Present knowledge of the longitudinal SPS impedance

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Abstract

The longitudinal impedance of the SPS has been a subject of study from the first days of commissioning of the machine. Our knowledge today allows many phenomena to be explained and has also led to a campaign to reduce the impedance. However studies continue especially in connection with new, future, roles of the SPS. An overview of our present understanding and latest results will be given.

1 INTRODUCTION

Present knowledge of the SPS impedance is the result of the work of many people over all the years of the SPS construction and operation. Due to their efforts the design beam intensity was exceeded by more than a factor 10. Future roles of the SPS as injector to the LHC [1] and a provider of the neutrino beam to Grand Sasso require another increase in both total and bunch intensities. Collective effects, mainly instabilities, may create serious limitations for the beam intensity and quality. Detailed knowledge of the coupling machine impedance allows the most effective ways of overcoming them to be found.

It is convenient to divide the various types of impedance in the accelerator ring according to the type of instability they lead to. Below we shall consider:

- Narrow-band impedances with $\Delta\omega \ll 1/\tau$, where $\Delta\omega$ is the impedance bandwidth (for a resonator with quality factor Q and resonant frequency $\omega_r = 2\pi f_r$, $\Delta\omega = \omega_r/(2Q)$) and τ is the bunch length. Their sources are the fundamental and HOMs in the different (at the moment 5) RF systems of the SPS. The wake field created by this impedance lasts during the passage of many bunches. These impedances lead to **coupled bunch instabilities**.

- Broad-band impedances with $\Delta\omega \gg 1/\tau$. Sources: space charge, steps in accelerator chamber cross-section, bellows, stripes and so on. The wakefield created by these impedances is very local and decays over one bunch length. So it can lead only to **single bunch instabilities**.

- Impedances with $\Delta\omega \sim 1/\tau$ lead usually to **batch type instabilities**. In this case a short-range wakefield can couple a few consecutive bunches but decays in any significant gap (as exists in the LHC type beam in the SPS). The sources are for example well damped HOM in the RF systems or resonant modes in accidental cavities (like vacuum ports, septa, kickers and others).

This division is nevertheless not absolute and depending for example on the bunch spacing the same impedance can lead to a single bunch or batch type instability.

The realistic impedance model of the accelerator should include all these types of impedance. Knowledge of the impedance is based on

- Measurements with the beam. This can be done either

  - with *stable* bunches, measuring bunch lengthening, quadrupole frequency shift, debunching rate and other parameters. From measurements with stable bunches only low-frequency (below $1/\tau$) part of the impedance can be probed.

  - or with *unstable* bunches. Measurements of the spectrum give information about impedance frequencies; measurements of thresholds and growth rates of instability - about the impedance value.

- Impedance calculations (analytical and with different numerical codes such as MAFIA, URMEL, ABCI, HFSS ...). This is done for RF cavities, vacuum ports, kickers and so on.

- Measurements in the lab (wire method, excitation with probes...). This is done for all RF cavities, vacuum ports, septa, kickers, BPMs and many other elements in the ring.

2 NARROW-BAND IMPEDANCES

In Fig.1 $\Re[Z]$ of different fundamental and HOMs of the existing RF systems in the SPS is shown as a function of frequency up to 1.2 GHz. These data were collected from different published and unpublished sources [2].

Three of the five SPS RF systems will be removed from the ring after the end of LEP since they are dedicated to lepton acceleration. To accelerate protons and ions TW (travelling wave) 200 MHz and 800 MHz RF systems are used. Their HOMs, see Table 1, apart from a few lowest modes are not very well known. Frequencies of different modes in the 200 MHz RF system were measured with short lepton bunches using the probes in the cavities [2]. For the 800 MHz RF system they were estimated in [3].

The narrow-band impedances cause coupled bunch instabilities which were observed in the past with different beams in the SPS [4]. The effect of these instabilities on the fixed target beam was measured in different MDs during 1997-1998 [5] and was described in detail in Chamonix IX [6]. Briefly it can be summarised as follows.

