Measures against longitudinal instabilities and beam loading

T. Bohl, CERN, Geneva, Switzerland

Abstract

Ongoing work in the SPS to avoid longitudinal instabilities of the beams for LHC and to overcome beam loading will be reviewed. Emphasis will be put on the consequences for RF installations but also for some other selected machine components. Different ways of approaching this problem will be discussed. Preliminary results as well as future plans will be presented.

1 INTRODUCTION

The single bunch intensity of the proton beam is 1.1×10^{11} to 1.7×10^{11} protons per bunch [1]. For the lead ion beam the number of charges per bunch is about 1.3×10^{10} [1] or about a factor ten lower. Regarding longitudinal beam instabilities and beam loading, lead ions should pose no problem as long as proton beams can be accelerated well, hence the acceleration of lead ions in the SPS will not be considered here.

The challenge consists in keeping control of the longitudinal emittance with a high single bunch intensity which is about 10 times higher than in fixed target operation [2] and a small bunch spacing (25 ns) which is about 150 times smaller than used in proton-antiproton operation [3].

The consequence of the high single bunch intensity can be microwave instability at injection [4]. The consequences of high single bunch intensity and small bunch spacing are beam loading in the 200 MHz travelling wave cavities and coupled bunch instabilities at high energy (as experienced with the fixed target operation beam [4]).

Beam loading, microwave instability and coupled bunch instabilities are the three topics that will be covered in the following. They have been studied in the SPS under different circumstances already 20 years ago [5, 6].

2 BEAM LOADING

There are four 200 MHz travelling wave cavities[7] installed in BA3 of the SPS. They are bar loaded transmission lines with a filling time of about 600 ns (given by their length l and group velocity $v_\mathrm{g} = 0.0946 \cdot c$, with c being the speed of light).

Their particularity is that the cavity impedance Z_1, seen by the RF generator current i_g, is not the same as the impedance Z_2 seen by the beam current, i_b .

In the central part of the passband, the impedance Z_1 is purely real

$$Z_1 \propto \frac{\sin \tau/2}{\tau/2} \ ,$$

whereas Z_2 has an imaginary part

$$Z_2 \propto \left(\frac{\sin \tau/2}{\tau/2}\right)^2 - j2\frac{\tau - \sin \tau}{\tau^2}$$

with the phase slip τ given by

$$\tau = \frac{l}{v_\mathrm{g}}(\omega - \omega_0) \ ,$$

where the RF frequency is given by ω and the cavity centre frequency by ω_0.

As a consequence the response of Z_1 to a step modulated carrier (frequency sufficiently close to ω_0) is essentially linear, whereas in the case of Z_2 it is a polynomial of second order during the transient period.

2.1 Effects

The effects of beam loading are mainly two-fold[8]. Firstly, emittance blow-up at injection due to unmatched buckets, i.e. amplitude and phase errors.

Secondly, at extraction, beam loading will lead to bunch length differences and phase variations mainly along the beginning of the batch (consisting of one or several CPS batches of 81 bunches and with a small gap of 8 bunches in between the batches [9]). It turns out that in the case discussed here, the bunch length variation is negligible[1] with respect to the phase variations. These latter have to be limited for reasons of LHC's longitudinal acceptance and LHC injection damping capabilities [10].

2.2 Measures

Feedback and feedforward [11, 12, 13]**.** To overcome beam loading effects several measures may be considered. RF feedback and feedforward can be employed to reduce the apparent impedance of the travelling wave cavities. Normal RF feedback is practically excluded because the long round trip delay surface-tunnel-surface of 2.3 μs severely limits the bandwidth and obtainable gain. Therefore a one-turn-delay feedback is already used in fixed target physics operation to reduce beam loading effects. It is our aim to obtain a tenfold impedance reduction at integer multiples of the revolution frequency within a bandwidth of about ± 7 MHz around the RF frequency. Transient beam loading compensation, during the filling time of the travelling wave cavities, is weak with the present one-turn-delay feedback because of a bandwidth limitation to ± 1.2 MHz. Concerning operational aspects, gain and

[1] For any other parameter fixed, the bunch length varies like the fourth root of the voltage seen by a bunch.

phase adjustments are uncritical in the case of the one-turn-delay feedback.

At present there is only one one-turn-delay feedback in operation. The input is the sum signal of all travelling wave cavities and the output acts on two of them. In the future there will be one complete feedback loop per travelling wave cavity. Its bandwidth will be increased because of (i) $\sin x/x$ filtering and (ii) a power amplifier upgrade. The corresponding low level modules are under construction, tests with beam are foreseen for 1999.

