INTENSITY (AND BRIGHTNESS) LIMITATIONS IN THE LHC PROTON INJECTORS

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Abstract

The presently known intensity and brightness limitations in the LHC Proton Injectors are reviewed and the possible cures 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.

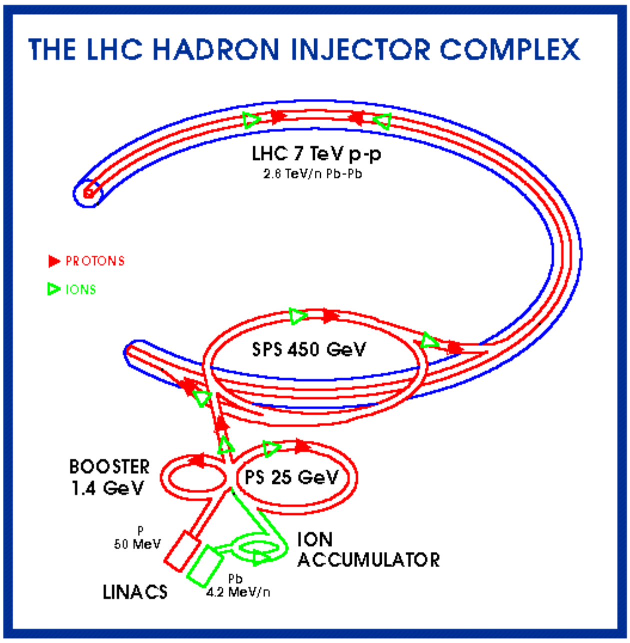

Figure 1. The LHC Hadron Injector Complex. Proton beams are indicated in red while Ion beams are indicated in green.

PS BOOSTER

Space Charge

As a result of the low injection kinetic energy (50 MeV) the main intensity limitation is space-charge at injection. In the transverse plane a vertical incoherent space charge tune spread ΔQ_V of up to 0.5 is expected for the ultimate LHC beam at injection (Fig. 2). The basic scaling law for the space charge tune spread is:

$$\Delta Q_{SC} \propto \frac{N_b}{B_f \beta \gamma^2}$$

where N_b is the bunch population β and γ are the relativistic factors and B_f is the bunching factor, i.e. the ratio between the average and peak beam currents.

The combined effect of space-charge and synchrotron motion in the presence of non-linear resonances might originate core-emittance blow-up, beam-halo formation, diffusion and losses [1][2].

The following solutions can be envisaged in order to reduce the space charge effects in the transverse plane:

- increase of the injection energy, e.g. the increase in the injection kinetic energy from 50 MeV to 160 MeV (as proposed with the construction of the Linac 4) would result in a reduction of the space charge tune spread by a factor 2;
- increase of the bunching factor by bunch flattening techniques, either by addition of a second harmonic on top of the main accelerating RF system or by deposition of high-harmonic, empty RF buckets at the centre of a unbunched beam before RF capture [3];
- correction of resonances and accurate selection of the working point in order to avoid crossing systematic resonances. Recently the PS Booster working point has been changed from 4.28(H)/5.60(V) to 4.28(H)/4.60(V) to avoid crossing the systematic resonance $3Q_V$=16 [4].

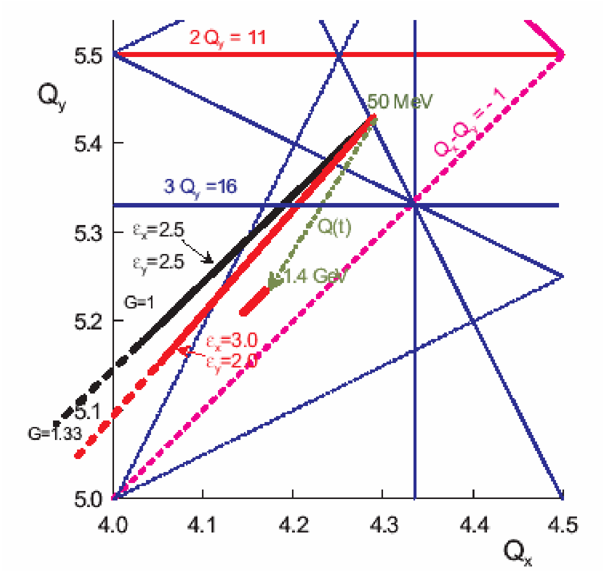

Figure 2. Tune diagram and maximum space charge tune spread for the ultimate LHC beam in the PS Booster at injection and at top energy for the working point 4.28(H)/5.60(V). Courtesy of K. Schindl.

Although the brightness of the nominal LHC beam is well within the requirements, space charge is presently considered to limit the LHC beam brightness for the ultimate LHC beam as shown in Fig. 3. This situation is made even more critical as a result of the losses observed in the PS and SPS leading to more demanding intensity requirements on the PS Booster.

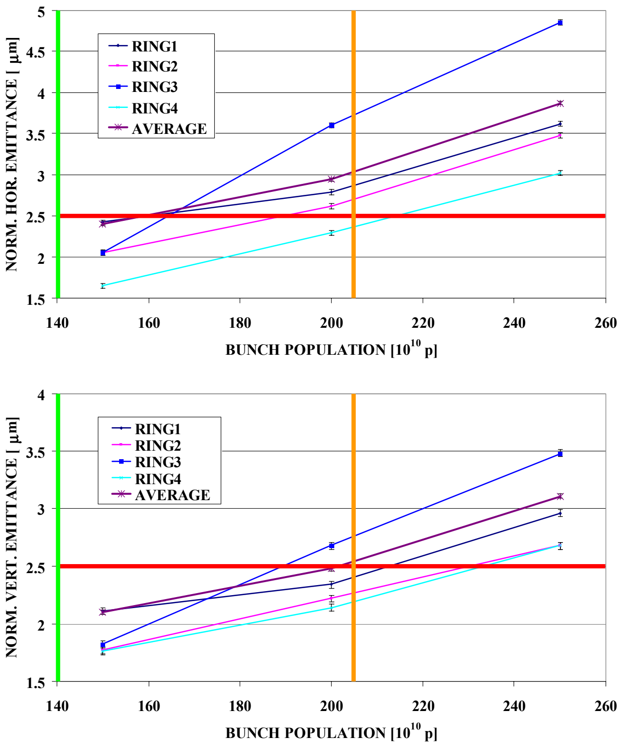

Figure 3. Measured normalized horizontal and vertical emittances for the LHC beam vs. bunch population in the PS Booster. The nominal and ultimate bunch populations are indicated by two vertical (green and orange, respectively) lines and the maximum transverse emittance is indicated by a red horizontal line. Courtesy of K. Hanke, B. Mikulec.

