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Summary of the LIU Beam Studies Review

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Summary

A review of the status of the LHC injector beam studies related to the LHC Injectors Upgrade (LIU) project took place on the 28 August 2012 at CERN. The main goal of the review was to define work priorities for the rest of the run before the Long Shutdown 1 (LS1) and be able to:

- specify the equipment to be built for the LIU project;
- estimate achievable beam characteristics in the various accelerators.

A team of external reviewers was also asked to participate in the event and comment on the status of the presently ongoing activities as well as give recommendations for future work.

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1 Introduction

During the 2012 run, a total of 216 hours of Machine Development (MD) have already taken place, while about 192 hours are still planned to be devoted to miscellaneous MD activities until the end of the run. It is still uncertain whether it will be possible to carry out further studies in the period January-February 2013, when the LHC will still be running in proton-Pb collision mode of operation and Pb ions will be also provided for the SPS North Area physics. After LS1, it is highly probable that the LHC will require 25 ns beams with nominal/ultimate intensity per bunch and smaller than nominal transverse emittances. Between 2018 and 2019 a new long shutdown (LS2) is planned to take place to implement all the necessary upgrades and consolidations in the LHC injectors, as foreseen by the LIU project, and enable them to increase their performance reach. After LS2, or after the following Winter Technical Stop, higher brightness 25 ns and 50 ns beams will hopefully be available at injection in the LHC. MDs until the end of the present run will help estimate how close the characteristics of the injected beam could then be to those required for the subsequent High Luminosity LHC (HL-LHC) era. Table 1 displays the beam parameters expected at the injection of all CERN synchrotrons (PSB, PS, SPS, LHC) at the different stages after the 2012-2013 run.

Table 1: Relevant beam parameters at the injection of each accelerator (50 and 25 ns, traditional production schemes)

		PSB (1 b/inj)			**PS** (4+2 b/inj)		
		N (10^{11} ppb)	ϵ (μm)	E (GeV)	N (10^{11} ppb)	ϵ (μm)	E (GeV)
Post LS1	50 ns	12.4	1.4	0.05	11.8	1.5	1.4
	25 ns	17-22	2.1-2.6	0.05	16.-21	2.2-2.8	1.4
Post LS2	50 ns	12.5	0.8	0.16	11.8	0.9	2
	25 ns	24.9	1.7	0.16	23.6	1.7	2
HL-LHC	50 ns	27.2	1.9	0.16	25.9	2	2
	25 ns	34.2	1.5	0.16	32.5	1.6	2

		SPS (4 $\times$ 36-72 b/inj)			**LHC** ($n \times$144-288 b/inj)		
		N (10^{11} ppb)	ϵ (μm)	p (GeV/c)	N (10^{11} ppb)	ϵ (μm)	p (GeV/c)
Post LS1	50 ns	1.9	1.6	26	1.7	1.7	450
	25 ns	1.3-1.6	2.3-2.9	26	1.2-1.5	2.5-3.2	450
Post LS2	50 ns	1.9	0.9	26	1.7	1	450
	25 ns	1.9	1.8	26	1.7	2	450
HL-LHC	50 ns	4.1	2.1	26	3.7	2.3	450
	25 ns	2.6	1.6	26	2.3	1.8	450

The values reported in Table 1 are based on the following assumptions. The post-LS1 row comes from the present known performances of the injectors assuming the traditional production schemes for both the 25 and 50 ns beams. The post-LS2 row is obtained assuming that the same intensities as in the LS1-to-LS2 era will be achieved within about half transverse emittances for both types of beams (allowing for about 10% margin), while the

intensity reach of the 25 ns was extended to ultimate thanks to the RF upgrade in the SPS. Finally, the parameters at the LHC injection in the HL-LHC line have been calculated from those specified at collision by the HL-LHC project requirements [1], assuming 5% beam loss and a transverse emittance growth by an additional 0.7 μm between injection and collision in the LHC. The values for PSB, PS and SPS are then computed by converting back the numbers at LHC injection, assuming emittance growth and beam loss budgets of 5% in the PS and PSB, and of 10% in the SPS and LHC. Applying this conversion, the HL-LHC values are found to translate into highly bright beams with direct space charge tune spreads exceeding 0.4 in the PSB, 0.3 in the PS and 0.15 in the SPS [2]. Obviously, the question of losses as well as of conservation of low transverse emittance under conditions of strong space charge will become central in defining the potential of the injectors to produce the requested beams. Other well-known potential bottlenecks for the production of the HL-LHC beams in the LHC injection chain are longitudinal instabilities and electron cloud (both in the PS and SPS).

