

DESIGN AND PROTOTYPING OF A 400 MHz RF-DIPOLE CRABBING CAVITY FOR THE LHC HIGH-LUMINOSITY UPGRADE*

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Abstract

LHC High Luminosity Upgrade is in need of two crabbing systems that deflects the beam in both horizontal and vertical planes. The 400 MHz rf-dipole crabbing cavity system is capable of crabbing the proton beam in both planes. At present we are focusing our efforts on a complete crabbing system in the horizontal plane. Prior to LHC installation the crabbing system will be installed for beam test at SPS. The crabbing system consists of two rf-dipole cavities in the cryomodule. This paper discusses the electromagnetic design and mechanical properties of the rf-dipole crabbing system for SPS beam test.

INTRODUCTION

The LHC High Luminosity Upgrade will be using crabbing cavities to increase the luminosity for the operation with 14 TeV proton beam collision. These crabbing systems will also reduce the pile up at the interaction point. Two crabbing systems will be installed at the ATLAS and CMS experiments where the former will be crabbing in vertical plane and the latter in the horizontal plane. The two parallel beam lines set a very tight dimensional constraint in designing a crabbing cavity operating at 400 MHz [1].

A compact 400 MHz crabbing cavity has been designed jointly by ODU and SLAC to meet the system requirements for LHC. A proof-of-principle cavity has been fabricated and tested [2, 3]. Currently the cavity design is being integrated into a cryomodule design intended for SPS test.

RF-DIPOLE CRABBING CAVITY

The 400 MHz proof-of-principle (P-o-P) rf-dipole cavity shown in Fig. 1-(left) is a cylindrical shaped cavity with trapezoidal shaped loading elements that operates in a TE₁₁ like mode. The prototype cavity shown in Fig. 1-

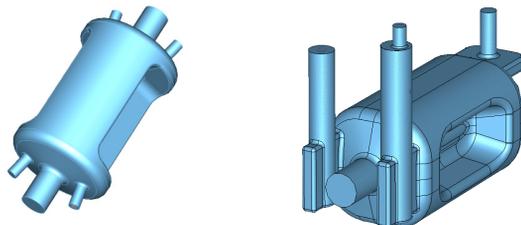


Figure 1: 400 MHz proof-of-principle (left) and prototype (right) rf-dipole cavities.

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(right) has a fundamental operating mode identical to the cylindrical shaped cavity. The cavity is designed with a square shaped outer body to reduce the transverse cavity size and have improved rf properties shown in Table 1.

Table 1: RF Properties of Cylindrical Shaped P-o-P and Square Shaped Prototype rf-Dipole Cavities

Parameter	P-o-P Cavity	Prototype Cavity	Units
Cavity length	542	775	mm
Cavity diameter	340	281	mm
Aperture diameter	84	84	mm
Deflecting voltage (V_T^*)	0.375	0.375	MV
Peak electric field (E_P^*)	4.02	3.7	MV/m
Peak magnetic field (B_P^*)	7.06	6.3	mT
B_P^* / E_P^*	1.76	1.71	mT/(MV/m)
Energy content (U^*)	0.195	0.13	J
Geometrical factor	106	107	Ω
$[R/Q]_T$	287	430	Ω
$R_T R_S$	4.0×10^4	4.6×10^4	Ω^2

At $E_T^* = 1$ MV/m

The P-o-P cavity was fabricated and rf tested at both 4.2 K and 2.0 K. The measured intrinsic quality factor (Q_0) as a function of V_T , E_T , E_P , B_P is shown in Fig. 2. The cavity achieved a V_T of 7 MV that exceeded the required V_T of 3.4 MV. The performance achieved by the P-o-P cavity shows that the rf-dipole cavity can be operated at 5.0 MV that would reduce the number of cavities required to achieve the total V_T of 13.4 MV. The Q_0 achieved during the first set of tests were low due to the surface losses at the SS blank flanges on the beam ports. The cavity was retested with Nb coated SS blank flanges and the cavity achieved a Q_0 of 1.25×10^{10} with reduced residual surface resistance (R_{res}) of 10 n Ω .

