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INTENSITY UPGRADE PLANS FOR CERN-LHC INJECTORS

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Abstract

With LHC coming into operation very soon 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 the period 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 twice 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 at the same time scale. The present status of proposals and ongoing studies for all accelerator injector chain is described with main emphasis on the SPS challenges and upgrade plans.

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INTENSITY UPGRADE PLANS FOR CERN-LHC INJECTORS

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With LHC coming into operation very soon 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 the period 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 twice 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 at the same time scale. The present status of proposals and ongoing studies for all accelerator injector chain is described with main emphasis on the SPS challenges and upgrade plans.

MOTIVATION FOR UPGRADE

LHC upgrade scenarios

The motivation for the future upgrade of the LHC injector chain includes the following main factors [1]-[3]. There is important physics motivation for a 10 times higher luminosity which would lead to 25% wider discovery range in particle mass and twice higher precision. The time scale is defined by the fact that for the main LHC experiments, the statistical error reduction saturates after a few years of nominal operation. On a similar time scale, which is estimated to be around 2016, operation with the nominal luminosity will also lead to radiation damage of the LHC IR quadrupoles. However the integrated and average ($\mathcal{L}_a$) luminosity are in fact more important figures of merit than peak luminosity $\mathcal{L}_p$. For any given peak luminosity they can be increased by minimising so called turnaround time T_a (time from the end of a physics run to the start of the next one). To get there one needs high availability of beam with the requested parameters. Taking into account the age of accelerators in the present LHC injector chain (from 1959 to 1978) as well as limited consolidation in the past, it is very difficult to provide reliable operation for the next 20 (?) years well above their design intensities [4]-[6].

The beam parameters required from the injectors for the present LHC upgrade scenarios [3]: “ES” - Early Separation, “FCC” - Full Crab Crossing, ”LPA” - Large Piwinski Angle, are summarised in Table 1. All these schemes have their own challenges. The ”FCC” scenario would require large aperture Nb_3Sn quadrupoles and crab cavities.

parameter	nom.	ult.	ES& FCC	LPA
$N_b/10^{11}$	1.15	1.7	1.7	4.9
ε_{tr} [μm]	3.75	3.75	3.75	3.75
T_{bb} [ns]	25	25	25	50
β^* IP1&5 [m]	0.55	0.5	0.08	0.25
θ [μrad]	285	315	0&673	381
$\mathcal{L}_p/10^{34}$ [cm^{-2}s^{-1}]	1.0	2.3	15.5	10.7
$\mathcal{L}_a/10^{34}$ [cm^{-2}s^{-1}]	0.46	0.91	2.4	2.5
event pile-up	19	44	294	403

Table 1: Beam parameters required for nominal and ultimate luminosities $\mathcal{L}$ as well as for the present LHC upgrade scenarios [3]. T_a of 10 h is assumed for $\mathcal{L}_a$. Here N_b is bunch intensity, T_{bb} is bunch spacing, θ is crossing angle.

The ”ES” scheme needs in addition the early separation dipoles deep inside the detector. In both these cases low luminosity lifetime due to a high peak luminosity and non-negligible beta-beating for off-momentum particles should be expected. Operation with large Piwinski angle is a new collider regime and still needs to be demonstrated. It relies on wire compensation of long-range beam-beam effects as well as a flat bunch distribution. The “LPA” scenario requires very high bunch and total beam intensities and is the most challenging for the injectors.

Limitations of present LHC injectors

The intensities required for the present LHC upgrade scenarios are well above the nominal value achieved so far at extraction from the SPS. The corresponding intensities in the LHC injector chain (for nominal transverse and longitudinal emittances) are presented in Table 2.

	Linac2	PSB (4 rings)	PS	SPS
E_{max} [GeV]	0.05	1.4	25	450
$N_b^{max}/10^{11}$		1.5	1.3	1.15
n_{bunch}		1/ring	6→72	4x72
pulses [s]	1.2	2x1.2	4x3.6	12x21.6

Table 2: Today’s performance of the LHC injector chain (for nominal bunch emittances).

