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SPS PERFORMANCE WITH PS2

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Abstract

The upgrade of the PS to the PS2 would allow injection into the SPS at higher energy (up to 70 GeV/c). Possible advantages deriving from a higher injection energy into the SPS include the improvement of space charge at flat bottom, absence of transition crossing for all proton beams and a higher threshold for the horizontal electron cloud coupled bunch instability. Transverse Mode Coupling Instability (TMCI) and vertical Electron Cloud Instability (ECI) thresholds are studied in greater detail. Their dependence on energy is defined in simulations with the HEADTAIL code and the results of this study are presented.

INTRODUCTION AND MOTIVATIONS

Studies for the LHC performance upgrade include the improvement of the existing LHC injectors and/or the design of possible new rings in the injector chain [1]. Several scenarios, aimed at overcoming the existing bottlenecks, are presently being taken into consideration. The crucial point of the most promising option consists in raising the injection energy into the existing SPS from the present 26 GeV/c to 50–70 GeV/c. This could allow first to better cope with some of the existing limitations and secondly, a future upgrade of the SPS to a higher extraction energy ring (1 TeV). This scenario would require the corresponding upgrade of the present SPS injector, the PS ring, to PS2 or PS2+ [2].

The first part of this paper will be devoted to the description of the present SPS intensity limitations, and how a higher injection energy could (or would not) help in this regard.

A specific question, which requires a deeper analysis and is addressed in the second part of this paper, is how raising the SPS injection energy would affect the transverse single bunch instability thresholds. In particular, TMCI is expected to be a potential danger in the SPS with the enhancement of the broad-band impedance due to the installation of 9 new MKE kickers in the ring since 2003 [3]. In addition, the vertical electron cloud single bunch instability (to some extent also TMCI type) is at present a limiting factor for the vertical emittance of the nominal LHC beam (the instability can be overcome by operating the ring with a rather high vertical chromaticity after a scrubbing run) [4]. The energy dependence of the threshold for the onset of these instabilities is therefore the subject of the second part of this paper. The study of the effect of higher injection energy into the SPS is carried out following the steps outlined below. We will consider an LHC-type beam interacting with a broad-band resonator impedance or an electron cloud. The essential parameters are listed in Table 1. Even if the LHC-type beam is injected at 26 GeV/c, energy is actually scanned between 14 and 450 GeV/c in order to cover a broader range for the energy dependence study.

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Table 1: Parameters used in our study

Name	Symbol	Unit	Value
Momentum	p_0	GeV/c	14–450
Norm. transv. emitt.	$\epsilon_{x,y}$	μm	2.8
Long. emitt. (2σ)	ϵ_z	eVs	0.35
Bunch length	σ_z	m	0.3
Bunch population	N		1.15×10^{11}
Vertical tune	Q_y		26.13
Momentum comp.	α		0.00192
Shunt impedance	R_T	MΩ/m	20
Quality factor	Q		1
Resonance frequency	$\omega_r/2\pi$	GHz	1.3
E-cloud density	ρ_e	m^{-3}	1×10^{12}

Taking the reference at 26 GeV/c (which corresponds to $\gamma = 27.7$), the main assumptions of our study are:

- The longitudinal emittance and the bunch length are kept constant at the values of 0.35 eVs and 0.3 m (having assumed the present beam production scheme in the PS). The momentum spread $\Delta p/p_0$ is scaled by $1/\gamma$ when changing the energy and the matched voltage is re-adjusted according to $|\eta|/\gamma$ (η is the slip factor) from the matched value of 700 kV at 26 GeV/c (see Fig. 1).

- The normalised transverse emittances are constant, 2.8 μm. Consequently the transverse beam sizes are re-scaled by $\sqrt{1/\gamma}$ when changing the energy.

