SPS UPGRADE POSSIBILITIES

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Abstract

The LHC beam with characteristics close to nominal was already obtained in the SPS a few years ago. The main beam-quality limitation comes from the e-cloud effect which seems also to be responsible for high beam losses. During MD sessions in 2008 and 2009 the total intensity of the LHC beam was limited to three PS batches. Intensities above nominal have not yet been seen in the SPS and possible limitations can only be estimated from the scaling laws and machine studies. Future upgrades aimed at removal of the known bottlenecks in the SPS are presented. The consequences of operating with SPL and PS2 as pre-injectors are also considered.

PRESENT STATUS AND MOTIVATION FOR UPGRADE

Various LHC upgrade scenarios which are presently under consideration [1] 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 much higher bunch intensity. All schemes have their own challenges in LHC. The SPS should be able to reliably accelerate much higher beam intensity than achieved so far and therefore significant improvements to the machine performance should be found and implemented on the same time scale as LHC upgrade.

At the moment the SPS is able to deliver at top energy the LHC beam (4 batches of 72 bunches spaced at 25 ns) with nominal intensity of 1.2×10^{11} per bunch. This beam has nominal longitudinal emittance (0.63 ± 0.1 eVs [2]) and close to nominal 3.5 μm transverse emittances ($\varepsilon_h = 3.0 \pm 0.3$ μm and $\varepsilon_v = 3.6 \pm 0.3$ μm [3]). The maximum total intensity was obtained for the CNGS type beam in 2004 [4]. A single bunch with 1.8×10^{11} (ultimate LHC intensity) was seen in the SPS at 26 GeV/c in 2006.

In 2008 4 batches of 36 bunches spaced at 50 ns were injected into the SPS for the first time. 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 an average bunch length of 1.3 ns (emittance of 0.4 eVs) [2]. 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 diagnostic systems installed in the SPS (see below).

In all LHC upgrade scenarios it is assumed that the SPS will be able to reliably provide a beam with characteristics significantly exceeding those obtained up to now. From a comparison of what has been achieved so far and what is expected from the SPS in the future, see Table 1, it is clear that a significant SPS upgrade is mandatory.

		SPS record 450 GeV/c		LHC request 450 GeV/c	
parameter		LHC	CNGS	nom.	ultim.
spacing	ns	25	5	25	25
N_b	10^{11}	1.2	0.13	1.2	1.8
n_{bunch}		288	4200	288	288
N_{tot}	10^{13}	3.5	5.3	3.5	5.2
ε_L	eVs	0.6	0.8	< 1	< 1
$\varepsilon_{h/v}$	μm	3.6/3.5	8/5	3.5	3.5

Table 1: Maximum intensities achieved in the SPS up to now and future requests. 5% beam loss assumed for SPS-LHC beam transfer. The CNGS beam has a maximum energy of 400 GeV.

The intensities from the injector chain based on the new accelerators Linac4-LPSPL-PS2 [5], [6] are even more challenging for the SPS.

The main tasks of the interdepartmental Study Group, SPSU [7], created in 2007 were first to identify limitations in the existing SPS, then study and propose solutions with a Design Report to be issued in 2011. This Study Group consists of some permanent members but contributions from different hardware group (in form of presentations) are also very important for both identifying limitations and their mitigations. A separate impedance team [8] led by E. Metral is also looking in detail into different issues related to the SPS impedance.

INTENSITY LIMITATIONS IDENTIFIED

Single bunch effects

Possible intensity limitations for a single bunch in the SPS are from space charge, TMCI (transverse mode coupling instability) and microwave instability.

For the LHC bunch at 26 GeV/c the space-charge tune spread ΔQ_{sc} is 0.05 for the nominal intensity and 0.07 for the ultimate intensity [9]. The tolerable limit for the space-charge tune spread in the SPS from past experience (ppbar) is believed to be around 0.07. At an injection energy of 50 GeV/c the space charge tune spread is less by a factor 4.

After the impedance reduction achieved in 2001 the microwave instability has no longer been observed in the SPS.

This is true even for very small longitudinal emittances (0.15 eVs) with nominal bunch intensity, indicating that this instability should not be a problem for bunch intensities significantly higher than ultimate.

