

IDENTIFICATION OF HIGH-FREQUENCY RESONANT IMPEDANCE IN THE CERN SPS

E. Shaposhnikova, T. Argyropoulos, T. Bohl, F. Caspers, J. Esteban Muller, A. Lasheen,
 B. Salvant, H. Timko, J. E. Varela, CERN, Geneva, Switzerland

Abstract

The spectrum of long bunches injected into the ring with RF switched off has been used in the SPS in the past to probe the longitudinal coupling impedance. After a large campaign of shielding of 800 inter-magnet vacuum ports in 1999 - 2001, the microwave instability threshold was significantly increased and the high-frequency spectrum of the beam became practically flat, apart from a prominent peak at around 1.4 GHz. As corresponding high-frequency impedance could potentially lead to microwave instability of high intensity bunches observed now at high energies in the SPS, a search of the source of this impedance was launched. Using a combination of impedance simulations and measurements, vacuum flanges that are present in a large quantity in the machine have been identified as a main source of impedance at this frequency. Particle simulations based on the SPS impedance model, which includes this previously unknown impedance, are able to reproduce the characteristics of the bunch spectrum and amplitude growth rates and hence, confirm that the impedance of the vacuum flanges is responsible for the observed spectral peak.

INTRODUCTION

A single bunch longitudinal instability driven by a high frequency impedance is usually called microwave instability. It leads to an uncontrolled emittance blow-up and was one of the main intensity limitations for the SPS as an injector of the LHC [1]. The inter-magnet pumping ports were identified as a source of this instability by measuring the spectrum of long (~ 25 ns) single bunches injected into the SPS with RF off and intensity ($\sim 2 \times 10^{10}$) above the instability threshold [2]. The unstable mode spectrum has a center frequency ω_r close to the resonant frequency of the impedance and a width given by either the impedance width $\omega_r/(2Q)$ or by the bunch length τ (if $1/\tau \gg \omega_r/(2Q)$) [3]; hence long bunches allow better resolution of resonant peaks.

In 2001, when the majority of pumping ports were shielded, practically no high frequency peaks were seen for intensity below 8×10^{10} . However, for higher intensities, bunch modulation at 1.4 GHz appeared. The microwave instability with RF on was also not seen anymore on the 26 GeV/c SPS flat bottom for the LHC bunches up to an intensity of 2.0×10^{11} . The instability threshold has been also increased due to the new optics (Q20) with lower transition energy, in operation since 2012 (transition gamma $\gamma_t = 18$ instead of 22.3 in the previous Q26 optics).

Recently, a strong dependence of bunch length on intensity, Fig. 1, was observed on the SPS 450 GeV/c flat top with the 4th harmonic (Landau) RF system in operation in both

Q20 and Q26 optics for single bunches with high intensities, similar to that required in the future for the LHC upgrade scenarios. This bunch lengthening cannot be explained by potential well distortion (PWD) due to the defocusing voltage induced in the SPS reactive impedance, and implies that most probably the threshold of microwave instability is hit during the acceleration cycle.

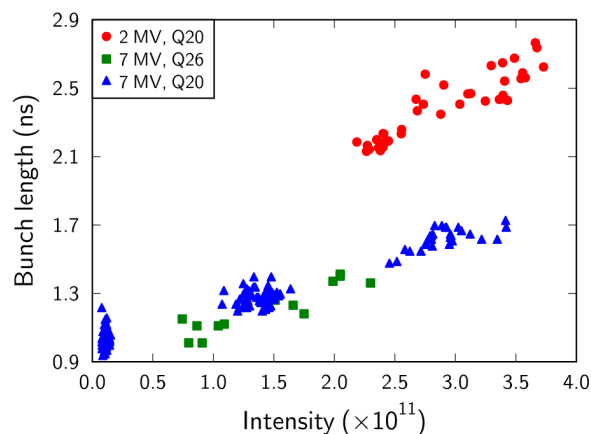


Figure 1: Bunch length on the SPS flat top measured as a function of bunch intensity after adiabatic voltage change to 7 MV or 2 MV (red symbols) in the two SPS optics: Q20 and Q26 (green symbols).

This instability is most probably driven by a resonant impedance at 1.4 GHz, observed already in 2001 and studied more recently in measurements with long bunches [4]. The possible parameter range (R_{sh} and Q) was found using a comparison of particle simulations with beam measurements, however the source of this impedance was not known till the last year, when it had been identified as an impedance of the vacuum flanges. These accidental cavities are damped by ceramic resistors (at least the majority of them) to reduce the risk of coupled-bunch instabilities.

IMPEDANCE SOURCE

A layout survey of the whole SPS ring has been carried out to determine the total number and type of various vacuum flanges and to estimate their impedance contribution [5]. One of them is shown in Fig. 2.