Due to $\sim$ 20% losses and $\sim$ 40% uncontrolled transverse emittance blow-up in the LHC injector chain for nominal values of the transverse emittances, the beam intensity at the extraction of the SPS at the moment can-not exceed the nominal by much. The PS Booster intensity is limited by the space charge effects at injection to $\sim 1.8 \times 10^{12}$ per bunch and therefore the ultimate LHC intensity seems to be out of reach for the required normalised transverse emittances [7]. To reduce the space charge the PSB operates with three RF systems which provide controlled longitudinal emittance blow-up and bunch lengthening mode (reduced line density). The PSB has 4 identical (optics and RF systems) rings which nevertheless demonstrate different behaviour for high intensity beams and the one with the lowest performance often determines the beam parameters at injection to the PS.

Space charge in conjunction with a long (1.2 s) injection plateau is also one of the main limitations in the present PS [8]. This limit was already pushed up by increasing the injection energy from 1 to 1.4 GeV in preparation for the nominal LHC beam. It is the oldest CERN ring, built in 1959, is practically on the surface with limited shielding and is very sensitive to beam losses due to radiation problems. The LHC beam production involves very complicated RF gymnastics (controlled emittance blow-up, one triple and two double bunch splittings plus bunch rotation prior to extraction) and still longitudinal matching with the 200 MHz Rf system (5 ns bucket) of the SPS is not trivial. The bunch length along the LHC batch at extraction from the PS is shown in Fig. 1 when using two (normal operation) and three (shorter bunches) 80 MHz cavities for bunch rotation before extraction to the SPS [9].

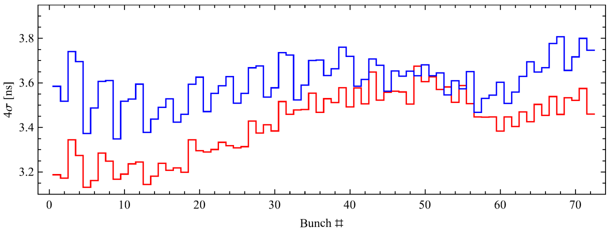

Figure 1: The bunch length (4σ Gaussian fit) along the LHC batch for nominal intensity at extraction from the PS after bunch rotation with two (top, blue curve) and three (bottom, red curve) 80 MHz cavities [9].

As is shown in Table 2 the LHC beam with nominal intensity has been produced in the SPS. A typical example for the bunch length over four LHC batches at injection and flat top of the SPS is shown in Fig. 2 [10]. At 450 GeV an average bunch length (4σ Gaussian fit) is 1.6 ± 0.1 ns. The longitudinal bunch position at extraction, also seen in this Figure, shows the residual effect of beam loading in the 200 MHz RF system (with feedback and feedforward systems in operation). This beam has a nominal longitudinal emittance (0.6 ± 0.1 eVs) and close to nominal transverse emittances ($\varepsilon_h = 3.0 \pm 0.3\ \mu$m and $\varepsilon_v = 3.6 \pm 0.3\ \mu$m [7]). The intensity limitations of the SPS are discussed separately in the last Section.

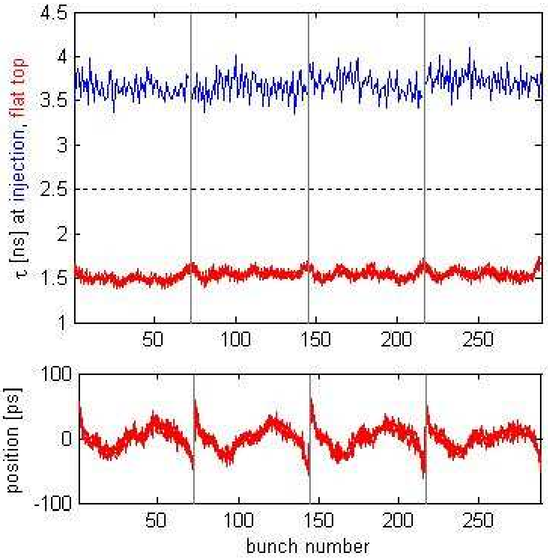

Figure 2: The bunch length (4σ Gaussian fit) along the 4 LHC batches for nominal intensity at injection (top, blue curve) and extraction (bottom, red curve) from the SPS - top figure. Bunch position over four LHC batches at extraction from the SPS - bottom figure.