On the other hand, after the impedance reduction campaign, targeted mainly on the longitudinal impedance, another instability, the TMCI, has been observed in the SPS for proton bunches with small longitudinal emittances [10]. With the impedance model obtained from a best fit to measurements for the LHC bunch at 26 GeV/c (2006) the threshold intensity at zero chromaticity is $N_{th} \sim 1.4 \times 10^{11}$ [11].

Multi-bunch effects

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 beam losses, coupled bunch instabilities, beam loading in the 200 MHz and 800 MHz RF systems as well as heating of different machine elements (e.g. MKE and MKDV kickers) and vacuum issues (beam dump, MKDV and MKDH outgassing, ZS septum sparking).

Beam losses In 2003 an LHC beam with nominal intensity and longitudinal parameters was accelerated in the SPS to top energy. However this could be achieved only by injecting 15% more particles due to significant beam loss. After intensive MD studies, a reduction of losses to 7% was obtained at the end of 2004 with a new working point and additional RF gymnastics on the flat bottom [3], [12].

During MDs in 2008-2009 particle loss (flat bottom plus capture) reduced from 20% at the beginning of year to 10% at the end probably due to scrubbing of the ring by the e-cloud (however machine tuning cannot be eliminated as a possible reason). In general the injection and capture losses of the LHC beam in the SPS have a strong dependence on the batch intensity and less on the number of batches in the ring. After some time in coast the LHC batch has a triangular shape due to a poor lifetime of bunches in the batch tail [12]. A reduction in relative loss to 3% for a beam with 75 ns bunch spacing and nominal bunch intensity shows that losses are most probably not due to a single bunch effect (e.g. space charge).

Usually the relative beam loss increases with intensity due to different collective effects (space charge, beam loading, instabilities, increased beam size...):

$$\frac{\Delta N_{loss}}{N} \propto N.$$

To keep the same absolute loss ΔN_{loss}, responsible for the radiological impact, the relative loss should be reduced at higher intensity proportional to $1/N_{tot}$. As a result, for higher beam intensities, significantly improved machine performance and radioprotection will be required. Beam collimation for beam loss control could be necessary as well.

e-cloud 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. They lead to transverse emittance blow-up (above the nominal LHC value) and instabilities - coupled bunch in the horizontal plane (seen at a few MHz) and single bunch in the vertical plane in the batch tail. They could also be at the origin of beam losses [13].

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 [14] 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 on the vertical e-cloud instability at different SPS energies in 2006 and 2007 (on a specially created magnetic cycle) confirmed this scaling law [15].

The simulations [16] 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.

Impedance 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. However during the period 2003-2006 the SPS impedance has increased, mainly due to the re-installation of 8 extraction kickers (MKE) for the LHC beam. The longitudinal impedance change can be followed by measurements of the quadrupole oscillation frequency shift with intensity, Fig. 1. 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 [17]. The impedance budget of the SPS is under construction by the Impedance team [8], [18].

The longitudinal impedance model of the SPS which includes contributions from the two TW RF systems (200 MHz and 800 MHz) and 18 different kickers is in good agreement with beam measurements. Indeed from measured synchronous phase [20] and synchrotron frequency [19] shifts with intensity the resistive and reactive parts of impedance could be evaluated. The largest contributors to the inductive impedance are the MKE kickers [21]. The reactive impedance is responsible for the loss of Landau damping stabilising the beam. The resistive impedance de-

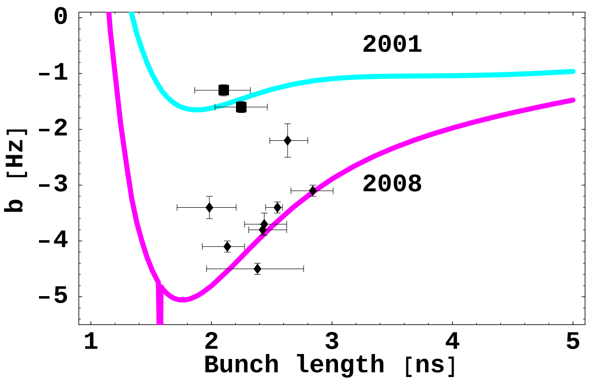

Figure 1: The slope b from measured (symbols) and calculated (solid lines) quadrupole synchrotron frequency shift with bunch intensity as a function of average bunch length (during oscillations in the SPS), data from 2001 and 2007-2008. Calculated slope b for known longitudinal SPS impedance in 2001 and 2008 [19].

termines the instability growth rate and leads to heating.

