THE SPS 200 MHz TWC IMPEDANCE AFTER THE LIU UPGRADE

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Abstract

As a part of the LHC Injectors Upgrade project (LIU) the 200 MHz Travelling Wave Cavities (TWC) of the Super Proton Synchrotron (SPS) will be upgraded. The two existing five-section cavities will be rearranged into four three-section cavities (using two existing spare sections), thereby increasing the total voltage from 7 MV (I_{RF} = 1.5 A, current LHC) to 10 MV (I_{RF} = 3.0 A, HL-LHC) [1,2]. Projections of the HL-LHC (High Luminosity Large Hadron Collider) era are conceived by the macro-particle simulation code BLonD [3], that makes use of an impedance model of the SPS, developed from a thorough survey of machine elements [4]. This paper analyses the impedance contribution of the 200 MHz cavities in the two configurations, using electromagnetic simulations. Measurements of the existing cavities in the SPS and a single-section prototype are also presented.

INTRODUCTION

The 200 MHz TWC system of the SPS currently consist of two four-section cavities and two five-section cavities. To guarantee stability of the future HL-LHC beams in the SPS, the required controlled longitudinal emittance blow-up will have to be increased. This implies a larger bucket and voltage amplitude, but one must not forget that the increased intensity will also cause more beam loading in the cavities, which has to be compensated by the RF system as well. The existing two five-section cavities with the available 1 MW power plant will struggle with the future HL-LHC beams, and solutions were proposed in [1]. The two existing five-section cavities will be rearranged into four three-section cavities (using two existing spares), and two additional power plants of 1.4 MW/cavity are foreseen. The two four-section cavities will remain in their current configuration. This will not only be beneficial for the fundamental mode, but the total impedance will reduce by 20% in this new configuration [1].

For projections of the HL-LHC era requirements, the macro-particle simulation code BLonD [3] is used. It relies on an impedance model of the SPS, developed from a thorough survey of machine elements [4]. In this paper the impedance contribution of the 200 MHz cavities in the two configurations is assessed using measurements taken in situ in the tunnel, laboratory measurements of a single section on the surface and electromagnetic simulations (CST Studio Suite [5]). In particular, attention will go to the 628 MHz Higher Order Mode (HOM) couplers, since recent studies showed that the intensity threshold for beam stability can be improved when, amongst others, the impedance contribution of the longitudinal 628 MHz HOM is reduced at least by a factor of 2 [6,7].

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SINGLE SECTION CAVITY

General Description

The currently installed SPS 200 MHz TWC system, described in [8], consists of two four-section cavities and two five-section cavities. A single section of 11 cells is available on the surface as well for additional measurements. This 11-cell section is a spare section, which is closed, as in the tunnel, by two lids to allow measurements. No power couplers are installed on this section and as for the HOM couplers only the four 628 MHz HOM couplers with detachable 50 Ω loads are put into place (Fig. 1). The couplers for the longitudinal 938 MHz HOMs and the couplers for the transverse 460 MHz HOMs were not installed. This choice is motivated by two aspects: In the first place their effect on the 628 MHz HOM damping is considered minimal to non-existing. In the second place, and more importantly, the single-section cavity study was done to reassure that a known setup could be modelled and simulated correctly. The requirement for the model is that it represents exactly the laboratory setup, and as such a laboratory setup with as little (unnecessary) complexity as possible is an obvious choice. It should be noted that spare 938 MHz HOM couplers are available, in the event this would be desired. On the other hand, no spare 460 MHz HOM couplers were available. Typical transmission and reflection measurements were performed between two probes, mounted on the beam pipe axis, between different 628 MHz HOM couplers, or combinations of both. In addition, the RF voltage feedback pick-up loops, used to measure the Fundamental Pass Band (FPB) field flatness, served as a measurement interface with the cavity as well.

Table 1: Resonant measurements of the SPS 200 MHz single-section cavity around 628 MHz, with no loads on the 628 MHz HOM couplers.

