LESSONS FROM SPS STUDIES IN 2010

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Abstract

The experimental studies done in the SPS in 2010 were devoted both to a validation of some already proposed upgrades (as chamber coating) and to uncovering new limitations by pushing up injected bunch intensity. The first results obtained for ultimate (injected) LHC beam with 25 ns and 50 ns bunch spacing, each beam available only during one MD session in the SPS, will be presented together with results for a single high intensity bunch. The limitations envisaged during these MD studies will be discussed together with other SPS bottlenecks. Possible cures and mitigation will be revisited. An option for improvement of beam stability in the SPS, opened again by successful demonstration of reduction of the SPS transition energy, will also be discussed. The potential for delivering small transverse emittances now and after upgrades will be analysed. An attempt will be made at summarizing the accessible range of beam parameters (intensity per bunch as a function of distance between bunches and emittance).

REVIEW OF 2010 MD STUDIES

Since a few years the SPS has been able to deliver at top energy up to four batches of LHC bunches spaced at 25 ns, 50 ns or 75 ns with bunch intensity of 1.2×10^{11} and nominal longitudinal (0.6 eVs) and transverse (3.5 μm) emittances. These beams suffer from various limitations which, together with their cures, were studied by the SPSU Study Group [1] with the help of the operation teams. Already at the end of 2010 the 50 ns and 75 ns spaced beams from MD-type became operational and were regularly taken by LHC. An overview of dedicated MD sessions available for studies with LHC-type beams is given in Table 1.

The main part of experimental studies in the SPS in 2010 was devoted to a validation of some already proposed SPS upgrades [2]. One is to use an amorphous carbon (a-C) coating of the vacuum chamber [3] as a mitigation measure against e-cloud effect, the main limitation for a 25 ns spaced beam.

Other important studies were done with ultimate (1.8×10^{11}) bunch intensities, available for the first time this year from the SPS injectors [4] both in a single bunch and in bunch trains. Even twice higher than ultimate intensity was available for single bunches. All single bunch studies were performed during the year using parallel MD cycles. The same is true for MD studies of a new optics with a low transition energy [5].

The most important results of these MD sessions are presented below with the exception of those concerning the e-cloud, which are reviewed in [6]. Due to different LHC upgrade scenarios based on smaller than nominal transverse emittances [7]-[9], special attention is paid to the transverse emittance measurements to estimate the potential for delivering small transverse emittances now and after upgrades.

W	date	bunch spac.	N_{max}^{inj}	comment
17	27-29.04	25 ns	nom.	“scrubbing” run ded. SC, low loss
22	02-03.06	25 ns	ult.	36 h, ded. SC
29	20-21.07	25 ns	nom.	almost lost
35	03-04.09	50 ns 25 ns	ult. nom.	8 h, 4 batches
42	19-20.10	25 ns 50 ns	nom. nom.	36-72 bunches ded. SC
45	09.11	50 ns	nom.	floating
46	17-18.11	75 ns	nom.	

Table 1: Overview of MD studies with LHC beams in the SPS in 2011, some of them done in dedicated supercycle (ded. SC).

SINGLE BUNCH

The main subjects of the different MD sessions in the SPS in 2010 were related to known intensity and beam quality limitations. For a single bunch these limitations are from TMCI (Transverse Mode Coupling Instability), loss of Landau damping, space charge effect and longitudinal instability.

Studies of single high intensity bunches in the SPS were done using two different MD cycles - MD1 cycle with 4 s flat bottom, no acceleration and LHCFast cycle with short flat bottom (60 ms) and acceleration to 450 GeV/c.

TMCI has been observed in the SPS for proton bunches with small longitudinal emittances [10]. Last year the TMC instability threshold was measured [11] for a single bunch with longitudinal parameters close to those of the nominal LHC beam (emittance of 0.31 eVs and 4σ bunch length 3.6 ns). The threshold of 1.6×10^{11}, found for vertical chromaticity $\xi_v \sim 0$, is very close to the prediction obtained from simulations with the SPS impedance model [12]. Up to 6% particle losses were observed for injected intensities of 1.8×10^{11} and practically no loss for an intensity of 1.4×10^{11}.

For a matched voltage the threshold intensity scales as $N_{th} \propto |\eta|\varepsilon$, where $\eta = 1/\gamma^2 - 1/\gamma_t^2$ and therefore has its minimum at injection (above transition, $\gamma_t = 22.8$).