During the first part of the 2012 run, the MD time could profit of five full days of dedicated scrubbing run in the SPS [3], three 24-hour blocks of dedicated blocks, which took place during technical stops of the LHC, and eight 12 or 24-hour floating blocks, which were carried out in parallel with LHC operation and therefore usually suffered from lower efficiency. Additionally, parallel MDs are regularly carried out during the working hours in all the accelerators of the LHC injector chain. In particular, both the PSB and the PS reserve one cycle per supercycle to MDs, while the SPS can include one short MD cycle in parallel to its fixed target physics operation. About the same amount of MD time that was spent up to now is still available before the end of the run. To optimize the use of the machine time, the remaining MD blocks will be arranged in weekly 10-hour blocks mostly placed on Wednesdays. A request to extend the studies into the first two months of 2013 could also be submitted if this could provide precious additional information needed before going into LS1.

Most of the items that were listed as LIU priorities earlier in 2012 [4] and then also later, after the MD requests had all been submitted [5], have been initiated and have been proceeding at a speedy pace, as will be outlined in the next section. The review of the studies, machine by machine, has tried to address the following set of questions:

- Are we collecting the necessary information to estimate the future LHC-type beam characteristics?
- Which studies will still require more information and significant MD time before LS1?
- Is any study presently limited by instrumentation or diagnostics? Is any improvement possible before LS1?
- Is any study strongly relying on the installation and test of new hardware before LS1?
- How can we optimize the use of the remaining available MD time? Do we need to request for more?
- Which MD activities would benefit from additional MD time in 2013?

2 LIU Beam Studies in 2012

2.1 PSB

In the PSB, the LHC beams are fully described by a curve showing the transverse emittance as a function of the bunch intensity, which is determined by the multi-turn injection process and space charge blow up. This dependence is found to be linear and the emittance values correctly reduce to those coming from the Linac2 when only one turn is injected into the PSB (i.e. about 1.1 μm). To maintain the PSB operation on the best emittance-intensity line requires steady optimisation and fine tuning. The transverse emittance in the PSB was also measured along the cycle, showing that no significant blow up occurs in the intensity range of the LHC beams. It is interesting that the slope of the line emittance vs. intensity becomes larger for smaller longitudinal emittances. This dependence is explained by the fact that producing bunches with lower longitudinal emittance in the PSB requires longitudinal shaving at the beginning of the cycle, i.e. controlled longitudinal losses at constant transverse emittance. This means that the potential of the h9 production schemes in the PS cannot be fully exploited as long as the RF manipulations in the PS are done at 1.4 GeV. Not much gain in the PSB performance is expected after LS1, because no important changes will be implemented in this machine during LS1. However, the ultimate 25 ns beam (1.7×10^{11} ppb within 2.5 μm) seems close to what the PSB can presently produce, suggesting that this beam could be delivered to LHC after LS1 if the emittance blow up along the injector chain is below the budgeted 30% (actually 22% would still guarantee ultimate beams within specs in the LHC). It is presently assumed that, when the beam will be injected into the PSB from Linac 4, LHC beams with doubled brightness with respect to the present values will be in reach thanks to the higher injection energy and the H^- injection. If this were true, 50 ns HL-LHC beams would be in reach at PSB ejection after LS2, while the 25 ns beam would still require either an even larger brightness increase or a relaxation of the loss/emittance budgets across the injector chain. Presently, there are no machine studies that could practically be performed to prove that this will be the case. The only feasible studies now consist of quantifying at best the effect of space charge at 160 MeV with the present machine optics and use it as an input for simulations of the future injection process. Space charge measurements have been performed at the PSB at 160 MeV. First, for a given working point, the transverse emittance blow up has been measured on the 160 MeV energy plateau. Second, the tunes have been moved closer to each other in order to increase the coupling between transverse planes, resulting into a measurable emittance exchange between the two planes. Random distributions of quadrupole errors in the machine have been used for fitting the experimental data with PTC-ORBIT. While this approach shows that the measured emittance growth can be explained as space charge driven in presence of a certain distribution of lattice errors and hints to the resonance lines seen by the space charge, the full nonlinear characterization of the machine at 160 MeV, which is the necessary input for future simulations of the H^- injection process, has not yet been determined. A possible useful tool to derive information on the resonances and resonance compensation at 160 MeV would also be the resonance driving term analysis based on turn-by-turn BPM data. However, the electronics that would allow this type of data acquisition is still under test and will become probably available only during the last part of the year.

In the RF domain, so far most of the PSB machine studies have been devoted to testing the prototype of Finemet® cavity installed in Ring 4 and deploying the Digital Low Level RF control system, while no tests on the transverse feedback system in view of its upgrade during LS1 have been conducted so far.

