RF MULTIPOLAR CHARACTERIZATION OF THE LATEST LHC DEFLECTING CAVITIES*

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Abstract

Deflecting cavity geometries considered for the Large Hadron Collider (LHC) crab scheme lack axial symmetry resulting in non-zero higher-order components of the deflecting field. A formalism to express the higher-order multipoles was developed and applied on previous cavity designs to characterize their influence on the beam stability. In this paper, the radio frequency (RF) multipoles are numerically estimated for the latest cavity geometries and compared to the older versions. A sensitivity study is carried out to understand the numerical errors levels and define mechanical tolerances.

INTRODUCTION

Three different crab cavities are presently being considered for the crab crossing scheme for the luminosity upgrade of the LHC [1, 2]. These cavities are, namely, the RF-dipole cavity (RFcav) [3], the double Quarter-Wave resonator cavity (QWcav) [4] and the Four-Rod resonator cavity (4Rcav) [5]. They are designed to deflect/crab the beam at 400 MHz, where the transverse kick results from the interaction of the particle with both the transverse magnetic and electric fields.

In order to meet the tight space between the two beam pipes of the LHC interaction region (see [6]), the three cavities have a very compact profile in the transverse plane. To achieve this transverse compactness, the cavity geometries deviate from the classical pill-box shape and are not axially symmetric along the beam axis. This lack of azimuthal symmetry is responsible for the appearance of higher-order components of the main deflecting mode. This may cause a particle off-axis to undergo a transverse momentum (kick) different from the desired dipolar one. The presence of non-negligible higher-order components may lead to perturbations in the beam dynamics, such as tune shifts, aberrations, coupling and higher-order effects [7]. Hence the importance of the RF multipolar characterization of the crab cavities prototypes.

The three cavity prototypes described in [3, 4, 5] were studied in detail from the RF multipolar viewpoint in [7], which also addressed the effect on the beam dynamic perturbations caused by the RF multipolar kicks. This study concluded that the QWcav prototype had to reduce the strength of the quadrupolar RF kick, which could cause undesired levels of tune modulation. The other two prototypes, RFcav and 4Rcav, were found to have acceptable levels for the RF multipolar kicks.

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In the first RF multipolar characterization performed in [7], the three prototypes studied were still at an early-state version without ports for the higher/lower-order mode extraction. The cavities since then have evolved from their original geometries, specially the QWcav, which was symmetrized to cancel the non-zero quadrupolar kick.

The latest geometries for the three crab cavity prototypes are shown in Fig. 1. The RFcav has been modified into a square-shaped outer conductor to meet the transverse constraints [8]. The new transverse cross section of the latest QWcav design has 2 planes of symmetry [9]. Ports for the mode extraction were included. For the latest 4Rcav geometry, no modification was performed except for the addition of ports [10].

UPDATED RF MULTIPOLAR KICKS

Following the formalism already developed in [7], the RF multipolar components of the main deflecting mode were calculated for the latest geometries shown in Fig. 1. This procedure makes a decomposition of the electromagnetic fields to express them as an infinite sum of multipoles, in a similar way to what is done for magnets [11].

The three cavities were analyzed by means of a commercial finite-element-method software, HFSS [12]. Special attention was made to ensure a fine mesh in the vicinity of the longitudinal z axis and the symmetry of the mesh in the azimuthal plane. The volume enclosed by the cavity walls were divided into slices along z and, for each of the slices, the electromagnetic fields were extracted along a discrete (16 points) circumference path. The perpendicular Lorentz Force $F_\perp$ was computed for each slice in z and expanded into their multipolar terms $F_\perp^{(n)}$.

For comparison purposes, it is convenient to express these RF multipoles in the same units as the magnetic multipoles [7]. Assuming that the particle velocity is equal to the speed of light c, the RF multipolar kicks, referred to as b_n, are obtained by performing the following integration:

$$b_n = \int_0^L \frac{1}{qc} F_\perp^{(n)}(z)\,\mathrm{d}z \qquad [\mathrm{Tm/m}^{n-1}] \qquad (1)$$

where L is the length of the cavity and q is the charge of the particle. It is worth noting that, although RF and magnetic multipoles can be compared, the former oscillate in time and depend on the longitudinal position of the particle, whereas the latter are static.