Possible measures to push this potential limitation up in intensity are: increased vertical chromaticity, capture voltage or longitudinal emittance, wide-band transverse feedback and of course impedance reduction (after identification). The first three options above could lead to continuous particle loss on the long flat bottom. A feasibility study of active damping of the single bunch vertical instability using a wide-band feedback system [13] is under way in collaboration with LARP [14].

The new possibility which was seriously studied at the end of the last year is an increase in $|\eta|$ by reduction of transition energy. Indeed at 26 GeV/c the TMCI threshold is higher for $\gamma_t = 18$ than for nominal $\gamma_t = 22.8$ by a factor 2.86. The preliminary results are presented below in a separate section.

For intensities up to 2×10^{11} the transverse settings in the SPS were optimised and the single bunch with ultimate intensity was accelerated to 450 GeV/s with low loss and low chromaticity. Even much higher than ultimate bunch intensities, up to 3.5×10^{11}, were prepared in the PS complex and injected into the SPS. To reduce losses it was necessary to follow an increase in bunch intensity by an increase in the vertical chromaticity.

The effect of a high harmonic (800 MHz) RF system on the TMCI threshold has been also studied both in MDs and by simulations [11] but results are not yet conclusive.

More problems (losses) were observed with smaller injected emittances. It was necessary to blow-up, the initially very small, injected transverse emittances in the PS (1.5 μm) in order to reduce their blow-up and particle losses in the SPS. Note that from theory and simulations a higher TMCI threshold is expected for smaller transverse emittances. Vertical and horizontal emittances measured at 26 GeV/s in the SPS during different MDs ([11], [15] and OP shifts) for various bunch intensities are plotted in Fig. 1. These measurements were performed with the 200 MHz RF voltage in the range (1.8-2.0) MV, $\xi_h = 0.25$ and ξ_v increasing with intensity from 0 to 0.3. The 800 MHz RF system was off.

The measurement point at the lowest intensity corresponds to the 50 ns spaced LHC beam with a very small transverse emittance (produced with the double batch injection scheme in the PS in 2008) and nominal bunch intensities, and is shown on these plots for comparison with single bunch data.

A linear fit to the dependence of the vertical and horizontal emittances (data shown with red circles) on bunch intensity has correspondingly following form

$$\varepsilon_H = -1.14 + 2.22N/10^{11}, \quad (1)$$
$$\varepsilon_V = -1.03 + 2.17N/10^{11} \quad (2)$$

As one can see, these fits (shown in Fig. 1 with a dashed line) don't go through the origin and therefore most probably describe emittance blow-up additional to the effect of space charge which for a simplified case would be proportional to the brightness $N_b/\varepsilon_{H,V}$. More accurate measurements are planned in 2011.

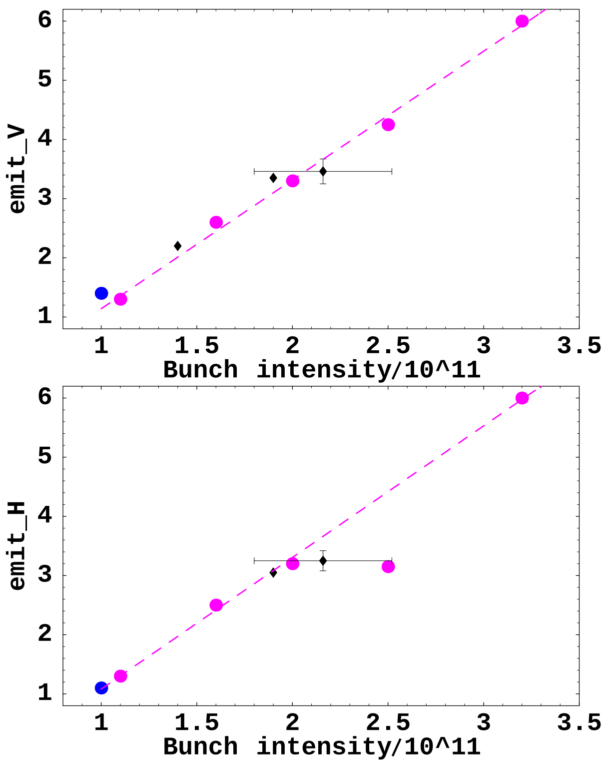

Figure 1: Vertical (top) and horizontal (bottom) normalised emittances measured at 26 GeV/s in the SPS for different bunch intensities together with linear fit (dashed line) to some data (big circles).

