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

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Abstract

Currently, applications of 800 MHz harmonic cavities in both bunch lengthening and shortening regimes are under consideration and discussion in the framework of the High Luminosity LHC project. In this paper we study electromagnetic characteristics of high order modes (HOM) for a single cell 800 MHz superconducting cavity and arrays of such cavities connected by drifts tubes. Different techniques for the HOM damping such as beam pipe grooves, coaxial-notch loads, fluted beam pipes etc. are investigated and compared. The influence of the sizes and geometry of the drift tubes on the HOM damping is analyzed.

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 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. So several design options of the second harmonic cavities with different higher order modes (HOM) damping techniques are under consideration.

In this paper we study electromagnetic characteristics [8] of HOMs for a single cell 800 MHz superconducting cavity and arrays of such cavities connected by drifts tubes. Different techniques for the HOM damping such as beam pipe grooves, coaxial-notch loads, fluted beam pipes etc. are investigated and compared.

SINGLE CELL CAVITIES

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 [9]. The cavity view is shown in Fig. 1 while the geometric dimensions are given in Table 1. It is assumed in [9] that higher order modes damping is carried out, as in the case of an 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 [10]. 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.

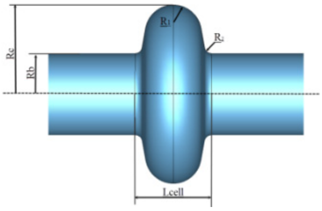

Figure 1: Accelerating cavity.

Table 1: Geometrical Dimensions of Initial Cavity Design

lc, mm	140
rc, mm	169.3
rb, mm	75
r1, mm	52
r2, mm	12.5

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 HOM lie below the cut-off frequency of the TE_{11} wave and therefore cannot propagate along the drift tube. HOMs couplers should be placed as close as possible to the accelerating cavity for the effective damping of such trapped modes.

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 corrugated structures [11], i.e. cavities with grooves, as shown in Fig. 2.

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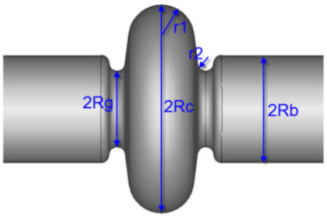

Figure 2: Cavity with corrugated beam pipes.

Figure 3 shows the distribution of the electric field of the dipole TM_{110} mode in "smooth" (Fig. 3a) and corrugated structures (Fig 3b). As it is seen, in the smooth structure the modes are trapped while in the corrugated one the fields propagate freely along the drift tube (beam pipe). For example, mode frequencies are 1077 MHz and 1080 MHz for the beam pipe radius of 85 mm, respectively, that are higher than the cut-off frequency of 1034 MHz.

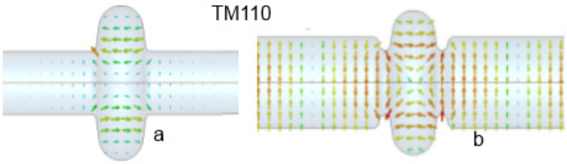

Figure 3: TM_{110} mode electric field dispersion in the structure with drift tube radius of 85 mm with no corrugations (a), with corrugations (b).

The main advantage of the corrugated 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 corrugation geometry in a proper way we have managed to obtain a truly "single mode" cavity. Figure 4a shows the simulated cavity shape, while Figs 4b show respectively 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.

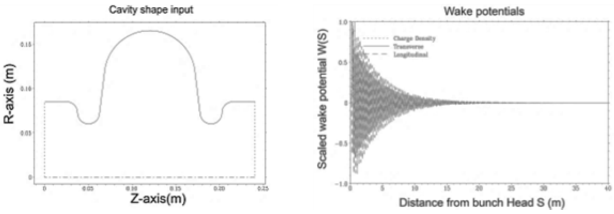

Figure 4: Structure profile (left) and wake potential (right).

Another method of HOM damping [13] consists in connecting the coaxial line to the drift tube with the HOM dissipative load at the end (see Fig. 5).

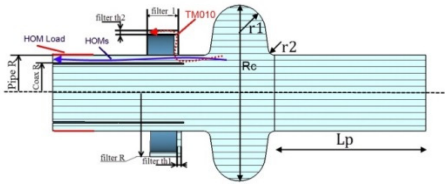

Figure 5: Demountable damped cavity.

In such a structure the operating mode TM_{010} can also propagate along the coaxial line and in this case a notch filter tuned to the frequency of the fundamental wave can be used to prevent its damping (see Fig. 6). The presence of the coaxial line can increase coupling between HOMs and the load and thereby increase the damping efficiency.

Demountable design of the load can facilitate access to the load for cleaning (as discussed in [13]) and the structure eliminates a kick-factor due to the cylindrical symmetry of the structure. This makes this damping technique very promising.