Table 1 shows the multipolar kick coefficients calculated for the latest prototypes, normalized to a deflecting voltage of 10 MV. For comparison, the previous results published in [7] for the older prototypes, normalized in the same manner, are also shown in Table 2.

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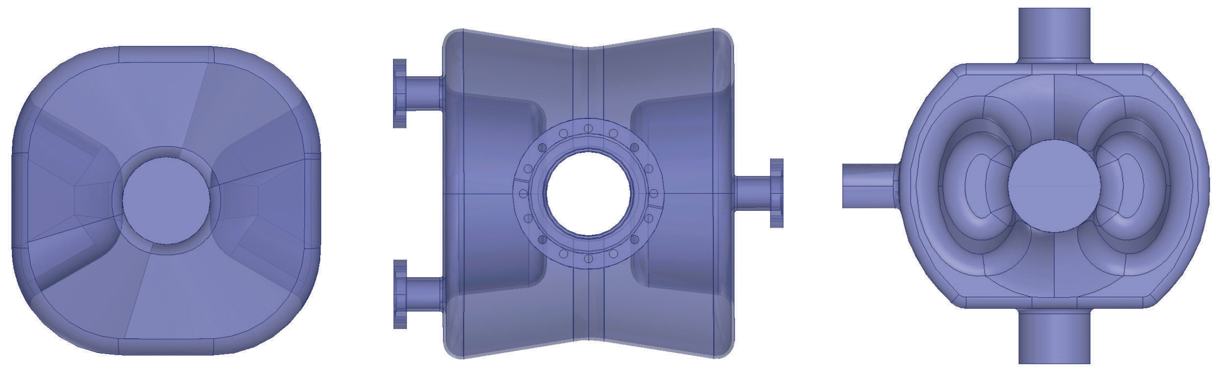

(a) RF-dipole cavity **(RFcav)** (b) Double quarter-wave resonator cavity **(QWcav)** (c) Four-rod resonator cavity **(4Rcav)**

Figure 1: Geometries of the latest crab cavity prototypes (not to scale). The longitudinal axis pointing outwards.

Table 1: Normalized RF multipolar kick coefficients at a nominal deflecting voltage of 10 MV, for the present prototypes [8, 9, 10] (b_n is in units of mTm/m^{n-1}).

b_n	**RFcav**	**QWcav**	**4Rcav**
b_2	0	0	0
b_3	4500	1070	1160
b_4	0	0	0
b_5	-0.40×10^6	-0.09×10^6	-2.29×10^6
b_6	0	0	0
b_7	-300×10^6	7×10^6	-638×10^6

Table 2: Normalized RF multipolar kick coefficients at a nominal deflecting voltage of 10 MV, for the previous prototypes [3, 4, 5] (b_n is in units of mTm/m^{n-1}).

b_n	**RFcav**	**QWcav**	**4Rcav**
b_2	0	114	0
b_3	3200	1260	900
b_4	0	1760	0
b_5	-0.52×10^6	-0.15×10^6	-2.44×10^6
b_6	0	-1.66×10^6	0
b_7	-140×10^6	0	-650×10^6

The b_2 and b_4 components are now zero for the latest QWcav prototype, due to the symmetrization of the geometry. For the other two prototypes, it can be noticed that the b_3 component has only a slight increment.

It can be noted that small changes in the geometries do not cause significant variations in the RF multipolar kicks. So it is expected that small variations on the cavity body have negligible effects on the RF multipoles.

SENSITIVITY STUDY ON RF KICKS

A sensitivity study to define the mechanical tolerances that should be respected during the fabrication is carried out. The cavity is not retuned to the nominal frequency for each geometry variation for the sake of simplicity. The dependence on frequency is also studied.

In this section, a preliminar sensitivity study on the QWcav prototype is presented. Fig. 2 shows a parametrization of the cavity. For this study, a prototype without ports was used for simplicity. The inclusion of the ports was proven to have a negligible effect on the RF kicks.

Since all the even RF kicks may be present due to up/down asymmetries (see Fig. 2), some parameters that break this symmetry were chosen. In Table 3, the parameters varied along with their nominal values are listed. Each nominal value was varied in small steps. The maximum net value variation considered is shown in Table 3.

