HIGHER-ORDER MODES DAMPING IN 800 MHz SUPERCONDUCTING CAVITY

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Electromagnetic characteristics of dipole higher order modes H_{111} and E_{110} for superconducting cavity operating at 800 MHz as a function of drift tubesradius were calculated. The possibility of higher order modes withdrawal and damping through drift tubes with corrugations, damping rings and radial loads was investigated. Wakefield calculations results are presented and discussed. The problems of a multipactor discharge were considered.

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INTRODUCTION

Currently the project of Large Hadron Colliderluminosity upgrade (High Luminosity Large Hadron Collider - HL-LHC) is being developed at CERN [1]. Upgrade design includes possible implementation of harmonic resonators in addition to the basic microwave accelerating cavities to increase or short circulating bunches length. The desired effect can be obtained if harmonic signal is phased properly with bunch center fall in zero field and the field itself will be either increasing or decreasing [2].

In case harmonic resonators operate in bunch extension mode charge density of the bunch decreases with almost constant energy acceptance. This leads to beam lifetime increase, number of events in the collision of beams per second decreases thus improving detectors operation. In addition, bunch length increase reduces the heating of the vacuum chamber elements due to wake potentials and an additional non-linearity of RF fields helps to suppress the beam instabilities.

In bunch shortening regime higher luminosity of collider can be achieved by reducing of the geometrical losses, which takes place in case of beams colliding at certain angle (Large Piwinski angle) or due to the "hour-glass" effect.

To achieve the positive effects a combination of operating frequencies 400 and 800 MHz cavities can be used. To do this new harmonic resonators of the frequency of 800 MHz are required to be developed.

1. HIGHER ORDER MODESIN SINGLE-CELL CAVITY WITH CONJUGATIONS

Initially, we calculated the electrodynamic characteristics (EDC) of HL-LHC superconducting resonator (SCR) basic version shown on Fig. 1.

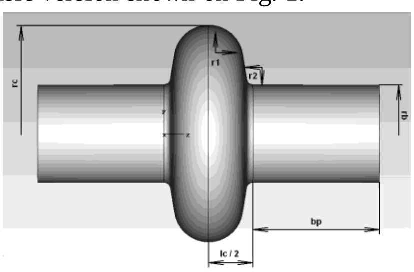


Fig. 1. HL-LHC harmonic cavity basic version

Dimensions of this cavity are given in [3]. Resonance frequency *f* and the shunt impedance R_{sh} to own quality factor Q_0 ratio as a function of the drift tube radius were calculated. The calculations were carried out for the operating mode E_{010} and higher order modes (HOMs) H_{111}, E_{110}, E_{210} and H_{211}.

Drift tube radius variations lead to the cavity resonant frequency shift. Therefore for each drift tube radius value cavity was tuned to operating frequency of 800 MHz by the cavity radius variation.

For the dipole HOMs transverse effective shunt impedance was calculated using method described in [4]. The losses in end walls of the structure were not taken into account. R/Q_0 value was calculated by numerical integration of the electric field along the length of the resonator. Parameters of modes with largest R/Q_0 values are summarized in Table 1. These data correspond to the drift tube radius of 75 mm. It is obvious that H_{111} and E_{110} dipole modes are the most dangerous.

Table 1

HOM EDCs

HOM	*f*, MHz	R/Q_0, Ohm	$Q_0 \cdot 10^{10}$
E_{010}	800	44.7	1.3
H_{111}	1047	2.2	1.3
E_{110}	1086	13.2	1.5
E_{210}	1486	$9 \cdot 10^{-3}$	1.6
H_{211}	1539	$5 \cdot 10^{-3}$	1.6

In order to provide effective damping of the HOMs their frequencies should be above the cutoff frequency of the drift tube. Different designs of resonator with a corrugated drift tube were considered.