To improve the impedance reduction, and especially the transient beam loading mentioned earlier, a feedforward system is under study. It uses a wideband beam current signal, applies an appropriate transfer function to this signal and and produces in this way a correction signal in the travelling wave cavities to cancel beam loading. Because of the zeroes in the cavity impedance Z_1 at frequencies where Z_2 is different from zero, a perfect cancellation is practically impossible.

A maximum tenfold impedance reduction is expected from the feedforward system. It is well suited for transient beam loading compensation, limited nonetheless by the power amplifier bandwidth. Gain and phase adjustments are more critical than in the case of the one-turn-delay feedback as they translate directly into a corresponding error signal.

Some preliminary results obtained with a simplified version of a feedforward (using a four section long travelling wave cavity and one batch of 81 bunches spaced by 25 ns) is shown in the following figures [14].

Fig. 1 shows the beam induced signal within the travelling wave cavity ("beam loading") and the correction signal ("feedforward") derived from a beam current monitor. The delay between these two signals is adjusted such, that they are clearly distinguishable.

With the delay between correction signal and beam induced signal properly adjusted, the beam loading is reduced by about a factor of three. The residual error is shown in Fig. 2.

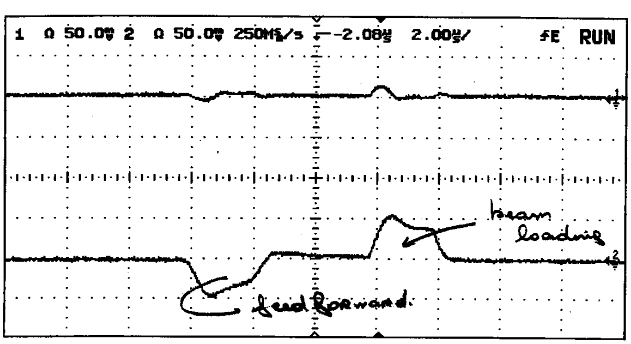

Figure 1: Feedforward. Lower trace: Correction signal and beam loading.

It is foreseen to have one feedforward chassis per travelling wave cavity. The hardware is under construction. Tests with beam are foreseen for 1999.

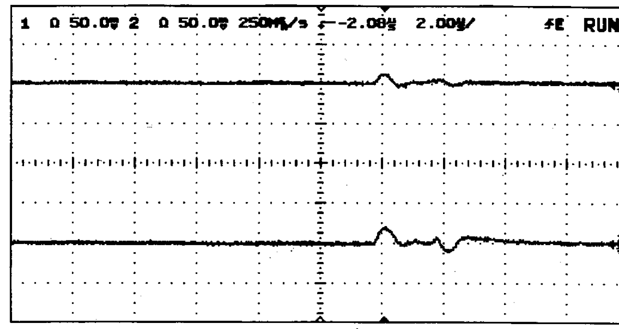

Figure 2: Feedforward. Lower trace: Residual of correction signal and beam loading.

Travelling wave cavity systems [7, 15]. At present the RF power amplifiers work at 500 kW (cw). They will be upgraded to 1.5 MW (peak) and a permissible average power of 750 kW. Maximum power will be available with a 50% duty cycle[2]. This is sufficient because the LHC type beam will occupy only about 3/11 of the SPS circumference[9] and because RF voltage is only needed when the beam passes through the travelling wave cavities. To deliver the higher power the anode power supplies have to work at a higher voltage and the filters have to be upgraded. No modifications are necessary neither for the high voltage transformers nor the amplifier tetrodes.

As the average power stays below 750 kW no modifications are necessary for the coaxial lines between RF amplifiers and travelling wave cavities.

The present RF windows are unsuitable for the high peak power of 1.5 MW and need modification. They will be replaced by a coaxial type capable of withstanding 1 MW (two windows are necessary at the input of each travelling wave cavity and two at the exit).

To cope with the increased peak power and the new RF windows the main couplers of the travelling wave cavities have to be modified accordingly.

For any other parameter fixed, the RF voltage increases linearly with the length, l, of the travelling wave cavity, whereas the beam induced voltage is proportional to the square of l. Therefore, for a given demanded voltage, absolute value V, and a given beam current I_{b}, the necessary RF power, P, is a function of l, which has a minimum for a given l_{opt}. A travelling wave cavity is made out of n sections, each consisting of eleven cells (length 0.374 m). Taking end effects into account, the length l can be expressed as $l = (11n - 1)\ 0.374$ m.