Freq [MHz]	R/Q [Ω]	Q_0
624.3	0.5	18400
626.8	10	22300
628.8	56	18000
631.6	27	19500
634.3	4.6	17800

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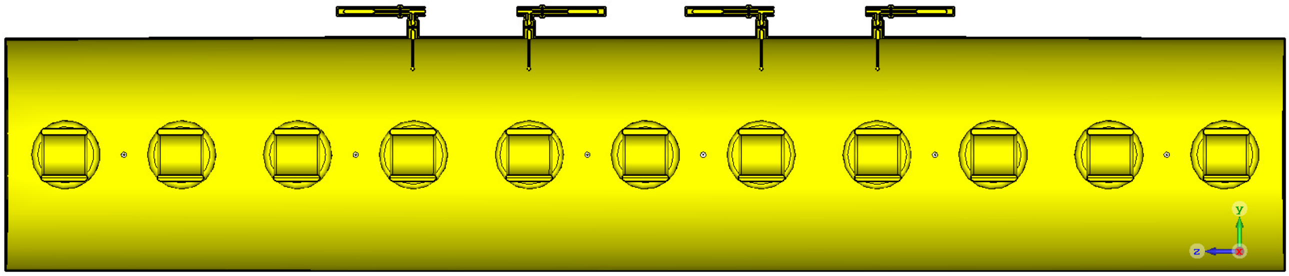

Figure 1: Simulation model of the 11-cell section of the SPS 200 MHz TWC with installed 628 MHz HOM couplers and RF voltage feedback pick-up loops.

Measurements

Figure 2 shows the cavity transmission characteristics around 628 MHz measured between two weakly coupled probes, installed on the beam pipe axis. The undamped cavity (50 Ω loads not mounted on the 628 MHz HOM couplers) has, as expected, several resonant peaks around 628 MHz. With the 50 Ω loads installed the input signal is considerably damped (-25 dB) and the Q is significantly reduced. The dip around 637 MHz for the loaded HOM couplers (blue curve) is assumed to be caused by destructive interference between the two probe's. This can be overcome by changing their relative positions. Table 1 shows R/Q and Q based on beadpull measurements for the unloaded section. The transmission measurements between a single probe and a HOM coupler allow to draw identical conclusions, though the data is more challenging to interpret.

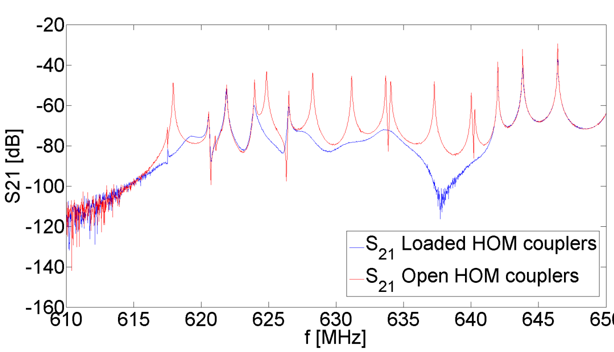

Figure 2: Measured transmission (S_{21}) characteristics around 628 MHz for two weakly coupled probes mounted in the centre of the beam pipe on each side of the single-section cavity.

Simulations

The position of the 628 MHz HOM couplers with respect to the drift tubes seems to be well optimised in the past. Simulations also show that certain modes preferably couple to one of the two HOM pairs (e.g. the 628 MHz mode couples stronger to the outer pair of HOM couplers, while the 632 MHz mode couples stronger to the inner pair of HOM couplers). This was confirmed by measurements as well. In order to get confirmation that the applied model represents the single section, actual measurement setups were simulated. Figure 3 shows the S_{21} for the single-section structure equipped with four 628 MHz HOM couplers. As an input interface the RF voltage feedback pick-up loop close to one lid was used to insert the signal (P1 on Fig. 3), the measurement was taken at the pick-up loop on the other side of the cavity section (P2 on Fig. 3). The frequency difference between measurements and simulations is within the uncertainty of the measurement, arising e.g. from a combination of tolerances and an expansion of the measured structure due to temperature differences. The seemingly strong resonance present at 629.6 MHz is in fact a transverse mode that manifests only in the single-section cavity with lids. Consequently, this transverse mode does not appear in the four- and five-section cavity simulations or measurements. The R/Q and Q_E (Q external) for a loaded single-section cavity were simulated as well (Tab. 2).