The narrow-band impedance responsible for the longitudinal coupled bunch instability (see below) is not known. Possible impedance sources of this instability are the fundamental and HOMs (at 629, 912 MHz...) of the 200 MHz and 800 MHz RF systems.

Longitudinal coupled bunch instabilities The longitudinal coupled-bunch instability of the LHC beam in the SPS is characterised by a very low intensity threshold [22]. A single LHC batch with 2×10^{10} p/bunch becomes unstable during acceleration at $\sim$ 280 GeV/c.

To stabilise the beam controlled emittance blow-up is performed twice during the cycle, in addition to the use of the 800 MHz RF system as a Landau cavity in bunch-shortening mode throughout the cycle. The first blow-up is with mismatched voltage at injection; due to filamentation the initial emittance of 0.35 eVs is increased to 0.42 eVs. The second takes place at around 200 GeV/c, with band-limited noise which blows up the emittance to 0.6 eVs. The emittance blow-up in a double RF system has its own limitations due to the presence of beam loading [23]. The Beam Quality Monitor, in operation from the end of 2009 [24], controls the longitudinal bunch parameters prior to the extraction to LHC.

At injection the coupled-bunch instability is observed at $\sim 1.1 \times 10^{11}$/bunch (with 800 MHz off). No significant change in threshold due to injection at 50 GeV/c is expected.

For ultimate LHC intensities controlled emittance blow-up to at least 0.75 eVs will be needed to stabilise the beam. It is also possible that for these high intensities larger longitudinal emittances are required at 450 GeV in LHC itself (IBS growth rate [25]). Then beam transfer to the LHC 400 MHz RF system from the SPS 200 MHz RF system becomes critical and two solutions are possible:

(1) to install the 200 MHz RF system in LHC (see [26]);

(2) to increase the voltage at extraction in the SPS 200 MHz RF system.

To have the same bunch length at the larger emittance, which is $\propto \sqrt{N}$, one would need a voltage N_{ult}/N_{nom} times higher than the present 7.5 MV, which means 10.5 MV for the ultimate bunch intensity. This in turn will require an upgrade of the SPS RF system as discussed in the next section.

Beam loading There are two RF systems in the SPS, 200 MHz and 800 MHz, both of TW (travelling wave) type. The 200 MHz RF system consists of 2 cavities of 5 sections and 2 cavities of 4 sections. Each section has 11 cells. Presently the total voltage available at nominal LHC intensity is 8 MV. The power per cavity is limited to 750 kW in continuous operation (full ring, CNGS type beam) by power amplifiers, couplers and feeder lines [27]. Theoretically, a higher value (1 or even 1.4 MW) is possible in pulsed mode for an LHC beam filling less than half of the ring. However this mode of operation is not fully tested yet. The power per 200 MHz cavity during the LHC cycle in the SPS is shown in Fig. 2 for different beam intensities. It corresponds to the voltage program with maximum of 4.5 MV during the ramp and 7.5 MV on the flat top.

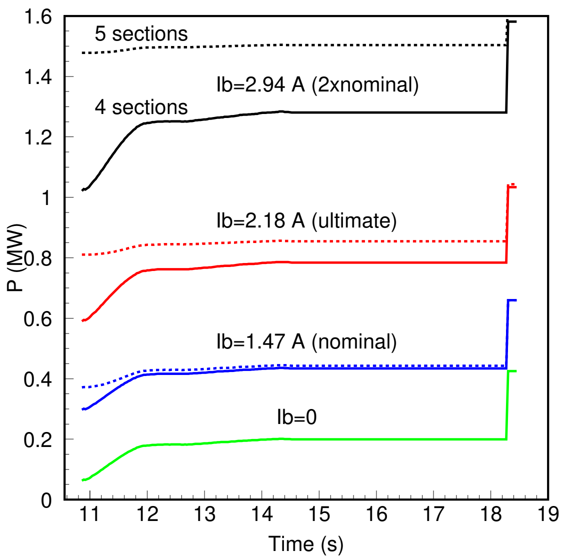

Figure 2: Power per SPS 200 MHz cavity having 4 or 5 sections for different beam currents during the LHC cycle.

The 800 MHz voltage during the cycle usually follows the 200 MHz voltage program at 1/10 level. After the ongoing upgrade, the required power for the 800 MHz RF system will be well below limitations [28].