Fig. 3 illustrates the change in the RF multipolar kicks as a function of the height HT, which differs up to ± 0.6 mm from its nominal value. The RF kicks follow a linear tendency with small variations in HT. It can be noticed that the maximum excursion of the b_2 and b_3 components is only of a few units, whereas the maximum excursion of b_4 is around 240 mTm/m^3. This information is compiled in Table 3, as well as for all the others parameters analyzed.

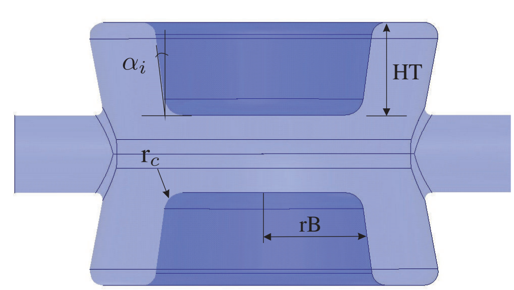

Figure 2: Geometry definition of the QWcav prototype without ports used for the tolerance study.

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Table 3: Variation of the normalized RF multipolar kick coefficients at a nominal deflecting voltage of 10 MV according to small changes in the nominal value of some parameters, for the QWcav prototype without ports (Δb_n is in units of mTm/m^{n-1}).

Parameter	Nominal Value ± Variation	$\max\{\lvert\Delta b_2\rvert\}$	$\max\{\lvert\Delta b_3\rvert\}$	$\max\{\lvert\Delta b_4\rvert\}$	Δf_o
HT (height top)	100.50 mm ± 0.60 mm	2	3	240	2.0 MHz/mm
rB (radius bottom)	112.62 mm ± 0.50 mm	1	11	40	0.2 MHz/mm
r_c (curvature radius)	20.00 mm ± 1.00 mm	0.2	8	50	0.3 MHz/mm
α_i (inner angle)	7.7° ± 0.3°	0.6	4	70	1.0 MHz/°

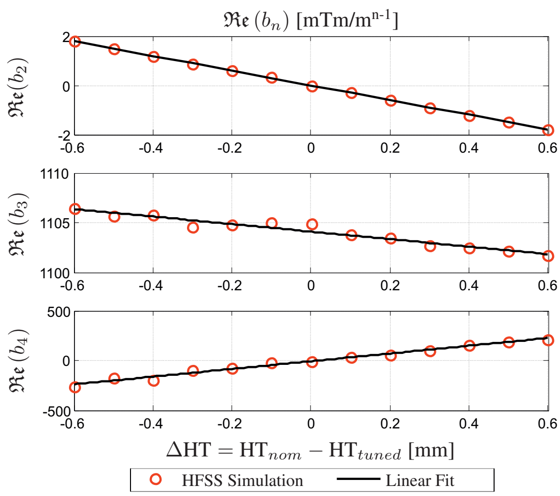

Figure 3: RF multipolar kicks versus the variation of the HT parameter for the QWcav prototype without ports.

From Table 3, it can be observed that negligible changes in the quadrupolar components occur when both r_c and α_i vary within the given variation range. The parameters HT and rB seem to be more sensitive, although the changes are quite small whenever the manufacturing error is less than half a millimeter. Note that, for the sextupolar component, the maximum change in b_3 is always below the 1 % of its nominal value. In all the cases studied, the change of b_2 and b_3 is linear with the variation of the specific parameter. However, the b_4 component only follows a linear tendency while varying HT, as shown in Fig. 3. For the other parameters, the change in b_4 is random and within the accuracy of the simulations.

For the sake of completeness, Table 3 also includes the change of the resonance frequency due to these variations in the nominal values. The maximum frequency shift would be of 2 MHz/mm, caused by a change in the HT parameter. This frequency shift has a negligible effect on the even multipoles, which primarily depend on the asymmetry of the cavity. However, the change in the odd multipoles has a dependency both on the asymmetry and the resulting frequency change, which cannot be easily dissociated due to the complex geometry. A detailed study is underway to precisely understand the behavior of the odd multipoles due to asymmetries.

CONCLUSIONS

The geometries of the three crab cavities under consideration have evolved from their original designs, for which the RF multipolar kicks were numerically calculated for the latest geometries. The new cavities behave similar to the previous prototypes, and an improvement is observed for the QWcav due to the symmetry. A sensitivity study on the RF kicks for the QWcav prototype was carried out. A reasonable asymmetry induced by varying the most critical parameters by approximately 1 mm shows no harmful influence on the RF multipolar kicks.

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