NEW ACCELERATORS

After a careful analysis of the present limitations in the LHC injector chain [4] and future needs for the LHC upgrade [3] as well as for other possible applications at lower energies [2] it was proposed by the CERN management to study the replacement of the existing accelerators (Linac2, PSB and PS) by new ones (Linac4, SPL and PS2), see Fig. 3. In this scenario only the SPS will not be replaced but will need an important upgrade. According to the present planning the final decision to construct the new accelerators will be taken after a few years of LHC operation, in June 2011.

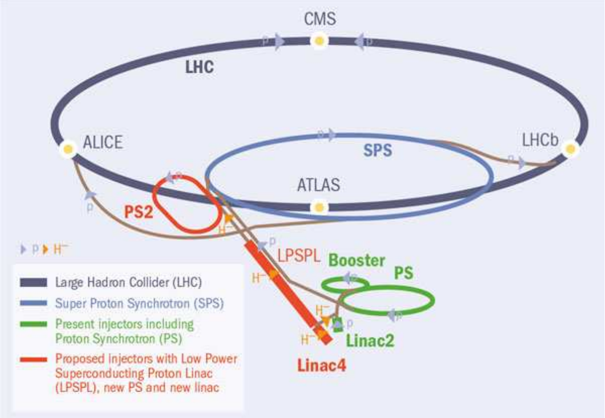

Figure 3: CERN accelerator complex now and in the future.

The decision to construct Linac 4 [11], [12] has been already taken. This H$^-$ linac will increase the injection energy of the PSB to 160 MeV removing the existing bottleneck due to space charge, for more details see [13]. The construction of Linac 4 should allow the ultimate LHC beam to be produced in the injector chain. Civil engineering work starts in October 2008 and beam commissioning is foreseen for 2012.

The site for Linac4, Fig. 3, has been chosen taking into account that in future it should become the low energy part of the SPL - Super Conducting Proton (H$^-$) Linac with a 4 GeV (kinetic) energy [14]. For the LHC upgrade a Low Power version (LPSPL) is sufficient and will be built first keeping possible future upgrade to higher energy (5 GeV) and repetition frequency (from 2 Hz to 50 Hz). The pulse length will also be reduced by a factor 3, from 1.2 to 0.4 ms. Ongoing studies include the choice between different frequencies (700 MHz and 1400 MHz) and cooling temperature (2 or 4 deg K) [15].

In fact, according to the present plans the commissioning of the LPSPL should be completed almost at the same time, at the end of 2016, as the PS2 [16] - the replacement of the PS. This will allow significant changes to be made in the LHC injector chain without interruption of LHC operation and therefore the integrated luminosity will not suffer from this change over. The size of the new synchrotron (15/7 of PS and 15/77 of the SPS) is mainly determined by its energy range (4-50 GeV) also taking into account filling the SPS with 5-turn extraction for other beams (Fixed Target - FT and CNGS type) as well as the harmonic ratios between the two rings needed for LHC beam with different bunch spacings (25 ns, 50 ns and 75 ns). The cycling time to top energy using normal conducting magnets (maximum ramp rate 1.5 T/s) will be the same as now with the PS - 2.4 s. With twice higher line density than in the present PS, the maximum effective beam power at extraction will reach 400 kW (60 kW in the PS). The optics versions include at the moment one with a real transition gamma (and transition jump) and a so called imaginary one (negative compaction factor) [17]. The options for the RF system include the enlarged copy of the existing multi-RF system (10 MHz, 20 MHz, 40 MHz and 80 MHz) which would require again bunch splittings and one based on a 40 MHz (SPL chopping frequency) RF system. In the last case a large tuning range is needed both for protons and especially ions.

SPS UPGRADE

In both 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. At the same time, the possibilities offered by a completely new SPS injector chain (Linac4-LPSPL-PS2) are even more challenging for the SPS [18]. From a comparison of what has been achieved so far and what is expected from the SPS in the future, both by LHC and other potential users, see Table 3, it is clear that a significant SPS upgrade is mandatory for optimum use of new CERN accelerators. The main tasks of the interdepartmental Study Team, SPSU [19], created by PAF [4] in 2007 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 3: Maximum intensities achieved in the SPS up to now and future requests. 10% beam loss assumed for PS-SPS and SPS-LHC beam transfer. The FT beam now has a maximum energy of 400 GeV and 5 ns bunch spacing. It will have 25 ns bunch spacing with PS2.