POSSIBLE MITIGATIONS

TMCI

The TMCI threshold scales as $\varepsilon|\eta|$ (for a matched voltage), where $\eta = 1/\gamma^2 - 1/\gamma_t^2$ and therefore has its minimum at injection (above transition $\gamma_t = 22.8$).

Possible measures to remove this potential bottle-neck are

- increased longitudinal emittance
- increased vertical chromaticity
- increased voltage at injection
- impedance reduction (after identification)
- transverse feedback [29]
- high harmonic (800 MHz) RF system
- increased injection energy (at 50 GeV/c the TMCI threshold is higher than at 26 GeV/c by a factor 2.5)

As already seen in MD studies devoted to loss reduction of LHC beam in the SPS [12] the first three options above could lead to slow particle loss on the flat bottom.

MD studies in 2010 with the maximum bunch intensity available from the PS would help to refine the TMCI threshold and possible cures.

e-cloud

Possible e-cloud mitigation is under extensive investigation by the SPSU Study Group [7]. The main options studied include

- grooves
- clearing electrodes along the beam pipe
- active damping system in the vertical plane
- surface coating

The positive effect of grooves was shown both in simulations [30] and measurements of the SEY [31]. However their manufacture and installation as well as the resulting aperture reduction and impedance are still unsolved problems for this option.

The installation of clearing electrodes (enamel based) all along the SPS ring requires heating to 600-800 deg [32] and is not feasible for the existing vacuum chamber inside SPS magnets. The impedance of the electrodes is another serious issue.

A feasibility study of active damping of the single bunch vertical instability using a wide-band feedback system [29] is also under way in collaboration with LARP [33]. Significant progress was achieved in improving beam diagnostics in 2009. The main problem for this option, apart from the technical challenges, are incoherent effects (emittance blow-up) below the instability threshold.

The last, but the most promising option at the moment, is a surface coating which should significantly reduce the SEY (secondary electron yield) without need for future reactivation, which could be done in-situ, without baking above 120 deg C, and which would not reduce the aperture. The best candidates found so far are a-C (amorphous carbon) coatings produced by magnetron sputtering on smooth or rough surfaces [34]. A SEY below 1 has been obtained - 1.3 is the critical value for the SPS.

The special experimental set-up in the SPS used for different e-cloud measurements from 2008 [35] includes a clearing electrode with button pick-ups and 4 strip-line detectors: one monitor with stainless steel liner without any coating for reference, and three others with different coatings under study (a-C, a-C on rough surface and StSt from 2010 for local pressure measurements). In addition a special vacuum chamber with removeable under UHV sample (StSt in 2008 and a-C in 2009) was used for analysis in the lab of surface conditioning with beam. This special vacuum chamber and all electron cloud monitors are installed in dipole magnets having a field variation from 0 to 2 kGauss (1.2 kGauss is the SPS injection value).

Main results obtained from liners [36]:

- 300 times smaller e-cloud signal in a-C than in StSt
- conditioning (scrubbing) effect observed even for small SEY (a-C)
- no ageing for a-C liners exposed to the beam (but not to e-cloud)

At the beginning of 2009 the vacuum chamber (60 mm on the top and bottom) of the three spare dipole MBB magnets was coated with a specially developed (crash program) coating system [37] which uses the dipole field of the magnets for sputtering. These magnets were installed in the ring (LSS5) with microwave transmission [38] and vacuum diagnostics (arranged for comparison in 3 pairs: coated-coated, coated-uncoated and uncoated-uncoated). Absence of e-cloud in coated magnets was finally confirmed by microwave measurements after overcoming a lot of difficulties in clean signal detection [39]. However no significant reduction in pressure rise was observed between coated magnets in comparison with reference uncoated magnets nearby. This was also true when at the end of the year the inter-magnet region (pumping port shield) was coated in addition. In general pressure in the coated magnets without beam is higher than in the uncoated. Note that a large variation (more than factor 10) in maximum pressure exists between the uncoated MBB magnets.

During the recent shutdown one coated MBB magnet (MBB51490) was removed and replaced by uncoated. After cooling down it will be open and carefully inspected. Endoscopy shows a lot of different traces, difficult to identify at the moment. Design of a new coating system (based on permanent magnets) is under way.

