# NECESSARY LIU STUDIES IN THE INJECTORS DURING 2012

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*Abstract*

A significant fraction of the Machine Development (MD) time in the LHC injectors in 2011 was devoted to the study of the intensity limitations in the injectors (e.g. space charge effects in PS and SPS, electron cloud effects in the PS and SPS, single bunch and multi-bunch instabilities in PS and SPS, emittance preservation across the injector chain, etc.). The main results achieved in 2011 are presented as well as the questions that still remain unresolved and are of relevance for the LHC Iinjector Upgrade (LIU) project. 2012 MDs will also continue exploring the potential of scenarios that might become operational in the future, like the development of a low gamma transition optics in the SPS or alternative production schemes for the LHC beams in the PS. A tentative prioritized list of studies is provided.

## INTRODUCTION ON MD'S IN THE INJECTOR COMPLEX

In 2011 there were 408 hours for dedicated machine studies in the LHC injectors. These hours were distributed in the following manner:

- Ten so-called floating MD blocks of 24 hours, which took place with a biweekly frequency from May to November. During these sessions MDs have priority over physics in all the machines of the injector chain, except when the beam is requested by LHC. Typically, fixed target physics in the SPS is stopped during these days and a full SPS-MD supercycle is played, while the beam is not being injected into LHC. In the PSB/PS, the required beams are still provided to the physics users, compatibly with the MD requests in these machines. The overall efficiency of these MD blocks is about 50%. They are called "floating", because, although their starting time is usually fixed to 08:00 am, it may actually shift due to the LHC status and requests.

- Four long fully dedicated sessions, which took place in parallel with the LHC Technical Stops. In practice, the time used for the LHC Technical Stops was always shared between injector MDs, injector Technical Stops and dedicated sessions for UA9 physics runs. The MD hours during these fully dedicated blocks are in general very efficient due to the absence of concurrent physics requests (including those from LHC).

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Besides the dedicated MDs, parallel MDs could also be performed in all the machines throughout the year. The supercycle played usually guarantees the presence of at least one parallel MD cycle during the week days and working hours. In addition, PS-Booster and PS also have at least one cycle per supercycle reserved for their MDs at all times. The parallel MD cycles can be sometimes taken for beam set up and MTE studies (PS).

## MACHINE STUDIES IN THE LHC INJECTOR CHAIN IN 2011

The program of the machine studies in 2011 was very dense. The general planning and a list of requests were presented at the Machine Studies Working Group meeting in order to finalize logistics and organization [1]. A large fraction of the studies performed in 2011 were related to the LIU project, as is discussed in the following subsections.

### *Linac2 and PS-Booster*

There were only two Linac2 MDs in 2011, and only the second one with a potential impact on the performance of the downstream machines in terms of LHC beam brightness.

(a) **3 February, 2011**: Correction of a new hot spot found during the 2010 Linac2 radiation survey..

(b) **3 October, 2011**: High current from Linac2 (180mA). The decrease in transverse emittance at the Booster extraction was measured for Linac2 high intensity settings, after adjusting the number of injected turns such as to have the same amount of beam at the entrance of the PSB. It was found that an increase of the Linac2 current by 6.7% can only result into a decrease between 0.7% (FWS) or 3.2% (SEM) in the sum emittance (horizontal plus vertical), averaged over 3 measurements, for the same extracted current.

Frequently, MDs in the PSB had to be oriented to the production of new beams requested by the downstream machines for either physics or their MDs, as well as to the optimization and fine tuning of the existing operational beams. Only few MD sessions took place for the improvement of the machine performance or for specific LIU studies. In particular, it can be mentioned that significant progress was achieved with the deployment of the digital RF control system [2]. Besides, during the last week of beam operation, several tune scans for different beam intensities were run over the flat top at 160 MeV of a special MD cycle, with the goal to identify the resonance lines at this beam energy. Unlike few years ago, when this type of measurement was first attempted at the PSB, this time the scans were automatized through a newly developed application and dynamically executed. Probably due to the small transverse emittances at low intensities and the speed at which the scans were run, the results from this measurement campaign cannot yet be considered conclusive and the scans will have to be repeated during the 2012 operation run.