- Fixed target proton beam in the SPS is unstable already at intensities of 4×10^{12} (10/11 of the ring).

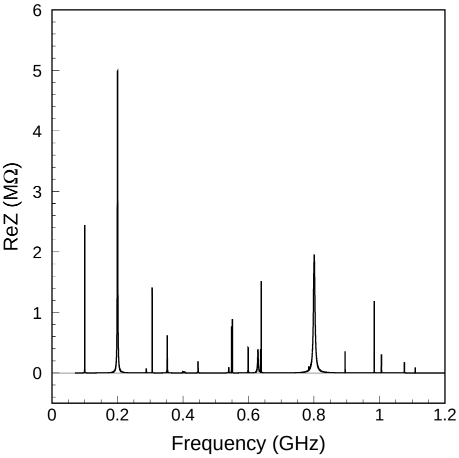

Figure 1: Real part of the impedance of the SPS RF cavities modes.

n	f_{res} MHz	Source	No. cav.
1	912	TW200	4
2	978	TW200	4
3	1075	TW200	4
4	1130	TW200	4
5	1284-1328	TW200	4
6	1334-1364	TW200	4
7	1395	TW200	4
8	1445	TW200	4
9	1503	TW200	4
10	1860	TW800	2
11	1910	TW800	2
12	2500	TW800	2
13	2780	TW800	2

Table 1: HOMs in TW RF systems.

- At intensities of 4×10^{13} in normal operation the longitudinal emittance blows-up by a factor 10 (from 0.2 eVs to 2 eVs), filling completely the bucket.
- Beam is more unstable towards high energies.
- Bunch shape oscillations (different multipoles, from dipole to octupole, depending on cycle time and intensity) are observed together with the growth of a wide band beam spectrum which reaches maximum amplitude on the flat top.

A few examples of this spectrum at different beam intensities and time in the cycle were presented in [6], where possible sources from HOMs were also discussed.

For the narrow band impedance with $\Delta\omega_r \ll M\omega_0$ (M - number of bunches, ω_0 - revolution frequency) the unstable spectrum for the coherent mode (m, n) consists of lines at frequencies

$$\omega_k = 2\pi f_k = (n + lM)\omega_0 + m\omega_s, \quad -\infty < l < \infty,$$

where ω_s is the synchrotron frequency, $n = 0, 1...M-1$ is the coupled bunch mode number, decribing the phase shift between adjacent bunches, $m = 1, 2...$ is the multipole number. Sometimes knowledge of n alone is sufficient to determine the resonant frequency of the guilty impedance $\omega_r \simeq (lM + n)\omega_0$. In the SPS with its 5 different RF systems and many other cavity like objects it is not always obvious.

Examples of the beam spectrum envelope calculated for different beam parameters were presented in [6] with the remark: "They suggest that it is difficult to make conclusions about the resonant frequency of the driving impedance from the shape of the spectrum envelope."

Later a more detailed study has shown [7] that the position of the maximum in the beam spectrum envelope f_{max} is defined by the parameter $f_r\tau$. This can be seen in Fig.2 where the value of $f_{max}\tau$ is plotted as a function of $f_r\tau$ for the dipole mode $m = 1$ and a binomial distribution function with $\mu = 1$. Together with consideration of instability growth rate as a function of $f_r\tau$ for different mulipole numbers m and types of particle distribution described in our case by parameter μ, one can come to following conclusions:

- f_r does not exceed f_{max} by more than $\sim 0.2/\tau$,
- if $f_{max}\tau < 1$, then $f_r\tau \leq 1.2$,
- if $f_{max}\tau > 1$, then $f_r \sim f_{max}$.