- The test of the prototype Finemet® cavity shows great promise, as the hardware issues were mostly understood. The MD time needed to continue the 2012 tests amounts to three half days per week during the first three weeks of October 2012. A 5-cell Finemet® cavity will be installed during LS1, and beam tests using exclusively the Finemet® cavity to accelerate the beam will be carried out before a decision can be made to commit to this system for the PSB upgrade. However, the decision must not be delayed after 2014 to have enough time for production before installation in LS2. Meanwhile, relevant information can also be collected from the JPARC experience, as they are currently testing a similar Finemet® structure with feedback and feed-forward. Another important point to be checked is whether the impedance of the Finemet® cavity might significantly differ from that of the present RF system and could harm the beam.

- The Digital LLRF Beam Control beam tests are also progressing well. MD time in September is needed to complete the tests with the prototype system. The final Digital LLRF Beam Control will be installed on Ring 4 and will first require a timing cycle for tests, followed by commissioning with beam (from 21 October until December, and possibly also into the new year, i.e. from 17 January to 11 February 2013). It is clear that MDs in 2013 would be highly beneficial to the Digital LLRF, in particular for the synchronization with the PS RF system. It is very important to progress as much as possible on this front before LS1, because the PSB will start up operationally with this system after the long shut-down.

- It seems unlikely that it will be possible to test a single plane of the upgraded transverse damper with beam before LS1, but the complete system for all rings should be available in parallel with the existing one after LS1. However, it should be pointed out that the present feedback system can already efficiently suppress the instabilities in the typical intensity range of both present and future LHC beams (assuming that the impedance of the machine will not be significantly increased by the installations required by the upgrade program). The power and bandwidth upgrade of the system aims at enabling the PSB to accelerate even higher intensity beams for the ISOLDE physics, although the questions of whether and by how much it is needed still remain unanswered. In this context, additional machine studies on the nature of the PSB transverse instabilities (source, dependence on machine and beam parameters) as well as on the efficiency of the damper to suppress them are advisable before LS1.

2.2 PS

A great deal of machine studies are presently taking place at the PS to tackle all known limitations in the transverse and longitudinal plane.
At injection, one of the principal worries for future high brightness operation is space charge.

The reason is that the injection of LHC-type beams into the PS is based on the so-called double batch scheme. A first batch of four bunches from the PSB is injected into the PS and remains for 1.2 sec at injection energy while waiting for a second batch of two bunches to be injected. Although this issue will be partly alleviated after LS2 with the upgrade of the injection energy to 2 GeV from the present 1.4 GeV, the space charge tune spreads foreseen for HL-LHC type beams are still supposed to extend beyond the value that is currently considered capable of guaranteeing preservation of the beam quality ($\Delta Q = 0.3$). The resonances potentially dangerous for the beam have been identified through loss measurements over tune scans, conducted at the current injection energy of 1.4 GeV (by using low energy quadrupoles) as well as at the future injection energy, 2 GeV (by using the Pole Face Windings, which allow controlling both tunes and chromaticities). The detailed study of the impact of chromaticity on beam losses and emittance growth is an important ingredient to evaluate the possibility of changing the working point to a region that allows in principle for a larger space charge detuning. Operational LHC beams, with space charge tune spreads close to 0.3 and a working point of (6.23, 6.24), do not exhibit transverse emittance blow-up in spite of their space charge neckties extending over the integer resonance. Studying further and explaining this behaviour through simulations is crucial to determine how much more margin we have in accommodating larger tune spreads without detrimental effects on the beam. The necessary inputs for the set up of a reliable simulation tool for predictions are

1. A systematic scan of working points and measurements of the associated losses and emittance blow up along the injection plateau for different space charge detunings, to be carried out before LS1;

2. A model for the magnetic error distribution to be used in simulations to reproduce the measured tune diagrams as well as the emittance behaviour, as found in the measurements proposed at the above point 1.

Furthermore, possible compensation schemes will be studied experimentally with the resonance driving terms based on turn-by-turn data, and the applicability of a new optics with larger dispersion (by means of the gamma-jump quadrupoles) is presently under study to ease space charge detuning at injection.
Another known problem due to the long flat bottom for LHC beams is the onset of transverse headtail instabilities. Up to now, machine operation with LHC beams has relied on linear coupling to cure such instabilities. Ongoing machine studies concentrate on additional countermeasures to ensure that they will not limit the intensity of the future LHC beams. In particular, the correction of chromaticity with the Pole Face Windings could be helpful to lower the unstable mode number (and hence, the frequency of the unstable intra-bunch motion), while either the octupoles or the transverse damper can be used for suppressing it. The vertical instability at transition has been studied in great detail in Ref. [6]. It can be suppressed at best with the usual gamma jump accompanied by a synchronized chromaticity jump at transition (to bring it close to zero from its negative value before transition). Applying this scheme should provide enough margin to stably accelerate all the future LHC beams.
The LHC 25 ns beams are presently observed to become horizontally unstable at flat top