## *PS*

Most of the MD activities in the PS in 2011 were either LIU driven or with a strong impact on the LIU studies. A non-exhaustive list of the main MDs is given in the following, inlcuding some short descriptions of the main achievements.

- Space charge studies at 1.4 and 2 GeV. The tune diagrams showing the excited resonance lines and their stop-bands were obtained by measuring the beam losses as a function of the measured working point for beams with low intensity and large transverse emittances. These diagrams were produced at both 1.4 and 2 GeV. This should in principle allow for identification of the best resonance free spot in the tune plane for the ideal placement of the working point at injection (also for the future injection energy). It should also indicate which are the most dangerous resonance lines, which might require the development of compensation schemes. During a campaign for the optimization of the working point at 2 GeV, the three working points illustrated in Fig. 1 were studied in a strongly space-charge dominated regime [3]. The calculated tune spreads (see Ref. [4] for the used formula) are also shown in the same picture. It is obvious that the tune spread neckties extend over integer tunes in all three cases. However, the experiment showed that, while the two blue points in the picture allowed keeping the beam on a long flat 2 GeV plateau without significant losses nor emittance growth, the red point was associated to strong losses and deformation of the longitudinal profile. Simulations with a detailed optics model of the PS are needed to explain this behaviour. From simulations we also expect to understand why neither emittance blow up of the beam core nor beam losses are observed when the calculated space charge necktie stretches over integer tunes. In fact, this might suggest that either the applied formula is overestimating the tune spread (e.g., due to real distributions, which might actually differ from the ideal Gaussian ones assumed in the theory) or the effect of the periodic crossing of an integer resonance due to space charge is actually less detrimental than it is believed to be.

- Adjustment of the working point at low energy with quads and PFW

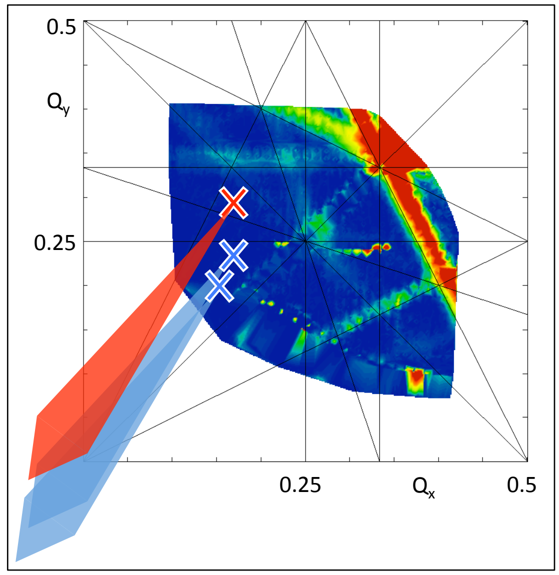


Figure 1: Measured tune diagram for the PS at 2 GeV (courtesy E. Benedetto). The working points studied in MDs are also shown, with the respective tune spread neckties.

- Fast instability at transition with TOF-like beams. Lots of studies were conducted in 2011 to pin down the thresholds of the fast instability at transition (both in terms of bunch intensity and longitudinal emittance) and find ways to extend the stability limits. It was found that the best strategy to keep the beam stable over transition up to high brilliance is to have an accurate control of chromaticity during the gamma jump, such as to keep it negative before transition and make it switch to a slightly positive value after transition crossing [5, 6]

- Tune shift with intensity at injection and extraction energy.to quantify the imaginary part of the impedance.

- Electron cloud at flat top with 25 and 50ns beams. Measurements of this type were already conducted in earlier years, testing the efficiency of the clearing electrode with and without external magnetic field [7]. Using the same set-up, several electron cloud build up measurements were taken in 2011 at the PS for 25 and 50ns beams, different intensities and three different values of bunch length. Two examples of these measurements are displayed in Fig. 2. Simulations are presently underway to benchmark these measurements and qualify the seconday electron yield of the PS beam chamber.