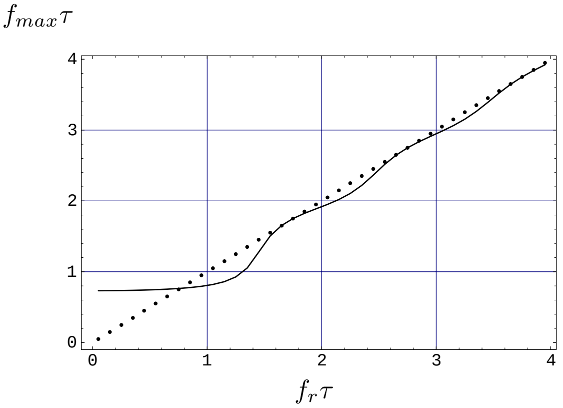

Figure 2: Position of the maximum in the beam spectrum envelope as a function of resonant frequency for dipole mode $m = 1$ and binomial particle distribution with $\mu = 1$.

Application of this analysis to some spectra observed in the SPS with $nf_0 \simeq$ 113 MHz suggests that the probable source of instability is a HOM of TW200 (see Table 1) with f_r = 912 MHz rather than the HOM of SW100 with f_r = 288 MHz. Indeed, the same maximum $f_{max} \simeq$ 700 MHz observed for different bunch lengths $\tau \sim$ (1.5-2) ns at end of the cycle and (2.5-3) ns - after transition, gives $f_{max}\tau = 1 - 2$.

3 IMPEDANCES WITH HIGH R/Q AND LOW Q

Measurements of the spectrum of unstable single bunches injected into the SPS with RF off allowed the impedances with high R_{sh}/Q and low Q to be seen up to 4 GHz, [8]. Apart from the fundamental and some high order modes of the 5 different RF systems installed at the moment in the SPS, less known sources were identified as well. They are vacuum ports – cavity-like objects between dipole magnets all over the ring, and extraction septa (MSE and MST).

First estimations of the impedance of the vacuum ports were made even before the building of the SPS [9] and two ceramic resistors were installed in each port lowering the value of Q on average by a factor 10. The quality factors Q measured in the laboratory for modes already damped are of the order of 50-100, [2]. The R_{sh}/Q values were calculated with MAFIA [10].

The frequencies calculated agree extremely well with beam measurements. We also made an attempt to estimate the impedance value from measurements of instability growth rate. From the linear theory for the fast microwave instability due to a narrow band impedance the growth rate

$$\Im[\Omega] \propto \omega_r \left(N \frac{R_{sh}}{Q}\right)^{\frac{1}{2}},$$

where N is the bunch intensity.

Due to the complicated structure of the signal in time the growth rate is in general ill-defined. In Fig.3 we present measurements of e-folding time done in 1996 at known frequencies in selected cases having a well-defined linear part. The impedance estimations have a huge scatter due to the quadratic dependence of R_{sh}/Q on growth rate. Nevertheless these measurements suggest that R_{sh}/Q of impedance at 400 MHz is only 4 times less than the 24 kOhm of the fundamental mode of the TW 200 MHz RF system. There is also some unknown impedance around 1 GHz.

The model containing the impedances from the four elements (travelling wave RF systems at 200 and 800 MHz, extraction septa and vacuum ports) and consisting of 12 resonant peaks have been used in numerical simulations to reproduce bunch lengthening measurements, [11]. While the dependence of calculated and measured bunch length and peak line density are in general very close, it seems that some impedance is still missing in the present model.

The programme developed to cure this instability, see [1], includes shielding the guilty elements found.

Below we present the status of the vacuum ports shielding project [12]. Project coordinators are P.Collier and A.Spinks.

- Last (1999) year the design was finalised for: 4 types of the most common SPS chambers: MBA-MBB, MBB-MBA, MBA-MBA, MBB-MBB; the RF contacts (fixed at the ends and sliding in the center) and the pumping slots (round with diameter of 3mm).

