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STUDIES FOR THE SPS TRAVELLING WAVE CAVITIES UPGRADE

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Abstract

The Super Proton Synchrotron (SPS) 200 MHz accelerating system poses an intensity limitation for the planned High Luminosity (HL)-LHC upgrade due to excessive beam loading as well as higher-order modes (HOMs) contributing to a longitudinal multi-bunch instability. The mitigation of these HOMs together with a shortening of the cavities is therefore an essential part of the LHC Injectors Upgrade (LIU) project. A brief introduction to the accelerating structure as well as its present and future cavity configurations is given. First conclusions are drawn from lab measurements performed on three spare cavity sections regarding tuning and beam impedances. The following studies on longitudinal impedance are targeted towards the shorter cavity configuration used in the future. The particular difficulties inherent to the HOM-damping of this configuration are identified and illustrated. Taking these findings into account, a first improved HOM-damping scheme with regard to the scheme in use today is developed.

INTRODUCTION

The accelerating system of the SPS in today's configuration cannot support beam intensities required for the planned High Luminosity (HL)-LHC upgrade [1, 2]. The limitation is twofold: Heavy beam loading at such high intensities limits the available accelerating voltage and higher-order modes (HOMs) drive the beam unstable, creating a longitudinal multi-bunch instability with a threshold of about 20% below the desired operational intensity of $2.4 \cdot 10^{11}\ p/b$. A large share of this known instability is expected to be driven by HOMs of the multi-stem Travelling Wave Cavities (TWCs) around 630 MHz. Macro-particle simulations show that an additional damping of these HOMs by a factor of two to three is required with regard to the HOM-damping already in place today [1]. Within the framework of the LIU project, the TWCs therefore undergo thorough studies in both their present and future configurations, especially regarding their longitudinal impedance. Implementation of the solutions to both of the above mentioned problems has to start already in 2019. The goal of the performed studies is to develop a broad understanding of the accelerating system that was developed almost half a century ago and also to establish new, reliable HOM-damping schemes that can ensure a good cavity performance for the required beams in the HL-LHC era.

GENERAL STUDIES ON THE SPS ACCELERATING SYSTEM

The periodic multi-stem drift-tube structure

A single cell of the periodic 200 MHz accelerating structure consisting of the outer envelope, drift tube, horizontal stems and pedestals was already introduced in [3] and is shown again in Fig. 1 for convenience. Basically, the longitudinal electric field necessary for particle acceleration builds up between the drift-tubes of two consecutive cells with $\lambda/2$ wavelength spacing. However, the stems also support unwanted longitudinal fields at the uneven harmonics of this fundamental mode which are possibly deteriorating to beam quality.

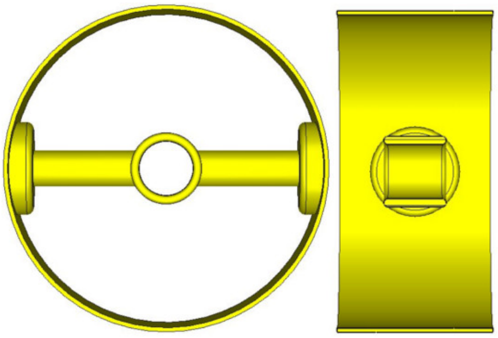

Figure 1: A single cell of the SPS 200 MHz accelerating structure (front and longitudinal-cut view).

For practical handling reasons the structure is divided into sections with a length of 4.114 m each consisting of 11 single-cells (inner diameter of circular envelope is 0.75 m). One of three spare sections is shown in Fig. 2 together with an end-plate terminating the periodic structure while providing access for the symmetric fundamental power couplers (FPCs) to the left and right of the beam axis as well as ports used for HOM-damping. An additional access port for this purpose is available on top of each cell. /

