximately 3% losses are observed during the 1.2 s long injection plateau. Courtesy of E. Métral.

Space charge and synchrotron motion induce periodic tune modulation and trapping-de-trapping on resonance islands leading to halo and losses [5][6]. This could explain low energy losses observed in the PS (Fig. 3).

This explanation is consistent with the observation that losses are affecting mainly shorter and/or more intense bunches and are normally involving particles with larger momentum offsets (Fig. 4).

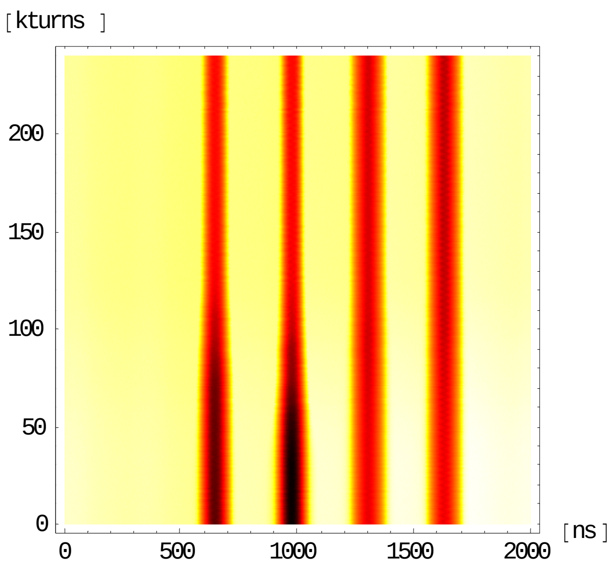

Figure 4: Density plot of the bunch profiles of the four bunches of the first PSB batch injected in the PS as measured with a wall current monitor as a function of the turn number. The most intense bunches are mainly affected by losses and their bunch length is decreasing. Courtesy of S. Hancock and E. Métral.

A higher injection energy and/or single batch injection could help in minimizing these effects.

Electron Cloud Instability

A horizontal instability with a rise-time of about 1 ms has been observed for the nominal LHC beam at top energy after the last bunch splitting leading to the 25 ns bunch spacing [7][8]. At nominal bunch population the beam becomes unstable for a total bunch length shorter than 12 ns (Fig. 5) which is close (within 10 %) to the typical bunch length of the beam few ms before extraction. For a bunch length of 12 ns the threshold bunch population is approximately 0.6×10^{11} p (i.e. approximately half the nominal bunch population).

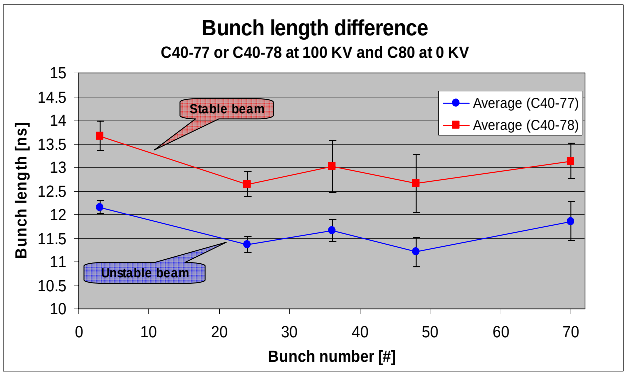

Figure 5: Measured full bunch length along the LHC beam bunch train for two different configurations of the 40 MHz RF system in the PS leading to different bunch lengths by approximately 10% because of a voltage calibration error in one of the cavities. The beam is transversally unstable when the bunches are shorter than 12 ns (blue dots). Courtesy of E. Métral and R. Steerenberg.

Studies are ongoing to better understand the electron-cloud build-up in the PS and possible solutions are being investigated. These include:

- a different RF programme to compress the bunch length to ~ 4ns before extraction to the SPS;
- the possibility of using the transverse feedback to damp this instability.