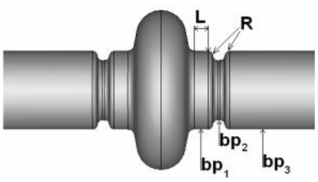


Fig. 2. Cavity with conjugated drift tube

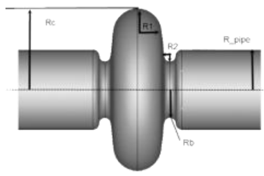


Fig. 3. Harmonic cavity with conjugations

The dependencies of the parameter R/Q_0 for the operating and two dipole modes in wide range of geometrical dimensions of drift tube were obtained. It is shown that increase of the drift tube radius can significantly reduce R/Q_0 of HOMs. Placement of the corrugations as presented in Fig. 2, can reduce dipole modes dangerous influence, but this design is possibility subject of multipactor discharge in numerous places at cavity roundings. To avoid this effect and in order to simplify the geometry we considered design with corrugations placed close to the cavity (Fig. 3).

We found that in the basic version of cavity geometry H_{111} mode electromagnetic field is concentrated within the cavity (Fig. 4). In this case the field of HOM called "trapped" within the structure [5] highly preventing its damping or withdrawal.

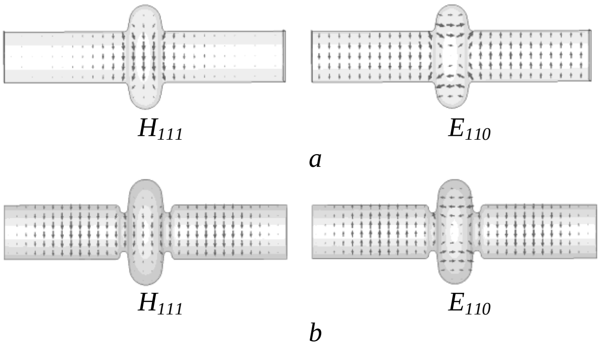
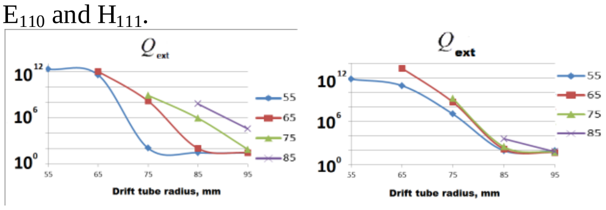


Fig. 4. Electric field of HOM in structure with conjugations (b) and without (a)

Fig. 4 shows that penetration of the dipole modes H_{111} and E_{110} into the drift tube could be improved by corrugations. The frequencies of these HOMs for R=85 mm tubes are higher than the cutoff frequency of 1034 MHz for the drift tube. The geometry shown in Fig. 4,b has been used as a basis for further studies of HOMs.

Fig. 5 shows dependence of the external quality Q_{ext} as a function of the radius of the drift tube for modes E_{110} and H_{111}.



a b

Fig. 5. Q_{ext} dependence for H_{111} (a) u E_{110} (b) modes

2. HOMs EXTRACTION FROMSTRING OF RESONATORS

Every LHC cryostat houses 4 accelerating cavities operating at 400 MHz (Fig. 6). For HOM dampings called HOM couplers are proposed. Each SCR has 2 broadband and 2 narrowband couplers to withdraw dipole HOM power. There are 16 couplers in four-cavity string assembly.

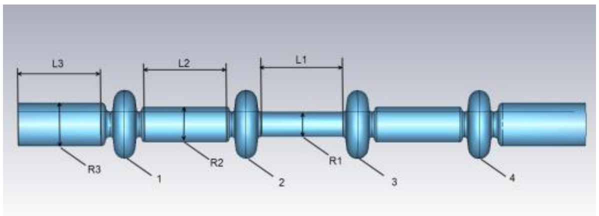
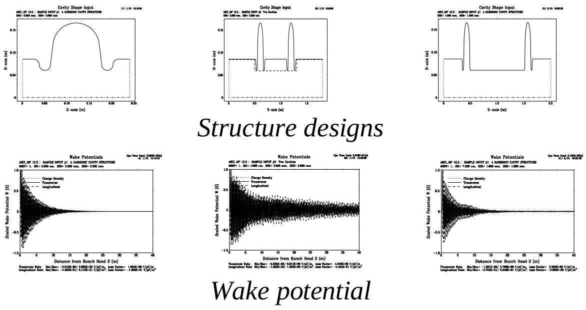


