# HIGH BRILLIANCE AND CLOSER BUNCHES FROM THE LHC INJECTORS

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*Abstract*

The challenges for increasing intensity and reducing bunch spacing in the present LHC injectors are discussed together with requirements for new machines to replace them for a future luminosity upgrade of LHC.

## INTRODUCTION

The main factors for the LHC luminosity increase expected from the injectors are the following [1], [2], [3].

(I) With existing injectors:

- factor 2.2 from increase of bunch intensity from nominal to ultimate, $N = 1.15 \times 10^{11} \rightarrow 1.7 \times 10^{11}$,
- factor 2 from reduced bunch spacing: 25 ns → 12.5 ns.

(II) With LHC injection energy of 1 TeV:

- further increase of bunch intensity with normalised transverse emittances of 7.5 $\mu$mrad,
- reduction of the LHC turnaround time,
- the possibility to increase the LHC top energy.

Below we consider first the limitations in the present injectors and then discuss the scheme with a new 1 TeV injector to the LHC (choice of the RF system, cycle length and required impedance budget).

## EXISTING LHC INJECTORS

### *High brilliance*

The present nominal scheme of producing the LHC proton beam in the CERN accelerator chain can schematically be presented as follows.

**Linac:** $H^+ \rightarrow$ 50 MeV.

**PSB:** 3 rings (1 bunch per ring), h=1 → 1.4 GeV.

**PS:** 2 injections (6 bunches), h=7, 14, 21 → 18 bunches → (25 GeV) 36 bunches, h=42 → 72 bunches, h=84, h=168 → **SPS:** 3-4 injections (216-288 bunches), h=4620 → 450 GeV.

In this scheme 12 LHC bunches are produced from one PSB bunch in the PS by different RF manipulations. The ultimate LHC intensity requires an increase of the brilliance in the PSB by factor 1.7 (for 85% beam transmission). Reduced bunch spacing requires an increase of the brilliance in the PSB by similar factor. However the brilliance (brightness in the USA) $\equiv N/\varepsilon_n$ ($\varepsilon_n$ is normalised transverse emittance) is limited by space charge in low-energy machines since the space-charge tune-spread is proportional to the brilliance/($\beta\gamma^2$). So far the PSB was able to deliver $\sim 20 \times 10^{11}$ ppb with the required $\varepsilon_n$ [4]. In the PS $1.4 \times 10^{11}$ ppb were obtained with nominal $\varepsilon_n$ and $1.7 \times 10^{11}$ ppb with slightly larger transverse emittances.

In the SPS the LHC beam with the following parameters was obtained at 450 GeV:

- 4 batches with 25 ns spaced bunches, $N = 1.15 \times 10^{11}$,

- longitudinal emittance ($2\sigma_\varepsilon$) of $\varepsilon = 0.6 \pm 0.1$ eVs, $\tau = 4\sigma_t = 1.6 \pm 0.1$ ns [5],

- normalised emittances of $\varepsilon_H = 2.99 \pm 0.26$ $\mu$m and $\varepsilon_V = 3.61 \pm 0.26$ $\mu$m in horizontal and vertical plane [6].

An emittance blow-up $\sim$ 20% in the vertical plane due to the e-cloud instability was measured in the SPS with 4 batches in the ring [7]. This could be slightly pessimistic due to the fact that measurements were done for bunches at the end of the batch.

The possibility of increasing the brilliance of bunches injected to the SPS in the future are based on the scheme with batch compression in the PS [4] leading to a reduced number of bunches (42 instead of 72) and therefore increased time of filling the LHC (by 33%). Realisation of the project for Linac 4 with $H^-$ injection at 160 MeV would allow 72 bunches to be produced with $N = 2 \times 10^{11}$ in 2.4 s giving a 17% reduction of the LHC filling time. Linac 4 combined with the batch compression allows 48 bunches with $N = 3 \times 10^{11}$ to be produced in 2.4 s.

The question as to whether the present SPS can digest this beam will be discussed in the next section.

### *Closer bunches*

Closer bunches with different bunch spacing can be produced by the RF manipulations in the PS.

For **12.5 ns bunch spacing** only one more bunch splitting is necessary in the PS which can be done with the existing RF systems, however a new RF system is necessary in the SPS at one of following RF frequencies:

- 160 MHz (easy for capture in the SPS, but worse for extraction due to transfer into the 400 MHz RF system of the LHC, this scheme will definitely need a capture system in the LHC).

- 240 MHz (could lead to more capture loss in the SPS). Most probably a similar RF system will be needed in the LHC - the present 200 MHz capture RF system will not work for 12.5 ns spaced bunches.

- 320 or 400 MHz. (In this case no capture system is required in LHC, but most likely a 160 MHz capture system will be necessary in the SPS. The voltage needed for transfer from capture to higher harmonic RF system can be reduced by injecting closer to transition. Beam is more stable in the longitudinal plane, but potentially more problems with e-cloud due to shorter bunches.)

For the 10 (15) ns bunch spacing no changes in the SPS RF system are needed, but in the PS a new RF system with frequency range 95.4-100 MHz (63.5-66.7 MHz) would be required [1].

In all scenarios the SPS transverse feedback system should be also upgraded (larger bandwidth).

### *Is the SPS a bottleneck?*

The present SPS impedance and main intensity limitations were discussed in [8]. They are summarised below and some new results are presented.