SPS INTENSITY LIMITATIONS AND EFFECTS OF A HIGHER INJECTION ENERGY

Limitations to the maximum LHC beam intensity that can be accelerated in the SPS can come from single-bunch or multi-bunch effects. In particular, the total beam current is obviously limited by coupled bunch phenomena, but then this current cannot be arbitrarily distributed in the machine, because the bunch intensity is also limited by single-bunch collective mechanisms. Single bunch intensity limitations in the SPS are determined by:

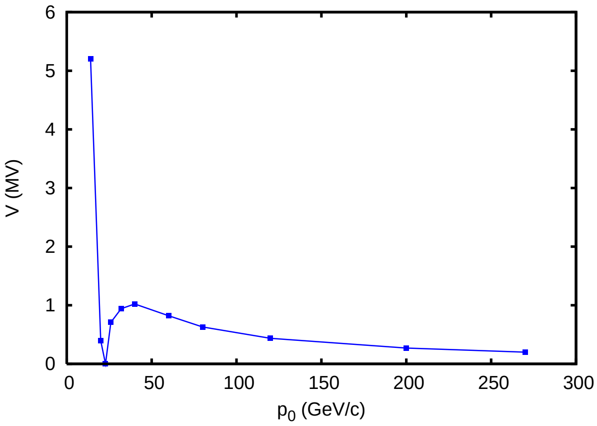

Figure 1: Matched voltage at 200 Mhz at injection in the SPS as a function of the beam momentum.

- Space charge and Intra Beam Scattering (IBS) at low energy (especially for ions).
- Injection losses, since they depend on the beam transverse size at injection.
- Transverse Mode Coupling Instability (TMCI).
- Electron Cloud Instability (ECI) in the vertical plane. We have chosen to put this limitation in this list because the instability mechanism per se is indeed single bunch. Nevertheless, the presence of an electron cloud inside the machine requires many circulating bunches, in this sense all electron cloud related effects should be regarded as multi-bunch.
- Microwave instability, which is presently suppressed with the 800 MHz cavities.

Multi-bunch intensity limitations in the SPS include:

- E-cloud horizontal instabilities
- Coupled bunch instabilities in the longitudinal plane both at injection and at high energy
- Capture losses
- Beam loading in the 200 MHz and 800 MHz rf-systems
- Transverse coupled bunch instabilities due to resistive wall impedance, which are damped by the transverse feedback system.

The LHC proton beam in the SPS is expected to have a space charge tune spread at injection energy of about 0.05 at nominal intensity, and 0.07 at ultimate intensity. The lead ion beam has a space charge tune spread of about 0.08 without bunchlets at nominal intensity, and a calculated IBS time of 300 s (with 43 s injection plateau). Experiments carried out in 2003 at 14 GeV/c and with a high intensity bunch (1.2×10^{11}) in order to maximize the space charge effect [5], showed lifetimes of more than 50 s for a number of working points chosen far from integers and space charge tune spreads estimated in the order of $\Delta Q_{x,y} \approx 0.14, 0.24$. Higher injection energy into the SPS can certainly contribute to remove this limitation, because the space charge tune spread scales like γ^{-2}.

The horizontal electron cloud instability, which manifests itself in coupled bunch fashion, was observed to become better behaved at higher energy. Its growth rate scales like $1/\gamma$, so that at 55 GeV/c the rise time has more than doubled from the 300-400 turns at 26 GeV/c to ≈900 turns [6]. The requirements on the feedback system to fight it would therefore become more relaxed with a higher injection energy.

Experimental studies conducted on capture losses have shown that they depend on batch intensity much more than on number of batches or single bunch intensity. It was observed, for example, that a 75 ns batch has less capture losses. Furthermore, a reduction of these losses from 10-15% to slightly more than 5% was achieved at the end of the 2004 run, with the change of working point $(26.18, 26.13) \rightarrow (26.13, 26.18)$ and some RF gymnastics. The loss mechanism is not clear, but if it is related to space charge, which is the main candidate together with electron cloud, it could be probably improved by raising the injection energy.

Injection losses can be certainly lowered at a higher injection energy, because beam sizes in x and y scale like $1/\sqrt{\gamma}$.