As for all other transverse emittance measurements presented below, these data were obtained from one wire scanner (WS) acquisition per cycle (due to a difference between "in" and "out" movement of the WS) with the first point (possible) at 10 ms after injection. In the case of many bunches in the ring, the average for all bunches is presented. Various improvements are foreseen by BE/BI Group for 2011 (e. g. the second, linear, WS with possibility to gate acquisition over 50-100 ns) [17]. Another problem with beam instrumentation for very high intensities (MOPOS) was solved towards the end of the 2010 run.

LHC BEAMS

Multi-bunch limitations

MD studies with nominal multi-bunch beams were also first of all connected with known intensity limitations. The e-cloud, generated by the presence of many bunches in the ring, is at the origin of the single bunch vertical instability and horizontal coupled-bunch instability (cured by the existing transverse damper). Other multi-bunch limitations are beam losses, longitudinal coupled-bunch instabilities, beam loading in the 200 MHz and 800 MHz RF systems as well as heating of different machine elements (e.g. MKE and MKDV kickers) and vacuum issues (beam dump, MKDV and MKDH outgassing, ZS septum sparking).

Most of the MD time with nominal LHC beams in 2010 was devoted to e-cloud studies, the results are presented in [6]. A summary of MD sessions available in 2010 is given in Table 1.

After intensive studies during first MDs in 2010 the settings on ZS kickers have been changed and limitations due to its sparking and outgassing have been removed [18].

The longitudinal coupled-bunch instability of the LHC beam in the SPS is characterised by a very low intensity threshold. Indeed a single LHC batch with 2×10^{10} p/bunch becomes unstable during acceleration at ~ 250 GeV/c.

To stabilise the beam controlled emittance blow-up is performed twice during the cycle, in addition to the use of the 800 MHz RF system as a Landau cavity in bunch-shortening mode throughout the cycle. The 800 MHz voltage during the cycle usually follows the 200 MHz voltage program at 1/10 level. The first blow-up is with mismatched voltage at injection. During the second one, above 200 GeV/c, the emittance is increased to 0.6 eVs. The emittance blow-up in a double RF system has its own limitations due to the presence of beam loading [24].

Ultimate intensities

25 ns beam As one can see from Table 1, there were two MD sessions in 2011 with LHC type beams having ultimate injected bunch intensity, first with beam spaced at 25 ns and then later with a 50 ns beam.

During the first MD in week 22 the maximum intensity injected into the SPS was 1.88×10^{11}/bunch, longitudinal emittance was 0.38-0.4 eVs and transverse emittance $\varepsilon_{H/V} = 4.5/5$ μm. Transverse emittance blow-up to $\sim 10\mu$m (larger in H-plane and for more batches in the ring) was measured at 450 GeV/c (with $\xi_{H/V} = 0.2/0.3$). A large variation in bunch length across the batch was observed both for the injected beam and on the flat top. Bunch length on the flat top was 1.6 ns (average over the batch) and 1.8 ns maximum. During this high intensity operation some issues with MOPOS and FBCT were seen. Maximum bunch intensity achieved at 450 GeV is 1.6×10^{11}/bunch for one batch in the ring. Increasing the number of batches led to a decrease in bunch intensity on the flat top with approximately 1.5×10^{11}/bunch for 3 batches in the ring, see Fig. 2 (top).

Already 12 bunches were unstable longitudinally on the flat bottom even with the 800 MHz on. During this MD particle loss (flat bottom plus capture) reduced from 30% at the beginning of the MD to 20% at the end, probably due to scrubbing of the ring by the e-cloud. However no direct e-cloud observations were possible due to the absence of the reference StSt liner. Capture losses were reduced after modification of the 200 MHz RF voltage program (from a 0.65 eVs constant bucket area to a 0.75 eVs bucket) through the cycle.