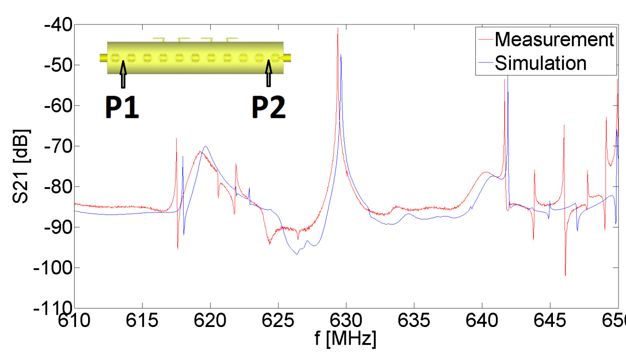

Figure 3: Comparison between simulation and measurement for an S_{21} between two RF voltage feedback pick-up loops (P1 and P2) in the single-section cavity.

IN SITU MEASUREMENTS

General Description

A large number of measurement data was taken during the technical stop in February 2016, most of it on cavity II, since this four-section configuration will remain in the machine after the upgrade. Fundamental power couplers, main load, all HOM couplers and all auxiliary equipment was connected, though no RF power nor beam was present. It is worth mentioning that the model size of a five-section cavity becomes cumbersome in the CST software due to its large

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Table 2: Resonant simulations of the SPS 200 MHz single-section cavity around 628 MHz, with loads on the 628 MHz HOM couplers.

Freq [MHz]	R/Q [Ω]	Q_E
620.2	0.145	156
622.3	2.83	7162
622.9	1.97	3.93e+004
624.4	12.1	2.58e+004
625.2	15.0	517
626.9	34.5	8013
628.6	1.87	472
630.9	14.5	56
631.4	45.4	258
634.4	0.899	446
634.6	30.4	742
637.0	48.5	255
638.3	20.0	110

dimensions (20.603 m, excluding the fundamental power coupler lines). Not only the number of required mesh cells is huge (>100 million tetrahedrons), also the ratio of the structure length to smallest component dimension reaches values that compromise adequate handling by the mesher.

Measurements

Form the measurements clear differences are observed between the four- and five-section cavities but also between the two 4 section cavities in terms of transmission characteristics. The exact reason for this difference is currently not well understood and the significance on the impedance model has not yet been studied. It also became clear that a single-section measurement cannot be easily scaled up to a multi-section equivalent: different resonances shift differently both in frequency and amplitude (Fig. 4). As for the 460 MHz transverse HOM couplers, these do not seem to have any contribution to the damping of the 628 MHz HOMs, as was confirmed by removing the loads on those couplers. This did not have any additional damping effect on the S_{21} in Fig. 4. From a frequency perspective their presence in the cavity induces a small frequency shift. At 460 MHz on the other hand the 460 MHz HOM coupler damping works as foreseen.

Simulations

For cavity II a measurement setup was simulated too: The S_{21} was evaluated for the four-section cavity equipped with power couplers, loaded 460 MHz, 628 MHz and 938 MHz HOM couplers. The connected input and output RF voltage feedback pick-up loops are indicated on Fig. 5. The difference in frequency can again be explained by a combination of tolerances and an expansion of the measured structure due to temperature differences. The comparison shows that the simulation model represents quite well the cavity in the actual machine.

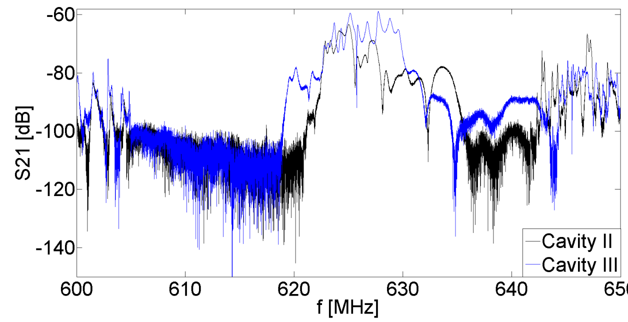

Figure 4: S_{21} characteristics around 628 MHz between the two most outer pickup loops for cavity II (four-section) and cavity III (five-section).