Losses are in general the main intensity limitation, especially for other types other than LHC accelerated in the SPS (like the SFTPRO ot the CNGS). The absence of transition crossing should significantly improve the situation.

A longitudinal coupled bunch instability ascribed to the fundamental and higher order modes of the 200 MHz RF-system, is observed in the SPS with a single batch having 2×10^{10} ppb above 280 GeV/c. It could be suppressed for the LHC nominal beam by means of the 800 MHz RF-system kept in bunch shortening mode throughout the cycle and with a controlled emittance blow up carried out in two steps: first, from 0.35 to 0.45 eVs ($\epsilon_{2\sigma}$) through injection into a mismatched bucket, and then from 0.45 to its final value of 0.6 eVs through beam excitation with band-limited RF-noise at 200 GeV/c. A calculation of the instability threshold throughout all the cycle shows in fact that also at injection the LHC beam is very close to instability. This is confirmed by the observation of a longitudinal coupled bunch instability at injection with 1.3×10^{11} ppb. Increasing the injection energy into the SPS would not change much these limitations, because the evaluated thresholds seem to be little affected. The LHC beam would still be close to instability at injection, and encounter instability during the ramp, if no longitudinal emittance blow up is applied beforehand.

TMCI and ECI will be separately treated in next section.

DEPENDENCE OF THE SINGLE BUNCH INSTABILITY THRESHOLDS ON ENERGY

Transverse Mode Coupling Instability

Transverse Mode Coupling Instability can be qualitatively described as an instability that shows when the single bunch intensity is sufficiently high to cause tail disruption due to the strong wake fields left behind by the bunch head. As the single bunch current is increased, azimuthal mode lines shift. When the threshold value is reached, coupling between a pair of adjoining modes occurs and the beam motion becomes unstable. When the instability growth time is very short compared with the synchrotron period, this instability is also known as "strong head-tail" or "beam break-up", recalling the single bunch instability in a linac, where the intra-bunch synchrotron motion does not play any role [7]. The TMCI threshold is one of the fundamental limitations in the performance of many machines. TMCI was observed in lepton machines, but detailed study of TMCI for hadrons (far from transition crossing) has been started in 2002 with the first observations in the SPS, when a single bunch with very low longitudinal emittance injected into the machine went unstable, showing very similar features to the typical TMCI [8, 9].

Transverse mode coupling by a resonator impedance can be calculated within the Sacherer model using the "Hermitian" modes for Gaussian bunches to get explicit expressions for the frequency shifts and instability thresholds [10]. The approximate expressions for the stability limit (as maximum number of particles per bunch, N_b) with a broad-band resonator impedance, for an ultra-relativistic bunch ($\beta \approx 1$) matched to its bucket and for zero chromaticity, can be written (symbols are explained in Table 1):

$$N_b = \begin{cases} \dfrac{3.75}{\sqrt{2}} \cdot \dfrac{Q^2 Q_y |\eta| \omega_r}{R_T c e} \cdot \epsilon_z [\mathrm{eVs}] & \text{if} \quad \omega_r \sigma_z / c \gg 1 \\ 11.25\pi \cdot \dfrac{Q Q_y |\eta| c^2}{\omega_r^2 \sigma_z^3 R_T e} \cdot \epsilon_z [\mathrm{eVs}] & \text{if} \quad \omega_r \sigma_z / c \leq 1 \end{cases} \tag{1}$$

Different expressions in the limits of very short or very long bunch are given. The longitudinal emittance ϵ_z is defined as 4π times the product between the r.m.s. values of bunch length and energy spread. For the SPS the N_b should be then multiplied by the inverse Yokoya factor $12/\pi^2$ (which is the scaling factor of the dipole wake field, the one responsible for the collective instability [11]) due to the flat structure of the SPS beam chamber. The dependence on the energy is in the slip factor $\eta = (\alpha - \gamma^{-2})$. Therefore, from Eq. (1) it is evident that, if the longitudinal emittance is kept constant, the TMCI threshold levels off as $\eta \to \alpha$ for $\gamma \gg 1/\sqrt{\alpha}$. In the general case one can show that for fixed beam parameters and zero chromaticity the scaling of the TMCI threshold with energy is $\propto p_0 Q_s$, where Q_s is the synchrotron tune. This translates into an energy dependence like $\sqrt{|\eta|\gamma}$ for fixed voltage or $\propto |\eta|$ for matched voltage.