Fig. 6. Four cavity string

The frequencies of dipole HOMs in this structure lie above the cutoff frequency of the drift tube. This guarantees that HOMs can be withdrawn from the structure through a drift tube to the load, located outside the cryogenic section. Fig. 7 shows the results of calculation of the wake potential, obtained by using ABCI code [6]. Fig. 7 shows that the structure design with conjugations provides rapid decrease of the wake potential.



a b c

Fig. 7. Structure geometry and wake potential

However, in the structure consisting of two or more resonators features more complex field pattern due to presence of trapped HOMs between the cavities (Fig. 8). High external quality factor of these modes does not allow rapid decreasing of the wake potential.

From the graphs of the wake potential in Figs. 7,b,c clear that the decay rate depends on the geometry of the drift tube connecting to the resonators. In order to choose drift tubes optimal sizes the dependence of HOM EDCs on radius and length of drift tube was studied.

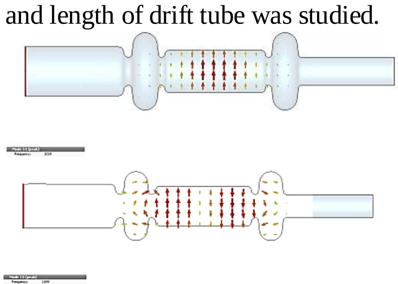
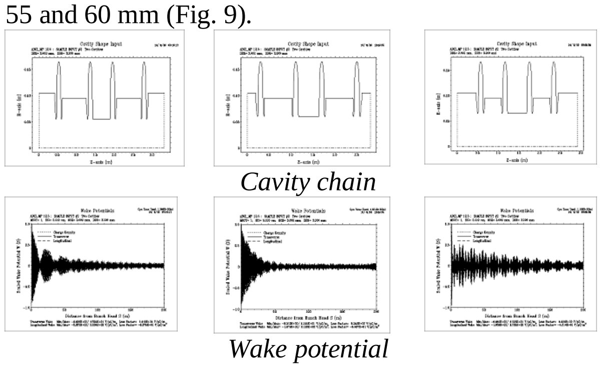


Fig. 8. HOMs electrical field trapped in drift tube

The drift tube radius increase leads to the growing of trapped HOMs influence. Therefore, the geometry with radius of the drift tubes equal to the one of conjunctions is optimal (Fig. 8). In this case HOM trapped between the resonators have the lowest Q_{ext} value.

However these dimensions are suitable only for chain consisting of 2 cells, since in this case the size of the intermediate drift tube will not allow HOM withdrawal from 2nd and 3rd cavities. Drift tube radius must be larger than 85 mm. Selection connecting drift tube length and radius can serve as one of the ways to eliminate the effect of the trapped modes. For three radius of the corrugation values length of the drift tube, providing the best damping of wake potential were chosen. The best results were obtained with a radius of corrugation 55 and 60 mm (Fig. 9).



a b c

Fig. 9. Four cavity chain and wake potential: R1=55 mm, L2=600 mm (a); R1=60 mm, L2=600 mm (b); R1=65 mm, L2=400 mm (c)

3. DAMPING RING AND RADIAL LOAD

One method of HOMs suppression is to use low conductivity material coating on the inner side of the drift tube. It is necessary to ensure the propagation of damped modes in the drift tube to the deposited coating area. For an optimized structure EDCs were calculated with basic cavity and the one having damping ring.

As the absorber material cesic was selected [5]. This material has a conductivity of about 10^{-4} Sm/m. The surface resistance of niobium and the absorber was calculated according to the formulas 1 and 2. EDC calculation results are presented in Table 2.

$$Rs(niobium) = R_{res} + 2\cdot 10^{-4}\cdot\frac{1}{T}\cdot\left(\frac{f}{1.5}\right)^2\cdot\exp\left(-\frac{17.67}{T}\right) \quad (1)$$

$$Rs(\text{absorber}) = \sqrt{\frac{\pi\cdot f\cdot\mu_0}{\sigma}} \quad (2)$$

Table 2

EDCs of HOMs and working modein SCR

		Without damping rings		With damping rings	
	f, MHz	*R*, Ohm	$Q_0\cdot 10^{10}$	*R*, Ohm	Q_0
E_{010}	800	$1\cdot 10^{12}$	1.9	$5\cdot 10^{10}$	$9.4\cdot 10^{8}$
H_{111}	1077	$1.4\cdot 10^{9}$	1.5	$1.3\cdot 10^{2}$	$1.4\cdot 10^{3}$
E_{110}	1080	$7\cdot 10^{10}$	1.6	$6.2\cdot 10^{3}$	$1.4\cdot 10^{3}$

Comparison analysis presented in Table 3.