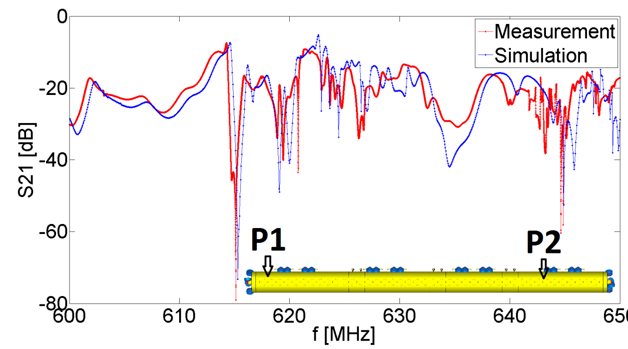

Figure 5: Comparison between simulation and measurement for an S_{21} between two RF voltage feedback pick-up loops (P1 and P2) in cavity II in the tunnel.

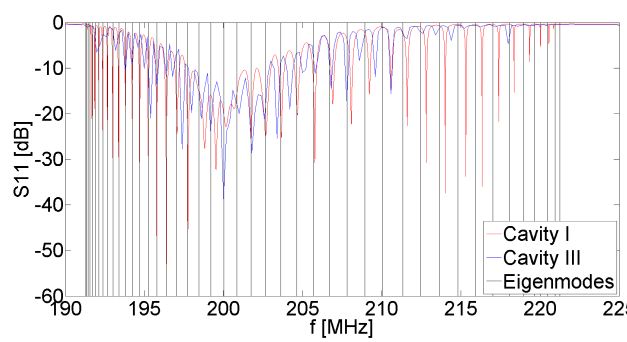

Figure 6: Fundamental passband reflections (S_{11}) for the feeder line measured into the cavity. Comparison between cavity I (four sections) and cavity III (five sections). In black the eigenmodes of a four-section cavity simulation are given.

FEEDER LINE

Reflections in the feeder line of cavity I (four sections) were investigated between 100 MHz–1000 MHz. The feeder line was disconnected from the (cold) generator on the surface at the last combiner and reflections were analysed both into the generator and into the cavity. Detailed measurements were taken in the fundamental passband region (190 MHz–225 MHz) and the HOMs at 460 MHz (400 MHz–500 MHz), 628 MHz (615 MHz–645 MHz) and 938 MHz (900 MHz–1000 MHz). Two cavity setups were measured:

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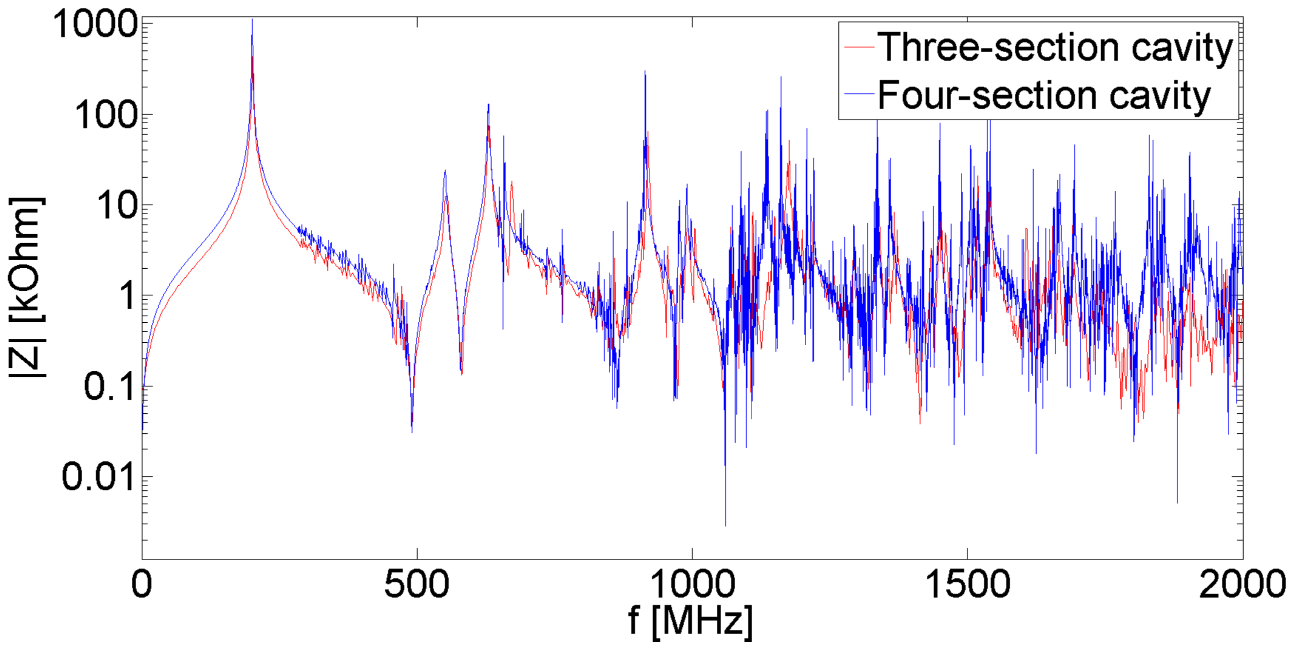