- Limitations from longitudinal coupled bunch instabilities (CBI). In the PS, longitudinal CBI are observed with 25 and 50ns beams (previously also with 75 and 150ns beams) during the ramp and flat top when ramping down the h=21 RF system during bunch splitting. A few lessons have been learnt with the 2011 machine studies. In particular, the instabilities during the ramp

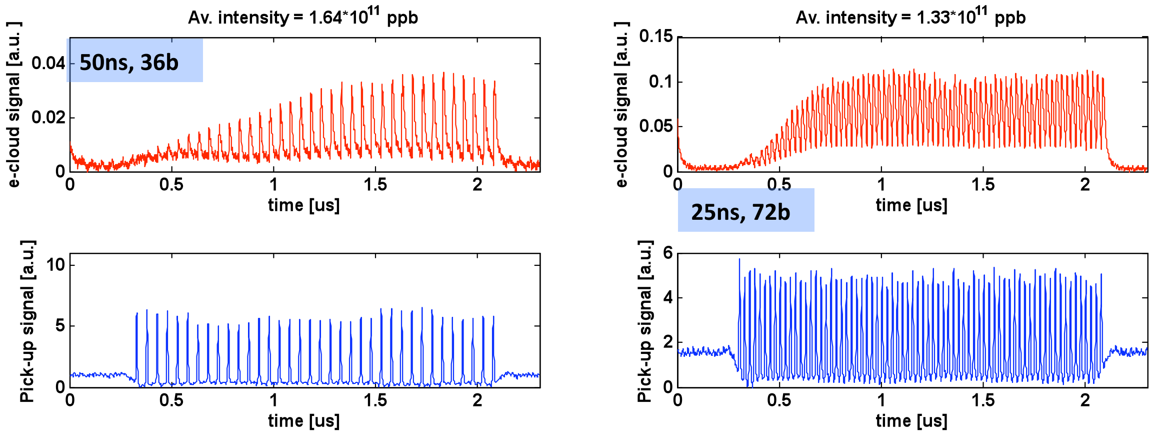


Figure 2: Electron cloud measurements with 50ns (left) and 25ns beams (right) and intensities per bunch higher than nominal (courtesy G. Iadarola and C. Yin-Vallgren).

are probably caused by the wide band impedance of the 10MHz cavities and the coupled bunch mode spectrum changes between ramp and flat top. The CBI have been found to hardly depend on the number of bunches in the batch, while the growth rates scale like $N_b/\epsilon_z$. In terms of curing this effect, a small improvement was observed with 2 gap relays, as well as the parking of the unused cavities has proved beneficial [8]

- Batch compression scheme h=9→10→20→21. First tests were made in 2011 to have bunch compression plus splitting at flat bottom but, due to RF hardware limitations, this beam could not be accelerated and extracted to the SPS. More details on this scheme and the achievements in 2011 can be found in Ref. [4]

- Longitudinal feedback studies against CBI and transient beam loading.

### *SPS*

In the SPS about 38% of the overall time for dedicated machine studies (and an even larger fraction of the parallel MD time) was spent on activities in the frame of the LIU project. The principal studies were:

- Define the SPS limitations in different regimes by pushing the performance. Studies were carried out with the present 25 and 50ns beams, as well as with single intense bunches (up to $4 \times 10^{11}$ ppb injected into the SPS) [9]

- Develop and optimize the low gamma transition optics (Q20) [10]. The most outstanding results will be recollected in detail in the following.

- Test the efficiency of electron cloud mitigation techniques (a-C coating, scrubbing, clearing electrodes). In particular, the efficiency of the clearing electrode with magnetic fields up to the nominal injection value was proven with a dedicated scan. The a-C coating was again tested both in the old liner (sample installed in the SPS in 2008, which still does not exhibit signs of aging) and in a one-sided new installation. The latter was found not to be able to completely suppress the electron cloud formation [12]

- Run beam tests for a high bandwidth feedback system [11]. In 2011, several excitation tests in open loop were run at the SPS during a few MD sessions that took place in August and November. The beam response was measured with an exponential strip-line pick up. By sweeping the excitation frequency close to the betatron tune, different coherent modes (azimuthal and radial) could be excited. Both cases with excitation of the main dipole mode of the bunch and differential head-tail modes could be distinctly observed. Measurements were taken with different settings of chromaticity and different intensities.