With the existing TW type RF systems in the SPS it is the local beam density (integrated over a distance of $\sim$ 600 ns) which usually counts for beam loading and coupled bunch instabilities. This means that similar effects can be expected with decreased bunch spacing and increased intensity per bunch. This is not the case for single bunch effects listed below, which give a preference for an increased number of bunches.

The main intensity limitations in the SPS to reach ultimate LHC intensity can be divided into single bunch and multi-bunch intensity limitations.

**Single bunch.** We start with a review of the transverse mode coupling instability (TMCI). This instability was observed in the SPS for the proton beam for the first time in 2002 [9] with more experimental data obtained in 2003. The threshold of $N_{th} = 1.2 \times 10^{11}$ ppb was measured for $\varepsilon = 0.3$ eVs, $\tau = 3.6$ ns, $V = 0.6$ MV, $\varepsilon_{H,V} = 1$ $\mu$m [10]. Results for threshold intensity for the LHC bunch at 25 GeV obtained from simulations with HEADTAIL code [11] (including effects of space charge and a realistic flat chamber geometry of the SPS) are shown in Fig. 1. The impedance found as a best fit to the experimental data obtained in 2002 (no MKE kickers in the ring) and 2003 (with 5 MKE kickers installed in the ring) is 20 M$\Omega$/m if space charge is included in simulations and 15 M$\Omega$/m if not. Taking into account that 4 more kickers will be installed soon for operation in 2006 ($\sim 3$ $M\Omega$/m, [12]) one can expect the instability threshold to be just above the nominal intensity.

Cure by higher chromaticity or voltage can lead to an increase of slow beam loss on the injection plateau.

On the flat top the threshold of this instability is significantly higher: $N_{th} = 1.9 \times 10^{11}$ ppb for $\varepsilon = 0.3$ eVs.

The space charge increases the TMCI threshold, but also causes the emittance blow-up for intensities well below this value. This effect could be seen, for example, from the results of simulations done at 25 GeV with $Z_t = 15$ M$\Omega$/m and $\varepsilon = 2.5$ $\mu$m shown in Fig. 2 [11].

The tolerable space-charge tune spread $\Delta Q_{sc}$ at injection in different CERN rings is believed to be: 0.5 in PSB, 0.3 in PS and 0.07 in the SPS (ppbar limit).

In the SPS for nominal (ultimate) LHC intensity $\Delta Q_{sc} = 0.05$ (0.07) [13]. Recent measurements in the SPS at 14 GeV [14] showed that an injected beam with $N = 1.2 \times 10^{11}$ ($\Delta Q_V = 0.3$) had $\Delta Q_{H,V} = 0.14, 0.24$ and a lifetime $\sim$ 50 s after a fast, $\sim 30\%$ loss at injection.

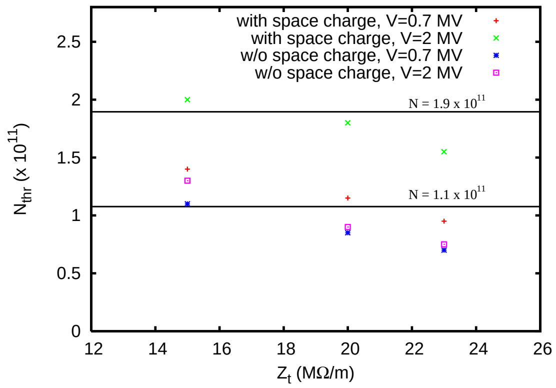


Figure 1: The TMCI thresholds for LHC bunch at 25 GeV for different transverse impedances and capture voltages, chromaticities $\xi_{x,y} = 0$.

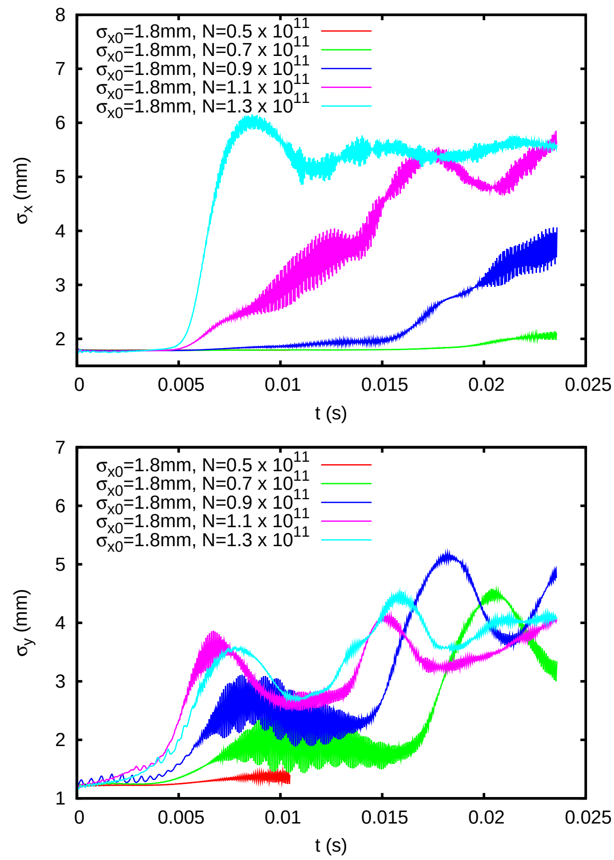


Figure 2: Vertical (top) and horizontal (bottom) emittance blow-up for different intensities of the LHC bunch at 25 GeV for transverse impedance of 15 M$\Omega$/m, space charge included, $\xi = 0$, $\varepsilon_n = 2.5$ $\mu$m