Figure 7: Impedance plots obtained from electromagnetic simulations with CST Studio Suite. Blue: Four-section cavity including 460 MHz, 628 MHz and 938 MHz HOM couplers, power couplers and RF voltage feedback pick-up loops. Red: Future three-section cavity, based on the layout of present four- and five-section configurations.

with and without the 50 Ω loads connected to the 628 MHz HOM coupler. The feeder line has an attenuation of about 0.2 dB/100 m and has a length of 90–180 m, depending on the generator distance from the cavity. Reflection measurements into the cavity show that the fundamental passband drops to -17 dB at 200 MHz (Fig. 6), which is comparable with the results found for cavity III, reported in [9]. Table 3 summarizes S_{11} near the HOM's, showing that the feeder line only provides a very limited amount of HOM damping and that the generator currently does not contribute to the damping of the 460 MHz or 628 MHz HOMs. When measuring the feeder line in the direction of the cavity, no change in S_{11} could be observed around 628 MHz if one removed the 50 Ω loads on the 628 MHz HOM couplers. Although not fully understood yet, this seems to imply that the excitation of 628 MHz through the feeder line does not reach the cavity, but is mainly reflected before.

Table 3: Average reflection measured on the feeder line of cavity I in the spectrum of 100 MHz–1000 MHz.

Freq [MHz]	Feeder line S_{11} [dB]	Generator S_{11} [dB]
460	0	0
628	-1 – -2	0
938	-4 – -5	-2 – -5

IMPEDANCE CONTRIBUTION OF THE 200 MHZ CAVITIES

Four-section Cavity

The above measurement-simulation comparisons give confidence that the models prepared for the impedance calculations are a proper representation of the actual cavities installed in the machine. The impedance result from wakefield simulations of the four-section cavity is shown in Fig. 7 and is used for BLonD simulations.

Three-section Cavity: Prognosis

Based on the experience with the existing cavities an impedance prognosis for the three-section cavities is simulated (Fig. 7). The used three-section model only differs from the existing model in its number of sections. All HOM couplers and power couplers are assumed to remain identical, since no upgraded designs are available yet. This impedance can now be included in the BLonD simulations to further predict future machine performance.

CONCLUSIONS

Confidence in the applied models was built up through comparison of electromagnetic simulations with measurements of both a spare section of the 200 MHz TWC and the actual cavities installed in the SPS. The transmission characteristic comparisons show a good agreement. The adequate damping of the 628 MHz HOM dampers of the cavities was assessed, and both the feeder line and 460 MHz HOM couplers do not appear to have a significant contribution to the damping in this frequency range. The good agreement

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between measurement and simulation allowed to construct the impedance model of the four-section 200 MHz TWC. The three-section cavity impedance model is obtained by a reconfiguration of the modelled sections. The impedance models can now be included in the studies on the HL-LHC beam requirements.

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