During this MD the temperature and pressure increase in

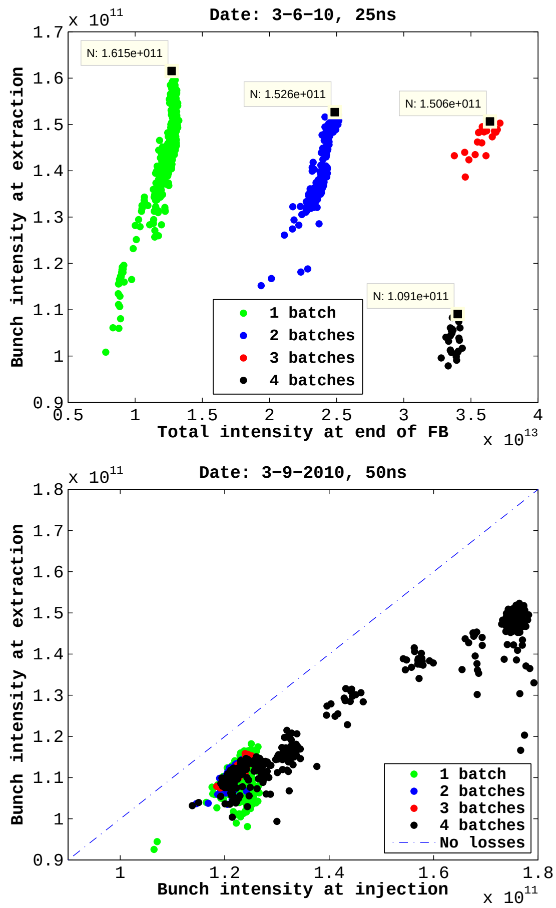

Figure 2: Bunch intensity at 450 GeV/c as a function of injected intensity for different number of batches in the ring during MD W22 with a 25 ns beam (top figure) and MD W35 with a 50 ns beam (bottom) [19].

the many special magnets became critical [20] aggravated by the fact that SPS supercycle consisted only of the LHC cycle (no other users). It was necessary to reduce the RF voltage on the flat top from 7.2 MV to 5.5 MV, limit the maximum number of batches in the ring to 3 and to stop the beam 3 times to permit cool-down of the MKE4. The MKE6 magnet (with serigraphy) had very high outgassing (maximum pressure of 9×10^{-7}) but a conditioning effect has been observed as well. The MKPs suffered from the outgassing in TIDVG (situated nearby) during beam dumps. It is planned to shorten the period of the installation of 5 serigraphed MKE4 magnets from 3 to 2 shutdowns [20]. The SEY of the silver paint and ferrite should be measured to study the reasons for outgassing of the MKE6. Transverse and longitudinal impedances of the MKP have been measured as well.

50 ns beam Only 8 hours at the end of the MD block were available for this MD, performed also in parallel with LHC setting-up with another type of the beam (150 ns spaced) - an experience to be avoided in future MD planning [21].

Maximum intensity injected into the SPS was 1.8×10^{11}/bunch in 4 batches of 36 bunches. Maximum bunch intensity achieved on the flat top was 1.5×10^{11} with losses increasing with bunch intensity and reaching 15% for the injected ultimate intensity, see Fig. 2 (bottom). Transverse emittances measured in the SPS at 26 GeV/c were $\varepsilon_{H/V} = 3.2/3.9$ μm. The nominal voltage program was used during this MD. Increasing the initially relatively small chromaticities did not have any effect on losses. Obviously more time for optimisation is needed in 2011.

The e-cloud signal for a 50 ns beam, being at least a factor 10 smaller than for the 25 ns spaced beam (for the same bunch intensity and twice smaller total), nevertheless grew slightly with bunch intensity above nominal [22].

Nominal LHC beam

Already during the first MD in 2010 (scrubbing run) a reduction of losses to 5% (from previous minimum value of 7%) was obtained for a 25 ns spaced beam with chromaticities much smaller than in the past [28]. One possible explanation is related to the short shutdowns during the last two years and as a result the much reduced venting of the SPS vacuum chamber. Indeed, the effects caused by the presence of the electron cloud are considered at the moment to be the most important intensity limitations for this beam. They lead to transverse emittance blow-up and instabilities. They could also be at the origin of beam losses. Note that careful low-level RF setting-up was also absolutely essential.

On a few occasions, Table 1, nominal 50 ns and 25 ns beams were studied using the dedicated MD cycle in the SPS (as in week 42). After some time during this type of MD, even with a single batch with a 50 ns spacing, this led to a problem with the MKE magnets heating.

