50 AND 75 NS OPERATION

G Arduini, CERN, Geneva, Switzerland

Abstract

Two machine development sessions have been performed in order to understand potential limitations for the operation of the machine with 50 and 75 ns beam spacing. The main results of the studies and a possible outlook for 2011 will be presented. The overview will focus on the electron-cloud related issues while beam-beam aspects will be discussed elsewhere [1].

INTRODUCTION

At the end of the proton run 2010 a series of Machine Development sessions, from Friday 29/10 to Thursday 4/11 were dedicated to the setting-up of the LHC with bunch trains with a spacing of 50 ns and the study of the beam dynamics at injection, ramp and high energy, including collisions. These sessions were interleaved with physics runs (TOTEM run, ALICE length scale calibration, longitudinal luminosity scan) and other machine development subjects (abort gap filling characterization and quench tests with a wire scan).

The main aim of the studies with 50 ns beams [2] was the investigation of potential problems for 2011 operation, e.g.:

- potential vacuum issues at number of bunches comparable with those achieved with 150 ns,
- long range beam-beam effects,
- electron cloud effects,
- RF and longitudinal aspects and issues related to the higher total intensity in the LHC and injectors (e.g. capture efficiency),
- background and luminosity/beam lifetimes in collision.

The setting-up and the studies with 50 ns beams spanned a period of 126 hours of which approximately 78 hours could be effectively used. The setting-up period took approximately 2.5 shifts (beam time) as initially expected [2].

After an initial physics fill with 108 nominal bunches (9x12 bunches) important dynamic pressure rises were observed at injection when filling with trains consisting of 24 bunches each. The first attempt led to the closure of the vacuum valves in point 7 (VVGSH.774.6L7.R) after the injection of 108 nominal bunches per beam as the vacuum interlock level of $10^{-7}$ mbar was reached on two vacuum gauges. The evolution of the vacuum pressure on the penning gauge VGBP.773.6L7.R on the (uncoated) cold-warm transition of Q6L7.B2 (warm-cold transition with NEG coating only on the warm side of the transition) is shown in Fig. 1.

In that area the two beams circulate in different vacuum chambers. It must be noted that pressure rises had been observed with 150 ns spacing beams only in common vacuum chambers.

![Fig. 1: Pressures and total intensity for the first two fills with 50 ns spacing.](image)

After this observation emphasis for the machine studies has been given to the characterization of the electron cloud build-up and its effects and possible cures as well as to the comparative study of the behaviour of the 75 ns beam which took place in another dedicated machine study period from Wednesday 17/11 to Saturday 20/11 for a duration of 74 hours of which 65 hours could be used for the setting-up of the injection and capture of the 75 ns beam and for the studies with 75 and 50 ns beams.

The electron cloud build-up with 50 and 75 ns spacing beams has been studied by means of vacuum pressure measurements in the straight sections and by cryogenic measurements for the arcs.

EFFECTS ON VACUUM (STRAIGHT SECTIONS)

50 ns beam at 450 GeV

The dynamic pressure rises have been measured at all the available vacuum gauges as a function of the bunch population for a given filling pattern. The evolution of the vacuum pressure (logarithmic scale) for three vacuum gauges VGBP.2.5L3.B (where the highest pressure rise was observed), VGI.461.6R2.R, VGBP.4.6R2.B is shown in Fig. 2. The filling pattern consisted of two trains of 12 and 36 bunches spaced by 35.7 microseconds.

The threshold for the onset of the build-up for the considered pattern is between 0.6 and 0.8x10^{11} p/bunch. The dependence of the dynamic pressure rise as a function of the number of bunches in the train has been studied by injecting 12+12 bunches, 12+24 bunches and 12+36 bunches. The distance between the two trains of 12 bunches and nx12 bunches ($n=1,\ldots,3$) was 35.7 microseconds. The pressure rise in the vacuum gauges previously considered is plotted in fig 3 (logarithmic
scale) together with the total beam intensity. The electron cloud build-up occurs after the first 12 bunches as no visible pressure rise is observed for 12+12 bunches.

