ANALYSIS OF HIGH ORDER MODES DAMPING TECHNIQUES FOR 800 MHZ SINGLE CELL SUPERCONDUCTING CAVITIES*

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Abstract

The High Luminosity LHC upgrade program foresees a possibility of using the second harmonic cavities working at 800 MHz for the collider bunch length variation. Such harmonic cavities should provide an opportunity to vary the length of colliding bunches. In order to supply the required harmonic voltage several single cell superconducting cavities are to be used. Different cavity designs and several higher order mode (HOM) damping techniques are being studied in order to reduce the cavity HOM impact on the beam stability and to minimize parasitic power losses. In this paper we analyze and compare the HOM electromagnetic characteristics and respective wake potential decay rates for cavities with grooves, fluted and ridged beam pipes. The problem of Lorentz force detuning is also addressed.

INTRODUCTION

At present the project aimed at Large Hadron Collider luminosity upgrade (HL-LHC) is being developed at CERN [1]. The luminosity increase is expected to be accomplished by increasing the currents of circulating beams, by reducing transverse beam sizes at the interaction points (applying smaller betatron functions) and using crab cavities to compensate the geometric luminosity loss in beam collisions [2].

The project considers also a possible implementation of harmonic cavities in addition to the main accelerating cavities working at 400 MHz to increase or to shorten the bunches [3-7]. In order to achieve the desired results a combination of the existing main RF cavities and harmonic cavities operating at 800 MHz is being studied.

In this paper we study electromagnetic characteristics of HOMs for a single cell 800 MHz superconducting cavity. Different techniques for the HOM damping such as beam pipe grooves, fluted beam pipes, ridged beam pipes etc. are investigated and compared.

HIGHER ORDER MODES DAMPING

Basic Design

An initial design of the harmonic cavity has been obtained by scaling (reducing) all the sizes of the LHC accelerating cavity operating at 400 MHz by a factor of 2 [8]. The cavity view is shown in Fig. 1. It is assumed in [8] that higher order modes damping is carried out, as in the case of the LHC accelerating cavity, with four couplers: two dipole and two broadband couplers. These couplers break the cylindrical symmetry of the electromagnetic field in the structure which gives rise to the transverse component of the electric field (kick-factor) causing a negative impact on the performance of the accelerated beam. Besides, the transient beam loading compensation in LHC requires a very high power main coupler [9]. Placing the robust main coupler and the HOM couplers on the same beam pipe may complicate the final design. That's why different HOM damping techniques were investigated.

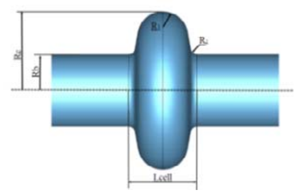

Figure 1: Accelerating cavity.

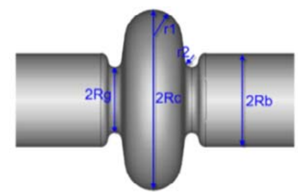

Figure 2: Cavity with grooved beam pipes.

We started our analysis by calculating the resonance frequency and the effective resistance to quality factor Q ratio (parameter R/Q_0) for the cavity shown in Fig. 1 by varying the drift tube radius. It was found that the most dangerous dipole HOM are TE_{111} and TM_{110}. The frequency of these dipole HOMs lie below the cut-off frequency of the TE_{11}wave and therefore cannot propagate along the drift tube [10]. HOMs couplers should be placed as close as possible to the accelerating cavity for the effective damping of such trapped modes.

Beam Pipe with Grooves

Another way to damp the HOMs is to cover the inner surface of the drift tubes with a dissipative material and let the HOMs propagate toward the absorbing load. This method is effective if the higher order mode frequencies become lower than the beam pipe cut-off frequency. Such a task can be accomplished by using grooved structures [11], i.e. cavities with grooves, as shown in Fig. 2.

The main advantage of the grooved structure is its cylindrical symmetry providing the same level of effective damping of HOMs with different polarizations. The absence of HOM couplers makes the design simpler and eliminates eventual negative impact of the couplers on beam dynamics due to the field distortion at their locations.