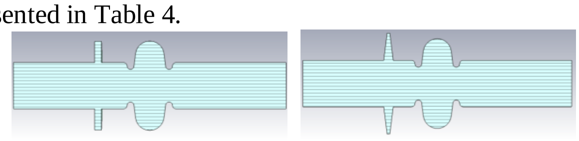
Thus, damping rings can reduce the quality factor of HOMs by 7 orders of magnitude, but it also reduces operating mode quality factor by factor of 2.

Table 3

R/Q_0 for different structure geometries

	Structure Fig.1	Structure Fig.3
	R/ Q₀	*R/ Q₀*
H_{111}	2.3	0.09
E_{110}	13.2	4.5
E_{010}	45.1	53.3

Using of radial type load made from cesic was considered for HOMs damping in SCR (Fig. 10). The radius of the radial line was chosen so that the resonance frequency of the E_{110} mode in the load was close to the frequencies of the most dangerous of the dipole HOMs. EDCs of some HOMs in structure with radial load presented in Table 4.



a *b*

Fig. 10. Cylindrical and tapered shapes radial line load

Table 4

HOMs EDC in structure with radial load

№ HOM	*f*, МГц	*R/Q₀*	$Q_0\cdot 10^{10}$	$Q_н$	$Q_{вн}$
1	1039	0.7	1.1	$3.0\cdot 10^{4}$	33
2	1046	0.2	1.3	$2.5\cdot 10^{6}$	45
3	1075	9.3	0.6	$5.3\cdot 10^{3}$	218
4	1116	2.9	1.3	$2.5\cdot 10^{5}$	68
5	1117	11.3	1.3	$9.9\cdot 10^{4}$	37
6	1169	6.1	1.7	$3.5\cdot 10^{5}$	45
7	1202	0.3	1.5	$1.4\cdot 10^{5}$	51

Tapered load was also considered (Fig. 10,b). As a result of the resonance tuning the following dimensions were obtained for the tapered load: the width of the top 10 mm, base width 35 mm and the radius of 185 mm. The frequency of the mode E_{110} in load was 1045 MHz.

4. NOTCH FILTER

To prevent damping of the accelerating mode E_{010} in the structure using of the notch filter was considered. By changing the geometrical dimensions of the device, it was possible to completely prevent damping. Table 5 shows the EDC of E_{010} mode at 800 MHz in the cell with the notch filter. Length of damping rings was 280 mm.

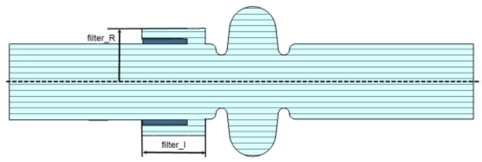


Fig. 11. Acceleration cavity with notch filter

Table 5

EDC of 800 MHz E_{010} mode

R/Q_0	Q_0	R_L	Q_d	R_d
With notch filter				
46.3	1.3e10	6.7e11	1.3e10	6.7e11
Without notch filter				
46.3	1.3e10	6.7e11	1.1e9	5.1e10

5. MULTIPACTOR DISCHARGE

Study of multipactor discharge possibility was carried out using of numerical simulation program Mult P-M [7]. Calculations of particles rate in structure from Fig. 11 in a wide range of accelerating field gradient (from 0 to 50 MV/m) were done. The results are presented in Fig. 12 and Fig. 13.