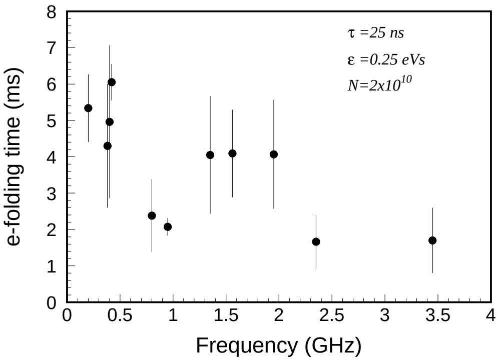

Figure 3: Measurement of e-folding time of instability at selected frequencies.

- The transitions for QF - ..., QD - ... and other special chambers are still to be developed.
- 30% of the SPS chamber dimensions have been surveyed [13].
- Installation during the shutdown 1999/2000 started on 12.01.2000 (2 magnets per day ≡ 4 chambers/day) and will be done in 50% of 3 sextants (∼ 20% total).

The magnets which will be displaced are shown in a schematic way below

QD=MBB=MBB=MBA=MBA==QF
⇓
QF=MBA=MBA=MBB=MBB==QD
⇓

The status of the SPS septa shielding [14] is shown in Table 2. Shielding design was done by F.Caspers and A.Rizzo.

year	shielded	unshielded
1997	0	16
1998	1 MSE	15
1999	3 MST + 5 MSE	8
2000	6 MST + 7 MSE	3
2001	6 MST + 10 MSE	0

Table 2: Status of the SPS septa shielding

Note that in the 2000/2001 shutdown, lepton equipment (2 MSL) will be removed from the SPS and later 8 more septa (already shielded) will be installed in the ring for beam extraction to the LHC.

4 LOW-FREQUENCY IMPEDANCE

The low-frequency inductive impedance is an important characteristic of the total coupling impedance of the ring. It can not itself cause an istability of the bunched beam but it leads to potential well distortion and, due to the coherent frequency shift produced, can cause loss of Landau damping. Both broad-band and narrow-band impedances contribute to the low-frequency inductive part of the machine impedance. Contribution from a resonant impedance at frequency $f \ll f_r$ is $\Im[Z]/n \simeq R_{sh}/(Qn_r)$, where $n_r = f_r/f_0$.

Known contributions from different elements in the SPS ring in the 1999 are shown in Table 4. Note that the impedance of the TW 200 MHz cavities becomes purely inductive only at frequencies much less than 200 MHz. A ”typical” proton bunch in the SPS has 2-5 ns bunch length and can sample the impedance up to 1 GHz.

Element	N	$\Im[Z]/n$ Ohm	Ref.
TW200-F cavities	4	4.9	[15]
TW200-HOM	4	0.25	
TW800-F cavities	2	0.35	[3]
Lepton RF cavities	28	1.7	[2]
Vacuum ports	900	3.0	[10]
MKE + MKP kickers	6	2.0	[16]
MSE + MST septa	8	0.1	[2]
Bellows	900	0.1	[17]
Total		12.4	

Table 3: Low frequency inductive part Z/n of different elements

The first low-frequency impedance budget based on impedance calculations for different elements was presented in [17], where $Z/n = 6.2$ Ohm was found.

Space charge impedance could be approximately estimated using the formula for a round beam pipe. At 14 GeV, for a fixed target beam with ratio of beam pipe to beam radius $b/a = 2$, one gets $\Im[Z]/n$ ∼-2 Ohm. For the nominal LHC beam at 26 GeV, $\Im[Z]/n \sim$ -1 Ohm for $b/a = 5$.

Change in bunch length, coherent frequency shift and debunching rate with bunch intensity were used in the past by different people to estimate $\Im[Z]/n$ from measurements with the beam. They give $\Im[Z]/n$ in the range (10 - 20) Ohm.

5 RECENT (1999) MEASUREMENTS WITH THE BEAM

A series of beam measurements were done in group SL/HRF last year in collaboration with SL/OP and PS division with the purpose of following up the longitudinal impedance reduction programme.

