CHARACTERIZATION OF RESONANT IMPEDANCES OF CERN-SPS GATE VALVES

T. Kaltenbacher*, J. Repond, C. Vollinger, CERN, Geneva, Switzerland

Abstract

For the CERN High Luminosity LHC project, a doubling of bunch intensity is foreseen. However, this intensity increase is currently limited by the LHC injector chain, in part due to longitudinal multi-bunch instabilities in the SPS. Therefore, the implementation of an accurate SPS impedance model was started some time ago in order to obtain a better understanding of instability sources and develop mitigation measures. In this paper, we present the electromagnetic characterization of commonly used all-metal gate valves with respect to their contribution to the SPS longitudinal impedance. The valve impedance was evaluated with commercially available EM-field simulation programs and verified with RF-bench measurements. Using this input, it was possible to obtain in particle simulations the dependence of the multi-bunch stability threshold on the number of these valves. The threshold can be increased by using commercially available impedance shielded valves. Consequently, we present the associated reduction in beam coupling impedance and the expected gain in beam stability if all existing unshielded valves are replaced by shielded ones.

INTRODUCTION

The upgrade of the CERN Super Proton Synchrotron (SPS) for the high luminosity LHC project (HL-LHC) requires a significant improvement in longitudinal beam coupling impedance to allow operation at the desired bunch intensities. One important part of the required impedance reduction is expected from the implementation of impedance shields in the vacuum flanges [1]. Vacuum flanges in the SPS were found to be mainly responsible for certain microwave instabilities [2]. Hence, the LIU (LHC Injector Upgrade) project baseline [1] foresees an impedance reduction campaign based on the shielding of several flanges interfacing vacuum chambers and bellows. Besides this, it was recently seen from beam dynamics simulations that the existing unshielded sector valves also give a significant contribution to the total beam coupling impedance and the respective beam instabilities [3]. In this paper, we concentrate on the evaluation of the most frequently used types of valves, labelled as *VVSA* and *VVSB*.

Table 1 gives the number of valves that are currently installed in the SPS, and their bore sizes. They are all-metal valves with a stainless steel body, differing only in bore size. Their main purpose is to allow a vacuum sectorization of the entire ring. Images of the installed VVSA (left) and VVSB (right) valves are shown in Fig. 1.

* Thomas.Kaltenbacher@cern.ch

Table 1: Number of Sector Valves Installed and Planned for Installation in the SPS. Note that DN100 and DN150 represents the inner bore diameter in mm.

Sector Valves	Bore Size	Number of Valves Installed
VVSA	DN100	19 (+11 planned)
VVSB	DN150	35

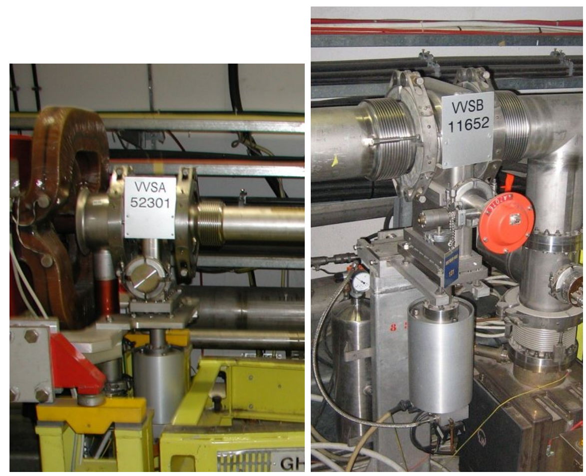

Figure 1: Images of installed sector valves; left: VVSA type and right: VVSB type.

SECTOR VALVES CHARACTERIZATION

EM-simulation and Measurement

For the EM-evaluation of these sector valves, the CAD model was imported into the EM-simulation programs for calculation of eigenmodes (HFSS [4] and CST [5]), S-parameter transmission (CST) in frequency domain to benchmark the RF-measurements and wakefields (CST) for coupling impedance calculation in time domain.

Figure 2 shows CAD models of a VVSA valve, with and without a shielding in the bore opening. The purpose of the impedance shield is to screen the valve body and its mechanism by providing continuity of the beam pipe via the RF-fingers (yellow in the figure). Note the larger body of the shielded valve version that is required for housing the impedance shield if the valve closes. The CAD model was provided by the valve supplier [6] and simplified for the EM-calculations. S-parameter transmission measurements with RF-probes were carried out to benchmark the simulation model for geometrical correctness. Figure 3 shows the schematics of the RF-measurement set-up where on-axis RF-probes were used to excite modes in the structure. In general, transmission measurements have superior sensitivity of

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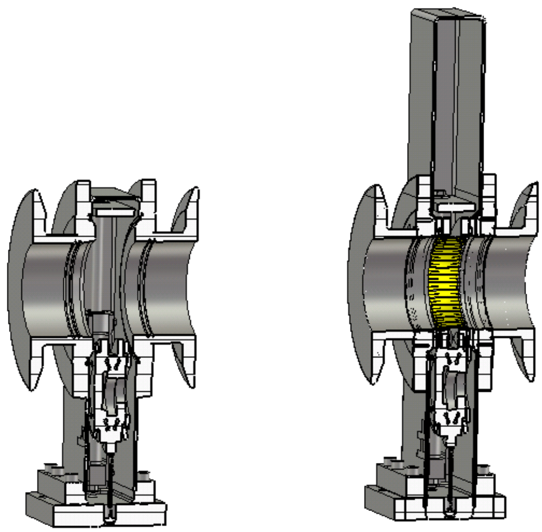