Space charge is also the major limitation for the high intensity beams limiting the intensity to approximately 10^{13} p/ring.

In the longitudinal plane, space charge leads to a reduction of the available bucket area with intensity and to a loss of Landau damping above a given bunch population due to the different detuning with intensity of the coherent modes as compared to that of the incoherent frequency bands (see Fig. 4). In the past (when the PS Booster was operated on harmonic 5) the loss of Landau damping corresponded to the appearance of coupled bunch instabilities. The threshold population N_{th} for the loss of Landau damping (for a single harmonic RF system and for a constant bucket filling factor) scales as:

$$N_{th} \propto \frac{V_{RF}}{h}$$

where V_{RF} is the RF voltage and h is the harmonic number.

The threshold bunch population for the cancellation of Landau damping measured in 1977 was 4×10^{11} p for the dipole mode (m=1) and $7\text{-}8\times10^{11}$ p for the quadrupole mode (m=2). This threshold is expected to have increased by more than a factor 3 after the change of harmonic number from 5 to 1 in 1998 and the expected N_{th} are now 1.4×10^{12} p (m=1) and 2×10^{12} p (m=2). Coupled-bunch instabilities are no more an issue at low energy due to the present choice of the harmonic number (h=1).

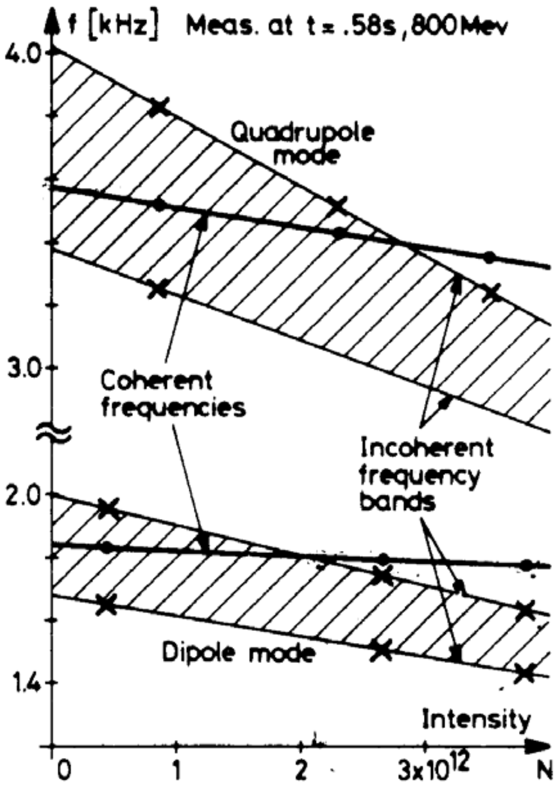

Figure 4. Coherent dipole and quadrupole mode frequencies and incoherent frequency bands vs. ring population (h=5) from coupled bunch mode Beam Transfer Function measurement in the PS Booster (1977). Courtesy of F. Pedersen.

Other potential limitations

Resistive wall is considered to be the main driving source of transverse instability. Growth times have been increased by operating the machine at tunes from below the integer to above the integer. At present only the transverse feedback is operated only in the horizontal plane. The reason why no vertical active damping is required is not clear, one possible explanation being transverse coupling. The maximum intensity for which the present transverse feedback is sufficient to damp the resistive wall instability is not known at present.

A microwave instability was observed in the pre-LHC era (coherent signals ~1GHz) for $N_b>1.3\times10^{12}$ p and disappeared after shielding the vacuum manifolds. The doubling of the longitudinal acceptance with the change from h=5 to h=1 has further increased this margin. The present threshold for the onset of this instability is not known.

PS

Space Charge

Double-batch injection has been implemented in the PS for the LHC beam (Fig. 5) in order to keep ΔQ_{SC} at injection in the PSB below 0.5. As a consequence of that the injected beam spends 1.2 s at PS injection momentum limiting the maximum acceptable ΔQ_{SC} in the PS to approximately 0.25.

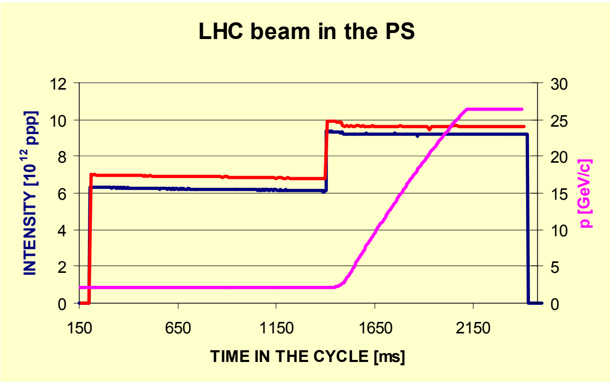

Figure 5. Double batch injection for the LHC beam in the PS. Approximately 3 % losses are observed during the injection plateau 1.2 s long. Courtesy of E. Métral.

Space charge and synchrotron motion could induce periodic tune modulation and trapping-de-trapping on resonance islands therefore producing halo and losses [1][2]. This could explain low energy losses in the PS (Fig. 5).

Higher injection energy would reduce the space charge tune spread and consequently losses. This could be also obtained by increasing the bunching factor B_f by creating flat bunches in the PS Booster. A simple scheme has been proposed for that and tested and it is described in [5].

