VERIFICATION BY RF MEASUREMENTS OF NEW HOM MITIGATION SCHEME DEVELOPED FOR FUTURE SPS 33-CELL ACCELERATING STRUCTURES

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Abstract

Longitudinal higher-order modes (HOMs) at a frequency of around 630 MHz in the 200 MHz travelling wave RF structures currently limit the beam intensities in the CERN SPS to less than that required by the High Luminosity (HL-) LHC. In the framework of the LHC Injectors Upgrade (LIU) project, the performance of the already existing HOM damping scheme for these standing wave modes must be improved. This involves improving the existing HOM-couplers as well as the possible use of a new mitigation technique via the insertion of resonant posts in some cells of the multi-cell structures. The development of the new damping scheme has been performed using theoretical analysis of the cavity-coupler interaction in conjunction with full-wave electromagnetic (EM) field simulations. This contribution will show the verification of the improved HOM damping performance by measurements on a single section with 11 cells and on the future 33-cell structures. The parasitic impact of the damping scheme on the travelling wave fundamental passband (FPB) will also be presented.

INTRODUCTION

Multi-bunch instabilities triggered by longitudinal HOMs in the (628–630) MHz range in the travelling-wave accelerating structures were already observed within the first year of SPS operation in 1976 [1]. The instability was mainly cured through the use of damping probes with resistive loads placed in the top of a number of cells. The probes couple as strongly as possible around 630 MHz while being equipped with a rejection filter for the 200 MHz fundamental mode. The HOM reduction of at least 35 dB was effective enough to mitigate this source of instability despite the increasing beam intensity over the last 40 years. For future HL-LHC intensities however an additional factor three in damping must be achieved to ensure the required beam stability [2].

Several options solving the numerous obstacles for improved HOM mitigation in the short, 33-cell accelerating structures, which will be used in the future, have been developed [3]. The most promising upgrade option of the current, now insufficient, damping scheme consists of three steps: First, additional HOM-couplers are placed in cells that feature a strong EM field of a mode specific to the 33-cell configuration. Second step is an improvement of the HOM-couplers themselves by deploying complex, instead of purely resistive 50 Ω, loads as the coupler termination. The complex load ensures near optimal, critical coupling of the coaxial HOM-coupler to the most detrimental modes. The third component of the new damping scheme is a novel type of HOM-mitigation through the implementation of resonant posts which are directly placed on the wall in the lower part of the cavity, where no dedicated access ports for HOM-damping exist [3].

The development of the new damping scheme has relied mainly on EM simulations as the new 33-cell configuration only recently became available for measurements. The goal of this contribution is therefore to confirm the promising performance observed in simulations using RF measurements. However, verification of the new mitigation techniques on a 33-cell structure of around 12.5 m length and with a large amount of components is quite cumbersome. This is especially the case for on-axis perturbation measurements of cavity geometry factors that are ideally included in the measurement program. The effectiveness of the new damping techniques is therefore also shown on a single, 11-cell section by comparing measurements to the corresponding EM simulations. Unfortunately, a setup for perturbation measurements has not yet become available so that the verification so-far relies on probe measurements only.

After an introduction of 11-cell EM simulations in the first section of this contribution, an improved damping with the complex load for critical coupling is shown. The third section is devoted to the measurement with the resonant posts, followed by a brief overview of the impact of the damping scheme on the accelerating FPB.

ELEVEN-CELL SIMULATIONS

The placement of the 630 MHz HOM-couplers in each 11-cell section of the 44- and 55-cell configurations that had been in use so far is shown in Fig. 1. For the future 33-cell structure, the two most detrimental HOMs in the 630 MHz frequency range have high-R/Q (≈90 Ω circuit definition) and a phase advance per cell of $14\pi/33$ and $15\pi/33$ respectively. In a single section only the latter of the two exists ($5\pi/11$) together with other HOMs of the same passband, which are less synchronous with the beam and therefore less

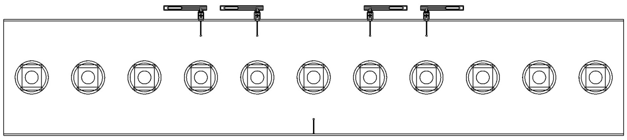

Figure 1: Coupler and resonant post configuration in 11 cells for measurement of HOM-mitigation performance.