A summary of beam parameters achieved in the SPS in 2010 both for nominal and ultimate (injected) beams is presented in Table 2.

parameter		LHC nominal			LHC ultimate		
spac.	ns	25	50	75	25	50	ind.
N_b	10^{11}	1.2	1.2	1.2	1.5	1.5	3.2
n_b		288	144	96	216	144	1
N_{tot}	10^{13}	3.5	1.7	1.2	3.2	2.2	0.03
ε_L	eVs	0.7	0.5	0.5	0.8	0.6	0.4
$\varepsilon_{h/v}$	μm	3.6	2.0	2.0	10		6.0

Table 2: Beam parameters achieved at 450 GeV in 2010 for nominal and ultimate injected intensities.

Transverse emittances The majority of MD sessions in 2010, see Table 1, was devoted to studies with nominal LHC beams with different bunch spacings. The collection of transverse emittance measurements done during these MD sessions by different people ([15], operation team and others) is shown in Fig. 3.

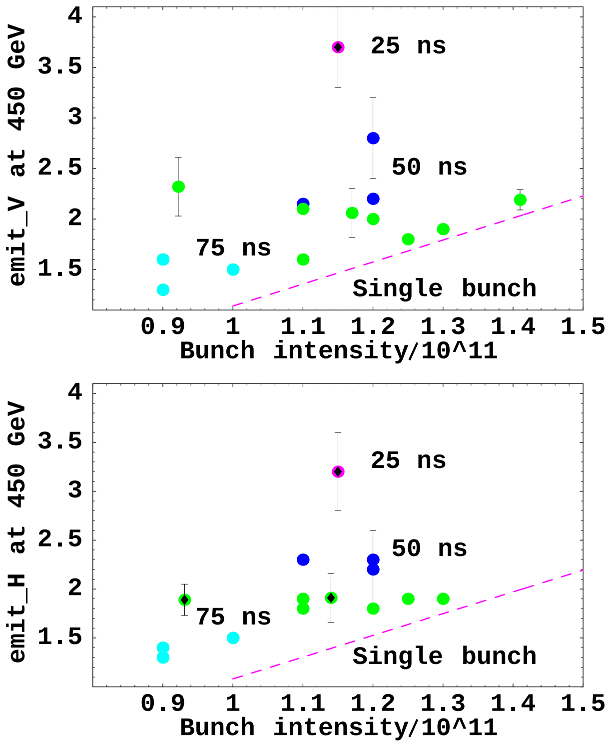

Figure 3: Vertical (top) and horizontal (bottom) normalised emittances measured at 26 GeV/s in the SPS for different bunch spacings and bunch intensities together with the fits (1-2) from single bunch data. The 200 MHz RF voltage was 2.0 MV, $\xi_h = 0.25$, $\xi_v = 0.3$. Low intensity points for a 75 ns beam were measured with 8 bunches per batch.

Transverse emittances of beams with 75, 50 and 25 ns bunch spacings measured in 2010 at various intensities are very different, with maximum emittances for a 25 ns beam and a 75 ns beam being close to the single bunch limit (1-2). These values are also often determined by the injectors. Indeed injected emittances for 50 and 75 ns beams were higher than in the past (with double batch injection in the PS). No transverse emittance blow-up was observed at the end of the cycle for a 50 ns beam (2.5 μm at extraction) while for a 25 ns beam with the same number of bunches per batch (36) the measured vertical emittance grew with the number of batches reaching a value of 3.7 ± 0.9 μm for 4 batches [15]. The blow-up of the 25 ns beam is most probably due to the e-cloud effect. The horizontal emittance was around 3.5 μm. Bunch-by-bunch emittance measurements with higher accuracy are required to investigate the origin of the observed emittance blow-up.

Longitudinal emittance The necessity of the longitudinal emittance blow-up for a 50 ns spaced beam was analysed. Stability of a 50 ns beam with the 800 MHz RF on in bunch-shortening mode seems to strongly depend on injected bunch length (emittance), Fig. 4. For the nominal voltage program the beam was unstable on the flat top for an injected bunch length below 3.5 ns (probably also more unstable towards the batch tail). This effect could be observed even locally, when only a few bunches had a smaller bunch length (emittance) at injection. On the other hand transmission in the SPS decreases from 95 % to 88 % when the injected emittance is increased from 0.33 eVs to 0.5 eVs due to the corresponding increase in bunch length [25]. In this case controlled emittance blow-up during the ramp is required for stability on the flat top. These observations could be an indication of the loss of Landau damping due to the reactive impedance of the SPS [2].