Under these circumstances, the required RF power, for $\tau = 0$[3], is given by Eq. 12 in [7] as

$$P = \frac{V^2}{R_2 l^2} + \frac{R_2 I_{\mathrm{b}}^2 l^2}{64} + \frac{V I_{\mathrm{b}}}{4} \cos \Phi_{\mathrm{S}}$$

with the cavity series impedance R_2 of 27.1 kΩ/m^2 and Φ_{S}

[2]The consequences for the feedback and feedforward systems are under study [24].

[3]For 450 GeV/c ($\tau \neq 0$) the result is the same within a few percent.

the stable phase angle (phase of the bunch with respect to the crest of the axial electric field in the cavity). Differentiation of P with respect to l yields

$$l_{\mathrm{opt}} = \sqrt{\frac{8V}{R_2 I_{\mathrm{b}}}} \quad (1)$$

showing that the optimum cavity length is independent of Φ_{S}. Fig. 3 shows the required RF power as a function of cavity length expressed in number of sections for two cases of Φ_{S} and 1.7×10^{11} protons per bunch. In this case $l_{\mathrm{opt}} =$ 4.1 sections.

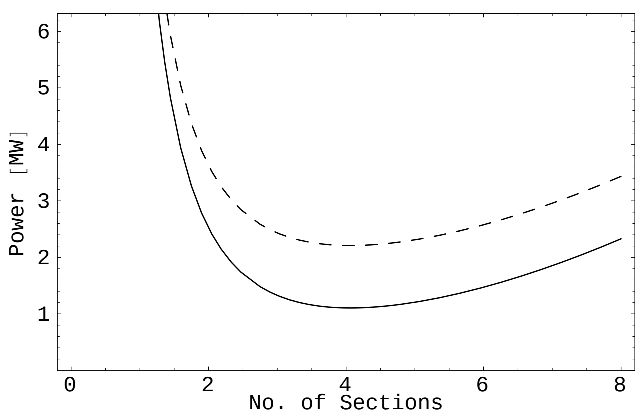

Figure 3: Required RF power for $\Phi_{\mathrm{S}} = 90°$ (straight line) and $\Phi_{\mathrm{S}} = 0°$ (dashed line). V = 2 MV, I_{b} = 2.2 A, $\tau = 0$.

At present there are two travelling wave cavities of four sections and two of five sections. In the future all four travelling wave cavities will be of four sections.

High γ_{tr} optics. The bucket area is inversely proportional to the square root of $|\eta|$. At 450 GeV, the bucket area is therefore to a very good approximation proportional to γ_{tr}. With every other parameter fixed, raising γ_{tr} at 450 GeV corresponds to having more RF voltage available, helping to overcome beam loading effects. This was tried in a machine development session in 1998 [16]. Observing the longitudinal bunch peak signal an increase of 11% was registered (equivalent to a corresponding bunch length shortening) providing a proof of principle.

3 MICROWAVE INSTABILITY AND COUPLED BUNCH INSTABILITIES

3.1 Introduction

The effects of microwave instability as well as coupled bunch instabilities are blow-up of longitudinal emittance. The consequences could be (i) bunches which are too long with respect to the LHC bucket size, (ii) an unacceptable increase in momentum spread which is restrained by the design of the transfer lines to LHC and for reasons of dynamic aperture in LHC and (iii) particle loss at capture in LHC.

Concerning both subjects, a review of measurements done so far in the SPS and their interpretation, please refer to the presentation by E. Shaposhnikova [4].

3.2 Microwave instability

Sources of microwave instability are elements with high R/Q and low Q (R being the shunt impedance of the element and Q its quality factor).

3.3 Measures against microwave instability

The measures discussed in the following are those listed in Ref. [17], and are updated as of January 1999.

Machine cleaning [1]**.** There is a permanent program ongoing to remove unused elements from the SPS tunnel, thus reducing the number of vacuum pipe cross section variations and accidental cavities.

Magnetic septa shielding [18]**.** A prototype of the septum shielding was installed. Measurements with existing beams show that the solution is viable under LHC beam conditions. Half the existing septa will be equipped with a shield at the beginning of 1999 and the remainder in 2000/2001.

Pumping port shielding [1]**.** The main purpose of the pumping port shielding project is the reduction of R/Q. There are, however, several additional benefits.