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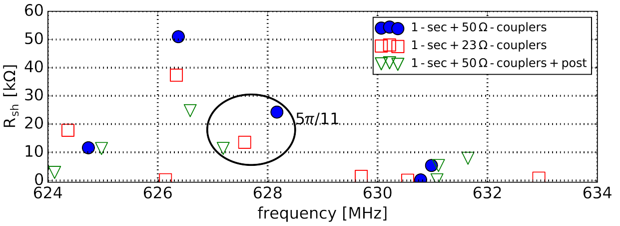

Figure 2: Results of eigenmode simulations for three different HOM-coupler and post configurations, refer to Fig. 1.

harmful. The new post is most effective for the mitigation of the $5\pi/11$-mode when placed in cell #6, where its electric field is maximum. Figure 2 shows the results of eigenmode simulations [4] for three setups. The first two do not include the resonant post and differ only in the characteristic impedance of the coaxial HOM-couplers and terminations. The usual 50 Ω standard couplers are used in the first case, and 23 Ω couplers are used in the second. Detailed studies suggest that this impedance leads to slightly overcritical coupling to the two high-R/Q HOMs in 33 cells as well as some other modes in the 630 MHz range [5]. This effect can also be observed in the 11-cell configuration in Fig. 1. The HOM-damping of the $5\pi/11$-mode at 628 MHz is improved and due to the overcritical coupling additional modes are found by the solver in the frequency range. The third case shown in Fig. 2 includes the resonant post together with 50 Ω HOM-couplers. We again observe a strong mitigation of the $5\pi/11$-mode. Some part of the impedance is however merely distributed to around 632 MHz, again due to resonant effects. This distribution of beam coupling impedance over a wider frequency range is nevertheless very helpful in the mitigation of multi-bunch instabilities. The simulated quality factors of around 400 in the original damping configuration with 50 Ω couplers are already very low so that a significant improvement of the impedance situation by merely targeting the Qs is very difficult.

VERIFICATION OF COMPLEX LOADS

In RF lab measurements, the cavity is typically excited on axis at the endplates and with electric probes, as this allows excitation of all longitudinal HOMs of interest. Figure 3 shows the measured transmission S_{21} in the 630 MHz frequency range for the undamped case, and for the damped cases with 50 and 23 Ω coupler impedances respectively. Already with the 50 Ω standard load, the Q of the $5\pi/11$-mode at around 627.5 MHz is so low that the typical resonant behaviour is not visible. The electrical length of the HOM-coupler from the base of the electric pickup to the load port was measured as 324° at 628 MHz. The appropriate complex load is deployed to achieve a 23 Ω coupler input impedance. The deployment of this complex load on all four HOM-couplers leads to a decreased transmission in the dangerous 627 to 630 MHz frequency range, cf. Fig. 3. This confirms an increased damping due to the complex loads. eigenmode simulations also suggest a significant decrease of the R/Q. This is possible due to the slight shift in resonance frequency of the mode when different loads are deployed. It is not possible to measure the R/Q using the probe measurement, therefore perturbation measurements will be performed and presented in the future.

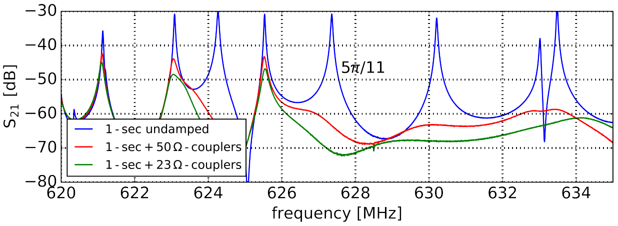

Figure 3: Measurements of transmission S_{21} for different HOM-coupler configurations (red, green) in one section with on-axis excitation.

VERIFICATION OF RESONANT POSTS

The transmission measurements for the configuration in Fig. 1 with and without the resonant post in cell #6 are shown in Fig. 4. We again observe a reduced transmission at the $5\pi/11$-mode frequency but also an increase at 633 MHz. This is in good agreement with the redistribution of impedance to higher frequencies as suggested by the eigenmode simulations, cf. Fig. 2. The post is resonant at 630 MHz leading to a larger transmission and the resonant feature in S_{21} at this frequency. The EM field profile of this resonance should however not be harmful to the beam, a fact which shall be confirmed by perturbation measurements. The dip in transmission at the post frequency can be reproduced in S-Parameter simulations, which again confirm the good agreement between simulations and measurements. The performance of the new, improved damping scheme obtained by simulations and presented in [3] should therefore be trustworthy.