With the FPCs being matched in the fundamental frequency range, the accelerating structure is essentially a stem and drift-tube loaded waveguide operated in travelling wave mode. Excess RF power not transferred to the beam is terminated in a load. However, as the cutoff frequencies of the first waveguide mode for the on-axis tube and the coaxial feeder lines to the FPCs are at 1.3 GHz and 0.74 GHz, respectively and as the FPCs act as near perfect reflectors for most frequencies outside the fundamental passband, the accelerating structure can be approximated as a standing wave cavity for large parts of the HOM spectrum. For convenience, the accelerating structure is in general called cavity in the fol-

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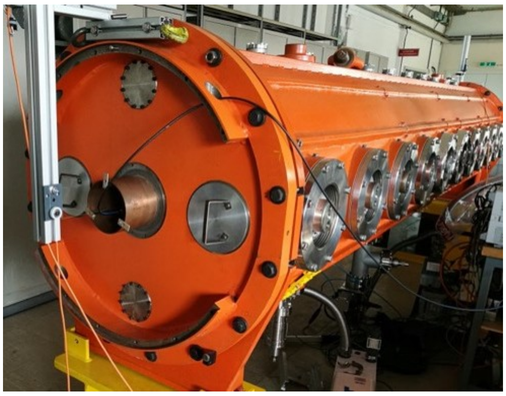

Figure 2: Spare cavity section with access ports for FPCs and HOM-damping. A part of the measurement setup used for on-axis perturbation measurements is shown as well.

lowing, keeping in mind that it is operated in travelling wave mode in the fundamental passband (FPB).

Present and future cavity configurations

Today's cavity configuration with two 4- and two 5-section cavities is in use since 1980 [4]. Since the first installation of the accelerating system in 1976, three types of HOM-couplers were added to each cavity. A transverse coupler working at 460 MHz and a longitudinal one for 628 MHz were already installed within the first year of operation after the corresponding transverse and longitudinal beam instabilities had been observed [5–7]. A third type of HOM-coupler was installed a few years later for a transverse instability caused by a HOM at 938 MHz [8–10]. A part of the simulation model for the cavities of varying lengths is shown in Fig. 3, indicating also the placement of the three HOM-coupler types. The 460 MHz and 628 MHz couplers are placed in a regular pattern on each individual section and are also independent of the section count. In total four 460 MHz HOM-couplers per cavity are situated on the two end-plates. Today's longitudinal damping scheme with four regularly placed 628 MHz couplers per section is shown as well. The 938 MHz HOM-couplers are placed in an irregular pattern, but are installed in pairs as this reduces their influence on the FPB.

The present cavity configuration is not suited for future HL-LHC beam intensities due to excessive beam loading. The SPS power plants will therefore receive an upgrade and the two long 5-section cavities will be rearranged to four 3-section cavities by also making use of two spare sections [1,2]. This reduces the total beam coupling impedance (including the impedance of the FPB), but also the beam loading per cavity, and therefore increases the available accelerating voltage for future beam intensities.

Cavity tuning

The relative frequency swing during acceleration in the SPS is small enough (0.44 % in the 70s, 0.065 % today), that a travelling wave structure can provide the required bandwidth in its fundamental passband. For a standing wave cavity however, the frequency swing would require tuning and therefore an adjustable element in the tunnel. As such devices often come with reliability issues, this is one of the main advantages that led to the use of travelling wave structures in the SPS [7]. The accelerating structure was optimized for acceleration with $\pi/2$-mode. As this mode features the largest spacing to adjacent modes, it has to the advantage that the FPCs can be designed fairly broadband so that other high impedance modes present in the FPB and excited by the beam are damped by the terminating loads. This is an important aspect that also has to be taken into account for the upcoming FPC upgrade. A redesign is necessary due to future increased power handling requirements as well as space restrictions in the long straight section housing the accelerating system [11].

Although the travelling structure does not have to be tuned during operation, it was necessary to conduct a one-time tuning per section before its first commissioning [7]. The tuning can thereby account for manufacturing tolerances and shifts the operating mode to the desired frequency that is common to all sections, putting the $\pi/2$-mode in perfect synchronism with the beam at this particular frequency. Tuning is accomplished by adjusting the length of the stems resulting in the pedestals protruding more or less into the structure (see Fig. 1), which increases or lowers the individual cell frequencies respectively.