Note that in 2008 for a 50 ns spaced beam the nominal bunch intensity (1.1×10^{11}) was achieved at 450 GeV/c with very small longitudinal (0.4 eVs) and transverse (1.2&1.5 μm) emittances [26]. This beam was stable on the SPS flat top without the controlled emittance blow-up required in 2010.

LOW TRANSITION ENERGY OPTICS

The decrease in transition gamma from 22.8 to 18 was proposed and achieved by lowering the present tunes (26.13 and 26.18) by 6 units [5]. Maximum dispersion is also increased from 4.8 m to 9 m. For a low transition energy the expected increase in TMC and longitudinal coupled bunch instability threshold is proportional to the factor η. However for the same longitudinal parameters the voltage also scales as η which could prove to be a limitation for fast cycles and beam transfer to LHC.

The new optics was confirmed during many MD sessions by measuring the optics functions and the synchrotron frequency from the quadrupole oscillations [27]. Chromaticity was also measured and calibrated. No signature of the TMCI was observed for injected single bunches with intensities in the range $(2.7-3.3)\times10^{11}$. Initially the voltage on the flat bottom was too low (1.8 MV) and this led to continuous particle loss ~ 10 %. No transverse emittance blow-up could be measured on the flat bottom for bunches with $\varepsilon_{\rm H/V} = 2.0/2.3\,\mu$m at 2.6×10^{11} and $\varepsilon_{\rm H/V} = 2.5/2.7\,\mu$m at 3.3×10^{11}. With limited time for optimisation, single bunches were accelerated to 450 GeV/s using the LHC-fast3 cycle. For an intensity of 2.6×10^{11} on the flat top emittances were $\varepsilon_{\rm H/V} = 2.4/2.9\ \mu$m. The next important step will be to inject bunch trains to study multi-bunch effects, in particular e-cloud effects and longitudinal coupled-bunch instability during the ramp.

For the same bunch intensity transverse emittances measured during MDs with low transition energy are significantly smaller than those with nominal optics, Fig. 5 (top).

This could be explained by the increase in beam stability and an absence of emittance blow-up related to the effect of transverse impedance below the TMCI threshold. However, in order to evaluate space-charge limit, the measured points should be scaled down in intensity due to the 10% losses and also longer bunches at the too low voltage of 1.8 MV (the same as with nominal optics), Fig. 5 (bottom). After scaling by 30% down in intensity these emittances

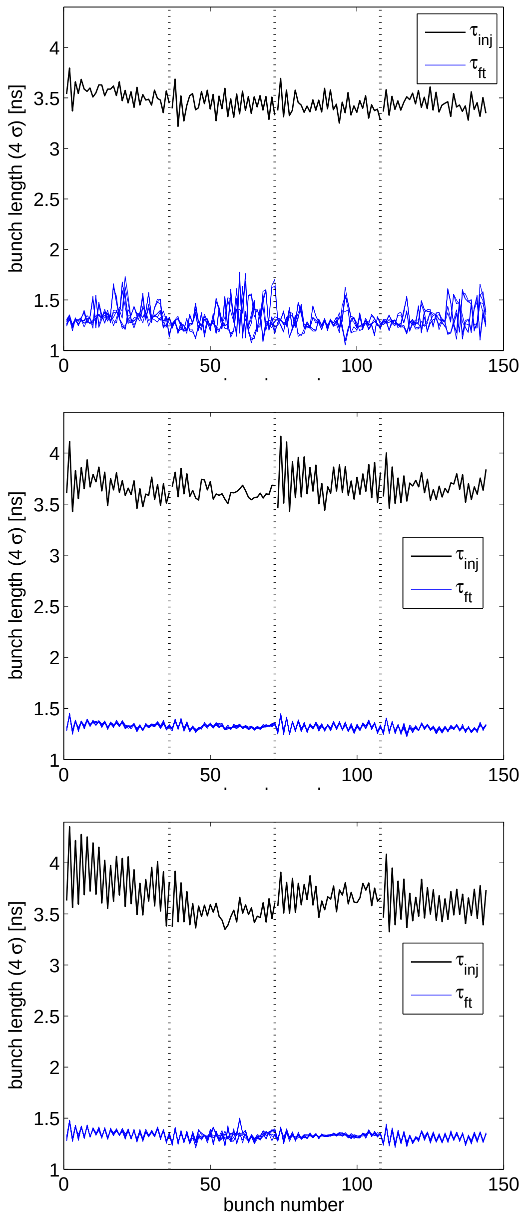

Figure 4: Bunch length at injection (upper trace) and on flat top (lower trace) for a 50 ns spaced beam with nominal bunch intensity and without controlled emittance blow-up [23]. The 800 MHz RF is on. Beam with small injected longitudinal emittance (top figure) is unstable on flat top but stable with larger emittances (middle). Bunches with small emittances can also become unstable locally (bottom).

