COMPACT 400-MHZ HALF-WAVE SPOKE RESONATOR CRAB CAVITY FOR THE LHC UPGRADE*

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Abstract

Crab cavities are proposed for the LHC upgrade to improve the luminosity. There are two possible crab cavity installations for the LHC upgrade: the global scheme at Interaction Region (IR) 4 where the beam-beam separation is about 420-mm, and the local scheme at the IR5 where the beam-beam separation is only 194-mm. One of the design requirements as the result of a recent LHC-Crab cavity workshop is to develop a 400-MHz cavity design that can be utilized for either the global or local schemes at IR4 or IR5. Such a design would offer more flexibility for the final upgrade installation, as the final crabbing scheme is yet to be determined, and save R&D cost. The cavity size of such a design, however, is limited by the beam-beam separation at IR5 which can only accommodate a cavity with a horizontal size of about 145-mm, which is a design challenge for a 400-MHz cavity. To meet the new design requirements, we have developed a compact 400-MHz half-wave spoke resonator (HWSR) crab cavity that can fit into the tight spaces available at either IR4 or IR5. In this paper, we present the optimization of the HWSR cavity shape and the design of HOM, LOM, and SOM couplers for wakefield damping.

INTRODUCTION

A small angle crab scheme has been proposed for the LHC Interaction Region (IR) upgrade [1,2] to obtain additional luminosity improvement by recovering the geometric luminosity loss due to the finite crossing angle. The crab compensation is realized by a set of deflecting cavities – aka crab cavities. In a crab cavity application, the beam is in phase quadrature with the deflecting RF, so that the bunch center experiences no deflection but the head and tail are kicked in opposite directions. The bunch rotates around the bunch centre as it travels down the beamline, establishing a head on collision at the IR. The luminosity increase due to the implementation of a crab cavity is expected to be up to 16% and 63% for nominal β* of 55cm and upgrade β* of 25cm respectively, depending on the choice of crab cavity frequency. There are two possible crab cavity scenarios for the LHC upgrade: the global scheme at IR4 where the beam-beam separation is about 420-mm, and the local scheme at the IR5 where the beam-beam separation is only 194-mm. An 800-MHz elliptical cavity shape [3] was initially considered as a baseline design for a global scheme for the upgrade. However, the space for the crab cavity in the global scheme at IR4 is reserved for a possible installation of a capture cavity. The likely space available for a crab cavity is at IR5 which can be used for either local or global schemes. Due to the tight beam-to-beam separation at IR5, a conventional elliptical cavity of 800-MHz would not fit. Cavities of frequencies higher than 800-MHz cannot be considered for the LHC since it will produce significant non-linearity in the crabbing kick along the bunch. One of the design requirements as the result of the recent LHC-Crab cavity workshop [4] is to develop a compact 400-MHz cavity that can be used for either the global or local schemes at IR4 or IR5. Such a design would offer more flexibility for the final upgrade installation options and save R&D cost. The transverse dimension of the cavity is thus determined by the beam separation at IR5, which can only be of 145-mm maximum in half size. To meet such a design constraints, we have investigated a novel 400-MHz cavity design that has a compact transverse dimension and can fit into the small beam separation at IR5. In this paper, we present the design of such a cavity and the design of LOM, HOM couplers for wakefield damping.

THE HWSR DEFLECTING CAVITY

The 400-MHz design in consideration is a half-wave spoke resonator (HWSR) as shown in Figure 1. The shape of the cavity can be considered as a half-wave segment of a coaxial line, with the coaxial axis in the vertical direction. The operating mode is the coaxial TE11 mode. The beam pipe passes through the electric nodes of the TE11 mode where the magnetic field is at maximum (Figure 2) and provides transverse deflection to the beam.

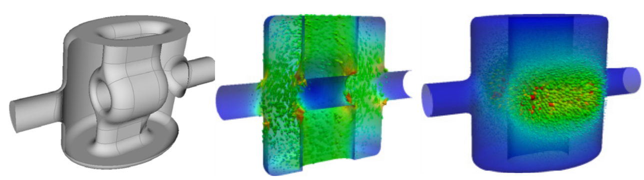

Figure 1. The half-wave spoke cavity. Middle) magnetic field distribution; Right) electric field distribution.

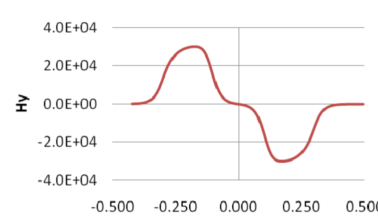

Figure 2. Magnetic field distribution along the beamline.