We have used the HEADTAIL code [12, 13] to perform instability simulations of a single bunch interacting with a broad-band impedance. The model uses a bunch made of macro-particles and then subdivided into N slices, such that each macro-particle in a bunch slice feels the sum of the wakes (those corresponding to a broad-band impedance, with their dipole and quadrupole components appropriately weighed with the Yokoya coefficients) of the preceding slices. Particles also move longitudinally according to the equations of synchrotron motion in a sinusoidal voltage. Scans for different intensities in ranges of plausible values have been done to find the thresholds at different energies. The simulations were run with and without space charge to assess how the additional tune spread introduced by space charge affects the instability dynamics and threshold.

The main advantages of the macro-particle simulation are:

- Simulations can be run for particles in a sinusoidal voltage, whereas the analytical formula is only valid in the linear approximation of longitudinal motion. Besides, the stability of an unmatched bunch can also be studied because the longitudinal dynamics is correctly modeled also when the bunch is not matched to the bucket and executes quadrupole oscillations.
- Both the effect of dipole and quadrupole wake fields for flat pipe can be included.
- Space charge can be included and its effect disentangled.

A simulation campaign was launched at 26, 40, 60, 270, and 450 GeV/c (taking other parameters from Table 1) in order to study the dependence of the TMCI threshold on energy. Applying Eq. (1) with the long bunch approximation ($\omega_r \sigma_z / c \simeq 8$) to the SPS bunch, we obtain at 26 GeV/c a TMCI threshold of about 1.3×10^{11}. The threshold value scales then like $|\eta|$, i.e. it increases up to about 100 GeV/c and levels off at about 4.5×10^{11} for higher energies. Figure 2 shows the results of the HEADTAIL simulations. Thresholds obtained in simulations have the expected energy dependence ($\propto |\eta|$), but are about a factor 2 below those analytically predicted. This is probably due to the approximations of the analytical model and to the fact that we are at the lower limit of the range of applicability of Eq. (1), close to where it breaks down. Besides, the value used for the voltage in the simulations is a factor about three below the value really used for capture in the SPS (2 MV). Simulations including space charge show that space charge can indeed raise the TMCI threshold up to energies of 60 GeV/c and probably higher, but becomes negligible at very high energies.

Electron Cloud Instability

Electron cloud instabilities can be also simulated with the HEADTAIL code, which was actually first written for this purpose. The kick approximation is used for the action of the electron cloud on the bunch, namely the ac-

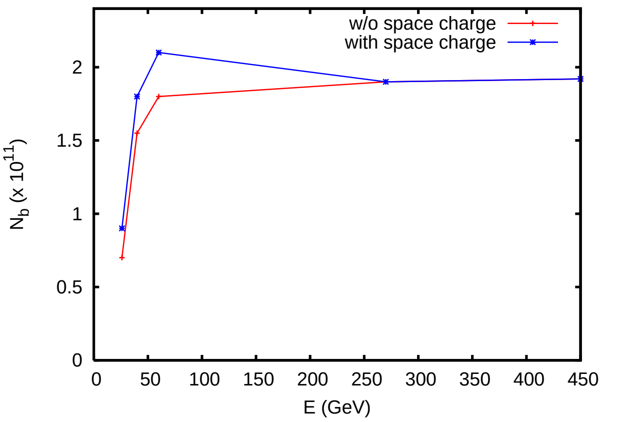

Figure 2: Simulated TMCI thresholds at different energies, with and without space charge.