**Multi-bunch limitations in the SPS (total intensity)**

**(I) Electron cloud** leads to emittance blow-up and instabilities, and could also be a cause of slow beam loss on the flat bottom (see below). The effect will be worst with smaller bunch spacing as can be seen from the multipacting threshold measured with different bunch spacing (1 batch at 26 GeV) [15] and shown in Table 1. For the fixed target (FT) beam presented in the last column the effect was observed for very low bunch intensity but during acceleration with shorter bunches (FT beam is debunched at injection which is at 14 GeV/c).

| Bunch spacing (ns) | 75 | 50 | 25 | 15/10 | 5 (FT) |
|---|---|---|---|---|---|
| $N_b/10^{11}$ | 1.2 | 0.6 | 0.3 | ? | 0.1 |

Table 1: Multipacting threshold for different bunch spacing in the SPS at 26 GeV/c (one batch).

**(II) Relative beam losses increase with intensity** and are dominated by capture loss (particles lost at the beginning of ramp). They have strong dependence on batch intensity, much less on total (number of batches) or bunch intensity. At the end of 2004 they were reduced at nominal intensity to $5.5 \pm 0.5\%$ due to a new working point [16] and RF gymnastics on the flat bottom [17]. loss mechanism is still not clear (e-cloud?) and more studies are needed including a careful analysis of the experimental data already acquired (in 2004).

**(III) Coupled bunch instabilities** are mostly defined by local intensity. At high energies, during the ramp one batch is already unstable with $2 \times 10^{10}$ p/bunch. This instability is cured by the operation of the 800 MHz RF system in bunch shortening mode during the whole cycle and preventive emittance blow-up (from 0.35 eVs to 0.45 eVs at injection and then to 0.6 eVs during the ramp). The voltage programmes for the 200 MHz and 800 MHz RF systems used for LHC beam operation in the SPS are shown in Fig. 3 together with corresponding threshold broad-band and narrow-band impedances through the cycle for nominal LHC intensity.

The threshold broad-band impedance leading to the loss of Landau damping during the cycle is shown in Fig. 3 (middle). At the end of the cycle it is below the present estimation of the low-frequency inductive impedance of the SPS of 7 Ω, which means that from this moment in the cycle, even with 800 MHz RF system on, the Landau damping of coupled bunch instabilities is lost.

It is an experimental fact that with the 800 MHz RF system on, but without additional emittance blow-up to 0.6 eVs around 16 s (280 GeV), the nominal beam on the flat top is at the limit of stability. So the value of 0.3 MΩ (the threshold on the flat top, see Fig. 3, bottom) is used below as an estimation of the narrow-band impedance in the SPS.

For coupled-bunch instabilities at injection, for bunch emittance of 0.45 eVs and with 800 MHz on, the limit of 0.3 MΩ is reached at bunch intensity of $1.5 \times 10^{11}$. To avoid uncontrolled emittance-blow-up up to ultimate intensity, beam with larger emittances (0.5 eVs) and the same (or smaller) bunch length should be delivered by PS. At the

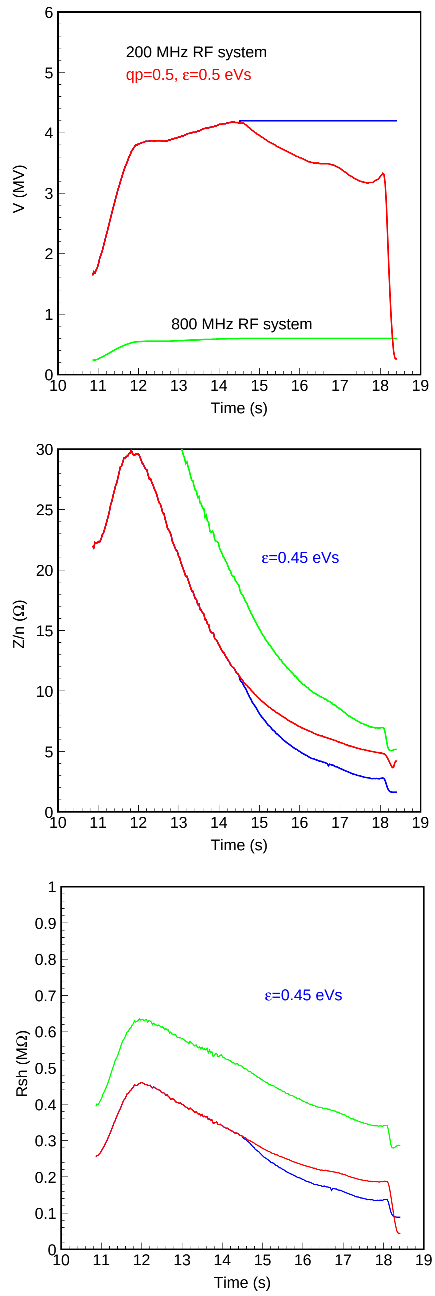


Figure 3: Voltage programmes for the 200 MHz and 800 MHz RF systems (top) and corresponding threshold impedances Im$Z/n$ (middle) and $R_{sh}$ (bottom) for the nominal LHC intensity in the SPS. Top curve in impedance plots: the threshold with the 800 MHz RF system on. Bottom curve: 4.2 MV constant at the end of the cycle, the 800 MHz off.

moment the voltage in the PS is not sufficient to deal with such emittances. In the SPS an emittance up to 0.8 eVs can be accelerated with the maximum available voltage of 8 MV at 200 MHz.