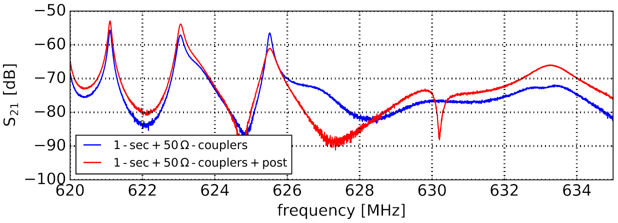

Figure 4: Measurements of transmission S_{21} for the damping configuration in Fig. 1 with (red) and without (blue) resonant post installed in cell #6.

Recently a 33-cell structure consisting of three spare sections became available for RF measurements. At present, one of the sections is however slightly detuned so that results have to be taken with care. In addition, a sufficient number of spare HOM-couplers to equip the 33 cells with the proposed new longitudinal damping scheme is not currently available. Therefore, only the old damping scheme (Fig. 1) consisting of 12 HOM-couplers is installed on the

33 cells. Figure 5 shows the comparison of on-axis transmission measurements with and without three resonant posts in the positions suggested in [3]. A lower transmission can be observed at the frequency of the $14\pi/33$-mode around 630 MHz. This is however not the case at the $15\pi/33$-mode frequency at 628 MHz. One likely reason is the missing additional HOM-couplers at the top of the cavity, for which the posts act as counterparts. Together, both devices are more effective than on their own. Using in appropriate cells slightly longer posts, which are resonant at 628 MHz in addition to the post resonant at 630 MHz, might also increase the impact at 628 MHz. Overall, the behaviour of the resonant posts needs to be studied in greater detail.

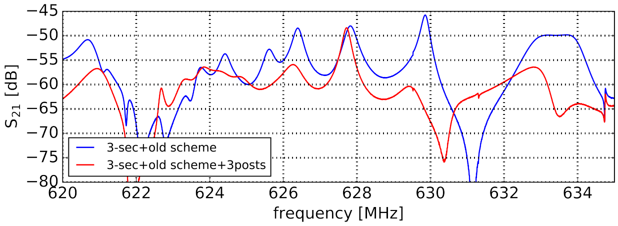

Figure 5: Measurements of transmission S_{21} in 33 cells with the old damping scheme installed and with (red) and without (blue) three additional resonant posts placed in cells 9, 17 and 25.

IMPACT ON THE FPB

The travelling-wave accelerating structures in the SPS are a fixed-tuned wideband system. The typical range of RF frequency required for acceleration of the LHC proton beam is from 200.265 MHz at 26 GeV/c to 200.394 MHz at 450 GeV/c. The fixed target beam is injected at 14 GeV/c and 199.946 MHz RF frequency. Fixed-frequency acceleration is used for heavy ions. The structures are designed to accelerate the particle beam using the $\pi/2$ travelling-wave mode and were originally tuned to the former transition energy frequency of 200.222 MHz [6]. Damping of this fundamental mode due to the HOM-couplers can be neglected as these are fitted with well tuned notch filters. However, each HOM-coupler and resonant post leads to a shift of the FPB impedance to a lower frequency resulting in a reduction of the impedance above 200.222 MHz and consequently a drop in the peak accelerating voltage [5]. One advantage of the travelling-wave structure however is its broadband characteristic, which enables efficient acceleration across a large frequency range. The improved stability of the LHC proton beam obtained from the increased HOM damping outweighs the small effect of the reduced accelerating voltage [7]. The proposed damping scheme for the future 33-cell structures includes three resonant posts resulting in a measured frequency shift of around -40 kHz. The frequency shift per post is of the same order as for one of the existing HOM-couplers.

CONCLUSION

Although the damping improvement by critical coupling to the $5\pi/11$-mode could not be quantified absolutely, it was shown that a 23 Ω load impedance leads to improved damping in the frequency range dangerous for the LHC proton beam. The complex loads will therefore be a valuable addition to the new longitudinal damping schemes for the 33- and the 44-cell structures. Measurements with the resonant posts are overall in very good agreement with eigenmode and S-Parameter simulations. It is planned to carry out more extensive measurements regarding the effects of the posts to confirm the promising behaviour observed so far. With previous simulation results and the work presented in this contribution, a factor three reduction in beam coupling impedance of the SPS accelerating system around 630 MHz seems within reach.

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