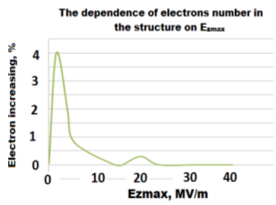


Fig. 12. The dependence of electrons number in the structure on $E_{z.max}$

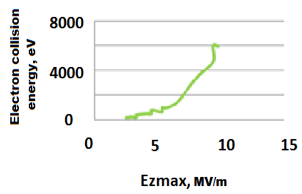
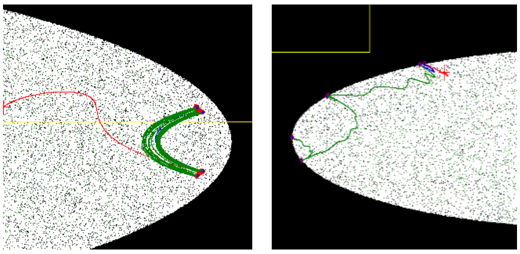


Fig. 13. Dependence of electron collision energy with the surface on E_{zmax}

E_{zmax} on the graph corresponds to the maximum value of field on accelerating cavity axis. The graph shows that there are two particles number peaks in the structure – in the 2…7 MV/m region and E_{zmax} = 20 MV/m. The study of the trajectories of electrons in these areas has shown the presence of stable multipactor trajectories of the first order in the equatorial region of the resonator (Fig. 14,a). In the transition region between the drift tube and the cavity stable trajectories weren't found. We considered a stable trajectory if the electron collision with the surface does not fade over 100 RF periods and not stable if it fades in 5…10 RF periods.

For the occurrence of the discharge, except for the stability of trajectories, it is necessary that the energy of the collision of electrons with the surface is within the range in which the coefficient of secondary electron emission is greater than one, hence, may cause an avalanche of electrons.



a b

Fig. 14. Example of stable (a) and not stable (б) trajectories in equator region of harmonic cavity

For niobium dangerous range lays from 50 to 1500 eV [7]. Fig. 13 shows the resulting graph of the dependence of the energy of the collision of electrons with the surface of the stable trajectories in the equatorial region for the initial range of field strengths.

Fig. 13 shows that at E_{zmax}> 7 MV/m energy of electron collisions with the surface is much higher than the energy at which the possible occurrence of secondary electron emission and discharge could take place. The study of the trajectories in the initial region (E_{zmax}<1.7 MV/m) are fade. Thus, the most dangerous from the point of view of the possibility by the appearance of multipactor discharge is the region of the equator in the range of field strengths E_{zmax} from 1.7 to 7 MV/m.

CONCLUSIONS

The research on HOMs damping options for 800 MHz HL-LHC cavities show the effectiveness of the proposed methods. Further researches will be continued.

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ДЕМПФИРОВАНИЕ ВОЛН ВЫСШИХ ТИПОВ ИЗ СВЕРХПРОВОДЯЩЕГО РЕЗОНАТОРА НА ЧАСТОТЕ 800 МГц

Н.П. Собенин, Р.О. Болгов, М.А. Гусарова, М.М. Зобов, Я.В. Шашков

Для сверхпроводящего ускоряющего резонатора на частоте 800 МГц рассчитаны электродинамические характеристики дипольных волн высших типов H_{111} и E_{110} в функции радиуса трубок дрейфа. Рассмотрена возможность вывода и подавления волн высших типов с помощью гофрированных трубок дрейфа, демпфирующих колец и радиальной нагрузки. Проведены расчёты наведённого потенциала. Рассмотрены вопросы возникновения мультипакторного разряда.

ДЕМПФІРУВАННЯ ХВИЛЬ ВИЩИХ ТИПІВ З НАДПРОВІДНОГО РЕЗОНАТОРА НА ЧАСТОТІ 800 МГц

Н.П. Собенін, Р.О. Болгов, М.А. Гусарова, М.М. Зобов, Я.В. Шашков

Для надпровідного прискорюючого резонатора на частоті 800 МГц розраховано електродинамічні характеристики дипольних хвиль вищих типів H_{111} і E_{110} у функції радіуса трубок дрейфу. Розглянуто можливість виводу і придушення хвиль вищих типів за допомогою гофрованих трубок дрейфу, демпфуючих кілець і радіального навантаження. Проведено розрахунки наведеного потенціалу. Розглянуто питання виникнення мультипакторного розряду.