The infrastructure for implementation of magnet coating in the SPS tunnel already partially exists due to refurbishing of the SPS dipoles. According to the estimates (see [40] for more detailed information on cost and planning) ~ 750 vacuum chambers inside the magnets can be coated during 3-4 normal (14 weeks of access) SPS shutdowns. Without any serious modifications the capacity of the underground workshop ECX5 (plus 100 m^2 floor in ECA5) is for 16 dipoles and would be 24 magnets with the additional 300 m^2 floor space in ECA5. The detailed comparison of work planning for 3 and 4 years, based on consultations with all groups involved in the project, shows that a 4-year scenario has many advantages and is also $\sim$ 30% less expensive (by 2 MCHF). It is expected that a 5 year-scenario will be again more expensive due to non-optimum use of manpower. With 4 days required for coating (with cleaning and installation) of one magnet and 4 magnets produced per day we will need 8 coating benches working simultaneously. One of the potential problems is the large quantity of contaminated water (after rinsing). Radiation level (ALARA) should be also taken into account for work planning after a beam stop.

Open questions presently under study are surface ageing with venting and scrubbing, magnet coating quality and outgassing. In addition, it is still not decided what else in the ring should be coated (quadrupoles, inter-magnet pumping port shields...)

These and other important issues related to coatings were addressed during the AEC0'9 workshop "Anti e-cloud coatings (that do not require activation)" organised by the SPSU SG together with ACCNET at CERN in October 2009 [41].

Venting must be avoided in future if coating is to be applied to the SPS vacuum chamber. This means also modifications to the SPS vacuum system.

Vacuum system

Future modifications to the SPS vacuum system, see [42], required for carbon coated magnets are mainly determined by the need to minimise ageing of the coating due to the air exposure of magnets which happens during shutdown work and interventions. Existing practice with parallel work in several sectors, transportation in the tunnel, disconnected or removed equipment, magnet's interchangeability, alignment procedure - all should be reconsidered from this point of view. Storage and transport of magnets will be done under vacuum or in N_2. Probably there is no necessity to refine sectorisation, delicate equipment is already protected. The list of required studies includes many issues (such as shutdown work-flow, installation procedures, monitoring, mobile pumping...) and should be prioritised.

Impedance reduction

Machine elements with high impedance become intensity limitations in two ways: by leading to beam instabilities and by their own heating and outgassing. The previous impedance reduction campaign was mainly looking after longitudinal impedance. Now it should be the turn for the transverse impedance, especially due to the now observed TMCI.

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 3 (MKE6) kickers [21]. 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 (factor 4 reduction in temperature rise for LHC beam) [43]. The reduction in the transverse plane is smaller. It is planned to equip 5 more MKE kickers during the next 3 shutdowns. All MKE kickers and one MKDV magnet have transition pieces between magnet and tank. Transition pieces are still to be installed in all MKDH and MKDV2 which show now (in 2009) more outgassing with 50 ns beam than MKDV1 (problem in 2008) [44]. The impedance reduction of other SPS kickers is also now under investigation.

Search for unknown impedances is a very important issue for the prediction power of the existing impedance models. The impedance reduction required for future SPS intensities assumes first of all its identification.

The impedance of the 800 MHz RF system is also seen by the beam. Beam loading in this RF system makes difficult precise control of the phase required for beam stabilisation. It is planned to have RF feedback and feedforward systems at the end of 2010. This requires installation of probes in each cell (37/cavity).

Another significant reduction in impedance can be achieved by rearranging the existing four 200 MHz cavities (see below).

RF upgrade

As was discussed above, more voltage is required for transfer of beams with larger emittance to LHC. On the other hand, the existing two 5-section cavities can provide much less voltage at ultimate LHC current for power limit of 1.4 MW/cavity [45] and become practically useless with 1 MW/cavity, Fig.3.

A possible solution to this problem is to rearrange the existing 4 cavities (with 2 spare sections) into 5 or 6 cavities of shorter length with 1 or 2 extra power plants which allow simultaneously to reduce beam loading per cavity, increase available voltage and even reduce total beam coupling impedance. The price to pay (for having more voltage) is corresponding total power increase by 25% or 50%.