Figure 2: CAD model of a VVSA sector valve (left) and the impedance shielded version (right). The body of the shielded valve version is significantly larger than the unshielded one. The extended size is required for housing the impedance shield if the valve closes.

the measured traces, and their evaluation for quality factor Q has a smaller systematic error than measurement of S_{11}. Note that this RF-probe (tip shown in Fig. 3 inset) will not excite all modes supported by the structure, thus some resonances cannot be detected with this method. Figure 4 shows a comparison of S_{21} measurement with calculated longitudinal coupling impedance which is in very good agreement for the modes that can be excited with these RF-probes. For instance, the mode at ~650 MHz couples very weakly to the probes and the resonance at ~1320 MHz is not excited at all. Moreover, due to the coupling of the probes to the EM-fields of the mode at ~1270 MHz, the resonant peak is slightly shifted in frequency.

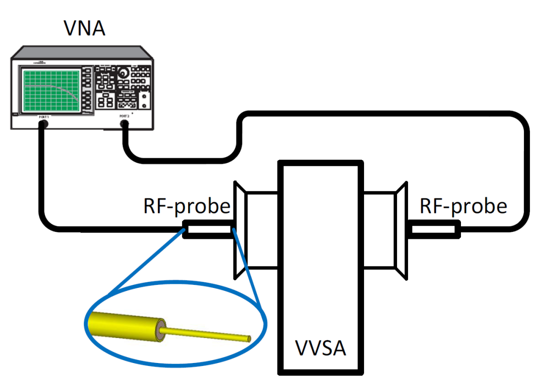

Figure 3: Schematic of the measurement set-up for benchmarking the EM-simulation model with S-parameter measurements via a vector network analyser (VNA). The inset shows the tip of the RF-probe.

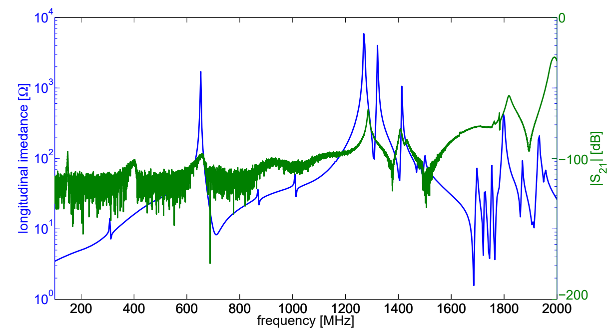

Figure 4: Comparison of S-parameter transmission measurement with calculated impedance spectrum of the VVSA.

Impedance Calculation

Figure 5 shows the simulated longitudinal beam impedances with and without impedance shield for the two valve types VVSA and VVSB.

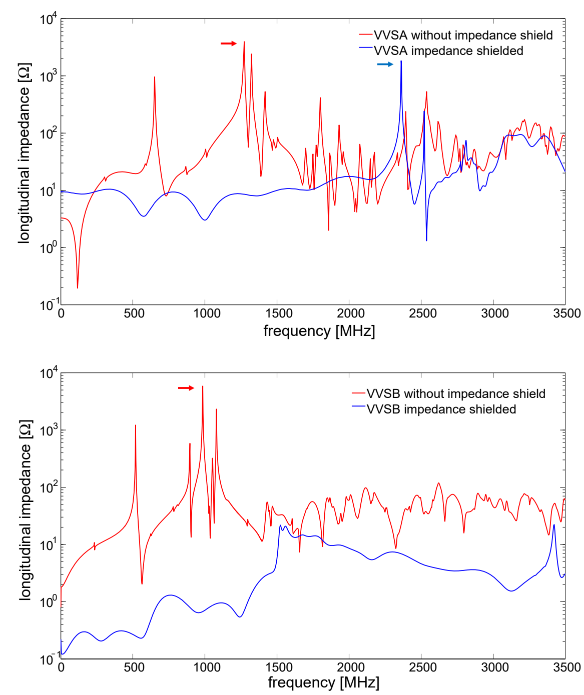

Figure 5: Calculated longitudinal beam-coupling impedance of VVSA valve (top) and VVSB valve (bottom) vs. frequency for cases without (red) and with (blue) impedance shields.

In both cases, the traces indicate a strong reduction in resonance peaks starting from low frequencies to about 2.2 GHz. For the VVSA valve, resonances above 2.2 GHz are also slightly reduced, except the resonance peak at about 2.35 GHz which is enhanced if the impedance shield is implemented (blue arrow in Fig. 5, top). Analysis shows that this resonance is caused by the cross-sectional change taking place when the DN100 bore of the valve reduces to the diameter of the beam pipe of 83 mm. The VVSB valve has no such a step in the cross-section, hence an impedance reduction over the entire frequency range can be achieved by implementing the impedance shield. These results were used as input to the beam dynamics calculations carried out with the Beam Longitudinal Dynamics code (BLonD) [7, 8] in order to evaluate the impact of the valve impedance on beam stability.