Transverse Mode Coupling Instability

A fast vertical single-bunch instability has been observed in the PS near transition (γ_{tr} = 6.11) for $N_b > 3\times10^{12}$ p and a longitudinal emittance $\varepsilon_L <$ 2eV.s leading to losses mainly located in the tail of the bunch [6][7] (see Fig. 6). This is a Transverse Mode Coupling Instability (TMCI) developing as a consequence of the PS vertical impedance. This has been confirmed by recent HEADTAIL [8] simulations where the machine impedance has been represented by a broad-band resonator with resonant frequency f_r^{BB}=1 GHz, a quality factor Q=1 and a vertical shunt resistance $R_{sh\ y}$=3 MΩ/m (see Figure 7).

For TMCI the following dependence on beam and machine parameters is valid:

$$N_{th} \propto |\eta|\varepsilon_L\left(1+\frac{f_{\xi y}}{f_r^{BB}}\right) \quad (1)$$

where $\eta = (1/\gamma_{tr}^2 - 1/\gamma^2)$ is the slippage factor, $f_{\xi y} = (\xi_y/\eta)\, Q_y\, f_{rev}$ is the chromatic frequency, Q_y the vertical tune and f_{rev} the revolution frequency [9]. Therefore the threshold for the onset of this instability can be increased by increasing the longitudinal emittance. A controlled longitudinal emittance blow-up (to ~2.5 eV.s) is routinely applied to the high intensity single bunch TOF beam in order to stabilize it up to bunch populations of ~8×10^{12} p. From Eq. 1 it is also evident that the threshold population increases the larger is the absolute value of the slippage factor.

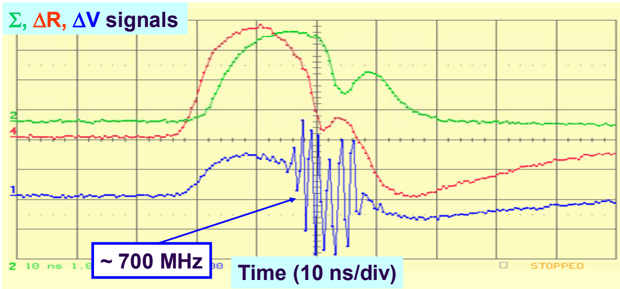

Figure 6. Sum (Σ - green), horizontal (ΔR - red) and vertical (ΔV - blue) delta signals measured with a wide-band transverse pick-up in the PS at transition. N_b ~4×10^{12} p and ε_L ~ 2eV.s. Courtesy of E. Métral.

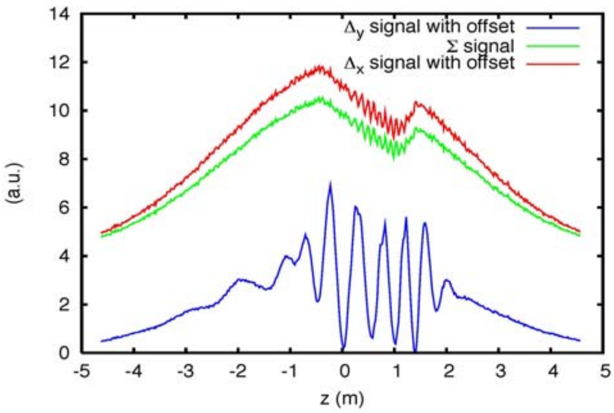

Figure 7. Sum (Σ - green), horizontal (ΔR - red) and vertical (ΔV - blue) delta signals provided by the HEADTAIL code for the beam conditions listed in Fig. 6. Courtesy of G. Rumolo.

Electron Cloud Instability

Electron cloud instability is another potential intensity limit in the PS [10]. The LHC beam is normally extracted just after a non-adiabatic bunch length compression from 16 to 4 ns has taken place. Figure 8 shows the amplitude of the first unstable horizontal betatron line (1-q_H ~ 357 kHz) over 200 ms as measured with a spectrum analyser connected to a horizontal wide-band pick-up. In the first 55 ms two consecutive bunch splittings (from harmonics 21 to 84) take place. The bunch length is then kept equal to 16 ns for approximately 40 ms and it is finally adiabatically compressed to 10 ns in 5 ms (Fig. 8a). A horizontal instability develops for $N_b \geq 0.46\times10^{11}$ once the bunch length is shorter, the growth time τ is a few ms and it is not very sensitive to the bunch population. For the higher bunch population ($N_b \geq 0.69\times10^{11}$) signs of the instability are observed already during the adiabatic bunch compression from 16 to 10 ns, as indicated by the red circles in figures 8 c and d.

The measurements cannot exclude a coupled-bunch nature of the instability. No vertical instability has been detected but its growth rate could be longer than that for the horizontal instability at the intensities considered.

An emittance growth of a factor 10-20 and of a factor 2 in the horizontal and vertical planes, respectively, has been measured for the largest bunch population.

The above measurements have been conducted under conditions which are different from those for the production of the LHC beam in order to enhance the phenomenon and to study it in detail. Nevertheless at intensities higher than nominal electron cloud instabilities could occur also for the standard LHC beam production scheme in the PS.

a) b) c) d)

