SPS UPGRADE

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MOTIVATION FOR SPS UPGRADE

An upgrade plan for the whole CERN accelerator complex has been proposed to allow full exploitation of the LHC potential in the future as well as giving increased support to traditional and possible new experiments at lower beam energies. This plan foresees replacing during 2011 - 2017 all the accelerators in the LHC injector chain (Linac2, Booster, PS) by new machines (Linac4, SPL and PS2) except for the last - the SPS. In this scenario the SPS should be able to reliably accelerate much higher beam intensity than achieved so far and therefore significant improvements to the machine performance, in addition to the increased injection energy due to PS2, should be found and implemented on the same time scale.

Various LHC upgrade scenarios which are presently under consideration [1] for injectors could be divided into two groups. Most of them are based on the ultimate LHC beam with bunches of 1.7×10^{11} pp spaced at 25 ns. One scenario, called "LPA" - Large Piwinski Angle, requires bunches spaced by 50 ns with 5×10^{11}/bunch. All schemes have their own challenges in LHC. The "LPA" scenario requires very high bunch and total beam intensities and is the most challenging for the injectors.

At present only the 400 MHz RF system is installed in LHC (the 200 MHz capture RF system is delayed). The LHC beam (4 batches of 72 bunches spaced at 25 ns) with nominal intensity of 1.2×10^{11} per bunch has been produced at top energy in the SPS [2]. At 450 GeV an average bunch length (4σ Gaussian fit) is 1.6 ± 0.1 ns. The longitudinal bunch displacement at extraction due to the residual effect of beam loading in the 200 MHz RF system (with feedback and feedforward systems in operation) is less than ± 100 ps. This beam has nominal longitudinal emittance (0.6 ± 0.1 eVs) and close to nominal transverse emittances ($\varepsilon_h = 3.0 \pm 0.3$ μm and $\varepsilon_v = 3.6 \pm 0.3$ μm [3]). Only a single bunch with the ultimate LHC intensity has been seen in the SPS so far.

This year 4 batches of 36 bunches spaced at 50 ns were also produced in the injector chain. The nominal bunch intensity (1.1×10^{11}) was achieved at 450 GeV/c with very small longitudinal and transverse emittances. This beam was stable on the SPS flat top without the controlled emittance blow-up required for stabilisation of the 25 ns spaced beam and had the average bunch length of 1.3 ns (emittance of 0.4 eVs). Transverse (V&H) emittances of 1.2&1.5 μm were measured on the flat top. Beam losses were also significantly less than for nominal beam with 25 ns spacing. No e-cloud signal could be observed in the special diagnostics installed in the SPS (see below).

In all LHC upgrade scenarios it is assumed that the SPS will be able to provide reliably a beam with characteristics significantly exceeding those obtained up to now. The intensities possible with the new injector chain (Linac4-LPSPL-PS2) [4], [5] are even more challenging for the SPS, see Table 1, and a significant SPS upgrade is mandatory for optimum use of the new CERN accelerators. The main tasks of the interdepartmental Study Team, SPSU [6], are first to identify limitations in the existing SPS, then study and propose solutions with a Design Report to be issued in 2011 containing a cost estimation and planning for proposed actions.

	SPS record 450 GeV		LHC request 450 GeV		PS2 offer 50 GeV		
T_{bb} ns	25	FT	25	50	25	50	FT
$N_b/10^{11}$	1.2	0.13	1.7	5.5	4.4	5.5	1.6
n_{bunch}	288	4200	336	168	168	84	840
$N_t/10^{13}$	3.5	5.3	5.7	8.4	7.4	4.6	12
ε_L eVs	0.6	0.8	< 1	< 1	0.6	0.7	0.4
$\varepsilon_{h/v}$ μm	3.5	8/5	3.5	3.5	3.5	3.5	15/8

Table 1: Maximum intensities achieved in the SPS up to now and future requests. The FT (Fixed Target) beam now has a maximum energy of 400 GeV and 5 ns bunch spacing. It will have a 25 ns bunch spacing with PS2.