These measurements can be divided in two parts:

- measurements with long bunches, RF off, to look at effect of impedance reduction at different frequencies,
- measurements with short bunches, RF on, to see overall effect of machine impedance change from
  - quadrupole frequency shift,
  - peak oscillation amplitude,
  - bunch lengthening.

In comparison with measurements done in 1996, in 1999 half (8 from 16) of the septa were shielded and the 400 MHz SC RF cavity was removed from the ring. All this would have very little effect on measurements of $\Im[Z]/n$, but we had hoped to see this in measurements with RF off and long bunches at frequencies around 400 MHz. To be able to calibrate the results we have done reference measurements at other frequencies for impedances which did not change (200 MHz and 800 MHz TWC). These results are shown in Fig.4. They should be compared with similar measurements done in 1996 and presented in [11].

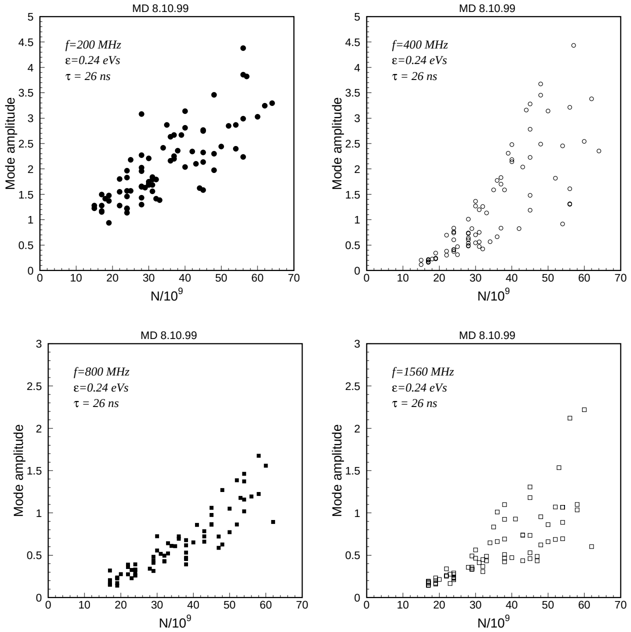

Figure 4: Measurements of threshold at different frequencies in 1999. Maximum amplitude of the signal as a function of bunch intensity.

Although definitive conclusions can be made only when all septa are shielded one already may express doubts that the septa are the only source of signal seen at 400 MHz.

The results shown in Fig.4 have quite a large scatter, however they do not have the intensity dependent initial bunch parameters which caused a lot of problems in the first MDs last year. The solution found in the PS (R.Cappi) was to use the so called internal target to scrape the beam before extraction to the SPS in vertical dimension without

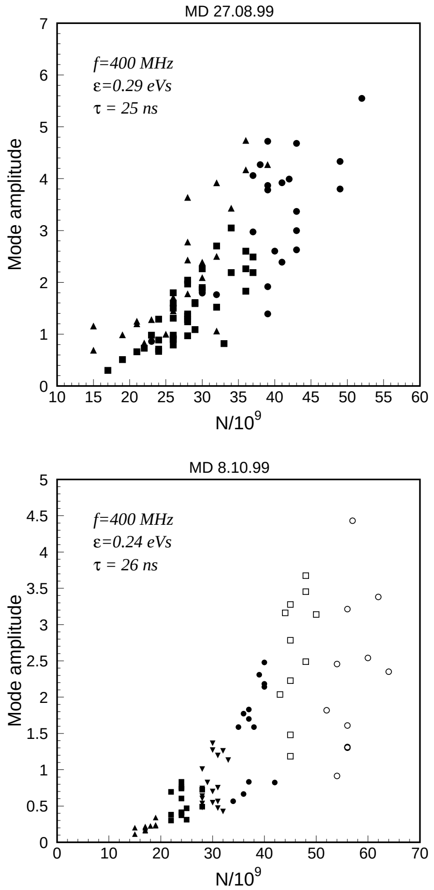

Figure 5: Maximum amplitude of the signal at 400 MHz as a function of bunch intensity. Intensity was changed in steps (shown by different symbols) in the Booster (top) and by vertical scraping in the PS (bottom).