The dependence of the dynamic pressure rise on the separation between two consecutive trains of 24 bunches for the vacuum gauge VGPB.2.5L3.B is shown in Fig. 4. The survival time of the electron cloud after the batch passage can be as long as 8 to 9 microseconds.

**75 ns beam at 450 GeV**

The studies with 75 ns beam where conducted by injecting trains consisting of 48 bunches obtained by injecting two trains of 24 bunches in the SPS spaced by 225 ns.

Fig. 5 shows the dependence of the dynamic pressure increase for the 75 ns beam measured at VGPB.2.5L3.B as a function of the beam total current. In comparison with the 50 ns beam the threshold for the onset of the electron cloud build-up with a train of 24 bunches is located between $0.9 \times 10^{11}$ p/bunch and $1.1 \times 10^{11}$ p/bunch.

As for the 50 ns beams pressure rise is observed in vacuum chambers where only a single beam is passing differently from what was observed with the 150 ns beam.

The reduction observed in the pressure rise for the fill with bunch population of $0.9 \times 10^{11}$ p/bunch (red curve) can be explained by the time elapsed between the 10th and 11th injections and could be a result of the emittance blow-up occurred at injection or even the sign of a reduction of the desorption yield and secondary electron yield. The same argument could explain the observed reduction of the rate of dynamic pressure increase for the nominal bunch population at injection when reducing the bunch train spacing from 1.85 µs to 1.005 µs, taking into account the non-nominal operation of the transverse feedback for this train spacing (which is not a multiple of 25 ns) and the temporal order of the fills (the initial bunch train spacing was 1.85 µs and only later it was reduced to 1.005 µs). The large deviation observed for the point correspondent to the largest current is due to the high losses recorded at the injection of the last batch and should be discarded. From the above graph we can also safely assume that the maximum increase in dynamic pressure rise to be expected when going from $1.1 \times 10^{11}$ p/bunch to $1.3 \times 10^{11}$ p/bunch is smaller than a factor 3.
The linear dependence observed for the vacuum pressure rise after the second or third injections indicates that the electron saturation density is achieved after a constant number of bunches after two to three trains of 48 bunches.

The pressure rise observed for the 50 ns beam is a factor 2 to 3 higher than that observed for the 75 ns beam for the same beam current and bunch population (see Fig. 6).

Although the observed pressure rise for the 75 ns beam is lower than that observed for the 50 ns beam it must be noted that without scrubbing it would not be possible to ramp a large number of bunches with 75 ns spacing taken into account the additional pressure rise observed during the ramp for energies larger than 1.5 to 2 TeV.

**Effects of the “scrubbing” run on the dynamic vacuum pressure rise.**

Electron bombardment of the vacuum chamber (respectively beam screen for the arcs) wall surfaces reduces the desorption yield as well as the secondary electron yield of the surfaces. A reduction by a factor seven of the dynamic pressure increase induced by the injection of a train of 12+36 bunches has been observed after approximately 16 hours of operation with 50 ns beams with configurations leading to pressure rises larger than $10^{-7}$ mbar. The measurements conducted at the beginning and at the end of the scrubbing period with 50 ns are shown in Fig. 7. Assuming an exponential decay of the pressure rise as a function of the beam time this would correspond to a time constant of approximately 8 hours.

Shorter time constants, of the order of 3.5 hours, have been measured from other pressure evolution data as shown in Fig. 8 corresponding at the initial phase of the scrubbing run. It must be noted that during the period considered in Fig. 8 a slight reduction of the bunch intensity has been observed (smaller than 10%).
**Effect of the fringe fields of the experimental solenoids**

Although solenoidal fields are very effective in suppressing multipacting (see [4]) scrubbing does not occur at those positions, this is for example the case of the experimental regions of ALICE, ATLAS and CMS and in their vicinity (i.e. in the areas where solenoidal stray fields are present). Fig. 9 shows the evolution of the pressure rise measured in different gauges located close to experimental region in point 2, affected by the stray field of the ALICE solenoid, as a function of the excitation current of the ALICE solenoid and of the injected beam current. This implies that any scrubbing run should be conducted with experimental solenoids OFF.