For stability on the flat top at higher currents, controlled emittance blow-up $\varepsilon \propto \sqrt{I_A}$ will be needed. Ultimate intensity would require $\varepsilon = 0.73$ eVs at 450 GeV.

In the LHC, with 3 MV at 200 MHz, capture and transfer to 400 MHz of bunch with $\varepsilon < 1.0$ eVs is possible [18].

**(IV) Beam loading in the 200 MHz and 800 MHz RF systems** is one of limiting factors for high beam current.

Maximum available RF power in one 200 MHz TW cavity in the cycling mode (limited by coaxial line and coupler-cavity connection [19]):

- 700 kW for full SPS ring

- 1.4 MW for 1/2 ring, this mode of operation is not tested experimentally.

The RF power needed in one 200 MHz TW cavity through the SPS cycle for different beam currents and voltage programme from Fig. 3 is shown in Fig. 4. As can be seen the major part of the power needed is due to beam loading and using the pulsed mode over one revolution period will allow the average power to be significantly reduced. The test of the pulsing mode is planned for the end of 2006 [19].

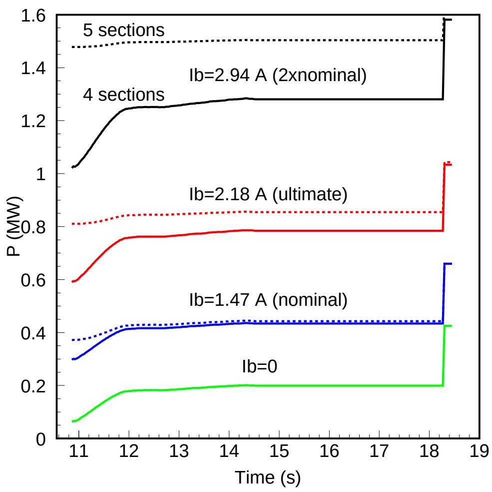


Figure 4: RF power needed in one 200 MHz TW cavity through the cycle in the SPS for different beam currents and voltage programme from Fig. 3. Solid and dotted lines show power needed in cavities with 4 and 5 sections correspondingly, assuming slightly different voltages calculated with the requirement that the RF power per cavity is minimised.

**(V) MKE heating due to its resistive impedance.** Possible solution (ceramic pipe with metallic strips inserted into kicker) [20] will be tested with the beam in 2006 on one MKE kicker.

### *Summary for the existing LHC injector (SPS)*

- **Higher brilliance:** nominal emittance is not yet reached in the SPS in the vertical plane due to e-cloud.
- **Closer bunches:** new RF system needed either in the PS (10, 15 ns) or SPS and LHC (12.5 ns). In the SPS more problems with e-cloud (V-emittance blow-up) and coupled bunch instabilities.

**Main limitations for intensity increase**

- Intensity dependent capture losses in the SPS. Were reduced in 2004, but their exact cause and therefore scaling is not clear.
- Coupled bunch instabilities in the SPS. Can be cured by controlled emittance blow-up but this would require the 200 MHz capture system in the LHC.
- Beam loading in 200 MHz and 800 MHz RF systems - limit at ultimate intensity for known performance.
- Fast transverse instability for more MKE kickers or higher bunch intensities. Below the threshold leads to transverse emittance blow-up. Cure by chromaticity at high voltage could increase slow beam losses.

**Possible improvements and machine studies**

- Further SPS impedance reduction (MKE screens, improved passive damping of HOMs, search for transverse impedances...)
- Capture loss studies with shorter bunches from PS, the same or larger emittance (extra RF voltage in the PS).
- Increased voltage of 800 MHz RF system (1 more cavity in operation in 2006).
- Emittance blow-up up to 0.75 eVs for ultimate intensity - study effect of the synchrotron frequency shift along the batch.
- Capture loss and beam lifetime studies (e-cloud, machine resonances, noise...) - analysis of 2004 data!
- High power RF tests in 2006 (pulsed mode).
- Ultimate intensity bunches injected into the SPS.
- Scrubbing runs at higher intensities.

## NEW INJECTORS

The following injector chain is analysed in this section: Linac $\rightarrow$ PSB $\rightarrow$ PS $\rightarrow$ SPS $\rightarrow$ Super-SPS $\rightarrow$ LHC. Since Super-SPS means Super - Super Proton Synchrotron, this name is replaced below by the HPS (Hyper Proton Synchrotron or High energy Proton Synchrotron).

We will start first with an analysis of acceleration in the SPS up to 150 GeV. Taking into account present limitations we will arrive at conclusions about the minimum cycle length and longitudinal emittance at top energy. Then consideration of the SPS-HPS beam transfer at 150 GeV and of the acceleration in the HPS should point out to the optimum RF system to be used in the HPS. This is followed by a discussion of beam stability in the future HPS.

The following assumptions are used for the analysis.