tion is lumped in one or more points along the ring. The N_p macroparticles of which a bunch is made are distributed over N_{sl}. The bunch slices interact with N_e macro-electrons, having initial uniform distribution with zero initial speeds in the cross-section of the pipe, after one another. Each slice sees the electron cloud as deformed by the interaction with the preceding slices. The distortion of the cloud distribution induced by the bunch that goes through it, is the mechanism that couples body/tail motion of the bunch with the head motion and potentially causes instability. HEADTAIL has been recently upgraded to deal with more realistic initial distributions of the electrons. The necessity of a more self-consistent model to gain more confidence in the predictions was evident, because the average electron density over the full pipe cross section can differ by a lot from the local density around the bunch, which is most probably more directly related to the development of instabilities. Therefore, HEADTAIL can now load the electron distribution directly from the build up code ECLOUD [14] and use it for the instability simulation. This has required a few changes both in ECLOUD and HEADTAIL.

ECLOUD has been modified to save to file the electron distribution snapshot at the time when a bunch starts going through the cloud. The reason why we chose to take the distribution at the beginning of a bunch passage rather than at the end of the inter-bunch gap lies in that ECLOUD runs a *clean* routine at the end of each inter-bunch gap, with which all macro-electrons with very low charge are suppressed and the number of macro-electrons is about halved.

HEADTAIL has been modified to read the electron distribution in the 4D transverse phase space from another input file. The macro-electrons from ECLOUD have different charges, therefore all the subroutines for field calculation had to be updated to deal with macro-particles having different charges. Upon being loaded, the charges are also re-scaled to model an electron cloud spread all over the ring, or over a known fraction of it that can also be specified in the second line of the new input file. The re-scaling coefficients assume that the build up simulation that generated the distribution file had been run for a 1 m accelerator segment.

The integration ECLOUD-HEADTAIL, though not completely self-consistent, is certainly a significant step forward with respect to the old model, which only interfaced the two codes through the value of the average density over the pipe section.
The dependence of the ECI on energy has been studied using the HEADTAIL code with the parameters in Table 1. To gain an insight into the physical mechanism that determines the dependence of the instability threshold on energy, we have first looked for thresholds at different energies with a fixed electron cloud density assuming that the electron cloud builds up in the dipole regions (which is supported by experimental observations and ECLOUD simulations). This last assumption causes the electron motion to be bound along the vertical direction. Preliminary results of this study were already presented in Ref. [15].

Figure 3 shows that the ECI threshold decreases with energy under the given assumptions. The reason is that, even if the bunch becomes more rigid at a higher energy, and therefore less sensitive to collective effects, it also becomes transversely smaller, which enhances the effect of the electron cloud pinch (higher electron oscillation frequency and stronger wake amplitude, see Fig.4). Besides, the matched voltage decreases like $|\eta|/\gamma$, which causes a decrease of the synchrotron tune with consequently less mixing due to the longitudinal motion.

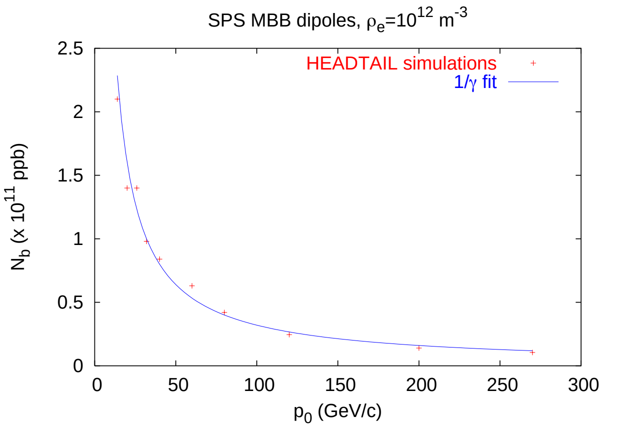

Figure 3: Simulated ECI thresholds at different energies, study done with fixed e-cloud density.