![Fig. 9: Dynamic vacuum pressure rise close to the point 2 experimental area vs. injected beam current and ALICE solenoid current.](image)

**EFFECTS ON CRYOGENICS (ARCS AND TRIPLET-D1)**

Electron bombardment of the beam screen walls in cold magnets is a source of heat load for the cryogenics. The amount of heat load can be determined by measuring the Helium temperature at the outlet of each beam screen cooling circuit if the flow of Helium is kept constant. Measurements of the heat load have been performed both with 50 and 75 ns beams and they are presented in Fig. 10. The expected contribution to the heat load due to synchrotron light and image currents is also shown.

While the heat load measured with the 75 ns beam is compatible with the contributions from image currents and synchrotron light, that measured with 50 ns beam exceeds the estimations by approximately 40 mW/m/beam and it is therefore expected to come from electron cloud. The expected resolution of the measurement is 5 to 10 mW/m/beam.

A significant temperature increase on the Helium outlet temperature at the beam screen circuits has been measured in the triplet-D1 circuits in point 2 and point 8 as shown in Fig. 11. The fast decrease in the temperature occurred at around 15:00 is due to the activation of the regulation of the cryo-valve opening to control the temperature of the beam screens. The observed difference between point 2 and 8 on one side and point 1 and 5 on the other might be due to the heat load deposition in the cold D1 magnets. The D1 magnets in point 1 and 5 are warm magnets and they have NEG coated vacuum chambers.

![Fig. 10: Heat load as measured in the arcs with up to 824 bunches spaced by 75 ns (top) and with up to 444 bunches spaced by 50 ns (bottom). The total beam current for beam 1 and beam 2 and the beam energy (kept constant at 450 GeV/c) are shown. The above data refer to cell 33L6 considered to be representative of the situation in the arcs (courtesy L. Tavian).](image)

![Fig. 11: Time evolution of the temperature of the Helium at the output of the beam screens for the D1-triplets in point 2 and 8 and for the triplets in point 1 and 5. The total intensity of the 75 ns beam during that time is also shown (courtesy L. Tavian).](image)
While the heat load measured with the 75 ns beam is compatible with the contributions from image currents and synchrotron light, that measured with 50 ns beam exceeds the estimations by approximately 40 mW/m/beam and it is therefore expected to come from electron cloud. The expected resolution of the measurement is 5 to 10 mW/m/beam.

A significant temperature increase on the Helium outlet temperature at the beam screen circuits has been observed in the triplet-D1 circuits in point 2 and point 8 as shown in Fig. 11. The fast decrease in the temperature occurred at around 15:00 is due to the activation of the regulation of the cryo-valve opening to control the temperature of the beam screens. The observed difference between points 2 and 8 on one side and points 1 and 5 on the other might be due to the heat load deposition in the cold D1 magnets (the D1 magnets in points 1 and 5 are warm magnets and they have NEG coated vacuum chambers).

**Effect of the “scrubbing” run**

The effectiveness of the scrubbing run conducted at 450 GeV/c with a 50 ns beam in reducing the electron cloud build-up and the heat load in the arc dipoles at injection and at 3.5 TeV has been proven by comparing the heat load in the beam screen of the reference cell 33L6 before and after the scrubbing run for beams consisting of 108 bunches with the same filling pattern and bunch population. The results are presented in Fig. 12.

After the scrubbing run only a single beam (Beam 2) could be injected due to a problem with the beam dump system for Beam 1. A reduction of the heat load from ~20 mW/m/beam to less than 5 mW/m/beam (which is also the resolution of the measurement) has been observed. This corresponds to a reduction of the heat load by a factor 4 after a scrubbing period of 16 hours.

**EFFECTS ON BEAM**

The electron cloud building-up along the bunch train interacts with the proton bunches and can couple the motion of consecutive bunches or even the motion of different longitudinal slices of a bunch as a result of the pinching of the electron cloud during the bunch passage. For that reason electron clouds can be responsible of single and coupled-bunch instabilities in the horizontal and vertical planes.

In a dipole field region electrons spiral around the magnetic field lines and their motion in the plane perpendicular to these lines is essentially frozen already at injection (magnetic field strength is 0.535 T). Therefore no pinching occurs in the plane perpendicular to the field lines and no horizontal single bunch instability is expected to originate from electron cloud in dipole field regions [5][6][7][8].