The results of simulations with ABCI code [12] clearly demonstrate that by choosing the beam pipe radius and the groove geometry in a proper way we have managed to obtain a truly "single mode" cavity. Figure 3a shows the simulated cavity shape, while Figs 3b shows respectively

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the dipole wake potential. We should not expect multibunch instabilities since the wake field decays completely at the distance of 15 m that corresponds to the actual bunch separation of 50 ns in LHC.

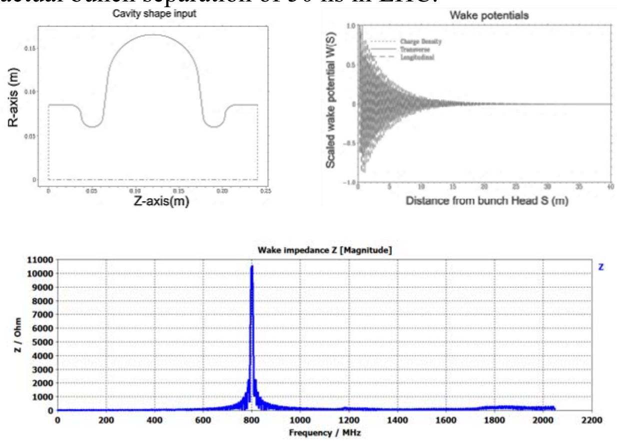

Figure 3: Wakefield results for the structure with grooved beam pipe (a. Structure profile, b. Wake potential, c. Monopole impedance).

Fluted Beam Pipe

Structure with fluted beam pipes [13] is demonstrated in Figure 4.

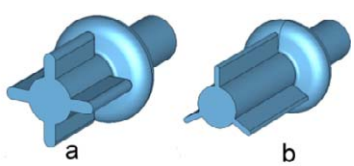

Figure 4: Structure with 4 (a) and 3 (b) flutes.

The effect of the fluted beam pipe size on cutoff frequencies of the TM_{01}, TE_{11}, TE_{21} waves was investigated with MWS program [14]. It was found that the sizes of the edges do not change the cutoff frequency of the wave TM_{01} but have a strong influence on the cutoff frequency of TE_{11} and TE_{21}waves and hence the damping of the TE_{111} , TM_{110}, TE_{211} , TM_{210} modes. It was found that the configuration with 3 flutes instead of 4, as in [13], has higher damping efficiency for quadrupole modes.

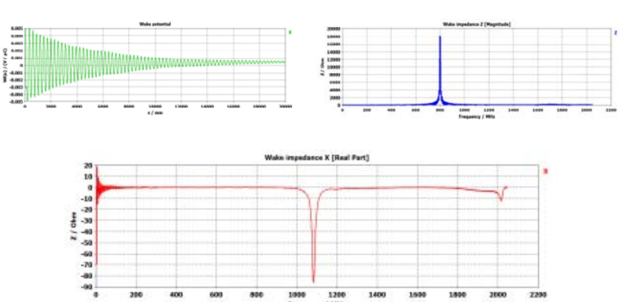

Fig 5. Wakefield results for the structure with fluted beam pipe (a. Dipole Wake potential, b. Monopole impedance, c. Dipole impedance).

In this structure Q_{ext} are below 100 for all HOMs except for a few modes with low R/Q ratio and the wake potential decays very fast (fig 5a). Respectively there are no sharp peaks on monopole (fig 5b) and dipole (fig 5c) impedance graphs except the one corresponding to the operating mode.

Ridged Beam Pipe

The fluted beam pipe damping efficiency could be improved if we reverse flutes inward the beam pipe (fig 6). In this case the cut off frequencies for quadrupole and dipole modes decrease and this allows reducing the beam pipe radius. The calculated wake field decays for this structure is presented in fig 7a.

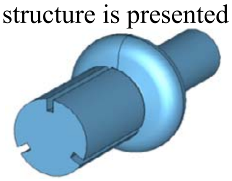

Figure 6: Structure with ridged beam pipe.

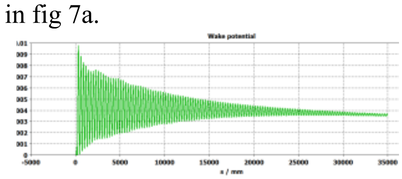

Figure 7a. Wake potential.