The single bunch performance of the SPS in 2011 with both Q20 and nominal optics was one of the hot topics for MDs. First of all, it could be clearly seen that, for very well corrected chromaticity, the Transverse Mode Coupling Instability (TMCI) causes a steep loss right at injection for intensities above $1.7 \times 10^{11}$ ppb in nominal optics, while it has not yet been encountered in the Q20 optics with the presently injected intensities (i.e., up to $3.8 \times 10^{11}$ ppb). This is consistent with the anticipated increase of the TMCI threshold by about a factor 2.2, due to the increase of the slippage factor at injection (2.8) at the expense of a slightly larger beta functions (1.3) with Q20 compared with the nominal optics. Higher chromaticity settings can be used to increase the TMCI threshold with the nominal optics and reduce the losses at injection with higher intensities. Figure 3 shows the vertical emittance measured after acceleration to 450 GeV/c as a function of the extracted intensity (chromaticity $\xi_y = 0.25$ over the cycle). The points are color coded according to the amount of loss along the cycle. We can see that intensities up to $2.5\times10^{11}$ ppb can be extracted from the SPS with about 10-15% losses. The transverse emittance measurements at the PS extraction for the same cycles, also plotted in the figure, show that for these intensities there is little emittance growth in the SPS. However, a hard limit (perhaps the TMCI threshold for the current chromaticity value) seems to be hit at an extracted bunch intensity of about $2.5 \times 10^{11}$ ppb, because any additional intensity injected into the SPS just results into a larger net loss and significant emittance blow up.

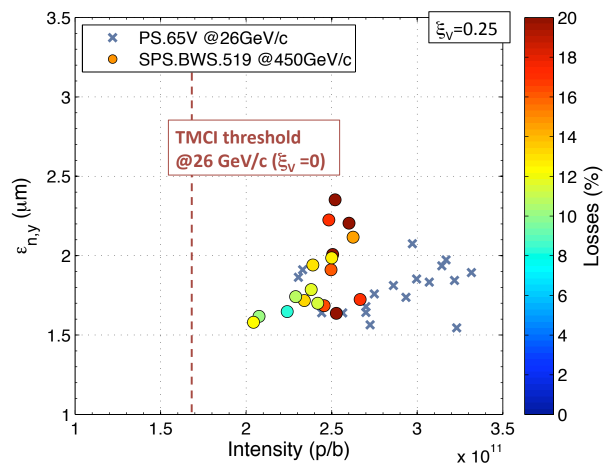


Figure 3: Vertical emittance versus intensity at the SPS extraction for a single bunch in nominal optics. The losses over the cycle can also be read from the color coding.

The situation looks certainly much better with Q20, even with a lower chromaticity setting ($\xi_y = 0.1$). Figure 4 shows that single bunches with intensities below $2.5 \times 10^{11}$ ppb can be extracted with basically negligible losses over the cycle. Losses still remain below 10% even for larger injected intensities. The vertical emittance measured at top energy can be fitted as a linear function of the extracted intensity, which raises the question whether the observed linear behaviour is produced in the SPS or reflects a trend from the injectors. During these measurements the single bunch was taken on a magnetic cycle with 10.8 sec flat bottom and ramp to 450 GeV/c. Therefore, a possible emittance growth could occur along the long flat bottom or during the ramp.