A full self-consistent scan would be much more CPU time consuming. For a “coarse” intensity scan we would at least scan 10 bunch intensity values for each energy value (10 x 10 runs if we are taking 10 different energy values). As many (100) ECLOUD runs are needed beforehand to get the electron distributions that have to be input into HEADTAIL. The number of macro-electrons N_e comes from ECLOUD and ranges usually between 5×10^4 and 10^5. N_p and N_{sl} need to be chosen as a balance between:

- The bunch slicing still assures a good resolution of the electron motion: $N_{sl} \gg n_{e,osc}$, with n_{e_osc} number of oscillations performed by the electrons during one bunch passage.
- All slices are sufficiently populated ($> 10^3$) , even those in the tails.

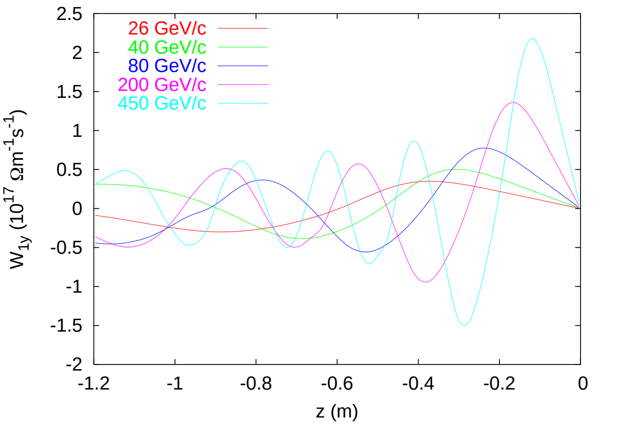

Figure 4: Electron cloud wake fields for beams at different energy ranging between 26 and 450 GeV/c.

Typical numbers are $N_p = 3 \times 10^5$ and $N_{sl} = 80$ and CPU times amount to about 10h per run (512 turns). Sample result of ECI as coherent centroid motion and emittance growth for different bunch intensities at 50 GeV/c is shown in Figs. 5 and 6 for secondary emission yields δ_{max} of 1.8 and 1.4, respectively. The threshold is about the same as the one previously found with the approximation of uniform electron distribution if $\delta_{max} = 1.4$. It is lower (about 5×10^{10}) for $\delta_{max} = 1.8$. Since the electron cloud build up hardly depends on the bunch transverse sizes, we can conclude that the dependence of the threshold on energy stays unchanged with respect to the fixed electron cloud density analysis presented above, except that it may become equal to the one for electron cloud build up for energies higher than ≈ 100 GeV/c.

Solutions that could be envisioned to circumvent the problem of ECI at higher energy are NEG coated or grooved surfaces in the SPS dipole pipes (which have secondary emission yields by far lower than regular surfaces). The space needed to accommodate the jacket for the NEG coating could cause a restriction in the pipe cross section. This could help more, as electron cloud build up is mitigated by having a smaller pipe radius. Furhermore, a 25% or 50% smaller beam pipe should not pose severe aperture problems, because the beam would be transversely smaller at injection (to be checked with the SFTPRO and CNGS beams). It has been calculated that $\delta_{max} = 1.4$ is at the limit for stability for a pipe which is 75% of the present one, and up to $\delta_{max} = 1.6$ could be tolerated for a pipe 50% smaller.

CONCLUSIONS

There are a few advantages to inject the beam into the SPS at higher energy (50-70 GeV/c), which are listed below:

- Less space charge and IBS
- Weaker coupled bunch ECI
- Less injection and capture losses
- Absence of transition crossing