(26 GeV/c), if they stay in the machine long enough with a reduced bunch length. The origin of this instability could be electron cloud, which is measured in the PS with a dedicated set up during the same part of the cycle. This is a potential limitation for future LHC-type beams and could require either a transverse feedback system with a wider band than the one presently being commissioned or machine coating. All the necessary studies to assess its nature and impact need to be carried out before LS1.
The transverse damper is presently being commissioned (horizontal plane, fixed frequency). So far, MDs have shown that it can cope with both damping injection oscillations and, at least to some extent, with the transverse instability at flat top discussed in the previous paragraph. Testing its efficiency against all types of known PS instabilities before LS1 is desirable to define its present capabilities as well as the specifications of new hardware for the post-LS2 era.
At the same time, a measurement campaign with the goal of identifying the impedance sources responsible for these instabilities is also ongoing in order to act on the front of possibly reducing the source of instability beside damping its effect.
In the longitudinal plane, the efficiency of feeback against coupled bunch instabilities has been tested in MDs but quite some work is still left to be done. The present coupled bunch feedback acts on 10 MHz cavities C86/96, but the use of the spare cavity C10-11 is also envisaged as feedback kicker. The ideal period to carry out this test would be beginning of 2013, when the coupled bunch feedback will no longer be required for the production of high intensity LHC physics beams. A dedicated broadband longitudinal feedback system using a Finemet® resonator is then planned for installation during LS1. Concerning the 1-turn delay feedback against transient beam loading, successful prototype tests for the 10 MHz cavities have already finished and the expected reduction of cavity impedance has been observed with beam on one 10 MHz cavity. To use the same electronics board on at least one of the high frequency cavities, its frequency range needs to be extended. This relies on the installation of an additional modulator/demodulator module, which should become available as a prototype soon. Tests will then be carried out, so that the applicability of this scheme will be assessed before LS1 also for the high frequnecy cavities.
Two alternative production schemes for LHC beams have been tested in the PS this year. Both are based on the transfer of eight bunches (4+4) from the PSB into the PS on h=9, profiting from the brightness of all four PSB rings during both injections. Then they evolve according to the following RF manipulations:

- At flat bottom, batch compression h=9 → 10, double splitting h=10 → 20, compression h=20 → 21. Then ramp to 26 GeV/c and one or two double splittings leading to either 32 bunches of 50 ns beam or 64 bunches of 25 ns beam.

- At flat bottom, batch compression h=9 → 10 → 11 → 12 → 13 → 14, merging h=14 → 7, triple splitting h=7 → 21. Then ramp to 26 GeV/c and one or two double splittings leading to either 24 bunches of 50 ns beam or 48 bunches of 25 ns beam.

The idea of these schemes is to increase the brightness of the final bunches by splitting each PSB bunch in fewer LHC-type bunches. In the nominal scheme, one PSB bunch gets split into 6× 50 ns bunches and 12× 25 ns bunches in the traditional production schemes, whereas it becomes 4× 50 ns bunches and 8× 25 ns bunches with the first scheme and 3×

50 ns bunches and 6× 25 ns bunches with the second scheme. Due to the linear dependence of the transverse emittance on the intensity extracted from the PSB, final bunches of the same intensity can be produced with transverse emittances that are only 2/3 or even half the value of those achievable with the traditional scheme. Obviously, the increased efficiency of the splitting comes at the expense of the final train length. In MDs 50 ns beams have been already produced at the PS using both production schemes and they have been transfered to the SPS/LHC resulting, as expected, in brighter bunch trains. 25 ns beams have not yet been produced in either of these schemes. Finally, to fully benefit from the increased efficiency, the low energy RF manipulations will need to be carried out and will be tested at energies larger than 1.4 GeV. Beside alleviating space charge effects, this would also remove the limitation in the bucket acceptance during the compression h=20 → 21, which is the current bottleneck of the gymnastics, and allow bunches with larger longitudinal emittances, and therefore smaller transverse emittances, to be injected from the PSB.