A hint for a possible answer to the above question is given by the plots displayed in Fig. 5, although they refer to measurements taken on different days. Here, in the same running conditions as for the previous plot (i.e. single bunch, same optics, same working point), vertical emittance measurements were run at the end of a short 3 sec flat bottom and the corresponding measurements at the PSB or PS extraction are also included. It seems evident that for intensities between 2 and $3 \times 10^{11}$ ppb losses start appearing (but only up to 5%) and an emittance growth becomes noticeable when we compare the SPS values with those measured in the injectors. The linear fit from the measurements at flat top of Fig. 4 provides a guess of what emittance we

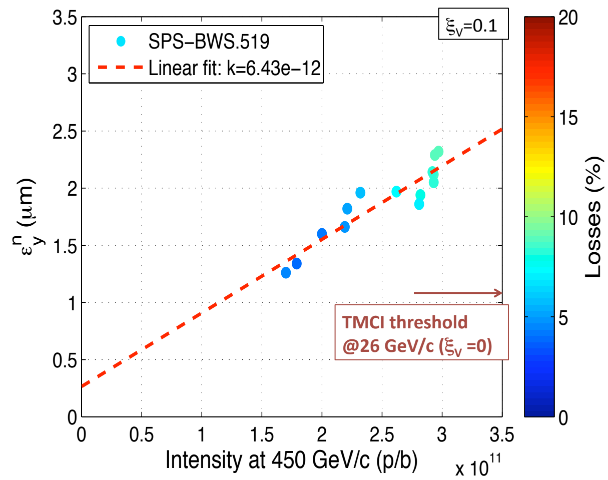


Figure 4: Vertical emittance versus intensity at the SPS extraction for a single bunch in low gamma transition (Q20) optics. The losses over the cycle can also be read from the color coding.

would have measured at the flat top of a long cycle also for these beams. Therefore, if we then include the fitting line in the picture, we will notice that in the range of intensities above $1.8 \times 10^{11}$ ppb, there is actually an emittance blow up over the long cycle, and most of it must take place during the additional 7 sec of flat bottom and ramp.

Machine studies with multi-bunch beams in Q20 optics were also carried out, especially towards the end of the run. In the last long dedicated MD session, up to four batches of both 25ns and high intensity 50ns beams were injected on the long Q20 cycle. It is worth mentioning that these beams exhibit a much better longitudinal stability in Q20 optics than with the nominal SPS optics, even in absence of controlled longitudinal emittance blow up [13]. Furthermore, four batches with intensities even slightly above $1.7 \times 10^{11}$ ppb could be extracted from the SPS with 50ns bunch spacing. This was possible thanks to the stable high intensity coming from the PS — $1.9 \times 10^{11}$ ppb — and a transmission of 90% through the full SPS cycle. This is depicted in Fig. 6, in which also the excellent performance of lower intensity 50ns beams with the Q20 optics is shown. Injecting four batches of $1.6 \times 10^{11}$ ppb from the PS, we can attain a transmission efficiency of almost 94%, with $1.5 \times 10^{11}$ ppb stably extracted from the SPS.

## PRORITIES IN 2012

Several studies have been already proposed for the 2012 run across all the machines of the injector chain, and priorities have been identified.
High priority PSB LIU MDs in 2012 include:

- Continuing the deployment of the digital RF control
- Testing the newly installed Finemet prototype cavity hardware
- Identifying the impedance source responsible for the