- Energy: SPS: 25 GeV → 150 GeV,
  HPS: 150 GeV → 1 TeV.
- SPS tunnel: R=1100 m, $\gamma_t = 22.8$ for both rings.
- No major changes in the PSB, PS and SPS.
- The HPS: the 400 MHz (SC) or 200 MHz (NC) RF system, advantages and disadvantages of choosing super- (SC) or normal-conducting (NC) system are discussed in detail in [21].
- Fast acceleration ramps in the SPS and HPS.

### *Present SPS up to 150 GeV*

**Acceleration in the SPS: 25 GeV → 150 GeV.** To see what can be the maximum rate of acceleration in the SPS one should take into account the following limitations:

- Magnets:

  - maximum rate 165 GeV/s,
- The 200 MHz TW RF system:

  - total $V_{max} = 8$ MV,

  - peak power 700 kW per cavity
- Longitudinal impedance:

  - Im$Z/n = 7\ \Omega$,

  - HOMs: $R_{sh} = 400$ kΩ at $f_r = 629$ MHz, ...

The total voltage and peak power per cavity required for different ramp lengths in the SPS are presented in Fig. 5. The voltage programme is designed for an acceleration of a bunch with emittance of 0.5 eVs with filling factor in momentum $q_p$ of 0.95 (as in the present SPS cycle).

As follows from Fig. 5 (top) the minimum length of acceleration ramp could be around 1 s. The values of maximum voltage needed for acceleration during different time and of beam with different longitudinal emittances ($q_p = 0.95$) are summarised in Table 2.

| ramp<br>s | $\varepsilon$<br>eVs | $V_{max}$<br>MV |
|---|---|---|
| 1.0 | 0.5 | 9.2 |
| 1.0 | 0.4 | 8.0 |
| 1.5 | 0.5 | 7.0 |
| 2.0 | 0.5 | 6.0 |

Table 2: Maximum 200 MHz voltage needed for different lengths of magnetic ramp and longitudinal emittances $\varepsilon$.

The present 200 MHz cavities could be used for 1.5 s acceleration time. For nominal intensity and present performance of the 200 MHz RF system the cycle with 2 s ramp is acceptable from the point of view of power requirements. A special test is planned at the end of 2006 to check possibility of running in pulsed (over revolution period) mode which will reduce average power consumption.

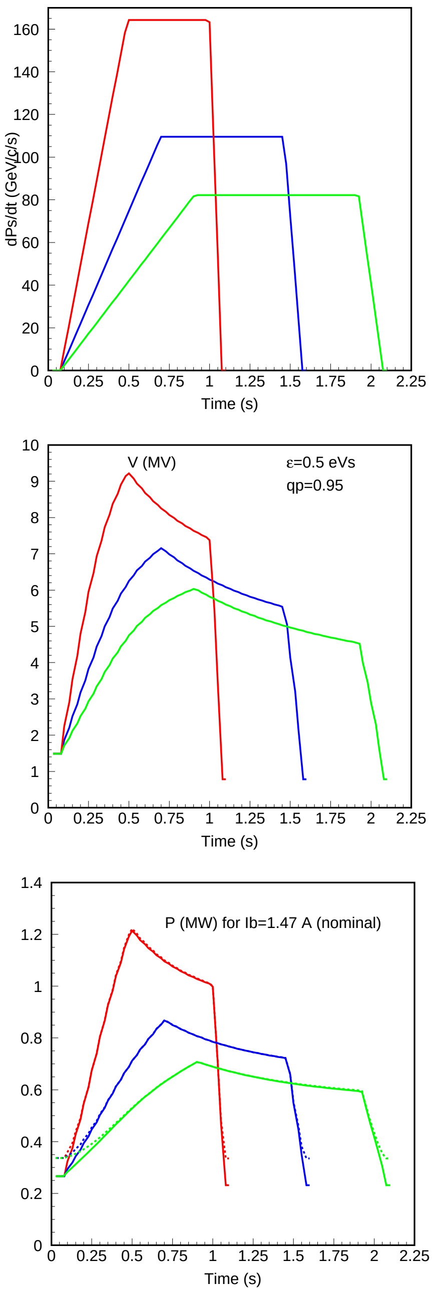


Figure 5: The derivative of the synchronous momentum $dP_s/dt$ (top), total 200 MHz voltage (middle) and required power (at nominal intensity) per cavity of 4 (solid line) and 5 (dotted line) sections (bottom) for different magnetic ramp lengths in the SPS.

**Beam stability in the SPS at 150 GeV.** The choice of the RF system in the HPS depends on the optimum SPS-HPS beam transfer scheme which in turn depends on the beam emittance at 150 GeV. In the present SPS the controlled emittance blow-up at about 270 GeV is necessary to provide beam stability at 450 GeV (see previous section). The analysis of beam stability in the SPS with a top energy at 150 GeV shows that controlled emittance blow-up on the ramp could still be needed. The threshold narrow-band impedances for beam with nominal intensity and emittance of 0.45 eVs are presented in Fig. 6 for cycles of different lengths and the corresponding voltage programmes from Fig. 5. This threshold impedance should be compared with limitation of about 0.3 MΩ (known threshold without controlled emittance blow-up at 450 GeV, see Fig. 3). Similar to the 450 GeV case, the threshold impedance on the flat top is again below this value even with the 800 MHz RF system on. The curves in Fig. 6 (bottom) represent the case when the voltage during the cycle does not go below 4.5 MV but is kept constant up to top energy.