The tuning of the available three spare sections of which two will be needed for the upgrade was already briefly studied. Whilst spares 1 and 2 were in storage in a fully assembled state, the envelope of spare section 3 first had to be equipped with separately stored drift tube assemblies of different stem lengths. The resonant frequencies of the FPBs were then measured in standing wave mode without FPCs, see Fig. 4. Although all three spare sections were measured with very weak coupling of the measurement probes to the cavity modes, a slight variation was inevitable, being most likely the source of the observed difference in S-Parameter amplitude during the transmission measurements. These measurements show clearly that the resonances of spare 3 are detuned with respect to the two other spares. This detuning amounts to around 300 kHz at the center of the FPB. Further studies regarding the tuning of the $\pi/2$ travelling mode and the possible influences of HOM-couplers are planned once the spare sections are available for further measurements. The goal is to carry out a tuning of spare 3, such that it can be used as a working backup for the HL-LHC era.

Verification of simulation models

New HOM damping schemes for future operation of the accelerating structure shall at first instance be found by simulation. To obtain confidence in the simulation models, agreement between simulated and measured results is constantly studied. Classic resonant bead-pull perturbation measurements were carried out on all three spare sections with the goal to verify geometry factors over the whole frequency

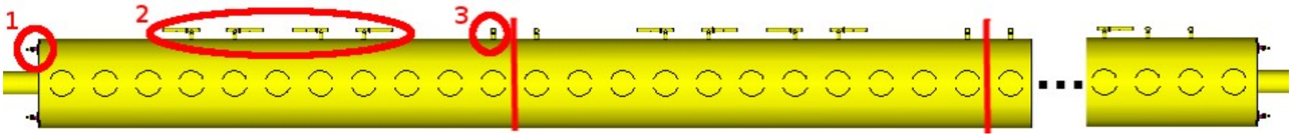

Figure 3: Clipped simulation model of a multi-section cavity showing the regular placement of 460 MHz (1) and 628 MHz (2) HOM-couplers as well as the irregular placement of 938 MHz couplers (3).

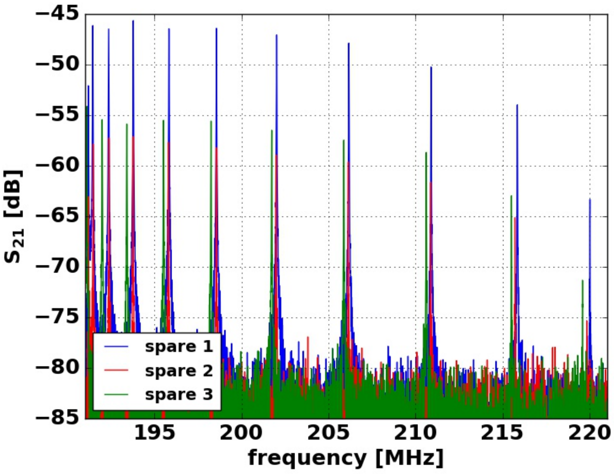

Figure 4: Comparison of the fundamental resonant frequencies in the three spare sections.

range of interest. The results and the comparison to simulation is shown in Fig. 5. Data points obtained by simulation seem to have the tendency to be below their measured counterparts. An obvious structural difference results from the use of a single stem length for all drift tube assemblies in simulation whereas in the actual sections the stem lengths vary on the order of several millimetres for tuning reasons. Slightly lower geometry factors can as well be observed for the detuned spare section 3, which is especially visible in the FPB. Overall, the agreement between simulation and measurement as well as amongst the three spare sections is good. We verified our simulation models also by other means like S-Parameter measurements on the full scale SPS cavities and so far we were able to provide for all cases good predictions for what could be expected from measurements.