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CAVITY SHAPE OPTIMIZATION

The frequency of the TE11 mode in such a cavity is determined mainly by the vertical and longitudinal (beam direction) dimensions. The horizontal dimension of the cavity has minimal effect on the frequency, thus is a "free" parameter that can be made compact to fit into the tight horizontal space available on the beam line. In such a design, the transverse profile of the cavity becomes a squashed elliptical or racetrack shape. One undesirable side effect of a strongly squashed shape, however, is the potential enhancement of the surface electric and magnetic fields. To minimize this effect, the design maximized the horizontal size of the cavity to the maximal dimension allowed by the beam-to-beam separation which is 194-mm. Considering the 42-mm beampipe for the second beam, and thickness of the cavity and the beampipe walls, the maximum horizontal (vacuum) dimension one can have for such a cavity is 145-mm half width. The cross section of the squashed cavity that satisfies this constraint is shown in Figure 3.

In addition to the compact size, one other advantage of the HWSR design is that there is no same-order mode (SOM) due to the asymmetry induced by the spoke. Both the lower-order accelerating mode (LOM) and the next higher-order dipole modes (HOM) of both polarizations are well separated in frequencies from the operating deflecting mode, which is advantageous for designing the damping couplers to minimize the adverse effects of these unwanted modes.

The length of the cavity and the shape of the spoke were optimized for higher shunt impedance and lower peak surface fields. The optimized RF parameters are listed in Table 1. The design deflecting voltage per cavity is 5-MV. Two such cavities are needed for each beam to provide the 10-MV deflecting voltage required for the crabbing.

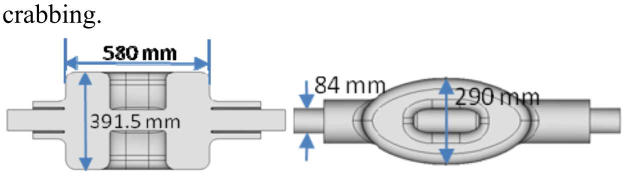

Figure 3: HWSR 400MHz crab cavity: left) cavity y-z cross section; right) cavity x-y cross section.

Table 1 RF parameters of the HWSR cavity

Operating mode Frequency	400 MHz
Operating Mode	TE11 mode (coaxial)
LOM Frequency	336 MHz
Lowest HOM-v Frequency	810 MHz
Lowest HOM-h Frequency	628 MHz
Iris aperture (diameter)	84 mm
Transverse dimension	290 mm
Vertical dimension	391.5 mm
Longitudinal dimension	580 mm
$(R/Q)_T$	215 ohm/cavity
$V_{deflect}$/cavity	5 MV
B_{Peak}	100 mT
E_{Peak}	52 MV/m

WAKEFIELD DAMPING

To achieve a clean crabbing to the beam, effective wakefield damping is crucial. Figure 4 shows the mode spectrum of the crab cavity up to 1.8-GHz obtained using parallel code Omega3P [5,6]. The mode at 400-MHz is the operating mode. All the LOM and the HOM modes need to be damped to meet the beam dynamics requirements, which are R<80-kohm for the accelerating modes and Z_T<2.5-Mohm/m for the dipole HOMs [7], where $R=(R/Q)\bullet Q_{ext}$ and $Z_T=(\omega/c)\bullet(R/Q)_T\bullet Q_{ext}$. The goal of damping coupler design is to lower the Q_{ext} of each mode so that the impedances will not exceed these limits. Figure 5 (left) shows the proposed damping couplers for the HWSR cavity.

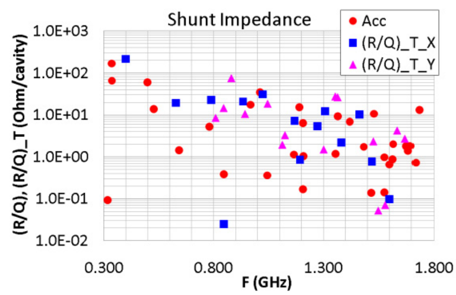

Figure 4: The calculated R/Q of accelerating modes and $(R/Q)_T$ of dipole modes.

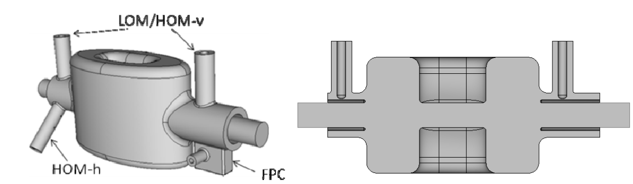

Figure 5: Left: HWSR cavity with FPC, LOM, and HOM couplers; Right: coax-to-coax LOM/HOM-v couplers.

The LOM and vertical HOM couplers

The LOM and HOM-v modes are damped by the same set of coax-to-coax couplers as shown in figure 5 (right). The coaxial beampipes are needed to enhance the coupling of the coupler to the cavity. To achieve stronger damping, the lengths of the beampipe coaxes were chosen such that the beampipe-coax modes resonant with the high R/Q modes in the cavity. The pickup coaxes of the LOM/HOM-v couplers are placed in the vertical plane. The center conductors of the vertical coaxes are at the electric node of the horizontal dipole mode, which naturally rejects the coupling to the operating mode, thus no notch filters are needed in the coupler design. This notch-less coupler simplifies the geometry and is advantageous in handling high power which could potentially be generated by the beam loading of the accelerating modes.