The threshold broad-band impedance $\mathrm{Im}Z/n$ leading to loss of Landau damping at nominal intensity is shown in Fig. 7. In this case some improvement can be noticed in comparison with acceleration up to 450 GeV. With the present SPS impedance estimated at $\mathrm{Im}Z/n \simeq 7\ \Omega$ this is just at the limit for the nominal intensity.

We can conclude that the stabilising effect of the 800 MHz RF system on the 150 GeV flat top is smaller than at 450 GeV. Therefore acceleration up to 150 GeV does not provide a significant advantage for beam stability and an emittance blow-up to (0.5-0.6) eVs even for the nominal intensity still could be necessary.

**Cycle length for SPS and HPS.** Options for the SPS cycle length for two different basic periods of the pre-injector are shown in Table 3 together with the additional voltage $\Delta V$ required in the SPS in some cases.

| PS | SPS | | | |
|---|---|---|---|---|
| basic period s | flat bottom length s | $\Delta V$ MV | ramp length up+down s | cycle length s |
| 1.2 | 3.6x3=10.8 | 0 | 3.6 | 14.4 |
| 1.2 | 3.6x3=10.8 | 3 | 2.4 | 12.6 |
| 0.9 | 2.7x3=8.1 | 0 | 1.5+1.2=2.7 | 10.8 |
| 0.9 | 2.7x3=8.1 | 3 | 1.0+0.8=1.8 | 9.9 |

Table 3: Possible SPS cycle length for different basic periods in the present pre-injector chain.

With the present pre-injectors the SPS cycle length $T_{SPS}^{cycle}$ cannot be less than 10 s. Assuming that $T_{SPS}^{cycle} = T_{HPS}^{cycle}$, we obtain the HPS ramp $\sim T_{HPS}^{cycle}/2 \simeq$ (5-6) s. The same total time is required for two injections of four batches from the SPS, but then the full HPS ring is cycling every (20-24) s.

## *SPS-HPS transfer*

The nominal longitudinal emittance at injection into the SPS is 0.35 eVs and after capture into the mismatched voltage it becomes 0.42 eVs. In the case of beam extraction at 150 GeV the bunch length $\tau = 4\sigma_t = 2.2$ ns for the emittance of 0.6 eVs with 7 MV at 200 MHz. Note that at 450 GeV for the same emittance and with the same voltage the bunch length is much smaller: $4\sigma_t$ =1.6 ns (this value was

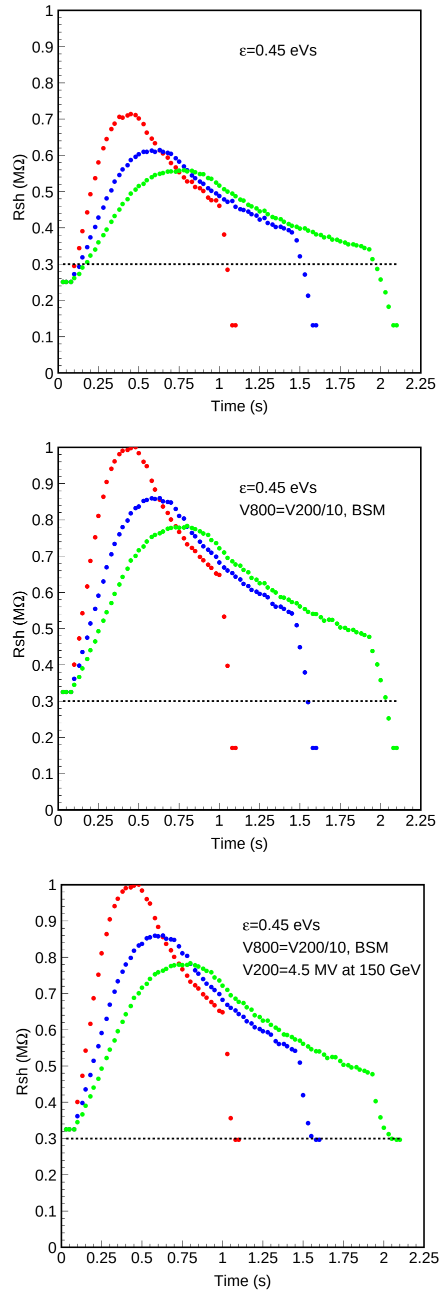


Figure 6: The threshold narrow-band impedance for coupled bunch instabilities at nominal intensity with (1) the 800 MHz RF system off (top), (2) the 800 MHz on in bunch-shortening mode with $V_{800} = V_{200}/10$ (middle) and (3) - the same as (2) but for voltage programmes from Fig. 5 with 4.5 MV to the end of the cycle (bottom).