LONGITUDINAL IMPEDANCE OF FUTURE 3-SECTION CAVITIES WITH TODAY'S HOM-DAMPING SCHEME

As already mentioned previously, the multi-stem structure also generates strong on-axis electric fields at its third harmonic passband around 600 MHz. Fig. 5 shows that this passband also features high geometry factors. The longitudinal impedance of a 3-section cavity including today's FPCs obtained from wakefield simulation is shown in Fig. 6 on a logarithmic scale. The impedances around 630 MHz are not fully converged despite a simulated wake length of 3 km. Eigenmode simulation suggests a peak impedance of 5.2 MΩ at this frequency. The impedance of this standing wave HOM is several times higher than the impedance of the FPB as it is not damped by the FPCs. The FPB however is simulated in travelling wave mode. Fig. 6 also shows the performance of the present 630 MHz damping scheme if it were to be applied to the future 3-section cavities. Obviously, the existing 628 MHz-coupler introduces significant damping over a wide frequency range and heavily damps the modes

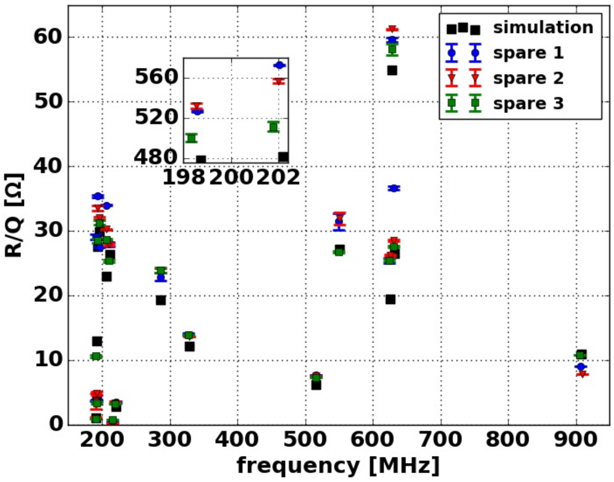

Figure 5: Comparison of simulated and measured standing mode geometry factors of single section cavities in the frequency ranges of interest.

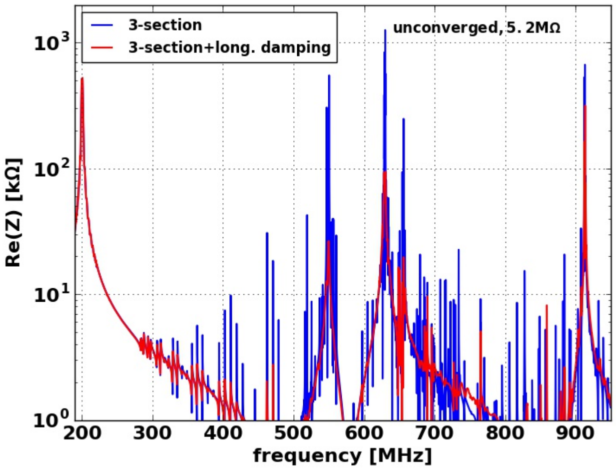

Figure 6: Longitudinal impedance of a 3-section cavity with and without the present longitudinal HOM-damping scheme.

around 630 MHz. This HOM-coupler basically consists of a notch filter for the FPB and a 50 Ω load for the HOMs. The good performance of the coupler has been confirmed by more detailed analyses and transmission measurements on full scale cavities installed in the SPS. More details of this coupler are shown in [3]. The addition of 12 couplers of the original damping scheme introduces merely a slight shift to higher frequencies on some modes of the FPB. Otherwise, the FPB is left untouched. Three impedance peaks can be distinguished in the potentially dangerous 630 MHz frequency range for this configuration. Particle simulations suggest no significant threat to beam stability for planned intensities due to the HOMs at 550 MHz and 914 MHz [12].