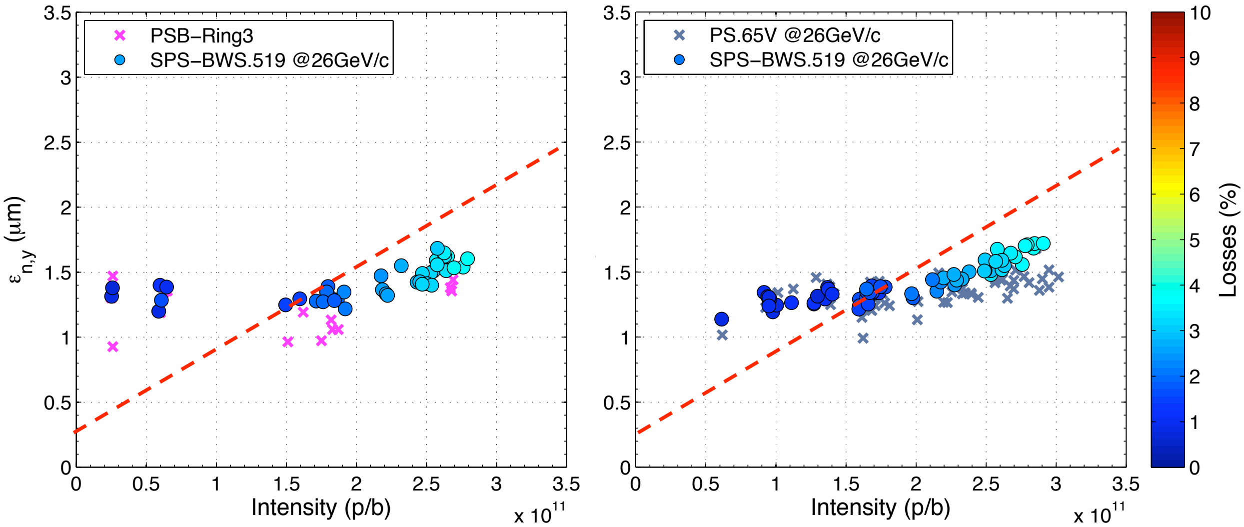


Figure 5: Vertical emittance versus intensity at the end of a 3 sec SPS flat bottom for a single bunch in low gamma transition optics. The losses over the cycle can also be read from the color coding. The emittances measured at the PSB (left) and at the PS extraction (right) are also plotted on the same graphs.

known instabilities to specify transverse damper requirements

- Determining resonance diagram with tune scans at 160 MeV to optimize placement of working point at injection with Linac4

The above list does not exhaust the machine studies envisaged in the frame of LIU-PSB in 2012. In particular, MD time should be also reserved for the optics model based on turn-by-turn data from the available BPMs (when available), the study of the efficiency of the resonance compensation schemes, and space charge induced emittance blow up. The progress on the PSB MDs in 2012 will

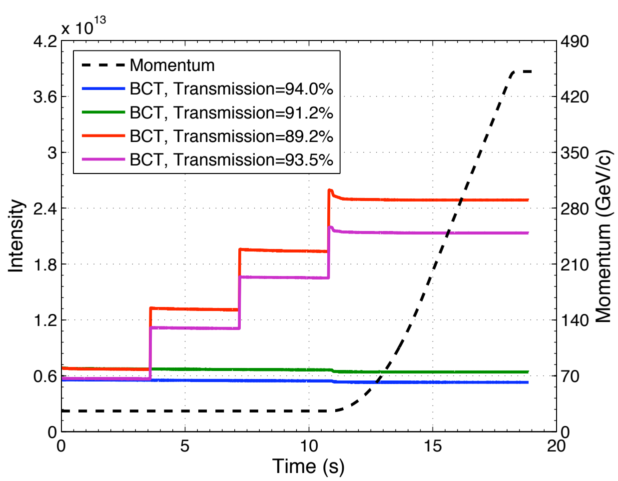


Figure 6: High intensity 50ns beam through the LHC cycle in the SPS. Sample shots with one and four batches are shown for intensities of $1.6 \times 10^{11}$ ppb and $1.9 \times 10^{11}$ ppb coming from the PS.

also strongly depend on the availability of resources to carry them out, as the lack of dedicated teams for the PSB machine development, other than the machine supervisor team, has been a limiting factor in previous years.
Top priority LIU-PS studies in 2012 will be

- Space charge limit at the PS injection. One of the key questions that need to be answered by means of machine studies is where the space charge limit of the PS lies. In other words, how large a tune spread can be tolerated at the PS injection, such as not to cause significant emittance blow up on the LIU-type LHC beams.

- Strategies to increase the longitudinal CBI thresholds. An additional feedback system will be studied and it will be decided whether more hardware is needed, to be installed during the 2013 long shutdown. Besides, PS/SPS transfer studies will also be carried on, to see whether some new settings can be found, which allow larger longitudinal emittance (more stable) to be also efficiently injected into the SPS

- Batch compression scheme h=9→10→20→21. This scheme will be in condition to be tested in the second part of 2012 with acceleration and transfer to SPS.

- Batch compression and bunch merging.

- One-turn feedback against transient beam-loading.