SPS

Design longitudinal (ε_L<0.8 eV.s) and transverse (ε^*_H=3.0±0.3 μm and ε^*_V =3.6±0.3 μm) parameters have been achieved in the SPS for the nominal LHC beam at extraction energy although no margin exists in particular for the vertical emittance. The main limitations towards the achievement of ultimate performance in the SPS are [2][9]:

- Fast Vertical Single Bunch Instability at injection due to machine impedance;
- Electron Cloud effects.

Fast Vertical Instability

A fast single-bunch vertical instability develops in the SPS right after injection at 26 GeV/c for bunch populations larger than 0.6×10^{11} p if the longitudinal emittance of the beam is smaller than 0.2 eV.s [10]. Figure 6 (left) shows the loss occurring few ms after injection for a single LHC bunch with nominal population (~ 1.2×10^{11} p) and low longitudinal emittance (~ 0.2 eV.s, to be compared with the design value of 0.35 eV.s). The RF voltage for that experiment was close to 600 kV which corresponds to a synchrotron period of 7.1 ms. The loss occurs when the bunch length is minimum (i.e. when the peak intensity is maximum).

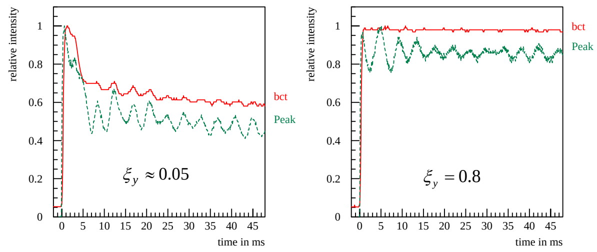

Figure 6: Measured relative bunch intensity (normalized to the value at injection) vs. time in the SPS machine for two values of the vertical chromaticity. bct stands for beam current transformer and Peak stands for peak intensity. Courtesy of H. Burkhardt.

The characteristics of the instability are typical of a Transverse Mode Coupling Instability (TMCI) and experimental and simulation studies are ongoing to better characterize it [11][12].

Simulation studies performed with the HEADTAIL code [13] taking into account the measured SPS broad-band impedance, space charge and the rectangular cross-section of most of the SPS apertures indicate that the threshold of this instability for the LHC beam parameters and operating conditions should be close to the ultimate bunch population.

High chromaticity (see Fig. 6) and high capture voltage have proved to be affective in suppressing this instability but both of them result in larger tune spread and therefore in a lower lifetime and losses.

Possible cures for the TMC instability are:

- identification of the impedance sources and reduction of their transverse impedance;
- operation far from transition (this would be the case if the injection energy of the SPS would be increased as foreseen with the PS2 upgrade [3][14]).

A measurement and simulation campaign to identify the major remaining sources of transverse impedance has started and it is reviewed in [15].

Electron Cloud Effects

Electron multipacting and electron cloud build-up along the bunch train have been observed with the LHC beam [16]. Above the threshold for the onset of electron multipacting (typically $N_{th}=0.2\times10^{11}$ p/bunch in the SPS arcs after a machine shut-down) 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.

An increase in the threshold bunch population required to induce multipacting can be obtained by reducing the SEY of the vacuum chamber surface by electron bombardment induced by the beam ("scrubbing"). This process has been thoroughly studied at CERN [17] and it has been observed in the SPS [16]. By scrubbing the SPS vacuum chamber with the nominal LHC beam the thresholds for the onset of the beam-induced multipacting can be increased from 0.3×10^{11} p/bunch to 0.8×10^{11} p/bunch in the arcs which are covering approximately 70% of the SPS circumference.

Experience shows that the electron cloud activity cannot be suppressed completely by scrubbing and the final threshold intensities and SEY depend on the operational conditions of the machine.

In the horizontal plane the electron cloud instability manifests as a coupled bunch instability in which low order coupled-bunch modes (up to few MHz) are excited and can be damped by means of the transverse feedback.

The vertical electron cloud instability is of single bunch type. The instability mainly affects the tail of the bunch train 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 (Fig. 7).