LONGITUDINAL HOM-DAMPING FOR FUTURE 3-SECTION CAVITIES

The longitudinal passbands around and above the third harmonic frequency of the periodic structure are shown in Fig. 7. These passbands were obtained from a single cell simulation with periodic boundaries on the two longitudinal boundary-planes of the model (see Fig. 1). A step in phase advance between these boundaries of integer multiples of $\pi/33$ was used to obtain the mode frequencies that exist in a 3-section cavity. The frequencies obtained from this infinite periodic set-up are in good agreement with the frequencies in a 33-cell cavity shorted by end-plates. The dashed line indicates that highest interaction between cavity and beam should be expected at 630 MHz. The passband around the third harmonic is also outlined in Fig. 7 for the case that a 628 MHz HOM-coupler is inserted at the top of the cell. Heavy perturbation can be observed in the frequency range with strong coupling of the HOM-coupler. The next higher passband is deformed by the presence of the HOM-coupler such that additional HOMs are created in this dangerous frequency range. The periodic simulation setup presumes that a coupler is positioned in every cell. This will not necessarily be the case in a final damping scheme. It is nevertheless obvious that the HOM field configurations inside the cavity can get highly perturbed by the presence of this coupler. The HOM-coupler itself is therefore an essential part in the analysis of cavity impedance and possibly poses itself an obstacle to HOM-damping.

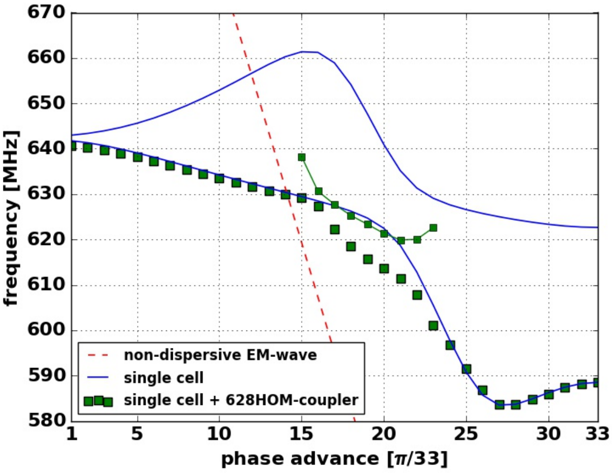

Figure 7: Dispersion diagram for the third harmonic and next higher longitudinal passbands for a single-cell (blue) and a single-cell with a 628 MHz HOM-coupler (green) simulation.

The performance of the present damping scheme with HOM-couplers placed on top of cells 4,5,7 and 8 on each section as shown in Fig. 3 was analysed on a 1-section cavity as an intermediate step. All modes of the 1-section cavity with an integer multiple of $\pi/11$ phase advance will also exist in multi-section cavities together with additional potentially hazardous modes. Nevertheless, as the mode with highest impedance is damped massively and as the HOM-coupler also acts on most other HOMs in the frequency range, it was sufficient for operations in the late 1970s to focus only on the damping of modes with a $\pi/11$ phase advance. For this purpose the damping scheme of a 1-section cavity could simply be copied to all other sections of the multi-section cavity to ensure sufficient HOM-damping. In addition, the technical means to investigate the impedance of long multi-section cavities with justifiable effort were most likely not available at that time. It can therefore also be concluded that the present 628 MHz HOM-coupler was solely developed on a 1-section cavity although the corresponding instability was observed during operation with 5-section cavities.

In a 1-section cavity, the most deteriorating mode with a shunt impedance of 1.8 MΩ is simulated at 629 MHz with a phase advance of $5\pi/11$ per cell. This mode receives huge damping by a factor of 80 when including the four HOM-couplers of the present damping scheme. Due to different stem lengths on the actual sections this mode is measured at a slightly lower frequency and therefore corresponds to the mode the 628 MHz-coupler was targeted to. Although also all other high impedance modes in the passband receive strong damping, nevertheless two modes with significant impedances remain at 623 MHz and 627 MHz.

It is investigated as a next step, if the HOM-damping scheme applied to a 3-section cavity is sufficient for planned future beam intensities. Particle simulations suggest that the beam coupling impedance of a 3-section cavity in the deteriorating frequency range from 620 MHz to 630 MHz ideally should not surpass 24 $k\Omega$ [12]. As roughly a dozen modes exist in this frequency range whose impedance spectra overlap, the impedance of each mode must be mitigated to values well below 24 $k\Omega$. The three modes with highest impedance in a 3-section cavity with today's damping scheme installed are shown in Tab. 1. Thereby, the mode with a phase advance of $15\pi/33$ was already mentioned above as it also exists in a 1-section configuration. Despite the damping by a factor of 80, its impedance is still too high for future beam intensities. The two other modes are special to the 3-section configuration. The mode with phase advance $14\pi/33$ is synchronous with the beam (cf. Fig. 7) resulting in its high geometry factor.