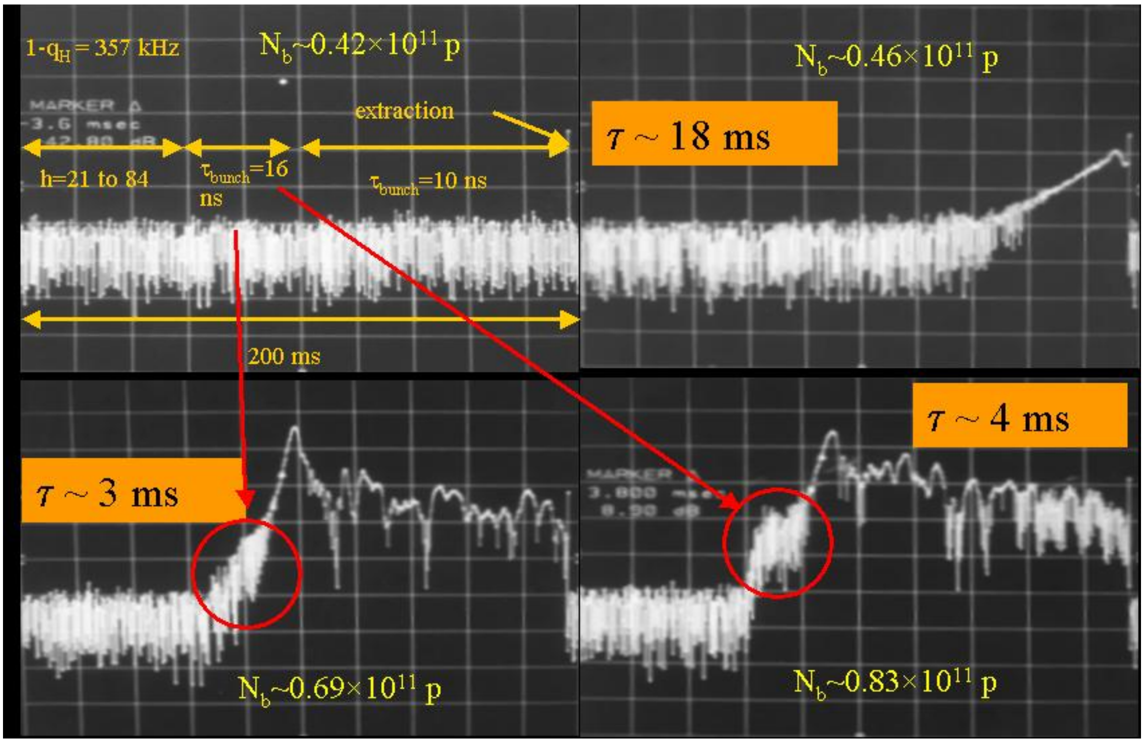

Figure 8. Amplitude of the first horizontal unstable line vs. time as measured by a spectrum analyser connected to a horizontal wide-band pick-up in the PS. Courtesy of E. Métral.

Recently a horizontal instability has been observed for the nominal LHC beam just before extraction. The following observations have been made so far (see Fig. 9):

- the threshold bunch population for a bunch spacing of 25 ns and a bunch train of 72 bunches is N_{th}~0.6-0.7×10^{11} p;
- a strong dependence on bunch intensity has been observed;
- the instability might affect either a few bunches or several bunches along the train;
- no instability is observed for trains of less than 48 bunches;
- the instability disappears if gaps (of at least 12 missing bunches) are created at any position in the train.

The exact origin of the instability is not known yet although the observations are consistent with an electron cloud instability as presented above.

Other limitations

Not only collective effects are at the origin of intensity and brightness limitations in the PS. The high intensity beams for fixed target operation or for TOF are mainly limited by the machine physical acceptance which has been measured to be 60 µm in the horizontal plane and 20 µm in the vertical plane and which is responsible of the low energy losses observed for these beams.

Extraction losses for high intensity beams are also a major concern for fixed target operation because of the remanent radiation in the tunnel and the prompt radiation induced outside the tunnel during machine operation due to the limited shielding. The new multi-turn extraction by capture of particles in stable islands should strongly reduce the extraction losses [11][12].

The PS, commissioned in 1959, is presently the oldest accelerator of the LHC Injector Complex and equipment lifetime and reliability issues could become a serious operational and performance limitation.

a)

b)

c)

Figure 9. Instability observed in the PS for the nominal LHC beam: a) horizontal and b) vertical bunch position vs. bunch number at the first turn in the SPS. c) Sum (yellow) and horizontal delta signal from a wide-band transverse pick-up in the PS over the last four turns before extraction. In the cycle shown in the left column only a few bunches are affected while in that represented in right column several bunches are affected. Courtesy of R. Steerenberg.

SPS

Transverse Mode Coupling Instability

The low-frequency longitudinal impedance of the SPS has been reduced by a factor of ~2.5 from 1999 to 2001 by shielding most of the vacuum pumping ports [13]. The threshold for the longitudinal microwave instability increased even more. The transverse impedance has been reduced by ~40% [14] and this improvement was since then partially cancelled by the installation of the extraction kickers required for the fast extraction of the LHC beams towards TI2 and TI8 the two transfer lines joining the SPS to the LHC.

Since 2002 a fast single-bunch vertical instability develops in the SPS right after injection at 26 GeV/c for bunch populations larger than 6×10^{10} p if the longitudinal emittance of the beam is smaller than 0.2 eV.s [14]. Figure 10 (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 0.35 eV.s which is the nominal value for the LHC beam). The RF voltage for that experiment was close to 600 kV which corresponds to a synchrotron period of 7.1 ms. The loss is observed to occur when the bunch length is minimum (i.e. when the peak intensity is maximum).

The above observations are consistent with the maximum bunch population (0.6×10^{11} p with ε_L~0.2 eV.s) that could be accelerated through transition in 2002 [15] after the impedance reduction campaign. Before the impedance reduction campaign this limit was ~0.2×10^{11} p.

Simulations performed using the HEADTAIL code [8] have shown that the measured evolution of the vertical motion of the bunch, showing a travelling-wave pattern propagating from the head of the bunch to the tail with a frequency of ~ 1 GHz, is consistent with a fast instability induced by the SPS vertical impedance represented by the "classical" Broad-Band (BB) impedance model deduced from beam-based measurements (f_r = 1.3 GHz and Q = 1) [16].

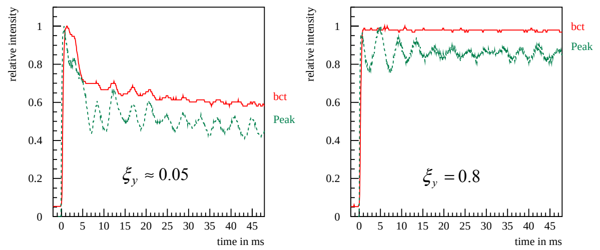

Figure 10: Plot of the measured relative bunch intensity (normalized to the value at injection) vs. time in the SPS machine for two values of the vertical chromaticity. bct stands for beam current transformer and Peak stands for peak intensity. Courtesy of H. Burkhardt.