There are nine main types of flanges in the SPS. They can be classified by the shape of the adjacent vacuum pipes which in turn depends on the type of magnet, see Table 1. In addition, the flange can have bellows and be enameled.

Different types of vacuum flanges have been simulated with the code HFSS and Fig. 3 shows a model for one quarter

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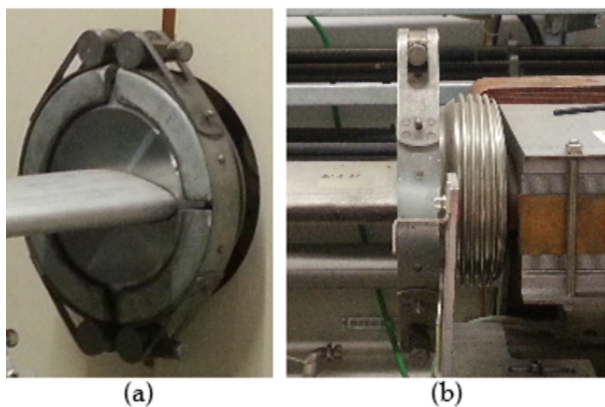


Figure 2: An SPS vacuum flange from the front (a) and the lateral (b) view.

Table 1: The total impedance R_{sh} and quality factor Q of the dominant resonance for the main SPS vacuum flanges types with n identical elements in the ring. All these flange have enamel coating (except both “QF-QF” types) and attached bellows (except “QF-QF-nb”). Short or long damping resistor should be inside every bellows (except “BPV-QD” and “QF-QF-nb”).

Flange type	n	f_r [GHz]	R_{sh} [Ohm]	Q
1 BPV-QD	90	1.21	630	315
2 BPH-QF	39	1.28	1030	400
3 QF-MBA	83	1.41	1600	268
4 MBA-MBA	14	1.41	300	285
5 QF-QF	26	1.41	3765	1820
6 QF-QF-nb	20	1.61	590	980
7 BPH-QF	39	1.62	120	120

of an enameled flange with short bellows between the two MBA (dipole) vacuum chambers. An on-axis plane wave was used as a source to obtain the beam-induced field inside the flange, similar to the method developed to calculate beam-loading in the CLIC main Linac [6].

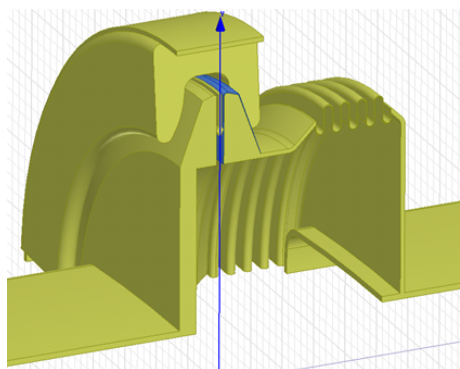


Figure 3: Model used to calculate the impedance of an enameled flange with short bellows.

Beam pipes and bellows in the SPS are made of 304L/316L stainless steel; a conductivity of 1.35×10^6 S/m

has been used in the simulations. A 0.2 mm thick enamel layer has been assumed for the enameled flanges.

Table 1 shows the most significant resonances found in the flanges. The first two and the last rows of the Table show resonances in the special cases where vertical and horizontal Beam Position Monitors (BPV and BPH, respectively) nearby are involved.

The enameled flanges are open and inhomogeneous resonators. Radiation losses are dominant for all enameled flanges in Table 1. Therefore, low Q values (< 400) are obtained in these cases and higher Q values have been found for the non-enameled flanges. The resonances can be divided in three groups: around 1.25 GHz, 1.4 GHz and 1.6 GHz. They all are visible in the beam measurements, Fig. 5. The 1.4 GHz resonances give the biggest contribution to the SPS impedance.

The longitudinal coupling impedance of the SPS was studied already in the early 80’s, and cylindrical ceramic damping resistors were placed in practically all cavity-like objects in the ring to damp their resonances. There are hundreds of them in the ring, not only in the flanges, but also in other elements (such as pumping ports, even behind the shielding), attached to the bellows by a spring. Depending on the size of the bellows, two types of damping resistors are used: short (25 mm) and long (54 mm). They are made from alumina and coated with a very thin (~ 50 nm) resistive (Ni-Cr) layer. The damping effect strongly depends on the conductivity of the resistive layer. The original layouts contain the locations where these damping resistors are supposed to be, but less and less care was taken about them last years during machine interventions and this information is not reliable anymore.