Horizontal HOM coupler

The HOM modes in the horizontal plane are damped by the HOM-h coupler. A notch filter is needed in the HOM-h coupler to reject the operating mode. The coupler is consisted of a loop antenna and a pickup probe as shown in Figure 6. The dimensions of the loop antenna and the pickup probe were optimized to achieve the notch rejection at 400-MHz, and to enhanced the coupling to the lowest HOM-h mode at around 600-MHz. The transmission property of the HOM-h coupler was calculated using S3P [5,6] and is shown in Figure 6. The notch tuning sensitivity is 1-MHz/20micron for the present design.

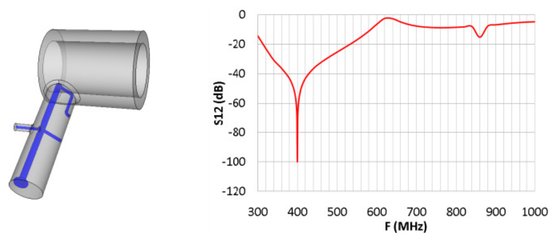

Figure 6. Transmission curve of the HOM coupler with notch rejection at 400-MHz.

The damping results

The damping Qext for the LOM and HOM modes were obtained using the parallel code Omega3P and is shown in Figure 7. The effective impedances of these modes are plotted in Figure 8, where the dashed lines are the impedance limits for the LHC crab cavity. All the unwanted modes are damped to below these limits with the proposed coupling scheme.

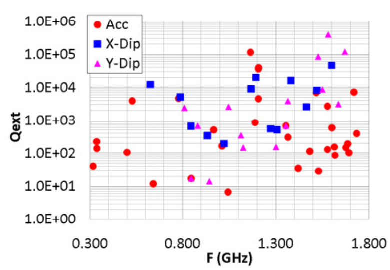

Figure 7: Damping Qext obtained using parallel finite-element code Omega3P.

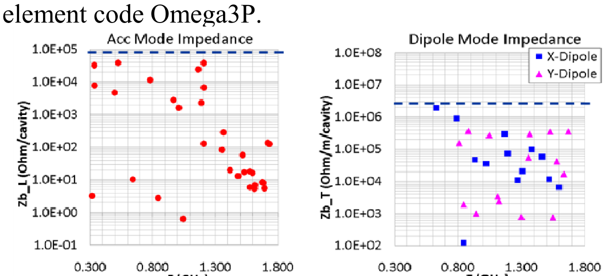

Figure 8: Left: impedance of accelerating modes; Right: impedance of dipole modes. The horizontal dashed lines are the impedance limits for the LHC crab cavity.

FUNDAMENTAL POWER COUPLER

A typical fundamental coupler (FPC) for such a cavity would be a coaxial coupler in the horizontal plane at the end beampipe that couples electrically to the cavity. However, such a coupling scheme was found to have significant coupling to the LOM/HOM-v coupler. The rejection of the operating mode of the LOM/HOM-v couplers relies on the dipole mode field symmetry in the coupler region since there is no notch filter included in the coupler design. In the electric coupling scheme, the input coaxial coupler couples to both the TEM and TE11 modes in the beampipe region. The TEM field causes the cross coupling between the input coupler and the LOM/HOM-v couplers. To avoid such coupling, we propose a magnetic coupling scheme as shown in Figure 9. In this scheme, the coaxial FPC coupler couples power into the cavity via a waveguide stub. The waveguide stub is placed on the opposite side of the LOM/HOM-v coupler and couples magnetically to the TE11 mode in the beampipe region but not the TEM mode. The fields of the operating mode in the coupler region maintain the TE11 symmetry, which eliminates coupling to the LOM/HOM-v coupler. The requirement for the FPC coupling for the LHC crab cavity is about $2x10^6$, which is easily achievable using this coax-stub coupler design.

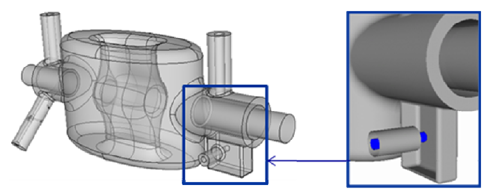

Figure 9: Input coupler for the HWSR crab cavity.

SUMMERY

A compact 400-MHz crab cavity was designed for the LHC IR upgrade. The cavity is a half-wave spoke resonator. It has a compact transverse dimension of 145-mm and can fit into both the IR4 and IR5 beamline spacings. The LOM and HOM couplers were optimized to meet the damping requirements for the unwanted modes. A magnetic coupling FPC coupler was designed to eliminate the cross coupling between the FPC and the LOM.HOM-v couplers. Multipacting analysis and further cavity optimization are in progress.

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