The expected dependence of the threshold bunch intensity on the vertical shunt impedance is presented in Fig. 11 for the LHC beam (ε_L=0.35 eV.s): the effects of space charge and RF voltage have also been studied. The vertical shunt impedance derived from the measurement of the vertical detuning vs. bunch population performed in 2001 after the impedance reduction campaign was 19.1±0.2 MΩ/m, while in 2003 this increased to 22.2±0.4 MΩ/m [17]. According to these estimations the nominal LHC beam should be close to the instability threshold when captured on matched voltage (~ 0.7 MV). However, capturing the beam in a 2 MV bucket, as normally done in operation, should considerably help.

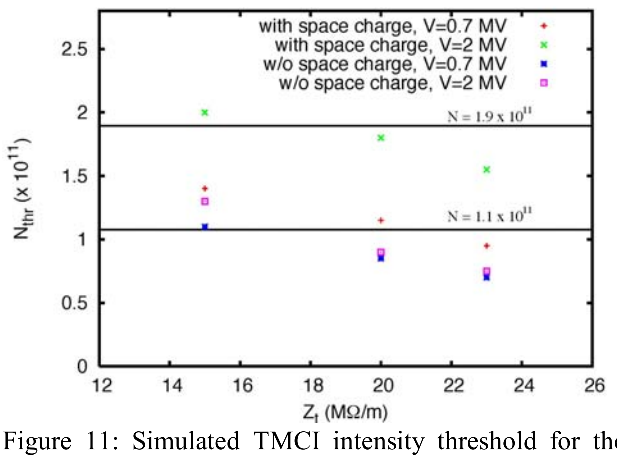

Figure 11: Simulated TMCI intensity threshold for the LHC beam with/without space charge for two different RF voltages, using the HEADTAIL code. Courtesy of G. Rumolo.

Space charge seems to be beneficial since it raises the TMCI threshold, but it is predicted to give rise to a fast emittance blow-up even below threshold. For the highest impedance, expected to be achieved with the installation of the additional kickers for the extraction to TI2 (performed during the shut-down 2004-2006), the ultimate LHC beam would be unstable even when the high capture voltage and space charge are included in the simulation.

The following means have been found so far to increase the threshold for the onset of the fast vertical instability:

- high chromaticity (see Figure 10 - right);
- high capture voltage (cfr. Fig. 11);

but both these settings result in larger tune spread and therefore in a lower lifetime and losses. From Eq. (1) it follows that increasing |η| would be an advantage.

Possible cures for the TMC instability are:

- identification of the impedance sources and reduction of their transverse impedance (in particular for the kickers);
- operation far from transition (cfr. Eq. (1)).

Electron Cloud Effects

Since the first tests performed with the LHC beam in 1999 electron multipacting and electron cloud build-up along the bunch train (see Fig. 12) have been observed as a consequence of the high bunch population and of the bunch spacing [18]. Above the threshold for the onset of electron multipacting (typically N_{th}=0.2×10^{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 (see Fig. 13).

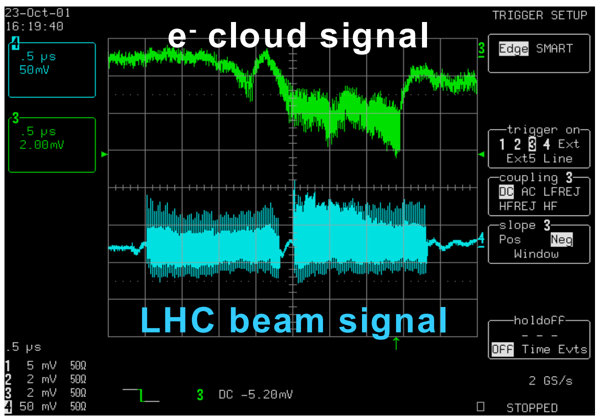

Figure 12. Electron cloud signal from a dedicated shielded pick-up in the SPS (green) vs. time along the LHC beam train (light blue) here consisting of two consecutive trains of 72 bunches with a bunch spacing of 25 ns. Courtesy of J.-M. Jimenez.

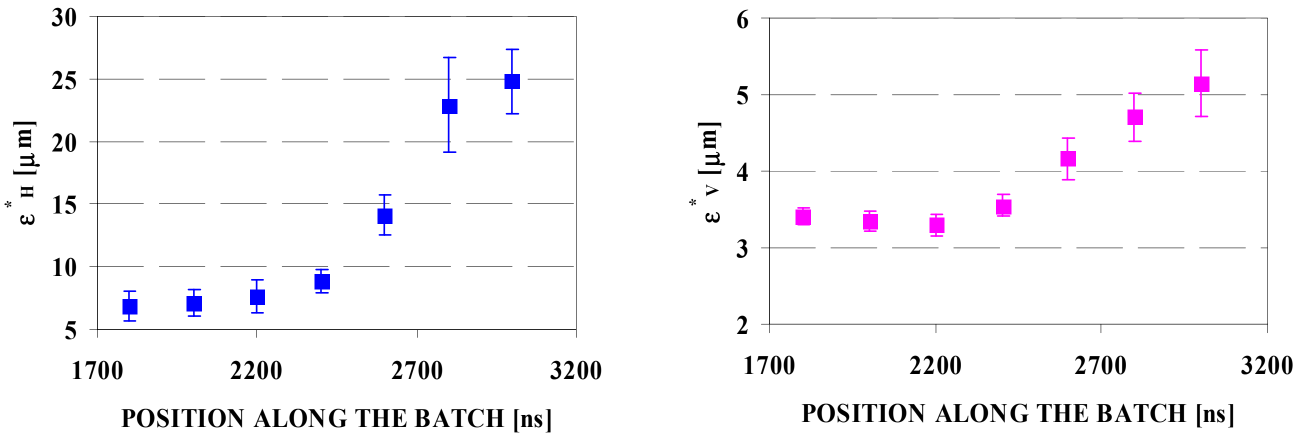

Figure 13. Rms horizontal (left) and vertical (right) normalised emittances along the LHC bunch train (first 48 bunches) few tens of ms after injection. $N_b= 0.8\times10^{11}$ p.