The single bunch instability occurs when electron cloud densities -before the bunch passage- exceed a certain threshold (typically in the range of $10^{13}$ electrons/m$^3$). Below this threshold density, blow-up is observed due to incoherent effects deriving from the highly non-linear fields generating during the bunch passage. As a result of these phenomena blow-up is observed along the bunch trains in correlation with the build-up of the electron cloud along the bunch train.

**50 ns beam at injection**

The transverse emittances measured along a bunch train of 36 bunches with 50 ns spacing (injected after a train of 12 bunches with a spacing of 35.7 microseconds) are shown in Fig. 13. A blow-up of the emittance is visible starting in the second half of the train. This is consistent with the observations on the dependence of the pressure rise as a function of the bunch train length presented in Fig. 3. These measurements were taken with typical machine settings at injection (damper gains close to maximum, 4 units of chromaticity in both planes).
The rise-time of the transverse instability observed at 450 GeV/c was ~1 s horizontally and a few tenths of a second vertically as shown in Fig. 14.

Fig. 14. Time evolution of the horizontal (top) and vertical (bottom) beam position as measured by the BBQ after the injection of a train of 36 bunches in addition to 12 bunches circulating in the machine (Courtesy E. Métal).

The transverse emittances measured along 4 consecutive trains of 24 bunches spaced by 1.85 µs (injected after a train of 12 bunches with a spacing of 35.7 µs) are shown in Fig. 15. The vertical blow-up is mostly affecting the last two trains.

Fig. 15. Transverse emittance along 4 trains (spaced by 1.85 µs) of 24 bunches. (Courtesy F. Roncarolo).

This is a consequence of the fact that decay time of the electron cloud after a bunch train passage is larger than the bunch spacing (in this case 1.85 µs) as shown in Fig. 4. These measurements were taken with typical machine settings at injection (damper gains close to maximum, 4 units of chromaticity in both planes).

The smaller vertical emittance of the last bunch of the last two trains is the result of the losses mostly affecting those bunches.

Large chromaticity and large injected emittance have proven to have a stabilizing effect on the single bunch instability induced by electron-cloud both in simulations and experiments in other machines and in particular in the SPS [5][9]. The effectiveness of these cures has been demonstrated also in the LHC and they could be used to increase the number of bunches during scrubbing while minimizing beam instabilities and losses.

The transverse emittances measured along 7 consecutive trains, each consisting of 24 bunches, spaced by 1.85 µs (injected after a train of 12 bunches with a spacing of 35.7 µs) after having increased the horizontal and vertical chromaticities to 14 units in both planes are shown in Fig. 16. The measured emittance blow-up is reduced by more than a factor two also for the trailing bunch trains. The blow-up is further reduced after having increased the chromaticity to 18 units and after increasing the transverse emittance of the beam delivered by the injectors from 2-2.5 µm to 3-3.5 µm (see Fig. 17).

Fig. 16. Transverse emittance along 7 trains (spaced by 1.85 µs) of 24 bunches. (Courtesy F. Roncarolo). Chromaticity was set to 14 units in both planes.

Fig. 17. Transverse emittance along 6 trains (spaced by 1.85 µs) of 24 bunches. (Courtesy F. Roncarolo). Chromaticity was set to 18 units in both planes and transverse emittance blow-up was applied in the injectors.

In spite of that some blow-up is still observed that could be related to the above mentioned incoherent effects of the electron cloud pinching.
50 ns beam at 3.5 TeV

At injection operation with large chromaticity seems to be required even for large gains of the transverse feedback pointing to single bunch instabilities at frequencies outside the bandwidth of the feedback as observed in the SPS [7].

At 3.5 TeV the instabilities have been observed, when the transverse feedback is switched OFF, with beams consisting of trains of 24 bunches (12+4x24) instead of trains of 12 bunches (9x12) for the same total number of bunches (108) and with the same settings (tune, chromaticity, octupole strengths). The rise time of the instability in the horizontal plane was few tenths of a second in the horizontal plane and 1 to 2 seconds in the vertical plane as shown in Fig. 18.