Both enameled (MBA-MBA) and non-enameled (MBA-QF) flanges have been measured in different configurations and by different methods to estimate the accuracy of simulations. Bead-pull measurements have been found to be the best way to characterize the resonances of vacuum flanges. The comparison between simulations and bead-pull measurements show a very good agreement for the R/Q values without damping resistors. The resonant frequencies were accurately predicted by simulations and do not shift significantly due to the presence of the damping resistors. In addition, these measurements show that the unloaded Q of the resonances is reduced by approximately a factor 5.5 and 3.5 for the non-enameled and enameled cases respectively. As expected, the presence of damping resistors does not reduce the R/Q of the resonances significantly. The damping resistors have not been included in EM simulations (Table 1), but their presence affects significantly the results of particle simulations (see next section) and there is an ongoing effort to accurately model them as well as to have full information about their locations.

PARTICLE SIMULATIONS

In the present SPS impedance model, see Fig. 4, the vacuum flanges together with the 200 MHz and 800 MHz

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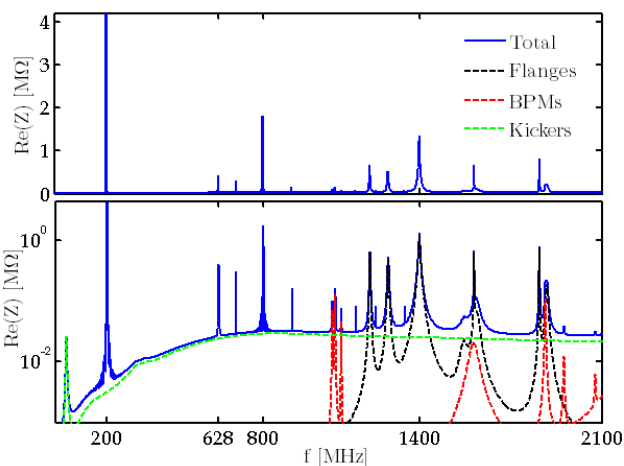


Figure 4: The longitudinal impedance of the SPS up to 2 GHz in the linear (top) and logarithmic scale (bottom).

cavities are the three dominant contributors to the resistive impedance. The main contributions to the R/Q come from the kicker magnets and again the 200 MHz cavities.

Beam simulations were done for different measured particle distributions using the SPS impedance model which includes the contribution from flanges (assuming 90% of damping resistors in place). The results strongly depend on the particle distribution [7].

Two sets of measured distributions were used: (1) reconstructed by the PS tomoscope and then tracked till the SPS injection, see Fig. 5, and (2) reconstructed from the bunch profiles at the injection (1st turn) in the SPS. The peak amplitude at 1.4 GHz (as compared to the 200 MHz peak with known impedance) varies a lot, but in the 1st case for 4 from 6 available examples it is lower than the average peak amplitude obtained in the measurements with the same bunch intensity. Better agreement is achieved if the impedance of vacuum flanges used in simulations is approximately 20% larger or we assume that much less flanges have damping resistors inside.

Particle simulations of the single bunch instability on the SPS flat top observed in a double RF system show the onset of the microwave instability at intensities higher than those observed in the measurements. They also show a non-monotonic dependence of the instability threshold on bunch emittance, pointing out that simulations through the whole acceleration cycle are necessary to get an accurate picture.

SUMMARY

The impedance of vacuum flanges has been identified as a possible source of the microwave instability observed in the SPS on flat top for high bunch intensities. The main resonant peak at 1.4 GHz has been found by observing the

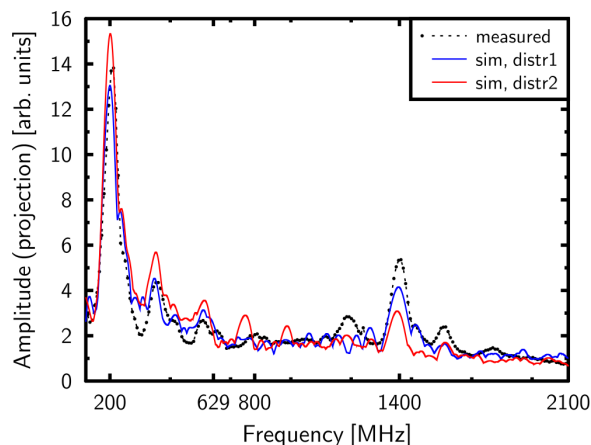


Figure 5: Projection of bunch spectrum evolution of long bunches injected into the SPS with RF off in measurements (black dashed line) and simulations with two different distributions (reconstructed from PS tomography) with the present SPS impedance model. Bunches had an average length of 25 ns and an intensity of 1.0×10^{11} .

spectrum of long single bunches injected into the SPS with RF off. These accidental cavities are damped by ceramic resistors, but their impedance can still lead to single bunch instability. Possible ways of impedance reduction (shielding) are under study.

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