measured on the flat top for the nominal intensity beam in 2004). This change is due to the fact that in a stationary bucket the bunch length scales with energy in the following way

$$\tau \propto \frac{\varepsilon^{1/2}}{(V\gamma)^{1/4}}.$$

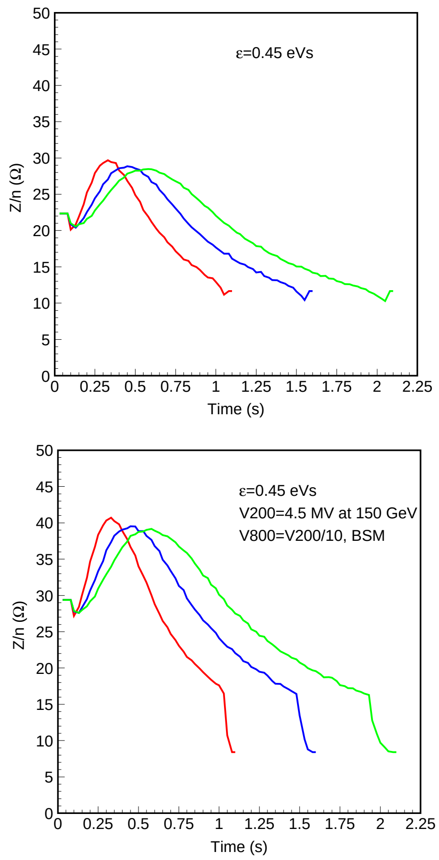


Figure 7: The threshold broad-band impedance leading to the loss of Landau damping at nominal intensity with the 800 MHz RF system off (top) and the 800 MHz on in bunch-shortening mode with $V_{800} = V_{200}/10$ and voltage programmes from Fig. 5 with 4.5 MV to the end of the cycle (bottom).

In the case of transfer into a 400 MHz RF system in the HPS with an RF period of 2.5 ns we need the bunch length to be less than 1.7 ns ($4\sigma_t$ =1.7 ns corresponds to $6\sigma_t$ =2.5 ns and $\varepsilon_{2\sigma}$ contains only 85% of particles). Even in the case with no emittance blow-up, $\varepsilon = 0.35$ eVs, the bunch length $4\sigma_t$ =1.65 ns. The 200 MHz voltage needed in the SPS to obtain shorter bunches at lower energy increases $\propto 1/\gamma_{ext}$ and correspondingly more cavities (practically a new RF system) would be necessary. Another option is a 400 MHz RF system installed in the SPS to shorten bunches before extraction to the HPS. Bunch rotation is another possibility which also needs more voltage (linear part of the bucket) to avoid distorted bunches and could have problems due to beam loading problem at low voltages in the initial stage of RF manipulations. A 200 MHz ("capture") RF system installed in the HPS is a solution similar to one foreseen in the future (for higher intensities) for the SPS-LHC transfer. However, in the SPS-LHC transfer at 450 GeV a voltage of 3 MV at 200 MHz in LHC provides $4\sigma_t = 1.7$ ns for 0.5 eVs whereas in the HPS, even with a much smaller harmonic number $h$, one would need 8 MV due to the fact that the bucket area scales with energy as follows:

$$A_{bucket} \propto \sqrt{\frac{V\gamma}{|\eta| f_{rf}^2 h}}, \quad \text{where} \quad \eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_t^2}.$$

Various options for the SPS-HPS transfer discussed above are summarised in Table 4, see also [21].

| SPS | | HPS | |
|---|---|---|---|
| $V_{200}$ MV | $V_{400}$ MV | $V_{200}$ MV | $V_{400}$ MV |
| 7+9 | 0 | 0 | 10 |
| 7 | 10 | 0 | 10 |
| 7 | 0 | 8 | 4 |
| 4.5 | 0 | 4.5 | 0 |

Table 4: Voltage required for transfer of a 0.5 eVs bunch from the 200 MHz RF system in the SPS to the HPS with the 400 MHz (above line) or with the 200 MHz (last line) RF systems.

As follows from this analysis, depending on the option, (8-10) MV extra voltage is needed for (200→400) MHz transfer at 150 GeV. From this point of view the solution of using the 200 MHz RF system in the HPS seems to be optimum.

## *HPS*

**Acceleration in the HPS: 150 GeV → 1 TeV.** The voltage required for acceleration with the 200 MHz or the 400 MHz RF system of beam with different emittances ($q_p = 0.95$) for different ramp lengths and also with different transition energies is shown in Table 5.

| $\gamma_t$ | $\varepsilon$ eVs | ramp length s | $V_{400}$ MV | $V_{200}$ MV |
|---|---|---|---|---|
| 23 | 0.6 | 3.0 | 23 | 13 |
| 30 | 0.6 | 3.0 | 19 | 12 |
| 23 | 0.5 | 3.0 | 20 | 12 |
| 23 | 0.6 | 6.0 | 16 | 7 |

Table 5: Maximum voltage required for acceleration with the 200 MHz or the 400 MHz RF system.

Using the 400 MHz RF system (SC) will provide easy transfer to the 400 MHz RF system in the LHC, but for the SPS/HPS transfer one needs the 200 MHz cavities in the SPS or HPS, in the latter case with sufficient voltage for acceleration in 6 s. For the 200 MHz RF system (NC) cavities already exist (8 MV) - this is the "capture system" of the LHC. Note that for beam transfer to the LHC at 1 TeV (compare with 450 GeV) for the same $V$ at 200 MHz it is possible to have 20% shorter bunches (for the same emittance) or $\sqrt{2}$ larger emittance (with the same bunch length).

**Beam stability.** As can be seen from Figs. 8-9, for the same acceleration cycle and bunch emittance, beam stability in the 200 MHz RF system is lower than in the 400 MHz RF system. In the absence of the 800 MHz RF system, the beam can be stabilised by a controlled emittance blow-up at high energy (for emittances below 0.85 eVs the 200 MHz RF system is still not needed in LHC) [18].

