THE PS UPGRADE PROGRAMME: RECENT ADVANCES

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Abstract

The LHC Injectors Upgrade project (LIU) has been initiated to improve the performances of the existing injector complex at CERN to match the future requirements of the HL-LHC (High Luminosity LHC). In this framework, the Proton Synchrotron (PS) will undergo fundamental changes for many of its main systems: the injection energy will be increased to reduce space-charge effects, the transverse damper will be improved to cope with transverse instabilities, and the RF systems will be upgraded to accelerate higher beam intensity and brightness. These hardware improvements are triggered by a series of studies meant to identify the most critical performance bottlenecks, like space charge, impedances, longitudinal and transverse instabilities, as well as electron-cloud. Additionally, alternative production schemes for the LHC-type beams have been proposed and implemented to circumvent some of the present limitations. A summary of the most recent advances of the studies, as well as the proposed hardware improvements is given.

INTRODUCTION

The PS upgrade program, as part of the LHC Injectors Upgrade project (LIU)[1], has the goal of improving the production of the LHC type beams to match the requirements of the HL-LHC (High Luminosity LHC)[2]. During 2012-13 the LIU project effort was focussed on the understanding of the different limitations for the production of the future LHC type beams [3]. The intention was also to start whenever possible the design, construction and eventually the installation of the new hardware required for the upgrade.

SPACE CHARGE STUDIES

Space charge constitutes the first PS limitation to overcome to meet the requirements of the future LHC-type beams. A series of studies, presented in detail in [4, 5], suggests that the maximum Laslett vertical tune shift, compatible with the allocated budget for beam losses and transverse emittance blow up, is about [-0.32,-0.34], if the vertical tune is kept below the $4q_y$=1 resonance. The transverse emittance blow up on the 1.2 s long injection flat bottom was measured for different Laslett tune shifts and for different working points: it became apparent that particles cross either the integer or the $4q_y$=1 resonance excited by space charge. About 80% of the transverse emittance blow up occurs in less than 200 ms. For this reason, production schemes with a single-batch injection from the Booster, after the connection of the Linac4, might suffer less than the double-batch schemes with a 1.2 s long injection flat bottom. The envisaged solution to increase the available space in the tune diagram and to maintain double injection production schemes is to test the compensation of the $4q_y$=1 resonance and to eventually move the working point to higher vertical tunes away from other resonances [6]. For this reason, tests were done first to compensate two resonances produced by lattice imperfections, $2q_x$+q_y=1 and $3q_y$=1. Special skew sextupoles were installed during the Winter stop 2012 for this purpose. The studies in 2013 demonstrated that both resonances could be effectively compensated, even if it was not possible to compensate both at the same time due to limitations of the maximum gradient of the correction magnets.

TRANSVERSE DAMPER

The commissioning of the transverse damper constitutes one of the important milestones achieved during the 2012-13 run. The system proved to be able to damp effectively injection errors, headtail instabilities at injection energy and transverse coupled bunch instabilities on the extraction flat top. Horizontal headtail transverse instabilities are present on the injection flat bottom and if not cured can cause transverse emittance degradation and large losses. Currently, the instabilities are eliminated by introducing transverse linear coupling by powering two dedicated families of skew quadrupoles [7]. This method, however, presents drawbacks that could limit the future performance of the machine. The transverse tunes have to be set close to the Q_x=Q_y resonance to enhance the coupling, causing also a measurable transverse emittance exchange. The transverse damper, as reported in detail in [8], proved to be able to damp this instability with an uncoupled machine, even for a variety of working points and chromaticities. The damper proved to be efficient also for the transverse coupled-bunch instability observed with the 25 ns LHC-type beam for bunches shorter than nominal, or appearing for nominal bunches kept in the machine for long time before extraction [9] for studies. The instability seems to be induced by electron cloud [9], even if studies are still in progress to corroborate this hypothesis. The damper was able to delay the appearance of the instabil-

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ity by 10 ms, which is sufficient since the beam would be already extracted. These results make the coating of the PS vacuum chambers with amorphous carbon for electron cloud suppression not mandatory. An upgrade of the system [8] is foreseen during 2013-15 to increase its power in view of the future increase of the injection energy. As the bandwidth will also be extended, this could further improve the damping of instabilities.