KNOWN LIMITATIONS AND POSSIBLE CURES

The main intensity limitations for a single bunch in the SPS are space charge and TMCI (transverse mode coupling instability). The e-cloud, generated by the presence of many bunches in the ring, is at the origin of the single bunch vertical instability. Other multi-bunch limitations are coupled bunch instabilities, beam losses, 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).

For future high intensity beams possible actions and cures to overcome these limitations include [7]

- Higher injection energy with PS2: 50 GeV/c instead of 26 GeV/c
- Vacuum chamber modification as a remedy against the e-cloud effects
- Impedance reduction after its identification

- Damping of coupled bunch instabilities
  - active damping will need an upgrade of beam control (transverse and longitudinal feedbacks)
  - passive (Landau) damping due to increased non-linearity (synchrotron frequency spread) with the 4th harmonic RF system (800 MHz) and increased longitudinal emittance.
- Hardware modifications: RF system, beam dump, beam diagnostics
- New hardware: injection kickers, beam collimation

The injection energy increase from 26 GeV/c to 50 GeV/c will reduce the space charge tune spread by a factor 4 so that even for a bunch intensity of 5.5×10^{11} in the "LPA" upgrade scenario it will be close to the (present) value for nominal LHC bunch intensity.

At 50 GeV/c the TMCI threshold will be higher than at 26 GeV/c by factor 2.5. Bunch stability with an intensity of 5.5×10^{11} can be provided by an increase of emittance to 0.6 eVs. Other possible cures for this instability are increased vertical chromaticity and transverse feedback (under study).

Due to the twice longer LHC batch produced by PS2 every 2.4 s at 50 GeV/c, the SPS will have a shorter injection plateau (2.4 s instead of present 10.8 s) and shorter acceleration time (by 10%); this should reduce the LHC filling time by 35%.

Other benefits of the SPS injection energy increase possible with PS2 include [8] smaller physical transverse emittance with less injection losses; no transition crossing for all proton beams and light ions; easier acceleration of heavy ions (lead): smaller IBS growth rate and no need for fixed frequency acceleration, in use now.

ELECTRON CLOUD MITIGATION

The effects caused by the presence of the electron cloud are considered at the moment to be the most important intensity limitations in the SPS [9]. They lead to transverse emittance blow-up and instabilities, pressure rise, septum sparking, enhanced beam dump outgasing [10] and probably even beam losses [11]. Present cures include an annual scrubbing run at the end of each SPS shutdown, operation with high chromaticity in the vertical plane and transverse damping in the horizontal plane.

Studies done with 1.1×10^{11} p/bunch on the coupled-bunch instability in the H-plane at different energies [10] suggest that the instability growth rate scales as $\sim 1/\gamma$ and improvement can be expected at higher injection energy. On the other hand, e-cloud simulations done for the vertical plane predict threshold reduction with energy which can be explained by the transverse beam size reduction with energy at constant normalised emittance. The intensive machine studies of the vertical e-cloud instability at different SPS energies in 2006 and 2007 (on a specially created magnetic cycle) confirmed this scaling law [12].

The simulations [13] of e-cloud build-up for 25 ns and 50 ns bunch spacings and intensities relevant to future SPS beams show non-monotonic dependence on bunch intensity for 25 ns bunch spacing and a fixed SEY (Second Electron Yield) value. For 50 ns bunch spacing a higher intensity (above the nominal LHC intensity) always seems to be better.

Possible SPS chamber modifications as measures against e-cloud effects are now under extensive investigation by the SPSU Study Team [6]. The first option is a surface coating which should significantly reduce the SEY (below 1.3) without need for future re-activation, which could be done in-situ, without baking above 80 deg C, and which would not reduce the aperture. The best candidates are amorphous carbon coatings (see Fig. 1) on a rough surface [14]. A SEY below 1 has been obtained, the main problem is surface ageing with venting which must be avoided in future if this solution is to be applied to the SPS. The infrastructure for implementation in the SPS tunnel already partially exists due to ongoing refurbishing of the SPS dipoles. According to the preliminary estimations ~ 750 vacuum chambers inside the magnets can be coated during three SPS shutdowns (years).