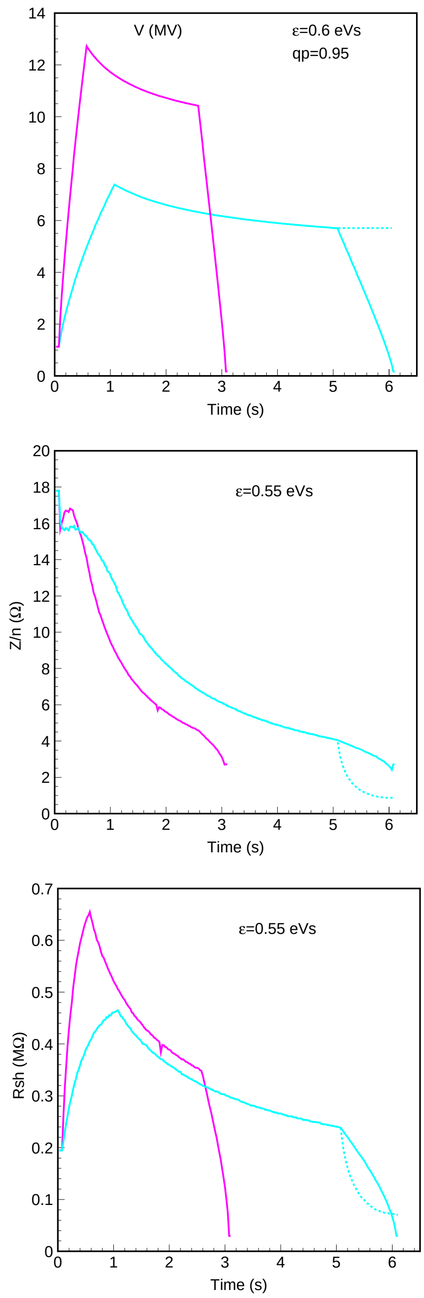


Figure 8: Voltage programmes (top) and corresponding threshold impedances Im$Z/n$ (middle) and $R_{sh}$ (bottom) through the cycle for beam with the nominal intensity and emittance of 0.55 eVs in **the 200 MHz RF system** in the HPS for two different cycle lengths: 3 s and 6 s.

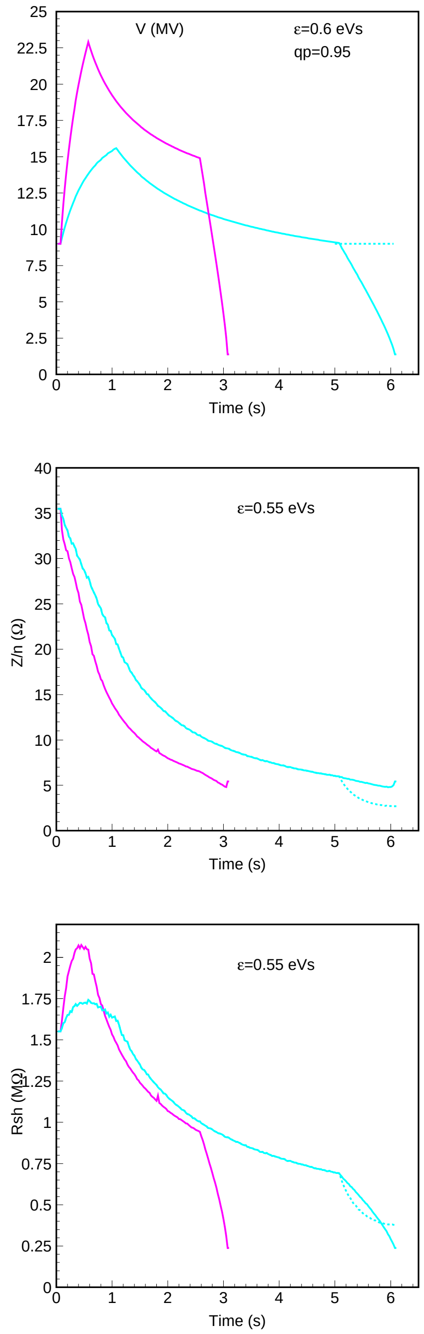


Figure 9: Voltage programmes (top) and corresponding threshold impedances Im$Z/n$ (middle) and $R_{sh}$ (bottom) through the cycle for beam with the nominal intensity and emittance of 0.55 eVs in **the 400 MHz RF system** in the HPS for two different cycle lengths: 3 s and 6 s.

With the 400 MHz RF system the impedance budget for the HPS would be significantly less tight than with the 200 MHz RF system: for nominal intensity Im$Z/n < 2.5$ Ω and $R_{sh} < 400$ kΩ, but probably with more impedance in the ring due to the need for a capture RF system.

### *Summary for a new injector*

**Reducing the top energy in the SPS to 150 GeV**

- allows the ramp length to be reduced to 2 s,
- does not improve longitudinal beam stability (coupled-bunch) on the flat top and controlled emittance blow-up at high energy may still be necessary,
- makes bunch-to-bucket transfer into 400 MHz RF system of the next ring more difficult.

**HPS (Super-SPS):**

- with the present SPS and pre-injectors the minimum ramp length in the HPS can be 6 s,
- using a 400 MHz (SC) RF system requires an additional capture RF system and twice more voltage than with the 200 MHz RF system,
- using a 200 MHz (NC) RF system seems to be optimum, but requires a tight impedance budget (probably achievable for a new machine).

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