ELECTRON CLOUD STUDIES

Electron cloud is regularly observed during normal operation, but without causing any degradation of the beam quality. Electron cloud appears only few ms prior to extraction, and the duration of the interaction with the beam is not long enough to trigger any instability. Even so, it is not clear yet if the beams foreseen for the upgrade will be intrinsically stable or not. A series of machine and simulation studies were done during the 2012 run, as summarized in [9]. An important result is that beam production schemes with lower number of bunches, using for example the one mentioned in the next section, or with single batch injection from the PSB, produces much less electron cloud compared to the nominal schemes. This could be an important alternative if electron cloud driven instabilities would appear for the future operational beams and if the damper would not be able to cope with them. It became also apparent that an important input missing for a full understanding of the observed phenomena is a measurement of the electrons produced inside the main magnet vacuum chambers. Two detectors will be installed in a main magnet (see Figure 1), a shielded pickup detector and an optical device to intercept photons produced by the electrons bombarding the vacuum chamber. The second technique is going to be investigated in a test stand to prove that it is possible to disentangle the photons generated by the electrons and the typical photon background that could be found in the machine.

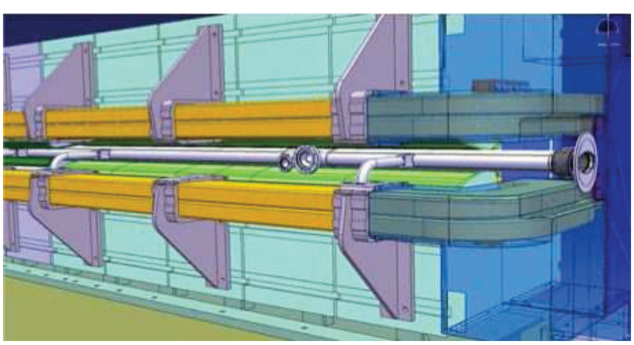

Figure 1: Location of the flanges for the new electron cloud monitors within a main magnet (Courtesy of T. Capelli).

LONGITUDINAL PLANE ADVANCES

Coupled bunch instabilities represent a major limitation for the production of the LHC-type beams, causing a noticeable increase of spread in bunch intensity and longitudinal emittance along a batch of the LHC beams [10]. For this reason a longitudinal damper based on wide-band Finemet® cavities, similar to the RF system foreseen for the PSB [11], is being designed and it will be installed during the 2013 shutdown. A sketch of the installation in the tunnel is shown in Figure 2. In parallel, a series of measurements were taken during the 2012-13 run of both naturally occurring instabilities and instabilities excited on purpose by the existing feedback [12]. The goal is to improve the understanding of the impedance creating the instability, but also to improve the simulation tools and to predict the efficiency of the longitudinal damper after the beam upgrade. Particular attention was thus dedicated to the development

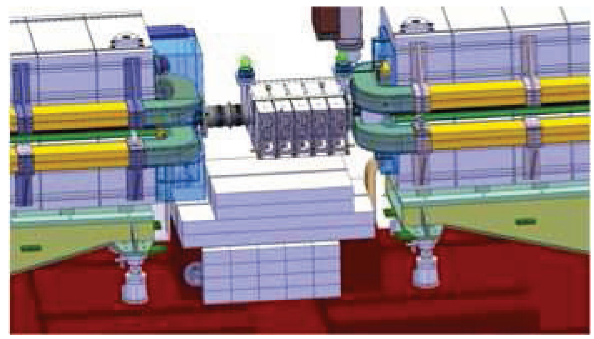

Figure 2: Finemet® cavities as to be installed in a PS straight section. The shielding blocks below the cavities protect the solid-state amplifiers from radiation.

of a precise longitudinal impedance model of the PS [13], supported by CST© simulations of various elements. In the same context, significant improvements were done also in the identification of transverse impedance sources [14]. The proof-of-principle test of the new 1-turn feedback on one of the 10 MHz cavities, with the development of a new fully digital, more flexible, and with higher gain than existing operational system was also successful.