Firstly, a reduction of the low frequency inductive impedance by 30%. The low frequency inductive impedance can otherwise lead to loss of Landau damping due to the coherent frequency shift.

Secondly, it could eventually help against coupled bunch instabilities since the Q of the present pumping ports is not extremely low.

The design of the pumping port shielding is an interdivisional project involving EST, LHC, PS and SL Division.

There are multiple design constraints [19]. The shielding has to be RF tight as much as possible, i.e. good RF contacts are needed between the various parts. Nevertheless there should be pumping holes to ensure a proper vacuum in the adjacent vacuum pipes. At both extremes of the pumping port fixed RF contacts are needed, where in the centre movable contacts are necessary. Those have to be designed such that they tolerate bellow movements. The design has to be compatible with the tungsten radiation shields. Finally, it must be relatively easy to install the pumping port shielding.

There are about 800 pumping ports around the circumference of the SPS. In principle they will look like that shown in Fig. 4. Fixed contacts on both extremes as well as the movable contacts in the central part are identified by the indication “clip”. Note also the key operated mechanism to open the central contact.

The status of the pumping port shielding project is as follows [19]: Prototypes have been tested in the laboratory and in LSS4 of the SPS. The design of the important end contacts at both extremes of the pumping port is right, although they are difficult to install. Prototypes of the central movable contacts are under construction and laboratory measurements show that things are on the right track. It is possible to cope with the tungsten radiation shields until the year 2000. A design for the time of LHC as e-p collider is at hand. For installation, eight different models of pumping port shielding are needed because of the different vacuum pipe cross section variations encountered around the SPS. The operational procedure for installation is established. Two SPS sextants will be equipped during the shutdown 1999/2000, the other four sextants during the shutdown 2000/2001.

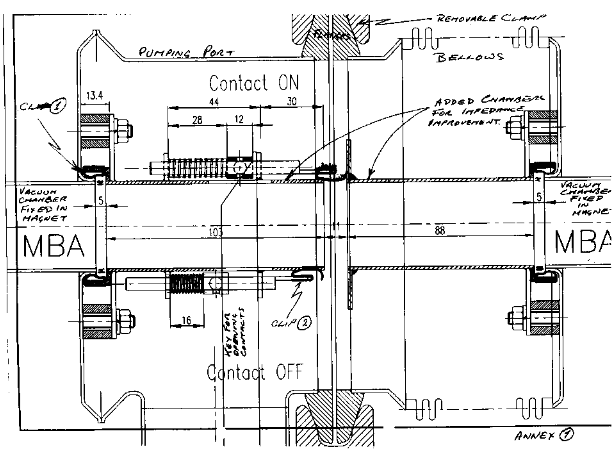

Figure 4: Pumping port shielding [19].

Lower $\gamma_{\rm tr}$ optics. The threshold of microwave instability is proportional to $|\eta| = |\gamma_{\rm tr}^{-2} - \gamma^{-2}|$. During a machine development session in 1997, η was changed at 26 GeV/c from its usual value of 0.55×10^{-3} to 1.3×10^{-3}. A corresponding change of the microwave mode amplitudes as a function of frequency was observed [20].

Advantages of a lower $\gamma_{\rm tr}$ optics at injection (26 GeV/c) are (i) an increase of η (increased threshold for microwave instability), (ii) an increase of the capture voltage from now 0.6 MV to 1.6 MV (good from the view point of beam loading), and (iii) it could be beneficial against coupled bunch instabilities.

The disadvantages are that it requires a change of optics in the SPS and that it may be insufficient for the ultimate intensity.

For a further discussion of a lower $\gamma_{\rm tr}$ optics see [21].

Larger momentum spread from injector. The threshold of microwave instability is proportional to the square of the momentum spread of the beam. Therefore a larger momentum spread from the SPS injector could be beneficial against microwave instability.

The additional advantages are an increased capture voltage (good from the view point of beam loading) and a reduced bunch length for a given longitudinal emittance, thus reducing the generation of satellite bunches at injection.

The disadvantages are that a larger RF voltage would be required in the CPS and the acceptance of the the CPS-SPS transfer line would have to be adapted accordingly. For these reasons this option is not considered further, but it is mentioned here for reasons of completeness.

Increased injection energy. The threshold of microwave instability is proportional to $\gamma\beta|\eta|$. Thus a new injector, PS-XXI [22], with a increased injection energy of 32 GeV/c instead of 26 GeV/c, could increase the threshold by a factor of 2.25.