2.3 SPS

Several MD sessions have been devoted in 2012 to improving the PS-SPS transfer in order to reduce the capture losses. These studies have also shown bunches with larger longitudinal emittance can be injected into the SPS by increasing the voltage for the PS bunch rotation. Systematic simulation studies, using the voltage of either the spare 40 MHz or the spare 80 MHz cavity, were used to determine the optimal bunch rotation timings for each case. Measurements using one batch of 50 ns LHC-type beam confirmed the timings and the transmission gain. In particular, using the spare 40 MHz cavity (not needed in operation) results in better transmission, shorter bunches, and can conserve the transmission with the operational settings with either 40% larger emittance or 15% higher intensity. This could provide the necessary emittance margin to stabilise the beam longitudinally at flat bottom for higher intensities with the nominal optics. In Q20 optics the new settings are also expected to be efficient, since the flat bottom voltage can be increased to capture larger emittance beams, which might then be accelerated without controlled longitudinal emittance blow up. The new rotation settings still need to be tested under operational conditions, i.e. with four batches from the PS. To use the spare cavity operationally, new, standard-type power supplies are desirable for increased operational availability.
The major development underway at the SPS in 2012 is the deployment of the Q20 optics for LHC-type beams and the transition to make it operational for LHC filling. The advantages of this optics are the increased instability thresholds for Transverse Mode Coupling Instability (TMCI), Electron Cloud Instability (ECI) and longitudinal single and coupled-bunch instabilities. Space charge and IBS effects should also be eased by the larger dispersion function associated to this optics. It is especially important that the threshold for the longitudinal coupled bunch instability is significantly increased at injection energy, because it is already at the limit for the 50 ns beams with the present intensities (1.7×10^{11} ppb) and the nominal optics, and the only margin left to improve the situation relies on the possibility to inject bunches with larger longitudinal emittance from the PS. Longitudinal instabilities along the ramp can be avoided with longitudinal emittance blow up, which is only required for higher intensities on the Q20 optics (for both 25 and 50 ns beams). The drawback of Q20 is the higher voltage needed to maintain the same bucket area. As the RF voltage is

currently limited to 7.5 MV, the longitudinal emittance injected into the LHC is lower for the same bunch length. Injection into LHC was proved to be successful with different bunch lengths: (i) short bunches of 1.45 ns created no instability at injection, however, the bunch length growth rate on the LHC flat bottom was larger than usual; (ii) long bunches of 1.70 ns showed no increase of losses on the TDI compared to short bunches, which indicates that capture losses are not a limitation; (iii) intermediate bunches of 1.65 ns exhibited the usual bunch length growth at flat bottom. In all cases, the transverse emittance measured at injection was the same as for Q26. It is planned to start injecting Q20 beams operationally into LHC after the LHC technical stop in the third week of September. Several machine studies are still left to be done with Q20 at the SPS, like measurements of tails at the SPS flat top and transverse emittance before the LHC ramp, set up of the 25 ns beams and space charge studies with high intensity single bunches.
A remarkable progress has been made in 2012 with electron cloud studies in the SPS. Thanks also to five days of dedicated scrubbing run, a series of systematic studies could be undertaken early this year and then followed up during the next MD sessions with 25 ns beams. Presently, no visible electron cloud effect (e.g. large pressure rise, beam instability, positive tune shift along the bunch train, transverse emittance growth) can be detected for the nominal 25 ns beam. The dynamic pressure rise is now four orders of magnitude lower than that observed during first operation of the SPS with 25 ns beams and, at least in 5/6 of the machine, it exhibits a closer correlation to beam losses than to electron cloud. The electron cloud can be revived in terms of pressure rise by either injecting the ultimate intensity 25 ns beam or radially displacing the nominal 25 ns beam. This could be explained by the fact that the electron cloud stripes move to un-scrubbed regions of the chamber wall in either case. The transverse emittance of the nominal 25 ns beams is also found not to be blown up along the trains, nor over a 20 sec long injection plateau. Transverse emittance measurements at top energy also suggest that there is no significant emittance blow up along the typical LHC production cycle for nominal 25 ns beams, although bunch-by-bunch measurements at this point of the cycle do not seem to be obvious with the present range of device settings that can be used. Beside all these direct beam observations, which are related to the integrated effect of the electron cloud in the SPS, dedicated electron cloud measurements have been carried out using the strip detectors installed in MBA and MBB-type chambers. Consistently with simulations, the results show that: (i) the electron cloud is quickly suppressed in MBA chambers with 50 ns beams by scrubbing with 25 ns beams; (ii) Cu produces in general less electron cloud and scrubs faster than stainless steel; (iii) a bunch intensity as low as 3e10 ppb is the threshold for electron cloud build up; (iv) the stripes move outwards and the central region gets depleted of electrons when the bunch current increases. Complementary direct electron cloud measurements were made with microwave transmission and using the signal from a shielded pick-up. The origin of the dynamic pressure rise in a-C coated chambers was investigated with a dedicated setup having two solenoids independently powered on a coated drift chamber and on the StSt peripheral regions. The pressure rise was found to decrease with the external solenoids on, while it did not change when the solenoid on the coated chamber was powered. This proved directly that electron cloud build up is suppressed in coated beam chambers. A few studies still remain to be done this year, like (i) vacuum conditioning with ultimate intensity; (ii) 25 ns beams coasted at 26 GeV/c to reveal possible residual incoherent effects; (iii) continue monitoring the scrubbing in the electron

cloud detectors. Since the conditioned status of the SPS seems to be the result of several years of scrubbing, it is critical to foresee a procedure for the interventions during LS1, such as to best preserve the vacuum in the machine. In any case, a scrubbing run for the SPS with a long flat bottom cycle should be scheduled in the time between the SPS and the LHC start-up in 2014. Its success will give a clear indication on how far we will be able to rely on scrubbing also for future operation with brighter LIU and HL-LHC beams, or we will need to coat a large fraction of the machine.