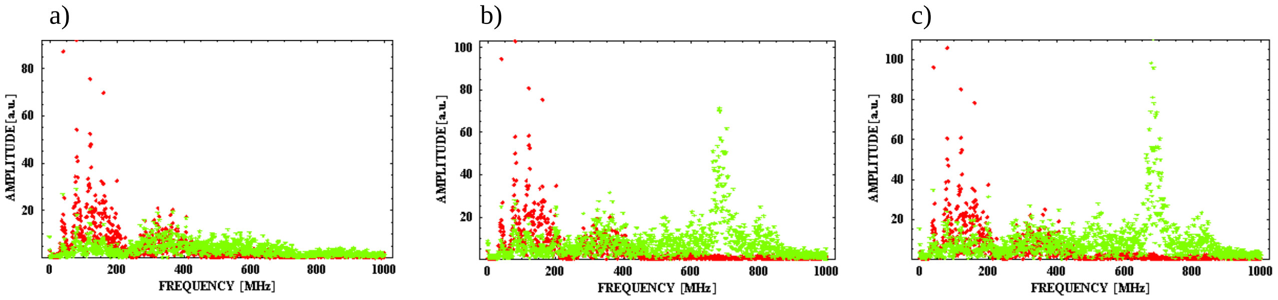

Figure 7. Fourier spectra of the sum (red) and delta (green) signals from a wideband vertical pick-up for the leading (a) bunch of the LHC bunch train and for bunch number 15 (b) and 39 (c). $N_b= 0.8\times10^{11}$ before scrubbing (when the threshold bunch population for the onset of electron multipacting is 0.2×10^{11} p) [16].

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>0.4-0.5) is the only cure found so far to fight the electron cloud instability but the lifetime of the nominal LHC beam at the injection plateau has been observed to be limited to less than 10 minutes as a result of that. Recently it has been proposed (G. Franchetti, E. Métral, F. Zimmermann) that the limited lifetime and the incoherent emittance blow-up could be the result of the strongly time-varying non-linear fields generated by the pinching of the electron-cloud during the bunch passage [18][19]. Indirect measurements of the non-linear fields generated by the electron cloud along the bunch train have been performed and are reported in [16]. No evident cure has been found so far for these phenomena induced by the electron cloud. Their impact can only be reduced but not suppressed by beam scrubbing.

No detailed measurement of the momentum dependence of the growth rate of the electron-cloud vertical dependence exists. Recent simulations seem to indicate that the threshold for the onset of this instability decreases with increasing energy for constant normalized transverse emittance, longitudinal emittance and bunch length [20]. A series of experiments has started in the SPS to verify the scaling predicted by simulations [21].

A possible radical solution would be to suppress the electron cloud build-up by coating the vacuum chambers with coatings with low Secondary Electron Yield or by inserting clearing electrodes. An experimantal programme is being set-up in this respect in the SPS [22][23].

SUMMARY AND CONCLUSIONS

The nominal LHC beam is at the performance limit of the LHC injectors. Space charge in the PSB limits the maximum bunch intensity within nominal transverse emittances to ~75 % of the ultimate bunch population. No sizeable margin exists for the operation above the nominal LHC beam in the PS and even more in the SPS. The main limitations towards the achievement of the ultimate LHC beam performance in the injectors have been briefly reviewed. Studies and experiments have started to address the PS & SPS limitations above the nominal and towards the ultimate beam but they need to be intensified. This will require the allocation of manpower and machine time.

A re-optimization of the design parameters for the LHC beam in the LHC Injector chain (keeping fixed the parameters at extraction from the SPS) based on the operational experience gained in the LHC Injectors with the LHC beam might be also beneficial as suggested by E. Métral at the workshop.

ACKNOWLEDGEMENTS

I would like to thank K. Hanke, S. Hancock, E. Métral, B. Mikulec, G. Rumolo, E. Shaposhnikova, B. Spataro (INFN-LNF), R. Steerenberg who provided me with most of the information presented here and for the interesting discussions during the preparation of the presentation and at the workshop.

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