Though with lower priority than for the above list, many more studies are planned at the PS during 2012. These include: Electron cloud at flat top (in presence of magnetic field and with double step rotation); Commissioning of transverse feedback system; Head-tail instabilities on the flat bottom with double batch injection from the

PSB; Transverse instabilities of short intense bunches at flat top (perhaps related to electron cloud); Impedance identification for modeling; Miscellaneous injection studies (e.g. tests of low energy elements, acceleration-deceleration scheme for double batch transfer).

Based on all the results of 2011 and a few still unresolved questions, the SPS MDs in 2012 have been thus prioritized:

- Development of the Q20 optics. Several studies need to be finalized, including: Evolution of the transverse emittances along the long cycle for all types of beams (to disentangle single bunch/space charge from multi bunch effects); Optimization of the working point along the cycle to minimize transverse emittance blow up for very intense single bunches and establish the single bunch SPS space charge limit; Longitudinal stability along the cycle with and without controlled longitudinal emittance blow up for multi-bunch beams; Transfer to the LHC. To have better continuity, it would be advisable to use weekly blocks of 12 hours during the day time (to have equipment experts available) instead of biweekly blocks of 24 hours. A few more studies are also strongly encouraged, like the development of a nonlinear optics model, the use of split tunes (20, 26), and the study of the electron cloud instability threshold in this optics.
- Electron cloud experiments to answer some pending key questions. One of those is how far we can go with scrubbing and whether we will be able to rely in the future on scrubbing alone to avoid coating of the beam chambers. In 2012 a dedicated SPS scrubbing run will take place in Week 13, in which for the first time a quantitative analysis of the scrubbing process in the different SPS regions will be made by using data from the direct electron cloud strip monitors and shielded pick-ups, as well as direct beam observables (i.e. instability and emittance growth). Since it will not be possible to produce in the PS exotic beams for efficient electron cloud enhancement in the SPS (e.g. high intensity 5ns beams, beams with hybrid 10+15ns spacing), the only attempts to increase the electron cloud dose, and therefore the scrubbing efficiency, will be made with uncaptured beam and shorter bunches [14]. Other electron cloud experiments will also take place in order to understand whether, despite the pressure rise measured in past years, the electron cloud is suppressed in the dipoles with a-C coated chambers. These include the use of a-C coated chambers with solenoids and the coating of a full half-cell with pressure gauges in several locations in order to reconstruct the full dynamic pressure profile in the coated region. Another important goal of these measurements should be also to discover the driving mechanism for the pressure rise in coated magnets, which was measured in previous years (e.g. not sufficiently good quality of the coating, strong multipacting in neighbouring locations, or desorption of the a-C coating)
- Tests with increased peak RF power by using a pulsed mode of operation. This is specially relevant for Q20 optics, which may need higher RF voltage to deliver to LHC beams with a sufficienty high longitudinal emittance. These tests will be conducted, with or without beam, close to the end of the 2012 run.

Other MDs planned in 2012 are: PS-SPS Transfer optimization (together with the PS); Completion of phase (2) for the high bandwidth feedback studies — which consists of closing the feedback loop and proving the damping of the head-tail modes; More impedance identification measurements, based on tune shift and turn-by-turn data from the BPMs in the two different optics.

## CLOSING REMARKS

To conclude, a remarkable progress has been made in the PS in 2011 concerning the studies on space charge, optics at injection, longitudinal coupled bunch instabilities, electron cloud and instabilities at transition crossing. Some questions, however, need to be again addressed in 2012 to improve our understanding and define possible hardware needs before LS1, like space charge limit, cures against coupled bunch instabilities, efficiency of the batch compression schemes to deliver brighter LHC-type beams. In the SPS, most studies in 2012 will still revolve around the Q20 optics and its possible implementation for operation with LHC beams. This will require a continuous development effort, which could be eased by a different MD time distribution based on weekly block of 12 hours instead of biweekly blocks of 24 hours. A scrubbing run will also take place at the beginning of the 2012 run with the goal to quantify the scrubbing process using laboratory data and simulations and to understand whether relying solely on scrubbing can be a feasible alternative as a future electron cloud mitigation strategy.

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