Table 1: Most deteriorating modes for a 3-section cavity with today's longitudinal damping scheme.

f [MHz]	Q	R/Q [Ω]	R [kΩ]	ϕ [rad]
627.7	5600	5.9	33.0	$17\pi/33$
629.2	445	92	40.9	$15\pi/33$
630.3	394	137	54.0	$14\pi/33$

The mode with $17\pi/33$ phase advance is peculiar as it features a significantly higher quality factor compared to the two other HOMs. This mode does not seem to undergo strong damping with the present HOM-damping scheme and considering again Fig. 7 it is determined to be merely created by the addition of the 628 MHz couplers. The electric field profiles of both $17\pi/33$ modes shown in Fig. 7 are presented in Fig. 8. Both modes seem to have approximately the same field profiles when mirrored at an imaginary horizontal axis centred on the stems. The mode with a frequency of 622.2 MHz has strong electric field in the upper half of the single-cell and is therefore well damped, whereas the undamped mode with the same phase advance has strong field in the lower half of the cavity. By adding HOM-couplers on-top of the cavity, the top/bottom symmetry is broken and the field profile of this mode is pushed into the lower part of the cavity. As a result, the mode receives less damping from the top ports. Due to this and due to the too low field strength in the upper cavity half, also other probe geometries for field pick-up were found to be insufficient. The situation will even deteriorate if more couplers are added for further damping of the two low-Q modes. This is confirmed by additional HOM-couplers in cells marked by red bars in Fig. 9 in which the electric field of these modes is strong. In this configuration the impedance of the $17\pi/33$ mode is increased to 47 kΩ. Considering that only four longitudinal HOM-couplers were added and that in the current overall HOM-damping setup also transverse couplers are placed on top of the cavities (cf. Fig. 3), this is an enormous increase. In addition, the impedance of the two low-Q modes is still not sufficiently reduced.

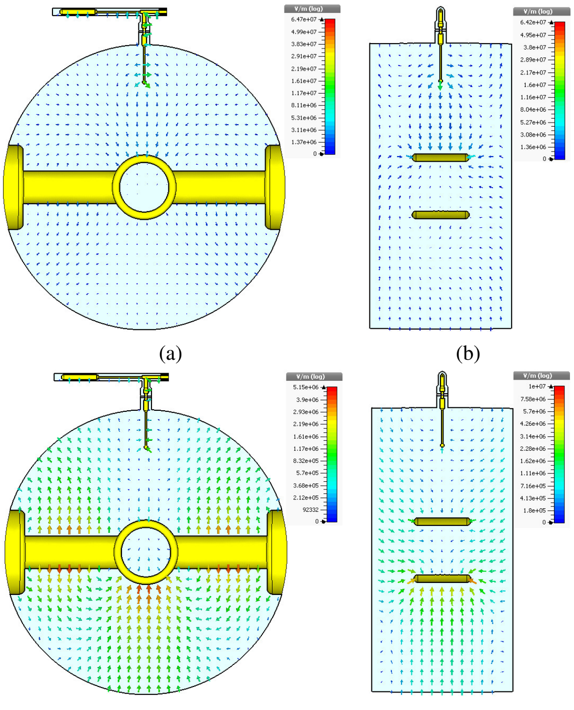

Figure 8: Field profiles of $17\pi/33$ modes with (a,b) damped mode at 622.2 MHz and (c,d) undamped mode at 627.7 MHz.