The longitudinal beam quality and stability has been the object of four dedicated MD sessions in 2012. First studies on the LHC 50 ns beams with nominal optics were triggered by recurrent BQM rejection issues during the LHC filling. It was found that, for injected intensities of 1.6e11 ppb, the beams were longitudinally unstable at flat bottom. Therefore the four batches, sitting at flat bottom for different time durations, had different longitudinal emittances on the ramp and reacted differently to the controlled longitudinal emittance blow up. With increased blow-up in the PS and removing the dips at each injection for the voltage program, a more uniform beam could be accelerated and extracted. The second MD session was devoted to probing the longitudinal impedance of the SPS. Long single bunches with small momentum spread were injected into the SPS with the RF off. From the bunch spectrum evolution during de-bunching, a clear 1.4 GHz component could be observed to rise faster than (and uncorrelated with) the 200 MHz one. This was seen also before in 2001 and 2007. The origin of this line should be investigated. The third dedicated MD was used to determine the single bunch instability thresholds with single RF. At flat top it was found that the single bunch grows unstable for intensities above 1.5e11 ppb for Q20 and above 1.0e11 ppb for Q26. For nominal intensity (i.e. 1.1e11 ppb) and with the phase loop on, the beam was also unstable at flat bottom with settings of both 2 and 3 MV on the 200 MHz RF system. The beam could be kept stable with 1 MV, but this value is of no operational use, because of beam loading and also because injection in higher voltage results in more emittance blow-up and, hence, more stable beam at flat top. The flat bottom instability threshold for Q26 was seen between 1.5e11 and 1.8e11 ppb. The flat bottom thresholds for single and multiple bunches are similar, but at flat top the threshold becomes much lower in the multi-bunch case. This is due to the beam-loading effect of the 800 MHz RF, which is more significant for short bunches. The phase of the 800 MHz RF is planned to be reprogrammed, with the control of feedforward and feedback, which is necessary for this and should be operational after LS1. The fourth MD session concentrated on 50 ns beams with Q20. It was observed that with a bunch intensity of 1.6e11 ppb, some bunches exhibited dipole or quadrupole oscillations at flat top without controlled emittance blow-up along the ramp. With blow-up, the beam is kept stable throughout the cycle, although the bunch length at flat top is increased with a growing trend along the bunch train, which is not yet understood. Future MDs will be necessary to study in detail: (i) high-intensity behaviour of 25 ns and 50 ns beams in Q20; (ii) single and multi-bunch instability thresholds with Q26; (iii) quadrupole frequency and stable phase shift to estimate the impedance before LS1. Simulations will be used to find a good SPS impedance model to reproduce the single bunch thresholds. Requirements for the 800 MHz system are: (i) possibly a second 800 MHz cavity (ii) FB and FF for phase and voltage control and (iii) phase calibration.

Transverse impedance measurements at the SPS usually rely on global estimations from tune shift with intensity or more refined localization techniques based on the turn-by-turn BPM

data (with both Q20 and Q26 optics). Unfortunately, the latter measurements have suffered this year from unavailability of the adequate instrumentation (i.e. reliability of the turn-by-turn MOPOS readings over a sufficiently high number of turns). The issue is presently under investigation from BI. Besides, the evaluation of the transverse impedance based on single bunch instability studies would strongly benefit from the possibility to resolve the intra-bunch motion through the head-tail monitor, which is also presently unusable.
The development of a high bandwidth transverse feedback system is following a plan of staged implementation, as follows. In phase 1, as a proof-of-principle experiment, the intra-bunch motion of a single bunch will be damped using the existing equipment. In phase 2, after LS1, a new system should be installed including new pick-up and kicker, which will be capable of stabilizing an LHC-type bunch train at injection energy. This year, the synchronised excitation signal resulting in the excitation of different headtail modes on a single bunch has been already studied. More MD slots are needed before the end of the run to continue excitation studies and also test the new hardware that will be shipped in November by the LARP collaborators. Additional MD next year would be of great help to perform extended demonstrator tests and define the prototype specifications.