ALTERNATIVE PRODUCTION SCHEMES

Beside the classical production scheme of the LHC-type beam, based on triple splitting at injection energy plus two double splitting on the extraction flat top and described in [4], alternative ones were proposed to overcome the current brightness limitation of the PSB [15]. The most promising one, described in [16] and named BCMS (Batch Compression Merging and Splittings), comprises the injection of eight bunches on the 9th harmonic, batch compression from h=9 to h=14, bunch merging followed by a triple splitting (see Figure 3) all done at low energy instead of the triple splitting only. These evolved RF gymnastics are performed at an intermediate kinetic energy (E_k=2.5 GeV) to avoid transverse emittance blow up due to space charge and to relax the requirements on the longitudinal emittance at injection. The resulting 12 bunches are accelerated to the extraction flat top where two bunch splittings occur to obtain the final 25 ns bunch spacing (only one splitting is done for the 50 ns bunch spacing) as for the nominal scheme.

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The advantage with respect to the traditional scheme results from the smaller splitting factor of the PSB bunches (6 instead of 12). Before extraction to the SPS, 25 ns spaced bunches have the same transverse emittance but twice the intensity. The BCMS beam was produced during the 2012 run, both for the 25 and the 50 ns bunch spacing. Both beams were sent to the LHC and the 50 ns could be put in collision to produce physics data. A single 24-bunch batch of 1.6 10^{11} ppb plus a 36-bunch nominal batch of 1.5 10^{11} ppb and 2×6 nominal bunches were injected on the same cycle. The BCMS beam showed a 50% gain in terms of emittance summing over both planes at SPS extraction, but yielded only about 30% more specific luminosity per crossing [17]. Thanks to this result, the scheme will be most probably used for the production of the LHC physics beam during the 2015 run. Table 1 compares the classical production scheme with the BCMS one as injected in LHC during the 2012-13 run.

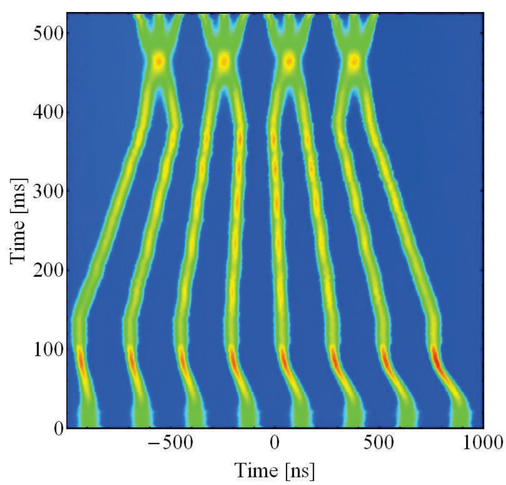

Figure 3: RF gymnastic for the production of the BCMS scheme at intermediate energy. The batch compression is followed by a bunch merging and a triple splitting.

Table 1: LHC beams for two bunch spacings and schemes.

Param. at LHC inject.	**2012-13 50 ns**	**BCMS 50 ns**	**2012-13 25 ns**	**BCMS 25 ns**
Int./b. [10^{11}]	1.7	1.6	1.1	1.1
$\epsilon^*(1\sigma)$ [μm]	1.7	1.1	2.6	1.3

RADIATION SHIELDING INCREASE

One of the main intensity limitation for the high-intensity beams used for neutrino production at the CERN SPS was due to the too large radiation levels observed outside the PS tunnel in the injection and extraction regions, already present for nominal intensity. The original shielding built in 1958 is not any longer sufficient for the current intensities and losses [18]. For this reason, following detailed Monte Carlo studies to asses the needed increase also considering future high intensity beams [19], civil engineering interventions are foreseen in both regions during 2013. Figure 4 shows for example the status of the worksite in the injection region during the spring 2013.

Figure 4: Civil engineering worksite on top of the injection region, Spring 2013.

CONCLUSIONS

Important progresses were achieved during the past year in terms of beam and simulation studies, in particular improving the understanding of the different limitations to overcome to match the requirements of the future HL-LHC beams. A major success of the last run consisted in the commissioning of the BCMS production scheme, with preliminary tests showing a relevant increase of the LHC luminosity thanks to the higher beam brightness. Whereas longitudinal and transverse instabilities seem to be well under control, thanks to the ongoing damper upgrades, the space-charge effects and their mitigation need further investigations. Transverse emittance blow up induced by resonance crossing caused by the large incoherent tune shift on the 1.2 s long injection flat bottom seems to constitute the main limitation for the beam brightness increase. Possible solutions to reduce the strength of the resonances and to reduce the tune spread are under investigation.

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