The positive effect of grooves was also shown both in simulations [15] and measurements of the SEY [14]. Their manufacture as well as the resulting aperture reduction and

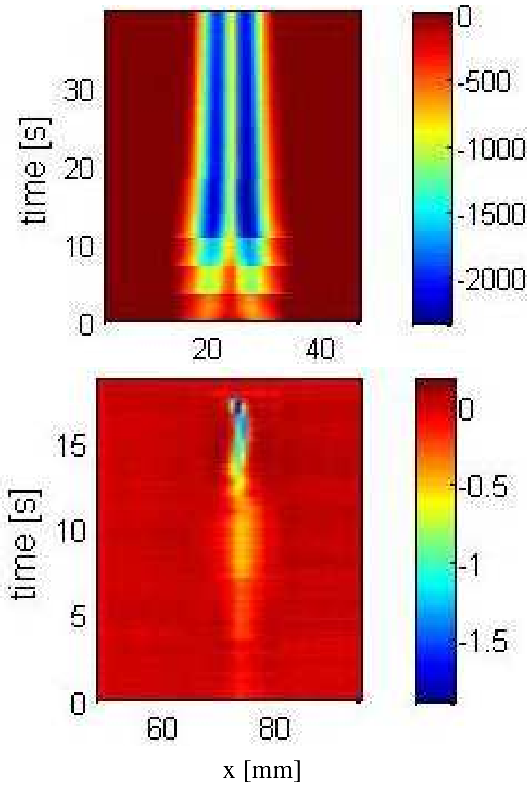

Figure 1: Electron cloud signal in strip line monitors with stainless steel (top) and amorphous Carbon (bottom) liners during acceleration of nominal LHC beam in the SPS [14].

their impedance are the main issues to be addressed for this option.

The installation of clearing (enamel based) electrodes all along the SPS ring is another solution to the e-cloud problem under development [16].

The special experimental set-up in the SPS used for different e-cloud measurements in 2008 includes a clearing electrode with button pick-ups and three strip-line detectors: one with stainless steel liner without any coating for reference, one with some new coating under study (TiN, Carbon...) and one with NEG. The e-cloud signal registered during the SPS cycle with nominal LHC beam for stainless steel and amorphous Carbon liners is shown in Fig. 1.

A feasibility study of active damping of the single bunch vertical instability using a wide-band feedback system is also under way in collaboration with LARP [17].

SPS IMPEDANCE AND RF SYSTEM

The SPS impedance was significantly reduced during the 2000/2001 shutdown in preparation for nominal LHC beam intensities. No microwave instability has been observed since then. During the period 2003-2006 the SPS impedance has increased mainly due to the re-installation of 9 extraction kickers (MKE) for the LHC beam. This impedance change can be followed by measurements of the quadrupole oscillation frequency shift with intensity, Fig. 2. The slope, being proportional to the effective longitudinal impedance, shows the expected variation. Similar measurements done in the vertical plane show changes in impedance with even higher precision, however only 50% of the transverse impedance budget is identified and a search for the rest continues [19].

To reduce the MKE kicker beam coupling impedance a technical solution based on an inter-digital comb structure printed on ferrite has been developed and is now implemented on one kicker [20]. Measurements in the lab show a significant improvement for the longitudinal impedance below 1.5 GHz and this is also confirmed by measurements of kicker heating by the beam. The reduction in the transverse plane is smaller. It is planned to equip all MKE kickers during the next 4 shutdowns. The impedance reduction of other SPS kickers is also now under investigation. Apart from heating, the kicker impedance is also responsible for the loss of Landau damping of high intensity beams during acceleration.

To stabilise the nominal LHC beam against coupled bunch instabilities, operation with the 4th harmonic RF system in bunch shortening mode is not sufficient and controlled emittance blow-up (from 0.35 eVs to 0.6 eVs) is necessary twice during the cycle (with injection into a mismatched voltage and band-limited noise excitation during acceleration). For the "LPA" LHC upgrade scenario with 50 ns bunch spacing and high bunch intensities, a controlled emittance blow-up to at least 0.9 eVs will be necessary at the end of the cycle (above 250 GeV). This in