(together with low intensity point at nominal optics) have a linear fit $\varepsilon_V = 1.2(N/10^{11})$, which goes through the origin and corresponds to a space charge limit of 0.13. For the nominal LHC bunch at 26 GeV/c the space-charge tune spread ΔQ_{sc} is 0.05 [28]. The tolerable limit for the space-charge tune spread in the SPS from past experience (ppbar) was believed to be around 0.07, but a much higher value

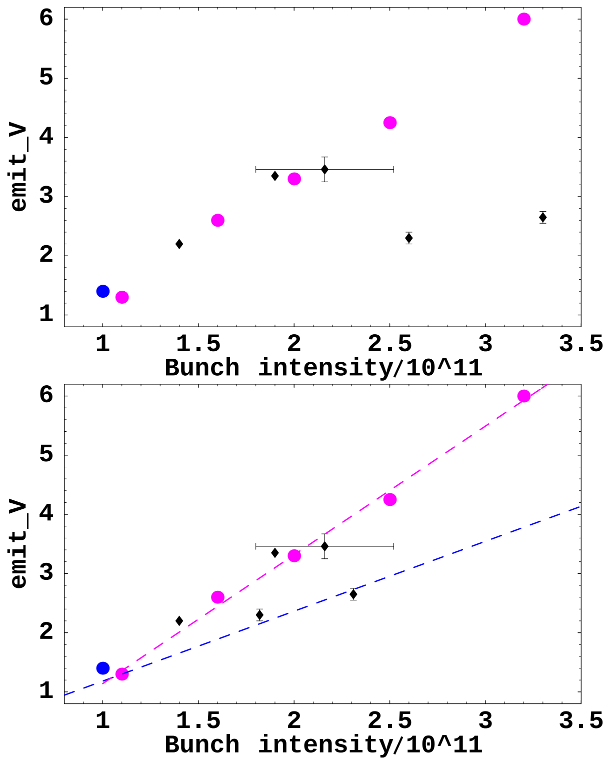

Figure 5: Top figure: vertical normalised emittances measured at 26 GeV/c in the SPS for nominal (as in Fig. 1) and low transition energy optics (two new points on the right). In bottom figure points for the low transition energy optics are scaled down in intensity and shown together with linear fits to both nominal and low γ_t data. The 200 MHz RF voltage was 2.0 MV, $\xi_h = 0.25$, $\xi_v = 0.3$.

has been achieved for ions [29]. Accurate measurements with correct voltage and after working point optimisation will be done in 2011.

Note that in order to obtain the same longitudinal parameters the RF voltage during the acceleration cycle should be increased $\propto \eta$, Fig. 6. Already the maximum voltage (7.5 MV) is used now for extraction to LHC, but probably controlled emittance blow-up for the same intensity can also be reduced. Indeed the threshold for the loss of Landau damping $N_{th} \sim \varepsilon^2 \eta \tau$. Taking into account that bunch length scales as $\tau \sim (\varepsilon^2 \eta / V)^{1/4}$, one will need for stability with low γ_t optics a smaller emittance $\varepsilon \sim \eta^{-1/2}$. This smaller emittance will then give the same bunch length in the new optics as with the present optics.

For ultimate LHC intensities N_{ult} larger controlled emittance blow-up will be needed to stabilise the beam. To have the same bunch length at the larger emittance, which is $\propto \sqrt{N}$, one would need a voltage N_{ult}/N_{nom} times higher than the present 7.5 MV, which means 10.5 MV for the ultimate bunch intensity. It is also possible that for these high intensities larger longitudinal emittances are required at 450 GeV in LHC itself. Then beam transfer to the LHC 400 MHz RF system from the SPS 200 MHz RF system