3 Final remarks

3.1 Wrap up

Are we collecting the necessary information to estimate the future LHC-type beam characteristics?
Both high intensity 50 ns beams and the nominal 25 ns beams, possible candidates to be requested by LHC after LS1, have been already available from the injectors in 2012. The ultimate 25 ns beam, which seems to be already produced almost within specifications in both the PSB and PS, still needs to be successfully accelerated in the SPS, as it is presently still limited by RF power, electron cloud, slow losses and degassing. Furthermore, two alternative production schemes in the PS have been developed and fully tested to provide shorter trains of even brighter beams already at this stage. To predict the performance of the injectors after LS2, it seems that several questions still need to be answered. Full simulations of the H^- injection at 160 MeV into the PSB have to be set up to determine realistic curves of transverse emittance versus intensity and fully justify the usual assumption that the brightness of the beams will be increased by a factor two. The PSB machine studies necessary to set up these simulations (i.e., those leading to a benchmarked nonlinear optics model of the PSB at 160 MeV) are still missing, even if an effort has been undertaken to describe the machine at 160 MeV in strong space charge regime. Similarly, space charge studies in the PS have not yet reached the maturity to create a model for reliable prediction in the future regimes. Suppression of the different types of instabilities and feedback studies (both transverse and longitudinal) in the PS are promising for LIU and HL-LHC beams. The limitations of the SPS also seem to be quite well understood and a large amount of work is being put in developing strategies and solutions to overcome them (Q20, larger longitudinal emittances, electron cloud suppression through scrubbing or coating, impedance identification and reduction). It is now clear that the SPS can rely on beam based scrubbing in order to stably run with nominal 25 ns beams, although it has to be fully clarified how

much net beam time it needs to reach this state and whether the same will apply to higher intensity beams, too. Some indications for the second point can still be given by ultimate intensity MDs in 2012, while the efficiency of scrubbing can only be fully assessed during the start up after LS1. In any case, the back up solution of coating with a-C (or inserting a-C coated liners in) at least a part of the machine remains still valid.

Which studies will still require more information and significant MD time before LS1?
A list of studies that need to be carried out in the second part of the 2012 run has been clearly identified:

- PSB: Space charge measurements (scan of working point); final Finemet® cavity tests; deployment of the Digital LLRF control system including synchronization with the PS (more than one ring? high intensity beams?); resonance driving term analysis based on turn-by-turn BPM measurements and using different working points to change the phase advance between BPMs and improve the resolution of the method; study of the transverse instabilities and damper capability.

- PS: Space charge studies at 1.4 GeV (scan of working point in extreme space charge conditions); resonance driving terms based on turn-by-turn data to set up compensation schemes; test of new optics with larger dispersion; tests of efficiency of the present transverse feedback system against the known instabilities to determine specifications for the post-LS1 era; use of the spare cavity C10-11 as kicker for the longitudinal feedback system; full validation of the 10 MHz prototype for the 1-turn delay feedback, possible modulator/demodulator tests if the prototype hardware becomes available by the end of the run; production of 25 ns beams with alternative productions schemes; RF manipulations for alternative schemes at 2 GeV.

- SPS: PS-SPS transmission studies with the spare 40 MHz cavity; measurements of tails and transverse emittance for Q20 beams; set up of the Q20 25 ns beams; space charge studies with high-intensity single-bunches with Q20; vacuum conditioning with 25 ns ultimate intensity; 26 GeV/c coasting with 25 ns beams for electron cloud incoherent effects; scrubbing evolution in the electron cloud detectors; transverse impedance localization studies in Q20 and Q26; high-intensity longitudinal quality of 25 ns and 50 ns beams in Q20; single and multi-bunch instability thresholds with Q26; quadrupole frequency and stable phase shift to estimate longitudinal impedance; demonstrator studies for the high bandwidth transverse damper with the new hardware.

Is any study presently limited by instrumentation or diagnostics? Is any improvement possible before LS1?
A few issues deriving from beam instrumentation and diagnostics were highlighted during this review: 1) The availability of multi-BPM turn-by-turn data in the PSB and in the SPS, which would be important for both optics and impedance localization studies; 2) The reproducibility of the transverse emittance measurements in the PS; 3) The extension of the bunch-by-bunch capability of the SPS wire scanners at top energy (profitable also for the PS), to fully characterize the LHC beams prior to extraction to LHC (it is important to extend also the intensity range at top energy to enable measurements of transverse emittances

for ultimate 25 ns beams without damaging the wires — here a possible alternative would also be reviving the SPS Synchrotron Radiation monitor); 4) The head-tail monitor in the SPS, to resolve intra-bunch unstable motion needed for impedance studies based on the instability patterns; 5) Reliable reconstruction of the emittances from the OTRs in TT2/TT10 would be desirable to determine the beam quality at the PS extraction, especially in view of a possible change of the extraction bump. The upgrade of the instrumentation to suit the specifications of the new LIU and HL-LHC beams as well as the users requirements is under discussion in the LIU-PSB, -PS and -SPS groups.