Again, this option is not considered further, but it is mentioned here for reasons of completeness.

3.4 Coupled bunch instabilities

Sources for coupled bunch instabilities are fundamental and higher order mode resonances in cavities with R and Q sufficiently high that the wakefield left by any one bunch is seen by the following.

3.5 Measures against coupled bunch instabilities

Machine cleaning. As already mentioned before in Section 3.3, there is a permanent program ongoing to remove unused elements from the SPS tunnel. The number of RF cavities in the SPS will be dramatically reduced after LEP has stopped. This includes the removal of all 100 MHz standing wave cavities, most of the 200 MHz standing wave cavities, all 352 MHz superconducting standing wave cavities and the 400 MHz superconducting standing wave cavity.

Impedance reduction at fundamental RF frequency. The aim here is to obtain a synchrotron frequency shift which is smaller than the spread in synchrotron frequencies thus satisfying Sacherer's criterion[23]. The impedance of the travelling wave cavities at the fundamental RF frequency will be reduced by using RF feedback and feedforward (see Section 2.2).

Improved higher order mode damping. Should it turn out to be necessary, the damping of the higher order modes of the travelling wave cavities will be improved.

Coupled bunch feedback [15, 24]**.** The requirements for a coupled bunch feedback are as follows: It should provide a voltage swing of $\pm$ 20 kV in 25 ns, it has to provide beam loading compensation and it should re-use existing hardware (200 MHz standing wave cavities and their 60 kW tetrode amplifiers) as far as possible.

The status of the system is that the wideband driver is available, the tetrodes are suitable and the amplifiers should be fine after some modifications. The coupling of amplifier to cavity is under study.

Increase of synchrotron frequency spread. In the past several methods were used to increase the synchrotron frequency spread. One method consists of a very careful programming of the RF voltage such that the bucket is practically always filled by the bunch emittance [25]. Another method consists of using the 800 MHz travelling wave cavities.

In the SPS there are two 800 MHz travelling wave cavities, each 3.5 m long, and fed by two sets of four klystrons providing about 200 kW per cavity. Together these cavities deliver up to 2.5 MV.

During machine development sessions the 800 MHz travelling wave cavities were used in bunch lengthening and bunch shortening mode [26]. However, only bunch shortening mode could stabilise the beam. This is due to the fact, that a large synchrotron frequency spread can be obtained in bunch lengthening mode, but only for a very precise phase between the two RF systems (200 MHz and 800 MHz), which is difficult to maintain during acceleration. In bunch shortening mode a considerable synchrotron frequency spread can be obtained for a large range of relative phases and is thus more convenient. Another advantage of the bunch shortening mode is, that in a typical case, emittance blow-up, for example due to an instability, leads to an increase of synchrotron frequency spread and therefore tends to stabilise the beam. In the case of bunch lengthening mode, on the other hand, this is not always the case.

The status of the 800 MHz travelling wave cavity system is as follows: the power amplifiers have to be brought into an operational state. This concerns the areas of high tension, controls and water cooling circuitry [27]. The low level electronics has to be improved to better cope with heavy beam loading. Work in these areas is underway.

Synchrotron frequency modulation. To avoid coupled bunch instabilities there are methods which introduce a synchrotron frequency modulation at the revolution frequency or faster. At ESRF it is the beam loading which leads to a strong amplitude and phase modulation of both the cavity voltage and the beam signal, giving sufficient spread of the synchrotron frequencies to damp any coherent longitudinal oscillation [28].

This method is unsuitable in our case, because we would not like to have phase variations along the batch (see Section 2.1).

Applying a small voltage modulation is another way to introduce a synchrotron frequency modulation along the batch.

4 ACKNOWLEDGEMENTS

I am grateful to T. Linnecar for all his advice. I would also like to thank P. Baudrenghien for his information about the new feedforward system, H.P. Kindermann for explaining to me the modifications foreseen for the 200 MHz travelling wave cavity system, E. Shaposhnikova for her advice on microwave instability. Last but not least I would like to thank A. Spinks for his complete overview of the pumping port shielding project.

5 REFERENCES

[1] "The SPS as injector for LHC, Conceptual Design", P. Collier (Editor), CERN SL 97-07 DI, Geneva, March 1997.

[2] M. Colin, G. Cultrut, B. Desforges, D. Picard, "1998 SPS & LEP Machine Statistics", CERN SL Note 98-068 OP, Geneva, 1998.