Known limitations and possible cures

The main intensity limitations for a single bunch are space charge and TMCI. 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 in the list 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:
- Higher injection energy with PS2: 50 GeV/c instead of 26 GeV/c
- Vacuum chamber modification as a remedy against the e-cloud effects
- Further 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 nonlinearity (synchrotron frequency spread) with the 4th harmonic RF system (800 MHz) and increased longitudinal emittance.

- Hardware modifications: injection kickers, RF system, beam dump, beam diagnostics, radioprotection
- New hardware: beam collimation (to be confirmed)

Injection energy increase

The tolerable limit for the space-charge tune spread in the SPS from past experience (ppbar) is believed to be

$\Delta Q_{sc} < 0.07$. For the LHC bunch at 26 GeV/c ΔQ_{sc} is 0.05 for the nominal intensity and 0.07 for the ultimate intensity. A bunch intensity of 5.5×10^{11} for the upgrade scenario with 50 ns bunch spacing will increase this value to 0.23. Sufficient improvement ($\propto 1/\gamma^2$) is expected due to higher injection energy. Indeed for planned increase of injection energy to 50 GeV, $\Delta Q_{sc} = 0.06$, so that the tune shift is almost back to its present value. This positive effect is even more significant for ion beam [8].

Another potential bunch intensity limitation is the TMCI, transverse mode coupling instability, observed in the SPS with smaller than nominal longitudinal emittance, see [20] for more information. With the impedance model obtained as a best fit to measurements for the LHC bunch at 26 GeV/c the threshold intensity $N_{th} \sim 1.4 \times 10^{11}$ [21]. For the matched voltage the threshold intensity scales as

$$N_{th} \propto |\eta| \varepsilon_L .$$

At 50 GeV the TMCI threshold will be already 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 capture voltage (also needed for larger emittance).

Due to the twice longer LHC batch produced by PS2 each 2.4 s at 50 GeV, 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 are

- smaller physical transverse emittance - less injection losses;

- no transition crossing for all proton beams and light ions;

- easier acceleration of heavy ions (lead): smaller IBS growth rate, smaller frequency sweep and therefore 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 as being the most important intensity limitations in the SPS [22]. They lead to transverse emittance blow-up and instabilities, pressure rise, septum sparking, enhanced beam dump outgasing [23] and even probably beam losses [24]. Present cures include an annual scrubbing run at the end of each SPS shutdown, operation with high chromaticity in the vertical plane and transverse damper in the horizontal plane.

Studies done with 1.1×10^{11} p/bunch on the coupled-bunch instability in H-plane at different energies [23] 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 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 specially created magnetic cycle) confirmed this scaling law [25].

A few examples of e-cloud build-up obtained from HEADTAIL simulations [26] for 25 ns and 50 ns bunch spacings and intensities relevant to future SPS beams are presented in Fig. 4. One can notice 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 always seems to be better.

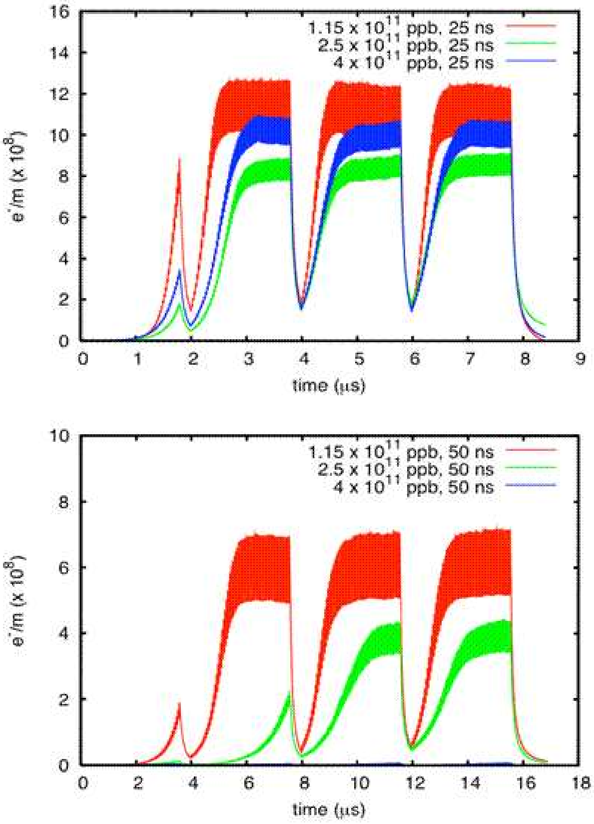

Figure 4: Electron cloud build-up in the SPS with different bunch intensities for 25 ns bunch spacing and SEY of 1.4 (top) and 50 ns bunch spacing and SEY of 1.6 (bottom) [26].