Total beam coupling impedance of the 200 MHz TW RF system (peak value at fundamental frequency) is [46]

$$Z = \frac{R}{8} \sum L_n^2$$

where $R = 27.1$ kOhm/m^2, $L_n = L_0(11n - 1)$, $L_0 = 0.374$ m and n is number of sections per cavity. The two most promising options for RF configuration are presented in Table 2 together with the actual situation. Even with two

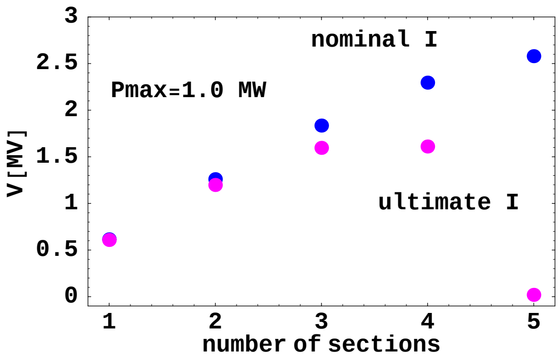

Figure 3: Voltage from one SPS 200 MHz TW cavity having different number of sections for nominal (top circles) and ultimate (bottom circles) beam current.

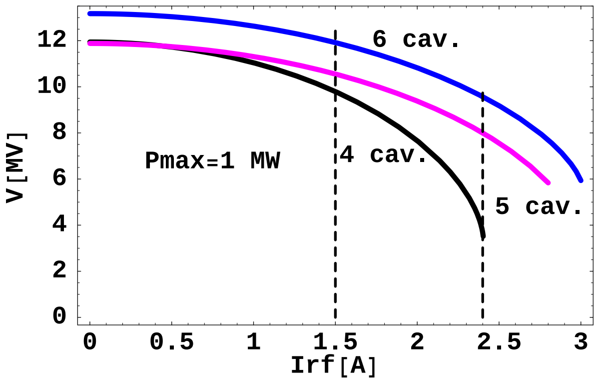

Figure 4: Total voltage possible with maximum power of 1 MW/cavity for different RF configurations with 4 (present situation), 5 or 6 cavities as a function of beam current. Total number of sections is 18 for 4 and 5 cavities option and 20 for 6 cavities. Nominal and ultimate beam currents are shown with a dashed line.

extra (spare at the moment) sections (the case of 6 cavities) the total impedance of shorter cavities will be $\sim$ 20% less than now.

total number n_{cav}	n_{cav} with n_{sect} 3	4	5	Z MΩ	V [MV] for 1 MW 2.4 A	3.0 A
4	0	2	2	4.5	3.7	0
5	2	3	0	3.6	8.0	3.6
6	4	2	0	3.7	9.6	5.9

Table 2: Beam coupling fundamental impedance Z and voltage V available at 450 GeV/c (for ultimate and twice nominal current with 1 MW power limit) with possible future configurations of the 200 MHz RF system in the SPS and the actual one (first row).

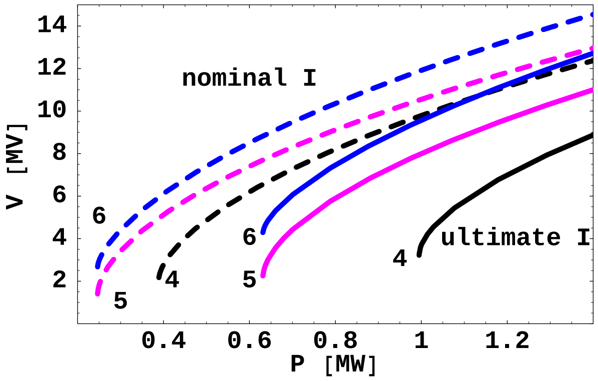

Figure 5: Total voltage possible for nominal and ultimate LHC intensity for different RF configurations from Table 2 with 4 (present situation), 5 or 6 cavities as a function of power limit per cavity.

The present power limitation applied in operation is 750 kW/cavity [27]. The existing configuration can only provide 4 MV at ultimate current even at 1 MW/cavity (possible in pulsed mode, but not tested yet). The same voltage for ultimate current as now for nominal can be obtained with 6 cavities and power of 1 MW, Fig. 4. Note that nominal and ultimate LHC intensities (plus 10% for losses) correspond in the SPS to the RF current of 1.5 A and 2.4 A (shown with dashed lines).

In Fig. 5 maximum total voltage achievable for nominal and ultimate current with different RF configurations is shown as a function of RF power available per cavity.

For the 6 cavity option the gain in available voltage (for a given current) is even more significant for fast cycles (FT and CNGS) with short acceleration time. Presently both voltage and power are at the limit since 7.5 MV are used after transition crossing. With 6 cavities almost 30% more voltage will be available for a given current or twice higher current can be accelerated with the same voltage (implies longitudinal emittance control), Fig. 6. Similar improvement can be expected with 6 cavities for the fast LHC cycle.