BEAM STABILITY

Since the sector valves are significant contributors to the current longitudinal beam coupling impedance model of the SPS, the impact on longitudinal beam stability with various options for shielding have been studied. The simulations were carried out with BLonD at SPS flat top for 72 proton bunches. The SPS impedance model is obtained from simulations of the main machine elements that were benchmarked by RF-measurements; then the impedance model was cross-checked via measurements with beam [9]. For the situation in the accelerator after the Long Shutdown 2 (LS2 in 2019-2020), a reduction of flanges impedance by a factor 20 in the 1.4 GHz range is assumed [10]. As discussed above, this reduction can be achieved by the installation of impedance shields in the SPS vacuum flanges, a measure that is to be implemented during LS2. In addition, a 26 dB reduction on main harmonic of the 200 MHz Travelling Wave Accelerating system (TWC) of the SPS is to be achieved via the low-level RF correction loops [11]. With these assumptions, a scan in intensity and bunch length is performed using one million macroparticles per bunch over 100'000 turns (~2.3 sec) that also allows the observation of slowly growing instabilities. After its foreseen upgrade, the double RF system of the SPS is assumed to deliver after upgrade a voltage of 10 MV in the 200 MHz TWC and 1 MV in the 800 MHz cavities. A bunch length of 1.65 ns (4σ), with parabolic profile and a spread of up to ± 10%, and 2.4 $\times 10^{11}$ protons per bunch are considered nominal parameters for HL-LHC [11].

Figure 6 shows the intensity threshold versus average bunch length for the different configurations of sector valves for the SPS machine situation as expected after LS2:

- Current situation with existing unshielded valves, including the 11 additional valves that will be installed for the SPS sectorisation, (red continuous line);
- Simulated situation in the SPS without impedance contribution of the sector valves VVSA and VVSB, (blue continuous line);
- Configurations with alternately VVSA sector valves and VVSB sector valves equipped with impedance shields, (dashed lines).

Assuming the nominal beam parameters, shielding only one type of valve allows increasing the stability threshold by 4% or 1% for valves VVSA and VVSB, respectively (see Fig. 6). If both type of valves are shielded, the the stability thresholds are very close to the case of no valves at all. A dedicated study has shown that the resonances affecting more the intensity threshold are at 1.27 GHz in case of the VVSA and at 0.992 GHz for the VVSB (see red arrows in Fig. 5).

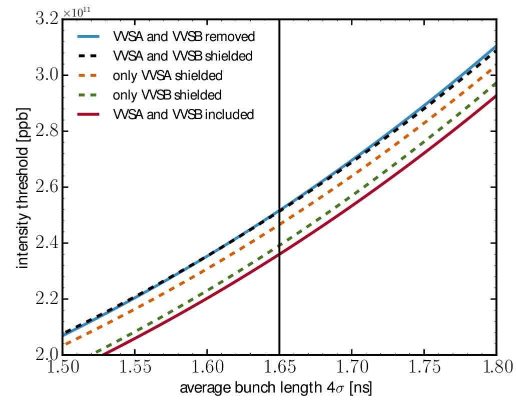

Figure 6: Results of macroparticle simulations (BlonD) for 72 bunches at SPS flat top in a double RF system (10 MV at 200 MHz and 1 MV at 800 MHz in bunch shortening mode) for the situation as expected after LS2. The plot shows intensity thresholds vs. average bunch length, for the situation with shielded and unshielded sector valves in the SPS ring. Three different scenarios for shielded valves are shown together with the case of no sector valves at all as well as the current status quo.

Note that for small average bunch lengths, intensity thresholds calculated for the situation without valves and shielded valves overlap. This leads to the conclusion that shielded valves are electromagnetically transparent to the beam with the given bunch length and suggests that any new all-metal sector valve installed in the SPS should be shielded.

CONCLUSION

After accounting for the general SPS impedance reduction foreseen in LS2, the SPS all-metal sector valves were identified to reduce the multi-bunch instability threshold significantly. This translates to an intensity limitation lower then the required 2.4 $\times$ 10^{11} p/b at a 4σ bunch length of 1.65 ns for the High Luminosity LHC project. Even if new installations requiring VVSA or VVSB valves will be of the shielded version, it is not yet decided if the already installed sector valves will be replaced. However, based on the existing data, it seems that all newly approved installations which require VVSA or VVSB valves, shall be of the shielded type.

OUTLOOK

The functionality of the VVSA and VVSB valves requires the connection of a pumping port in certain locations. Since both valve types are available from suppliers with equipped pumping ports, a further reduction of impedance could be achieved by removing existing pumping ports next to the valves and using the the valve pumping port instead, as this allows to reduce the overall number of pumping ports. Such an approach would need to be examined in detail as part of an impedance consolidation of the long straight sections of the SPS.

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