For the nominal LHC beam the only cure found so far to reduce multipacting is the reduction of SEY by electron bombardment induced by the beam ("scrubbing"). This process has been thoroughly studied at CERN [19] and it has been observed in the SPS [18]. 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 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 a coupled-bunch instability while in the vertical plane a single bunch Transverse Mode Coupling like instability occurs [18].

In the horizontal plane, low order coupled-bunch modes (up to few MHz) are the most unstable (see Fig. 14). The rise time of the instability is of the order of 40 turns and it 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. It is expected that the growth time of this instability is proportional to the beam momentum [18] as confirmed by measurements performed in the SPS [20]. No significant gain can be expected from an increase in the injection energy of the SPS as the strength of the kick provided by the transverse feedback decreases with the beam momentum for given transverse feedback characteristics.

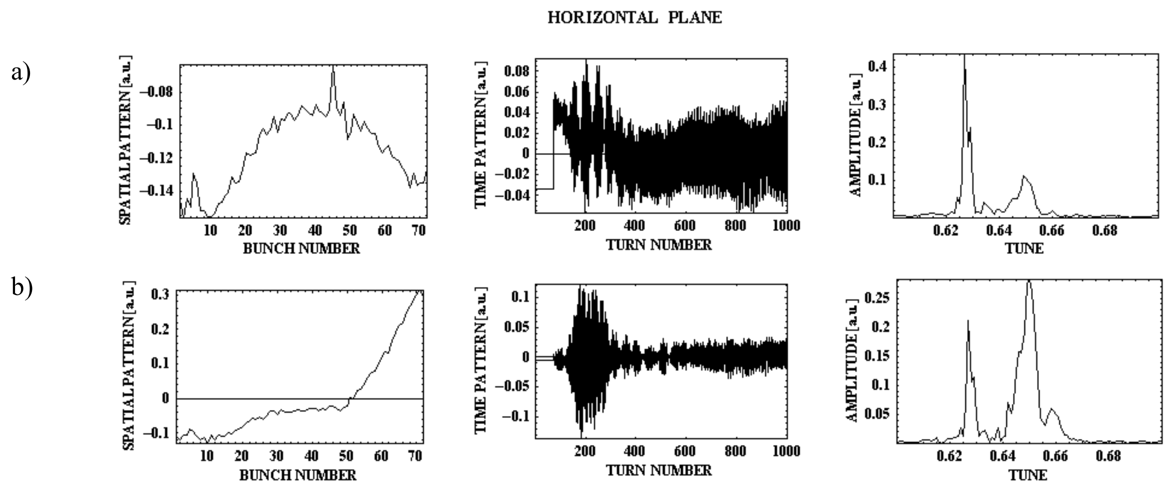

Figure 14. Two most important spatial and temporal patterns together with the Fourier transform of the temporal pattern for an LHC bunch train consisting of 72 bunches with bunch population $N_b=0.3\times10^{11}$ p before scrubbing (when the threshold bunch population for the onset of electron multipacting is 0.2×10^{11} p) [18].

The vertical electron cloud instability is of single bunch type. 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=0.3×10^{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 (see Fig. 15).

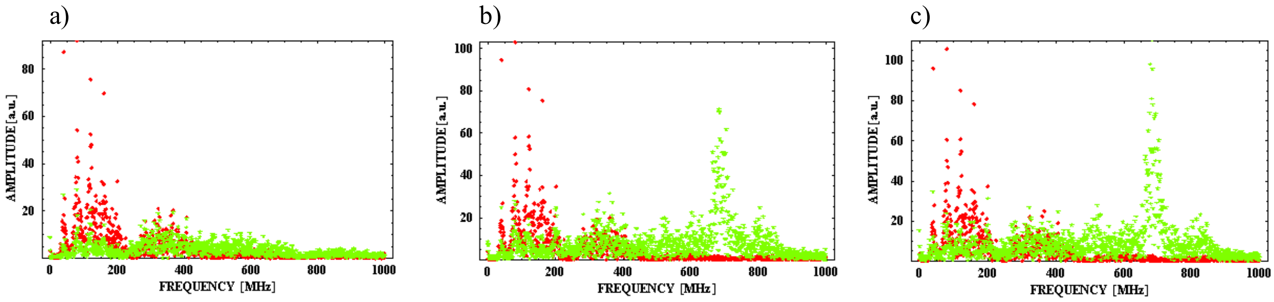

Figure 15. Fourier spectra of the sum (red) and delta (green) signals from a wideband vertical pick-up for the leading (a) bunch of the LHC bunch train and for bunch number 15 (b) and 39 (c). N_b= 0.8×10^{11} before scrubbing (when the threshold bunch population for the onset of electron multipacting is 0.2×10^{11} p) [18].

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 in the vertical plane. Another possible remedy for the vertical single bunch instability might consist in using linear coupling [21]. No detailed measurement of the momentum dependence of the growth rate of the electron-cloud vertical dependence exists. Recent simulations seem to indicate that there is no evident gain in a higher injection energy assuming constant beam parameters (normalized transverse emittance, longitudinal emittance and bunch length) [20]. These assumptions might be pessimistic and probably longitudinal parameters at extraction should be re-optimized in case a different extraction momentum is considered.

As a result of the large momentum spread at injection (±2.4×10^{-3}), of the large chromaticity (in particular in the vertical plane) and of the large space charge tune spread (~0.055 in the vertical plane) the total momentum spread of the beam cannot be neglected and a detailed study of the working point has been conducted and the working point optimized [22]. In spite of that the lifetime of the of the nominal LHC beam at the injection plateau is limited to less than 10 minutes as shown in Fig. 16.