Much higher RF power per cavity (3.3-4.5 MW) is required for the maximum PS2 intensities (RF current of 5.2 A). This implies more short cavities and power with 2 power plants (2 feeder lines) per cavity [27].

Internal beam dump

The TIDVG is one of 4 beam dumps/collimators installed in LSS1. It serves to absorb all types of the SPS beam dumped with energy above 105 GeV/c. Below 37 GeV/c beam is dumped at the TIDH. No dumping is possible between these two limits. In a design made in 2000 for high intensity beams, the Aluminum core (primary dump) was replaced by Graphite and the cooling system was modified [47]. The Graphite was covered by Titanium foil which was damaged during operation and became an SPS aperture limitation. Due to the high radioactivity repair was not possible and the dump was replaced in 2006 by one of the two spares produced in 2000. This time the Graphite

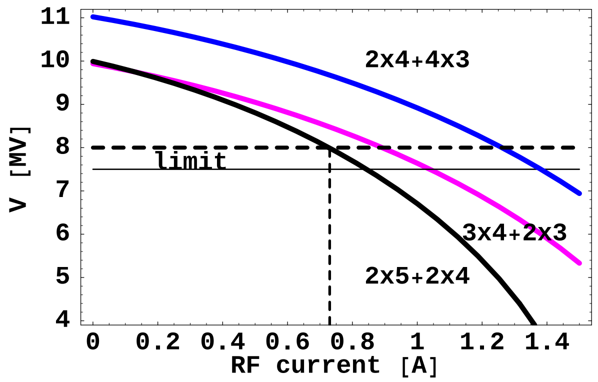

Figure 6: Total voltage possible at maximum acceleration during FT/CNGS cycle for CNGS type beam (5 ns bunch spacing) as a function of RF current (0.73 A corresponds to total intensity of 4.8×10^{13}) for different RF configurations from Table 2.

was baked to 1000 deg before coating and to 150 deg in situ (250 deg was recommended but could not be achieved due to limitations in the bake-out system). From 2006 dumping of the LHC beam during MDs caused significant pressure rises and beam interlocks, in particular from that protecting the MKP. This is explained by the fact that operational temperatures (T) are higher than the final bake-out T (150 deg).

The limits of TIDGV for dumping current and future LHC and CNGS-type beams in the SPS were explored using ANSYS and FLUKA simulations [48]. The main limitation is the Antico (aluminum) temperature which should not exceed 450 deg. The proposed slight design modification should increase the number of allowed consecutive dumps by up to 50%. Currently the dump absorbs at 450 GeV only 155 GeV/p.

New design and materials can significantly increase performance and should be used for the long-term solution.

Hardware modifications needed

- ZS (electrostatic septa) - show-stopper for nominal LHC beam in 2008 and 2009
- Impedance reduction: MKE, MKDV, MKDH and other (as identified)
- SPS magnet coating after successful tests
- Vacuum system (for coated chamber)
- 200 MHz RF system and beam control
- Transverse damper low-level control [49]
- Beam dump (TIDVG)
- Beam instrumentation (MOPOS, BCT and BWS) [50]
- Beam collimation (under investigation)
- Radioprotection

SUMMARY

The main SPS limitations for ultimate intensity have been identified. They are the e-cloud effect, beam loading in the 200 MHz RF system, transverse mode coupling (TMCI) and longitudinal coupled bunch instabilities.

Machine development sessions with higher than nominal intensity are needed to see other possible limitations (obtained by scaling laws and simulations so far).

Proposed measures to overcome the known limitations are under study; they could help even for nominal LHC beam operation and can be implemented earlier. Main proposals are e-cloud mitigation, impedance reduction and RF upgrade. Recent work in the SPSU SG has mainly concentrated on e-cloud mitigation; amorphous carbon coating of vacuum chamber is the best candidate for implementation in the SPS. The increased number of shorter (than present) 200 MHz cavities with 2 extra power plants should restore the performance for ultimate LHC intensities, this modification will also reduce the pressure for the installation of the capture (200 MHz) RF system in LHC.

In the injector upgrade plan with LPSPL and PS2, the SPS would have a higher injection energy which helps to overcome some intensity limitations (single bunch, injection losses) and avoid transition crossing for CNGS/FT beams. This path needs many extra studies and hardware modifications.

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