Possible SPS chamber modifications as measures against e-cloud effects are now under extensive investigation by the SPSU Study Team [19]. The first option is a surface coating which should significantly reduce the SEY (below 1.3) without future re-activation and could be done in-situ, without baking above 80 deg C and without any aperture reduction. The best candidates are carbon based composites and rough metal surfaces (copper black) [27]. The infrastructure for implementation in the SPS tunnel already partially exists due to ongoing refurbishing of the SPS dipoles. According to the preliminary estimations ~ 1000 vacuum chambers inside the magnets can be coated during three

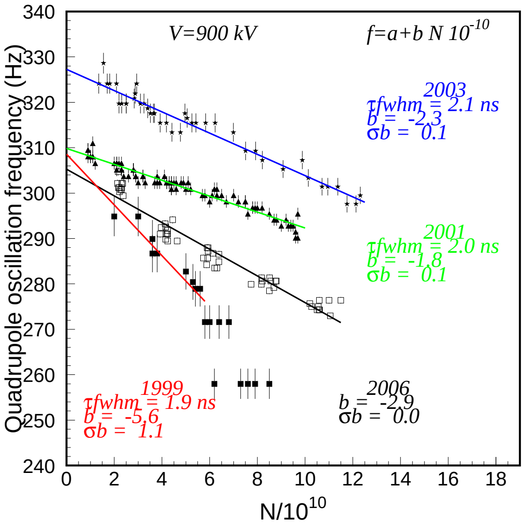

Figure 5: Quadrupole synchrotron frequency shift as a function of bunch intensity indicating the changes over time in the SPS ring.

SPS shutdowns (years). The positive effect of grooves was also shown both in simulations [28] and measurements of the SEY [27]. Their manufacture as well as the resulting aperture reduction are the main issues to be addressed for this option. The installation of cleaning (enamel based) electrodes all along the SPS ring is another solution to the e-cloud problem under development [29].

The special experimental set-up in the SPS used for different e-cloud measurements in 2008 includes a cleaning 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.

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 [30].

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. 5. The slope, being proportional to the effective longitudinal impedance, shows the expected variation. Similar measurements done in the vertical plane show a relative change in impedance with even higher precision, however only 50% of the transverse impedance budget is identified and a search for the rest continues [31].

To reduce the MKE kicker beam coupling impedance a technical solution based on inter-digital comb structure printed on ferrite has been developed and is now implemented on one kicker [32]. 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 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. 6 for 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 doubled and R&D for the re-design of couplers and coaxial lines is required [33].

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 [34].

SUMMARY

The upgraded CERN injectors will produce high intensity beam with high reliability both for LHC and other users. All machines in the LHC chain will be replaced around 2017 by new ones except the SPS, which will profit from a higher injection energy. The SPS upgrade is a key

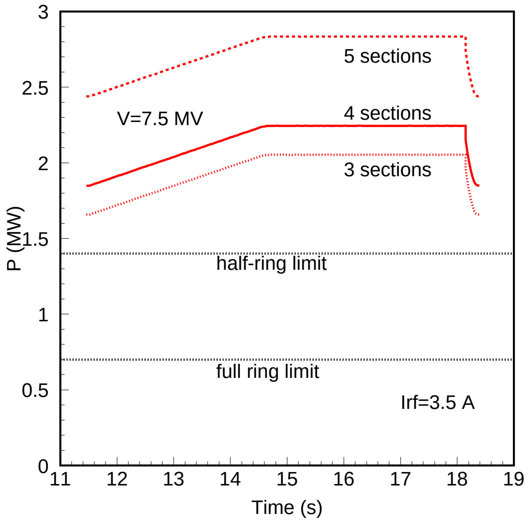

Figure 6: Power per SPS 200 MHz cavity having 3, 4 or 5 sections for a beam current corresponding to the "LPA" LHC upgrade scenario.

element for the LHC to benefit fully from new upstream machines. New physics programmes requiring high beam power at a few GeV (e.g. neutrino and radioactive ion beam facilities) could later be possible by upgrading the LPSPL to SPL.

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