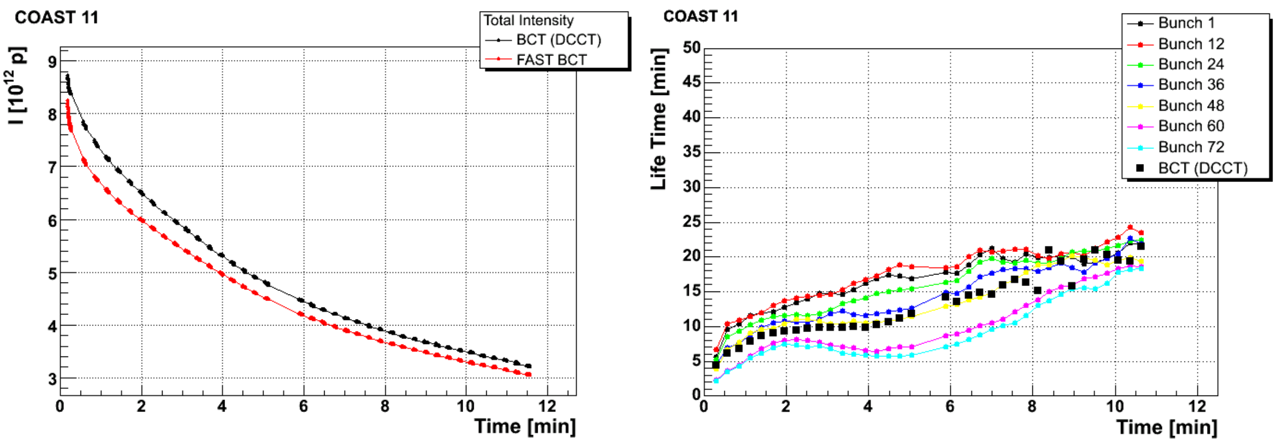

Figure 16. Left: Time-evolution of the LHC beam total population as measured by a Beam Current Transformer (red - measuring the DC component of the beam) and by a Fast Beam Current Transformer (black – measuring the population of the bunches). Right: lifetime of the bunches along the bunch train vs time. Courtesy of F. Roncarolo.

In the first seconds the effect of the capture losses is observed and the particles are leaving the bunches, for that reason the bunched beam lifetime (a few minutes) is shorter than the beam lifetime as measured by the Beam Current Transformer measuring the DC component of the beam, but after a few tens of seconds the lifetime increases and a clear difference appears between the lifetime of the leading bunches and the lifetime of the trailing bunches which exhibit a shorter lifetime. The lifetime increases with time i.e. as the bunch population decreases.

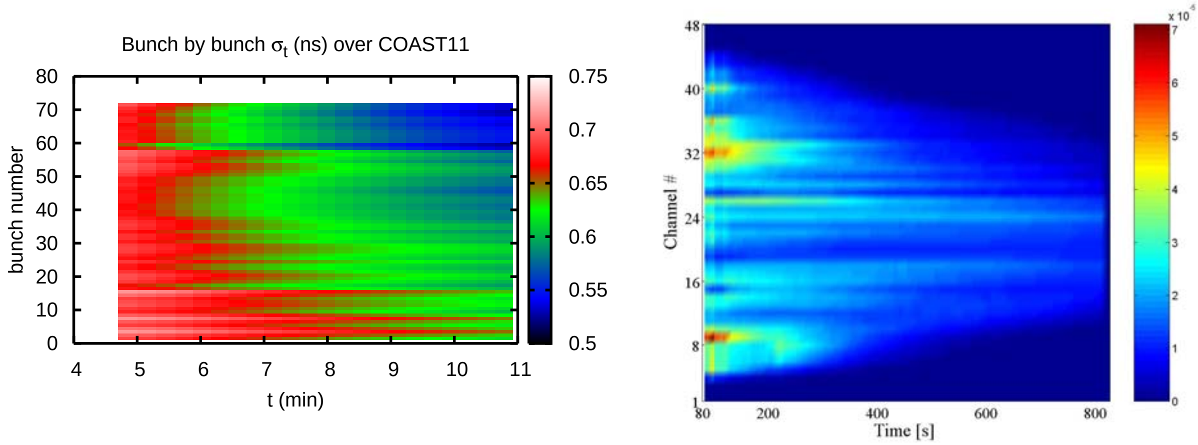

Figure 17. Left: rms bunch length vs. bunch number and time. Right: electron cloud signal vs. channel number (defining the horizontal position) and vs. time. Courtesy of E. Benedetto and G. Rumolo.

The bunch length decreases with time in particular for the trailing bunches as shown in Fig. 17 (left). In particular the rate of at which the bunch length decreases diminishes with the bunch population together the density of the electron cloud (as measured by an electron cloud monitor in a bending magnet – see Fig. 17 - right). An emittance blow-up and tail population (in particular in the horizontal plane and mainly in the second half of the bunch train) is also observed (see Fig. 18).