![Fig. 18: Time evolution of the horizontal (blue) and vertical (black) beam position as measured by the BBQ at 3.5 TeV when the transverse feedback is switched OFF. The accuracy of the logged timing of the transverse feedback switch OFF is approximately 1 second (Courtesy of H. Bartosik and B. Salvant).](image1)

75 ns beam at injection

Coupled-bunch oscillations at low frequency (~1-2 MHz) were observed also for the 75 ns beam at injection (see Fig. 19), mostly in the horizontal plane, although it is not clear whether they are induced by the electron cloud. In the vertical plane blow-up was observed even when operating the machine to high chromaticity (Fig. 20). This is compatible with instabilities and incoherent effects generated by the electron cloud close to threshold electron density.

![Fig. 19. Snapshot of the delta signal (product of the horizontal displacement and of the bunch profile) provided by the Head-Tail monitor for a train of 24 bunches at injection. (Courtesy B. Salvant).](image2)

![Fig. 20. Transverse emittance along 14 trains (spaced by 1.005 µs) of 48 bunches (Courtesy F. Roncarolo). Chromaticity was set to 20 units in both planes.](image3)

The typical signatures of electron cloud instabilities have been observed with 50 ns beams. For the 75 ns beam vertical blow-up correlated to coherent and incoherent effects typical of electron cloud densities close to threshold have been evidenced. For both beams these effects translate into low beam lifetime and losses.

The comparison of the dynamic pressure rise in the uncoated portion of the straight sections and the heat load in the beam screens of the arcs for a 50 ns beam at injection, during the ramp and at 3.5 TeV before and after scrubbing at 450 GeV clearly shows a reduction of both phenomena with a reduction by more than a factor 7 in the dynamic pressure rise and by a factor 4 in the heat load after 16 h of scrubbing with beam.

Experience in the SPS (see Fig. 21) shows that scrubbing with 25 ns beams allows operation with 50 and 75 ns beams with no significant electron cloud build-up.

SUMMARY AND RECOMMENDATIONS

Electron cloud effects (vacuum pressure rise in the straight sections, heat load in the arcs, instabilities and transverse emittance blow-up) have been observed for 50 ns beams. Although a reduced vacuum activity has been measured with 75 ns beams, acceleration of nominal trains of 936 bunches would lead to vacuum pressures larger than 2x10^7 mbar (interlock level). No significant heat load due to electron cloud in the beam screens has been measured for the 75 ns beam while a clear increase of the temperature of the beam screen of the triplet-D1 magnets in point 2 and in point 8 has been observed and in particular on the left side of point 8.
Operation with 75 ns beams requires a scrubbing run with a 50 ns beam which would allow scrubbing the arcs as well. The extrapolation of the experimental data collected so far and the SPS experience indicate that a dedicated period of 1 week for scrubbing with 50 ns beams with $1.3\times10^{11} \text{ p/bunch}$ should allow running with $1.3\times10^{11} \text{ p/bunch}$ (maximum possible in the PS at present) with 75 ns beams for physics. This would also allow studying the behaviour of 50 ns beams during machine studies to prepare a run with 50 ns beams later in the run.

The following prerequisites must be present before the start of the scrubbing run:

- injection of at least 4 trains of 24 (possibly 36) bunches (50 ns spacing) per SPS extraction up to nominal transverse emittance should be set-up;
- machine protection should be set-up for high intensity at 450 GeV/c;
- RF should be conditioned for operation at high intensity;
- solenoids (experimental and anti e-cloud) should be OFF in order to condition all the machine;
- vacuum interlock levels should be temporarily set to $2\times10^{-6} \text{ mbar}$ when and where pressure rises limit the progression of the scrubbing and compatibly with machine and experiment protection.

**ACKNOWLEDGEMENTS**

The author would like to thank V. Baglin, P. Chiggiato, J-M Jimenez, G. Lanza, E. Métral, F. Roncarolo, G. Rumolo, B. Salvant, M. Taborelli and F. Zimmermann for their contribution to the measurements and to their analysis. Discussions with R.-W. Aßmann and P. Collier and the support of the operation and injection teams are gratefully acknowledged.

**REFERENCES**