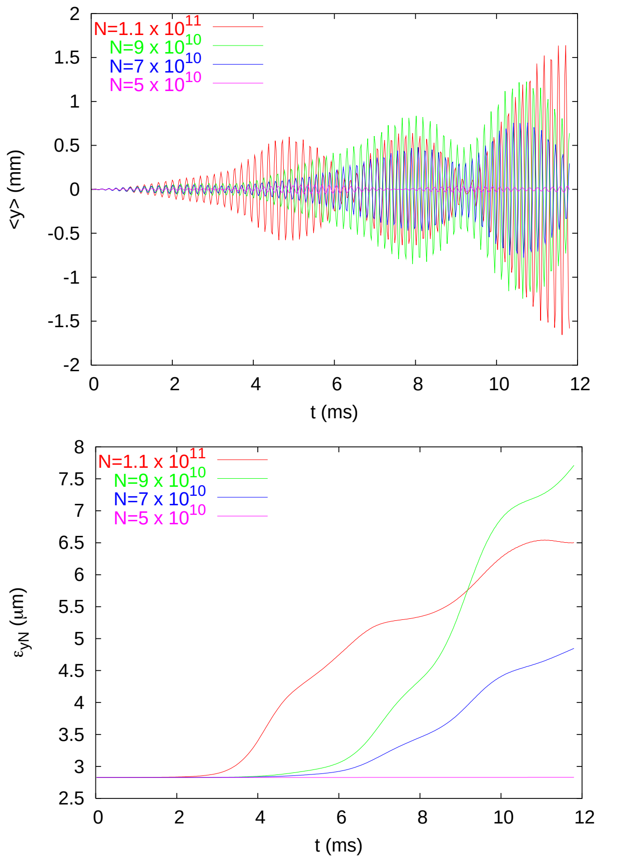

Figure 5: Vertical centroid motion (above) and emittance growth (below) with self-consistent electron cloud for different bunch intensities and $\delta_{max} = 1.8$.

- Higher threshold for TMCI
- Weaker coupled bunch instability from resistive wall impedance.

Nevertheless, no significant improvement is expected for the longitudinal coupled bunch instability. Moreover, the threshold for the vertical single bunch ECI, one of the known present limits of the SPS performances, decreases with energy (assuming constant bunch length, longitudinal emittance and transverse normalized emittances).

This could be in principle overcome by suppressing the e-cloud build up with NEG coated or grooved surfaces, which could entail a smaller beam chamber vertical radius, and therefore even better suppression if tolerable in terms of aperture.

ACKNOWLEDGMENTS

The authors would like to thank G. Arduini, W. Fischer, R. Garoby, T. Linnecar, and F. Zimmermann for encouragement, collaboration and fruitful discussions.

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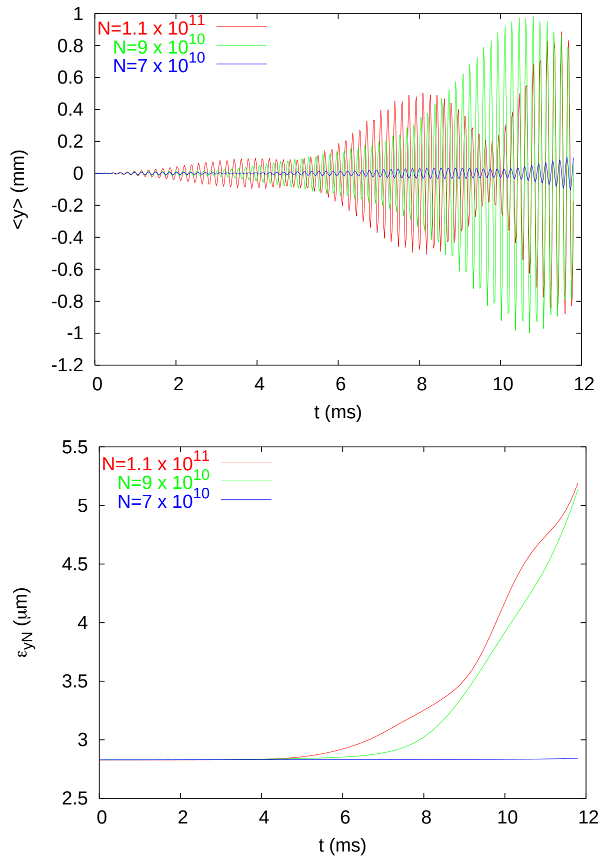

Figure 6: Vertical centroid motion (above) and emittance growth (below) with self-consistent electron cloud for different bunch intensities and $\delta_{max} = 1.4$.

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