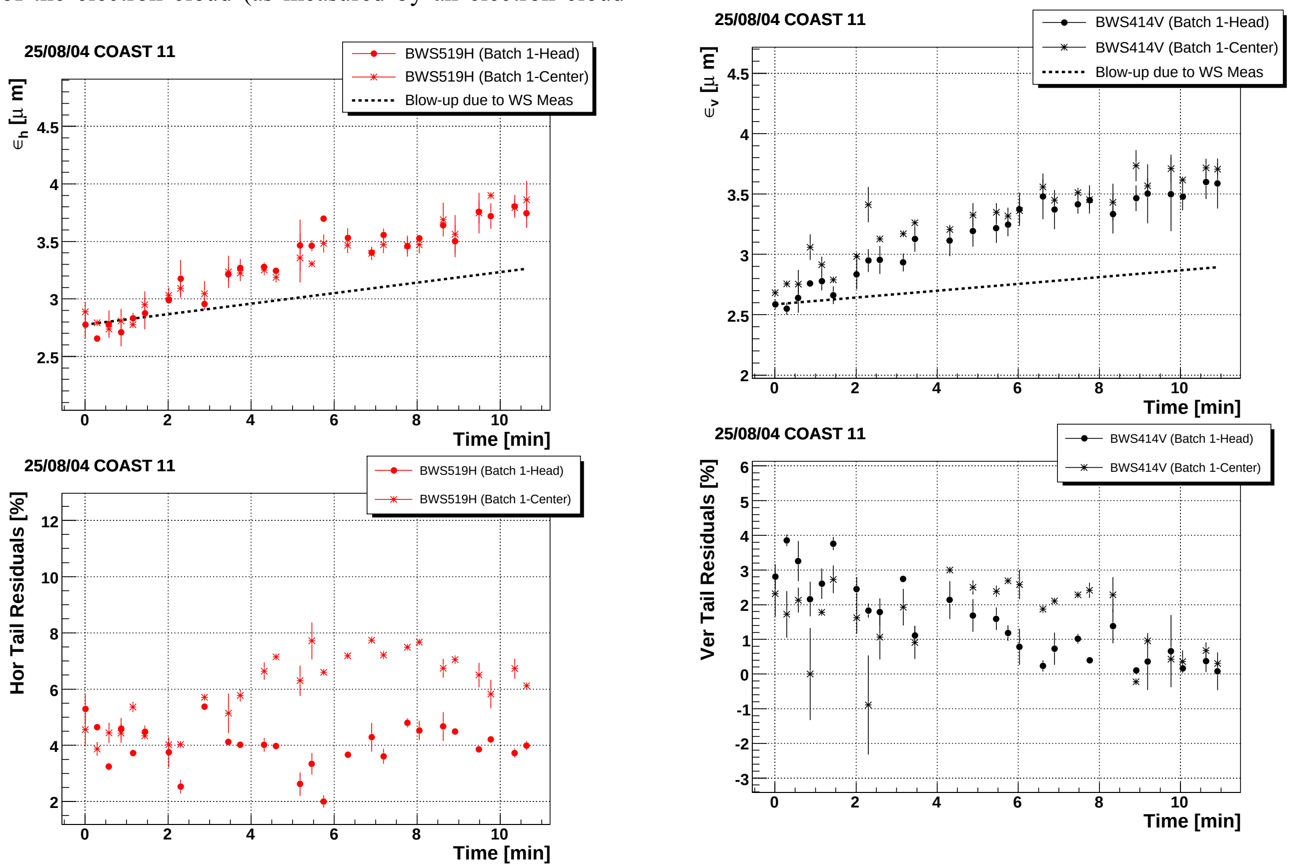

Figure 18. Horizontal (red) and vertical (black) emittance (top) and tail residuals (bottom) vs. time for the nominal LHC beam. The residuals are calculated as the difference between the integral of the measured transverse beam profile and the integral of a gaussian fit to the core of the beam profile normalized to the latter. Measurements of these parameters have been performed both starting at at the head and at the centre of the bunch train. Courtesy of F. Roncarolo.

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. That, combined with the synchrotron motion, could lead to periodic tune modulation and trapping/de-trapping on resonance islands whose size and location varies with time during the bunch passage. The particles can then be trapped inside a resonance island and during the synchrotron motion they might be transported to larger or smaller amplitudes. As a result of that tails and halo can be generated and losses might occur. The tune shift attained on the beam axis, close to the tail of the bunch, might be so large to make the linear motion unstable provided that the electron cloud is not uniformly distributed along the ring. In that case particles can cross the unstable region several times because of the synchrotron motion producing therefore a blow-up of the core of the beam [23]. Indirect measurements of the non-linear fields generated by the electron cloud along the bunch train have been performed and are reported in [18]. 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.

Coupled-Bunch Instabilities

Coupled bunch instabilities are observed in the SPS for the LHC beam both in the longitudinal and transverse planes.

In the longitudinal plane the threshold bunch population is 0.2×10^{11} p (72 bunches) at 280 GeV/c and 1.3×10^{11} at injection momentum (26 GeV/c). This instability is mainly driven by the fundamental and HOM of the SPS accelerating cavities: the 200 MHz Travelling Wave Cavities. Controlled longitudinal emittance blow-up and Landau damping with a higher harmonic RF system (800 MHz) have proven to be effective to stabilize the beam. No significant gain is expected by increasing the injection energy, on the other hand a larger longitudinal emittance at injection would be an advantage [20].

In the transverse plane the main sources of coupled-bunch instabilities are electron-cloud and resistive wall. The latter is the main instability mechanism for the fixed target beam [24]. It can be cured with a transverse feedback although increasing the intensity might require an upgrade of the present system in terms of power.

Other Intensity Limitations

Other potential intensity limitations for the SPS are:

- space charge. The long injection plateau for the LHC beams and in particular for the ion beam limits the acceptable space charge tune spread to about 0.1 although there is some evidence that this could be a pessimistic assumption [25]
- vertical physical aperture (~5 μm) which is one of the main limitations for the high intensity beams for fixed target physics.

The impact of the above two limitations would be reduced if the injection energy in the SPS would be increased. As for the PS, component aging is a major issue that might become a performance and operational limitation for the SPS machine.

SUMMARY AND CONCLUSIONS

An overview (far from being exhaustive) of the known and possible intensity and brightness limitations for the PS and SPS Complex has been given with particular emphasis for the LHC beams.

Although the nominal LHC beam parameters have been practically achieved in the LHC Injector Complex no margin could be buiilt to guarantee sufficient reproducibility and good beam availability during operation. The ultimate LHC beam performance is out of range for the time being.

Not only accelerator physics issues limit the performance of the PS-SPS complex, in particular for high intensity fixed target beams where ambient radiation, air activation and component aging are presently the most stringent limitations.

Some of the limitations like those related to space charge and aperture are common to all injectors. They are well known as well as their scaling. They could be relaxed by increasing the injection momentum. The PSB in particular would profit of a new higher energy Linac although a more detailed study of the causes of transverse instabilities is needed and an upgrade of the transverse feedback is required in order to fully profit of this upgrade.

Transverse Mode Coupling Instability is a limitation for PS and SPS and operation far from transition would be beneficial.

Electron cloud remains the main limitation for the SPS, which is presently the main bottleneck for any intensity or brightness increase in the whole injector chain.

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