Cavity parameters adjustment has been carried out in several steps by carefully choosing the cavity dimentions, coaxial line penetration and by fine tuning the notch filter sizes. The transmission coefficient S_{12} dependence on frequency for the configured notch-filter is shown in Figure 6 and the Q_{ext} of the E_{010} mode dependence on cell radius is shown in Fig. 7. The filter bandwidth is 31 kHz. These dependences show that fine-tuning is required to assure the high values of the external quality factor of the fundamental mode. The Q_{ext} of the HOMs obtained with this method are below 10^4. Damping of some modes is difficult and therefore they may pose a threat.

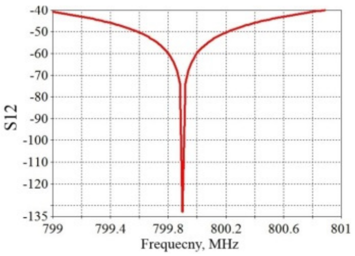

Figure 6: Transmission coefficient S_{12} dependence for adjusted notch filter.

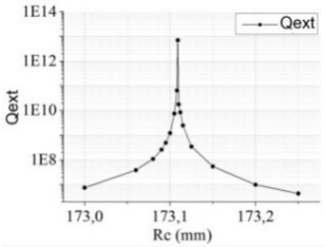

Figure 7: Q_{ext} for E_{010} dependence on cavity radius.

HOMs damping method using fluted beam pipes [14] is demonstrated in Figure 8.

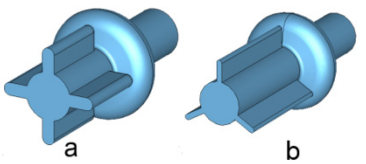

Figure 8: Structure with 4 (a) and 3(b) flutes.

The effect of the fluted beam pipe size on cut-off frequencies of the TM_{01}, TE_{11}, TE_{21} waves was investigated with MWS program [15]. It was found that the sizes of the edges do not change the cut-off frequency of the wave TM_{01} but have a strong influence on the cut-off frequency of TE_{11} and TE_{21}waves and hence the damping of the TE_{111} , TM_{110}, TE_{211} , TM_{210} modes. The dimensions of the drift tube and flutes can be adjusted in such way so that the operating mode will be locked and all other modes including the dipoleand quadrupole will easily propagate into the drift tube with subsequent absorption in the load. However, it was found that the cut-off frequency of the H_{21} wave has significantly different values in a case of different polarizations. External quality factors of modes with different polarizations differ by more than 5 orders of magnitude. Therefore an option with three ribs, placed at 120 degrees with respect to each other (see Fig. 8b), was finally considered.

The high HOM damping efficiency was achieved in the structure with three flutes while maintaining high Q_{ext} of the operating mode without the choke filter. It was found that Q_{ext} is below 100 in this structure for all HOMs except for a few modes with low R/Q ratio.

ARRAY OF CAVITIES

It is desired to place more harmonic cavities in a single cryostat in order to avoid multiple transitions between cryogenic and "warm" areas. However, in the structures that we are discussing, HOMs propagate along the beam pipe toward the loads located outside the cryogenic environment. Therefore dimensions of the connecting drift tubes were optimized to ensure the most effective HOM damping in a chain of cavities.

Despite that the chosen geometry of the single cell cavity with grooves provide a rapid decay of the wake potential, the situation becomes more complicated for an array of two or more such cavities due to presence of trapped electromagnetic fields between them. This can potentially create problems in multibunch operations.

The problem can be solved by reducing the radius of the drift tube connecting the two cavities. In this way the HOM frequencies get lower and their fields do not penetrate inside the connecting tube. As it is seen in Fig 9, now the wake field decay rate is comparable to that of the single cell cavity (Fig. 4b). In our opinion, the configuration shown in Fig. 9 can be considered optimal for several reasons: the geometry is perfectly azimuthally symmetric; there no dangerous HOMs; there is no need to use any additional HOM couplers; cavities do not communicate with each other due to the small radius of the connecting beam pipe. The main coupler can be placed on the beam pipe with a smaller radius. In this way the central conductor of the main coupler should not penetrate deeply inside the beam pipe.

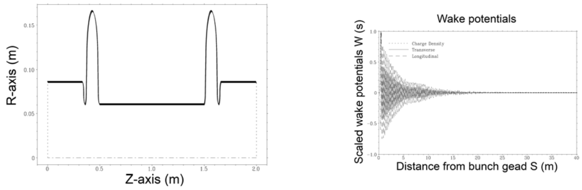

Figure 9: Structure view and wake potential.

Following the same strategy one can think of connecting more cavities in a chain. Fig. 10 shows an example of "optimized" configuration with decaying wake potentials.

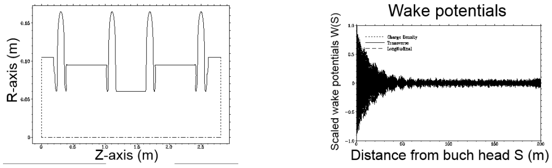

Figure 10: Structure view and wake potential.

A disadvantage of such a structure is that because of different drift tube radiuses the main couplers should have different designs. Besides, an impact of the HOMs with the external quality factors as high as 10^4 on beam dynamics should be carefully evaluated. As an alternative approach one can consider an application of dedicated couplers to extract HOMs from the beam pipes connecting the cavities.

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.

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