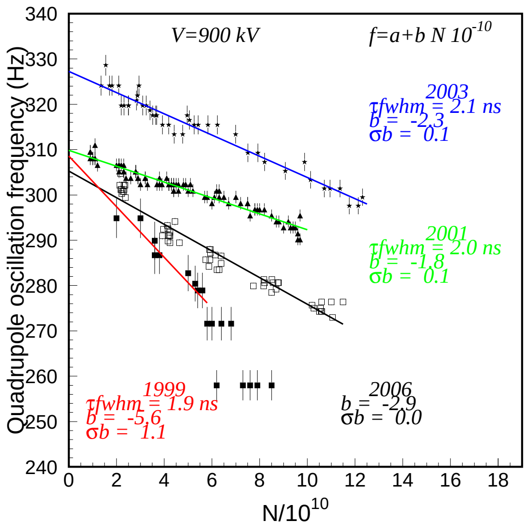

Figure 2: Quadrupole synchrotron frequency shift as a function of bunch intensity indicating the changes over time in the SPS ring [18].

turn will require an upgrade of the SPS RF system. If the voltage presently available (7.5 MV at 200 MHz) is still sufficient to accelerate LHC beam with a large longitudinal emittance, the RF power required for beam loading compensation is significantly higher than actually possible. The power per 200 MHz cavity with total voltage of 7.5 MV is shown in Fig. 3 for a beam current corresponding to the "LPA" scenario together with existing limitations for pulsing mode (LHC beam fills the half of ring) and continuous operation (FT/CNGS type beam fills practically the whole ring). The length (number of sections) of half of the SPS cavities has been already reduced from 5 to 4 sections in preparation for high intensity operation. The effect of a possible further optimisation of the number of sections is also shown. In any case it is clear that the 200 MHz (and 800 MHz) power plant should be significantly increased and R&D for the re-design of couplers and coaxial lines is required [21].

Even higher RF power per cavity (3.3-4.5 MW) is required for the maximum LHC beam intensities possible with PS2. For future FT/CNGS beam in the SPS more RF cavities are necessary to provide the 10.5 MV voltage needed for the same acceleration time as today (3 s). The potential proton flux at 450 GeV with the maximum intensity from PS2 of 1.2×10^{14}, 200 days of operation, 80% beam availability and 85% beam sharing is 2.5×10^{20} pot/year [22].

SUMMARY

The upgraded CERN injectors will produce high intensity beam with high reliability both for LHC and other users. All machines except the SPS in the LHC chain will

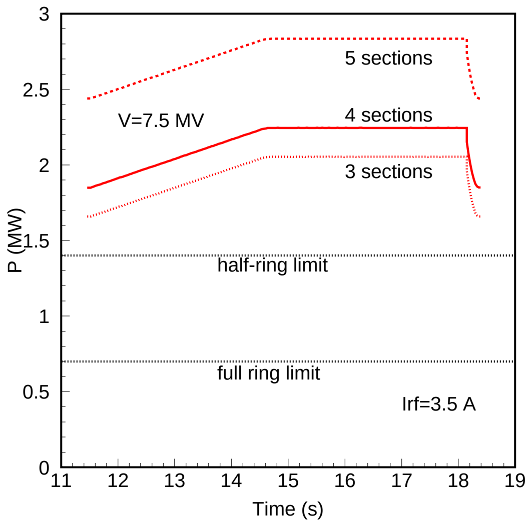

Figure 3: Power per SPS 200 MHz cavity having 3, 4 or 5 sections for a beam current corresponding to the "LPA" LHC upgrade scenario. Constant voltage of 7.5 MV.

be replaced around 2017. The SPS will profit from the higher injection energy, but the SPS upgrade is a key element for the LHC to benefit fully from new upstream machines.

The project proposal for the SPS upgrade should be issued in 2011. The SPS commissioning with new injectors (LPSPL and PS2) is planned for 2017 with ultimate LHC beam produced in the SPS in 2018. Further intensity increase depends very much on the success of the SPS upgrade. Increasing the SPS injection energy opens the door to increasing the energy of LHC (DLHC) with SPS+ (new magnets from 50 GeV to 1 TeV).

I am grateful to the many colleagues whose work, absolutely essential for the SPS upgrade studies, is described in this paper.

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