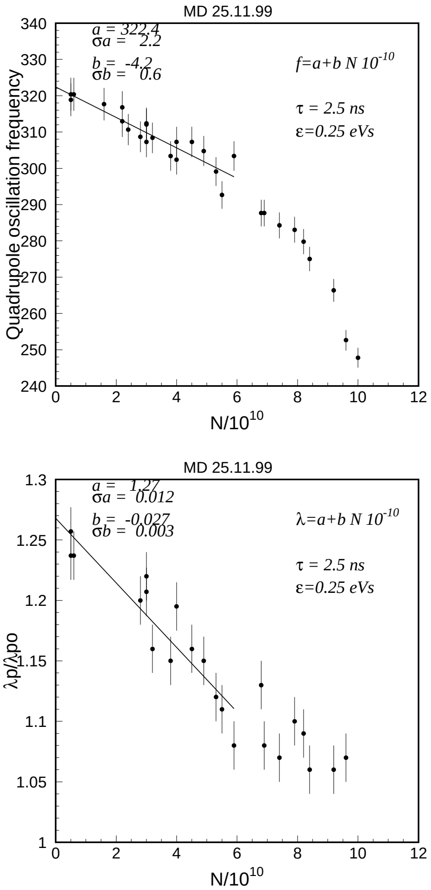

Figure 6: Quadrupole oscillation frequency (top) and peak oscillation amplitude (bottom) as a function of bunch intensity. Intensity was changed in the PS using vertical scraping.

affecting the longitudinal bunch parameters. Another option which became available at the end of the year in the SPS (R.Jung) was to scrape the bunch vertically during the first 10 ms after injection. This worked well, however it was not obvious how the continuous change of intensity would affect final results of instability measurements.

In Fig.5 the difference between measurements done using 2 different methods of intensity change: in the Booster (top) and by scraping in the PS (bottom) is well seen. Different symbols show different steps in measurements when the PS was asked to change the bunch intensity. In the first case these steps are seen as clusters in measurements showing that parameters other than intensity were systematically changed as well. With vertical scraping in the PS we see only random scatter.

Using the same technique for intensity variation we have done measurements with short single bunches captured in 200 MHz RF system. These bunches were specially prepared in the PS (R.Garoby, S.Hancock) for this type of measurement using the maximum voltage available before extraction to the SPS.

The results for quadrupole oscillation frequency and peak oscillation amplitude are shown in Fig.6. The voltage of 910 kV - much higher than matched one was chosen for measurements to avoid losses at highest intensities. Bunch emittance of 0.25 eVs was calculated using the bunch length (2.5 ns) measured from the bunch profile and an energy spread estimated from the low intensity debunching rate. Line density distribution was assumed to be parabolic.

The parameters of these bunches are quite close to the nominal LHC beam and these results also show that a single bunch becomes unstable at intensities 6×10^{10}.

It is very important that these types of measurements can be reproduced this year (2000) and later.

6 SUMMARY

- Narrow band impedances:

  - the situation will be improved with the removal of lepton equipment,

- HOMs in 200 MHz and 800 MHz TW RF systems should be studied in more detail,

  - progress in analysis of the beam spectrum can help to identify sources of coupled bunch instabilities.

- Shielding of vacuum ports and septa should increase the threshold of microwave instability.
- Measurements were done to follow up the impedance upgrade programme both for total impedance and different elements. It is very important to have conditions which are reproducible from year to year.
- Most of the dominant sources of the longitudinal SPS impedance seem to be identified but some surprises are still possible and the search for them should continue.

Our knowledge is changing, but impedance also... Hopefuly the first is increasing and the second - decreasing.

7 ACKNOWLEDGMENTS

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