One can now think of basically two strategies to achieve the required damping: First, avoiding the $17\pi/33$ mode impedance to become pronounced while still sufficiently damping the two other HOMs. And second, damping not only the low-Q, but also the $17\pi/33$ mode. It has to be considered, that due to the existing damping the quality factors are already quite low and that there are no access ports in the bottom of the cavity dedicated to HOM-damping. No further access ports can be drilled into the cavity sections. It is therefore obvious that increased HOM mitigation by a factor of three and more is a very challenging task - no matter the strategy chosen. The remainder of this contribution will investigate if sufficient damping can be achieved by only using the dedicated HOM-ports at the top of the cavity.

Essentially, one would think that less invasive, shorter pick-up probes are necessary to avoid the $17\pi/33$ mode impedance become pronounced. Indeed, simulations on an infinite periodic single-cell show that by reducing the probe length of the existing 628 MHz HOM-coupler the quality factor of the $17\pi/33$ mode is reduced. However, reduced damping of the $14\pi/33$ mode due to this measure is even more significant. A change in geometry factors in the same manner can also be observed. From this trade-off a probe configuration can be expected that levels the impedance of the $17\pi/33$ mode with at least one of the low-Q HOMs. One such configuration is shown in Fig. 9. Here, the probes of the HOM-couplers were shortened in the positions in which the field profile of the $17\pi/33$ mode is most susceptible to the perturbation of the 628 MHz HOM-couplers. Most HOM-couplers however have to remain untouched to ensure sufficient HOM-damping in general. The damping performance of this configuration is illustrated in Tab. 2 showing the characteristics of the three modes with highest impedance. The trade-off described above leads to a balancing of the HOM impedances around 30 kΩ. Although this is already a considerable improvement, the HOM impedance is still to high

Table 2: Most deteriorating modes for a 3-section cavity with HOM-damping scheme marked blue in Fig. 9.

f [MHz]	Q	R/Q [Ω]	R [kΩ]	ϕ [rad]
627.6	5172	5.8	30.0	$17\pi/33$
629.2	325	90	29.3	$15\pi/33$
630.2	244	125	30.5	$14\pi/33$

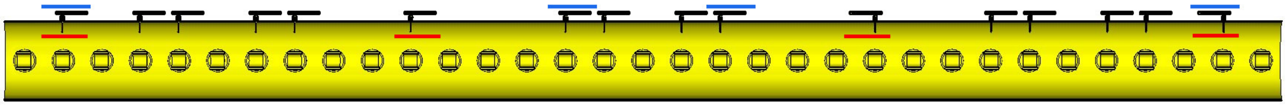

Figure 9: A first improved HOM-damping scheme for future 3-section cavities with added HOM-couplers marked by red and couplers with shorter probes by blue bars.

for HL-LHC beam intensities. All simulations in this contribution were conducted with CST Microwave Studio [13] and the essential results confirmed by ACE3P [14].

CONCLUSIONS AND OUTLOOK

As two additional sections will be required for the 200 MHz accelerating system, the three available spare sections were evaluated regarding tuning and beam coupling impedance. It was shown that one section is out of tune with respect to the others. The tuning mechanism as well as possible tuning procedures need to be studied in more detail. Proper tuning should lead to even better agreement in geometry factors amongst the spare sections. This contribution also showed that today's longitudinal HOM damping scheme applied to 3-section cavities is not sufficient for future HL-LHC beam intensities. The problems inherent to damping improvements were illustrated by simulation of a periodic single-cell approach incorporating the existing 628 MHz HOM-coupler. The effect that couplers installed at the top-ports can push electromagnetic fields in the lower cavity half was identified. This results in the creation of a high-Q mode in addition to the high-R/Q modes present in the 33-cell cavity geometry. It was demonstrated that sufficient damping of this high-Q mode from the access ports available at the top of the cavity can not be achieved. Satisfactory damping of the high-R/Q modes is challenging as well as their quality factors are already very low by employing today's damping scheme. Therefore, the following problem has been identified that needs to be overcome to achieve LIU goals: HOM-mitigation is required in the lower cavity half where access ports are scarce. Merely nine ports for vacuum pumping are available as well as one access on the two cavity end-plates each.

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