[3] R. Bailey, E. Brouzet, K. Cornelis, L. Evans, A. Faugier, V. Hatton, J. Miles, R. Schmidt, D. Thomas, "High Luminosity of the SPS proton-antiproton collider", CERN SPS/89-17 (AOP), Geneva, April 1989.

[4] E. Shaposhnikova, "Longitudinal instabilities in the SPS", these proceedings.

[5] D. Boussard, G. Dôme, T. Linnecar, A. Millich, "Longitudinal phenomena in the CERN SPS", IEEE Trans. Nucl. Sci., Vol. NS-24, No. 3, June 1977, p. 1399.

[6] D. Boussard, G. Dôme, T. Linnecar, "Acceleration in the SPS: present status and future developments", IEEE Trans. Nucl. Sci., Vol. NS-26, No. 3, June 1979, p. 3231.

[7] G. Dôme, "The SPS acceleration system travelling wave drift tube structure for the CERN SPS", Proceedings of the 1976 Proton Linear Accelerator Conf. Sept. 14-17, 1976, Editor S.O.Schriber, Chalk River Nuclear Lab., Chalk River, Ontario, November 1976, p. 138.

[8] T. Linnecar, "Preparing the SPS for LHC", CERN-SL-97-018-RF, Geneva, April 1997.

[9] "The Large Hadron Collider", P. Lefevre, T. Pettersen (Editors), CERN AC 95-05 (LHC), Geneva, October 1995.

[10] J. Tückmantel, these proceedings.

[11] D. Boussard, "Possible ways of improving the longitudinal behaviour of the high intensity beam at injection in the SPS", SPS/ARF/Technical Report/DB/gs/81-2, Geneva, January 1981.

[12] D. Boussard, G. Lambert, T. Linnecar, "Improved impedance reduction in the CERN SPS superconducting cavities for high intensity proton operation", CERN SL/93-20 (DI), Geneva, May 1993.

[13] D. Boussard, G. Lambert, "Reduction of the apparent impedance of wide band accelerating cavities by RF feedback", IEEE Trans. Nucl. Sci., Vol. NS-30, No. 4, August 1983, p. 2239.

[14] P. Baudrenghien, private communication, January 1999.

[15] H.P. Kindermann, private communication, January 1999.

[16] T. Linnecar, "High γ_{tr} at 450 GeV", CERN SL Performance Committee, Geneva, May 06, 1998.

[17] E. Shaposhnikova, "Microwave instability in the SPS: causes and cures", CERN SL Seminar, Geneva, April, 1997.

[18] B. Goddard, "The hardware changes in the SPS for LHC", these proceedings.

[19] A. Spinks, private communication, January 1999.

[20] T. Bohl, M. Lamont, T. Linnecar, W. Scandale, E. Shaposhnikova, “Measurement of the effect on single bunch stability of changing transition energy in the CERN SPS”, Proceedings 6th European Particle Accelerator Conference: EPAC ’98 Stockholm, Sweden; June 1998.

[21] K. Cornelis, “Additional quadrupoles in the SPS, what can they be used for”, these proceedings.

[22] B. Autin, R. Cappi, R. Garoby, J. Gruber, J.P. Riunaud, K. Schindl, “PS-XXI, a new synchrotron for the LHC injector”, 3rd International LHC Workshop: High-brightness Beams for Large Hadron Colliders : LHC ’96 Montreux, Switzerland, Particle Accelerators Vol. 58, Numbers 1-4 (1997), p. 103.

[23] F. Sacherer, “A longitudinal stability criterion for bunched beams”, IEEE Trans. Nucl. Sci., Vol. NS-20, No. 3, June 1973, p. 159.

[24] T. Linnecar, private communication, January 1999.

[25] T. Bohl, T. Linnecar, E. Shaposhnikova, “Emittance control by modification of the voltage programme”, CERN SL MD Note 246, Geneva, November 1997.

[26] T. Bohl, T. Linnecar, E. Shaposhnikova, J. Tückmantel, “Study of different operating modes of the 4th RF harmonic Landau damping system in the CERN SPS”, Proceedings 6th European Particle Accelerator Conference: EPAC ’98 Stockholm, Sweden; June 1998.

[27] E. Montesinos, private communication, January 1999.

[28] J. Jacob, “Mastering HOMs at the ESRF”, ESRF Newsletter, No. 22, November 1994.