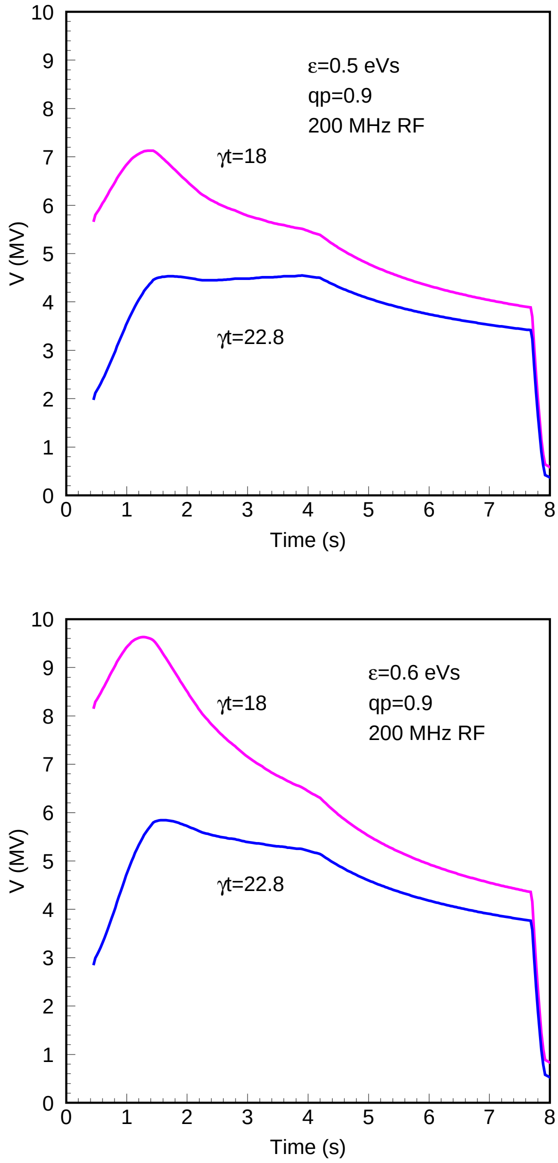

Figure 6: The 200 MHz RF voltage program required for a constant filling factor in momentum (0.9)i for two longitudinal emittance of 0.5 eVs (top) and 0.6 eVs (bottom) in nominal and low γ_t optics.

becomes critical.

On the other hand, the existing two 5-section cavities can provide much less voltage at ultimate LHC current. A solution to this problem is to rearrange the existing 4 cavities (with 2 spare sections) into 6 cavities of shorter length with 2 extra power plants which allow simultaneously to reduce beam loading per cavity, increase available voltage and even reduce total beam coupling impedance, see [2] for more details.

The most critical question to answer in 2011 is what, smaller, emittance is required for longitudinal beam stability on the flat top in low γ_t optics.

SUMMARY

While the nominal 25 ns beam is in a good shape (low beam losses with low chromaticity), ultimate LHC beams need many more studies and much optimisation. Due to large losses only a maximum bunch intensity of 1.5×10^{11} could be obtained on the flat top both for 50 ns and 25 ns spaced beams. The 25 ns beam also suffered from longitudinal instabilities on the flat bottom and large transverse emittance blow-up during the cycle.

The threshold of the TMCI was measured as a function of vertical chromaticity and was found to be at the ultimate intensity for zero chromaticity. Increased losses and blow-up were observed for smaller injected emittances.

Very promising results for beam stability and transverse emittance preservation were obtained with the low γ_t optics.

Analysis of the available transverse emittance measurements done in 2010 allows to hope for a 3 μm emittance for the ultimate beam spaced at 50 and 75 ns already now, and with the 25 ns spacing after e-cloud mitigation. Even lower emittances, 2.5 μm, can probably be obtained now with the low γ_t optics for 50 and 75 ns ultimate beams if RF voltage (during the cycle and at transfer to LHC) turns out to not be a problem. After upgrades (e-cloud and impedance reduction) one can hope to be at the space charge limit (2.5 μm for ultimate intensity) for both 50 ns and 25 ns beams. These values are nevertheless very preliminary and should be carefully checked. For experimental studies one needs small PS beams and improved transverse emittance measurements in the SPS.

The main SPS limitations for ultimate intensity have been identified. They are the e-cloud effect, beam loading in the 200 MHz RF system, transverse mode coupling (TMCI) and longitudinal coupled bunch instabilities. Hardware modifications needed for the SPS upgrade were summarised in [2] and reviewed by the SPSU Task Force (led by V. Mertens). Proposed measures to overcome the known limitations are now under study by the LIU-SPS in the frame of the LIU project [7]; they include e-cloud mitigation, impedance reduction and RF upgrade.

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