Is any study strongly relying on the installation and test of new hardware before LS1?
The studies that need hardware installation/repair before LS1 are: turn-by-turn measurements in the PSB, modulator/demodulator tests for the 1-turn delay feedback in the PS, PS-SPS transmission studies (relying on the repair of the spare 40 MHz cavity to be continued), high bandwidth feedback studies in the SPS, SPS impedance/instability studies (which would benefit from re-programming of the 800 MHz phase)

How can we optimize the use of the remaining available MD time? Do we need to request for more?
The floating 24-hours MD blocks until the end of 2012 will be re-distributed and split into shorter blocks of 10-12 hours, taking place exclusively during day time and almost every week. The parallel MDs will also continue in all machines with the same organization for the time sharing as is done presently.

Which MD activities would benefit from additional MD time in 2013?
There are strong requests from some of the MD users to have a chance to extend the MD run into 2013. In particular, the following studies could benefit from additional MD time in 2013:

- PSB: Deployment of the Digital LLRF control system (it will be operational after LS1 and it would be good to test synchronization to PS already before LS1); resonance driving term analysis with turn-by-turn data from three BPMs (studies with different working points); new instability measurements with detailed study of the effect of feedback and working point.

- PS: Tests of C10-11 as longitudinal feedback kicker (it is better to make them when the coupled bunch feedback system is not used for the production of high intensity beams for the LHC); full validation of the 1-turn delay feedback prototype with beam and modulator/demodulator tests (depending on new hardware); new injection optics tests, which needs dedicated MD time.

- SPS: High bandwidth transverse damper studies for damping a single bunch TMCI (relying on new electronics to be installed in November to close the feedback loop); longitudinal and transverse impedance studies with Q26 (to be done before LS1, as long as Q26 is still available in the SPS for LHC-type beams); PS-SPS transmission studies with the spare 40 MHz cavity (it might become again available only in 2013); space charge studies at flat bottom.

3.2 Recommendations from the reviewers

The external reviewers generally congratulated on the impressive amount of work ongoing for all the accelerators of the LHC injector chain and also observed that presently the PS and the SPS appear to have more resources allocated for machine studies than the PSB. Their suggestions are enclosed hereafter. The experimental program proposed for the rest of the run is mainly consistent with the given recommendations.

- Space charge studies in the PSB: The experimental activity should cover a more systematic analysis of working points in terms of stop-band and emittance growth. This is essential for understanding the high intensity effects in the PSB. Measurements of emittance growth seem to need further refinement (those for the integer crossing are affected by large error-bars, while those for the Montague resonance are mixed with the effect of skew gradient error). The benchmark with simulations is found to depend on the random error strength, which should mainly influence the width of the stop band, instead. In fact, the stop band itself is not at the moment the focus of the experimental studies and the nonlinear model relies on the attempt of modeling the emittance growth. It is necessary to perform further experimental studies to better model the integer resonance and check the schemes of resonance compensation.
  It is also recommended to perform detailed simulations of the future H^- injection at 160 MeV and painting schemes, instead of naively assuming that this will just be able to increase the brightness of the LHC beams by a factor two from the improved space charge tune spread at injection.

- Space charge studies in the PS: In general, it is stated that the maximum acceptable tune spread at injection is 0.3, but it is not explained what limits it to this value. Experimental tests pushing this limit further are not shown and the sources of the limitations are not identified (in particular, which resonance? Is it only the integer or are there other resonances?). Benchmarking of simulations with the measurements made is still at a very early stage of development. A new magnet model with error distribution is being prepared and therefore no simulations at low intensity show whether the numerical prediction is consistent with tune scan. In the study presented, the integer resonance is still relatively unknown, in the sense that there is no clear set of measurements that allows having a quantitative modeling of the stop-band. By changing the optics to reduce the space charge tune-spread, it is not clear how the excitation of the integer would correspondingly change. It is important, as a first step, to verify that the lattice model allows the reproduction of the resonances and their stop-band. For instance, the resonance 2Qh+Qv=1 is extremely strong and needs to be explained and mitigated. A resonance driving term study could be helpful to correctly model the relevant resonances.

- Electron cloud in the SPS: All the studies on electron cloud presently ongoing at the SPS do not seem to be able to answer yet the question whether the SPS can rely on scrubbing alone for future operation, or it needs coating.

- Transverse feedback system: Since one of the main limitations of PSB, PS and SPS is the beam coherent stability and one of the main tools to suppress beam instabilities is

a damper, it is important to distinguish between instability and injection dampers. Although both are still dampers, they serve different purposes and could be also designed and installed separately in order to be independently optimized in their functions. For best operation, any instability damper has to be analyzed within the framework of the beam stability theory, in a global picture that also includes impedance, coupled-bunch interaction, chromaticity and Landau damping. Without this analysis, any damper design is blind, as are also its MD study and use. Beam physics has to specify the required gain and frequency profile, the level of noise, and the optimal chromaticity for the damper, assuming some desired beam current and existing impedances.

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