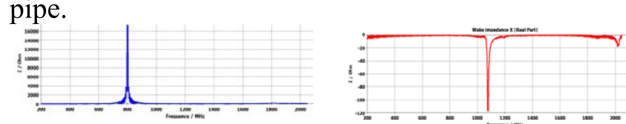

Fig 7b-c. Wakefield results for the structure with ridged beam pipe (7b. Monopole impedance, 7c. Dipole impedance).

As it can be seen the wake potential decays very fast also in this case. On the other hand, the cut-off frequency of E_{010} mode is also lower for this configuration which can lead to a deeper penetration of the working mode towards the load. To prevent decreasing Q_0 of the working mode beam pipe length can be chosen longer than that in fluted bam pipe case. Sharp peaks on the HOM monopole (fig 7b) and dipole (fig 7c) impedance graphs are not observed.

LORENZ FORCE DETUNING

Lorenz force frequency detuning was investigated for the discussed HOMs damping methods. As an example deformations of the grooved structure due to the influence of the Lorentz force are shown in Figure 8.

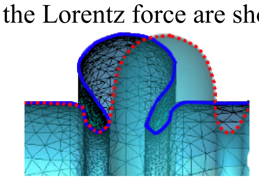

Figure 8: Grooved structure deformations due to the influence of the Lorentz force (dotted line – structure, solid line– deformed structure).

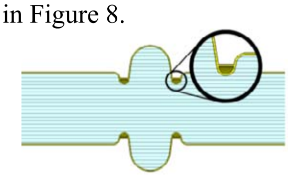

Figure 9: Structure with grooves and stiffeners.

The ratio of frequency detuning to the square of the electric field strength can be considered as a quality criterion for the influence of the Lorentz force on the structure. The Lorentz force sensitivity can be decreased by increasing the cavity wall thickness or by adding of specific stiffeners schematically depicted in Fig. 9 to the structure design [15].

The calculations were carried out for the structure consisting of copper with Young's coefficients 120 kN/mm^2 (Table 1). One end of the cavity beam pipe is considered rigidly fixed during the calculations of frequency detuning.

Table 1. Lorenz force frequency detuning

Structure type (beam pipe/beam pipe outer radius, mm)	Copper structure $\Delta f/\Delta E^2$, Hz
Smooth structure(75)	-6.3
Grooved structure(75/105)	-6.3
Grooved structure with stiffners (75/105)	0.2
Fluted beam pipe structure (75/120)	-6.1

Table 1 shows that the $\Delta f/\Delta E^2$ ratio is smallest for the structure with grooves and stiffening ribs.

COMPARISON OF DESIGN SOLUTIONS

Table 2 shows that each of the considered methods of HOMs damping has its own advantages and disadvantages.

Table 2. Comparison of characteristics of calculated structures

	Grooved structure	Fluted beam pipe structure	Ridged beam pipe
Q_{ext} in single cell cavity	$<10^2$	$<10^2$	$<10^2$
Lorenz force detuning $\Delta f/\Delta E^2$, Hz	0.2	-6.8	-6.8
Symmetrical structure	Yes	No	No
Additional	Easy in manufac-turing	Quadrupole modes damping	Quadrupole modes damping

In our opinion, the structure with grooves seems to be a more suitable candidate for the 800 MHz cavity design since: a) it has simplest azimuthally symmetric geometry; b) there are no dangerous HOM created in the structure; c) no dedicated HOM couplers are required; d) an eventual multipacting discharge in the equatorial region at rather low accelerating gradients can be cured by an additional purification of the cavity surface and subsequent training; e) the Lorentz force detuning can be significantly reduced by inserted ring stiffeners in the grooves.

In the following we also consider a possibility to combine several such structures in a chain of non-communicating cavities in order to place them in a single cryostat.

CONCLUSION

We have compared four different HOM damping techniques for the 800 MHz harmonic cavity. In our opinion, the solution with grooves is preferable due to its cylindrical symmetry, design simplicity and absence of dangerous HOMs. We have also proposed to combine two such cavities connected by smaller radius beam pipe in a single cryostat [16].

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