Table 2: Operating Parameters at 3.4 MV and 5.0 MV

Parameter	(A)	(B)	Units
Deflecting voltage (V_T)	3.4	5.0	MV
Peak electric field (E_P)	34	50	MV/m
Peak magnetic field (B_P)	57	84	mT
Power dissipation (P_{diss})	2.8	6.2	W

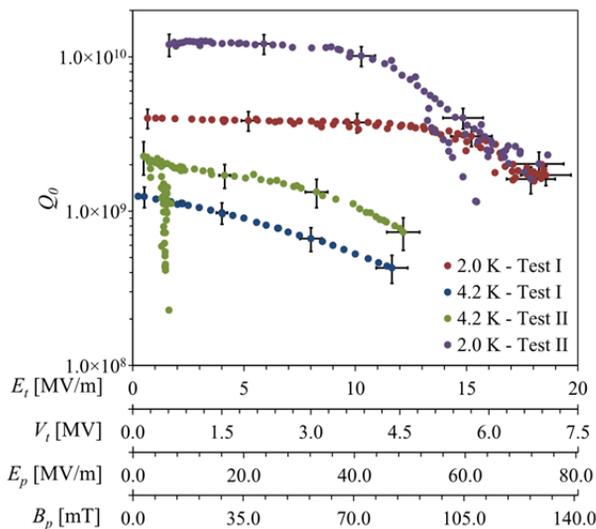


Figure 2: Quality factor at 4.2 K and 2.0 K of the 400 MHz rf-dipole cavity.

Table 2 shows the operational parameters for the rf-dipole cavity at 3.4 MV and with the projected parameters for operation at 5.0 MV for 2.0 K with $R_{res} = 10 \text{ n}\Omega$.

CRABBING CAVITY FOR LHC HIGH LUMINOSITY UPGRADE

The rf-dipole cavity has been designed to meet the system requirements for the LHC high luminosity upgrade including all the ancillary components such as fundamental power coupler (FPC), higher order mode (HOM) couplers, tuning system. The current crabbing system is designed for horizontal crabbing of bunches and it is designed such a way that it can be easily adapted to support vertical crabbing of bunches [4].

Fundamental Power Coupler and Higher Order Mode Couplers

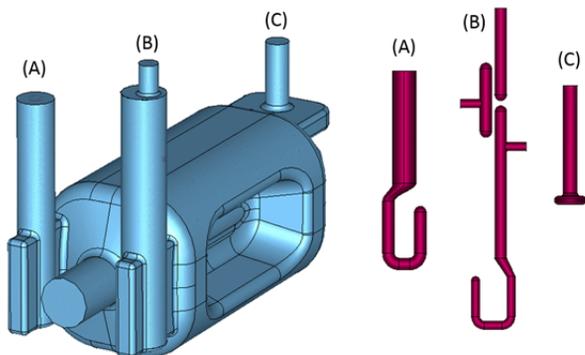


Figure 3: Complete rf-dipole cavity with (A) FPC, (B) HHOM filter, and (C) VHOM probe.

The FPC is a hook shaped coax coupler shown in Fig. 3 that couples to the fundamental mode to achieve a coupling of $Q_L = 5.5 \times 10^5$. The optimized hook reduced the rf heating to 69 W. Currently CERN is fabricating two FPC couplers for each cavity in the SPS cryomodule [5].

The HOMs in the rf-dipole cavity is well separated and does not have any lower order modes. The cavity design uses only two HOM couplers, one in each plane to couple to the higher order modes. The HHOM coupler is a high pass filter that couples to the modes and VHOM coupler is a coax coupler that couples to the modes in the vertical plane that does not couple to the HHOM. The HHOM coupler is a demountable filter that is advantageous during the processing and assembly of the cavities.

The detailed FPC and HOM coupler designs are described in Ref. [6]. The mechanical study of the HOM couplers are completed and fabrication plan is outlined [7] including detailed tolerance study [8].

Multipacting Analysis

The multipacting levels were easily processed during the P-o-P cavity rf tests and did not reoccur throughout the following tests [3]. The prototype rf-dipole cavity has improved multipacting levels compared to P-o-P cavity [9]. The multipacting levels at FPC can be conditioned and HOM couplers show no levels of multipacting [6].

Multipole Analysis

The rf-dipole cavity is designed with curved loading elements as shown in Fig. 4, where the higher order multipole components are shown in Table 3. The even order components are zero for the rf-dipole geometry. The primary requirement is to minimize the b_3 component below 10^3 mT/m^2 .

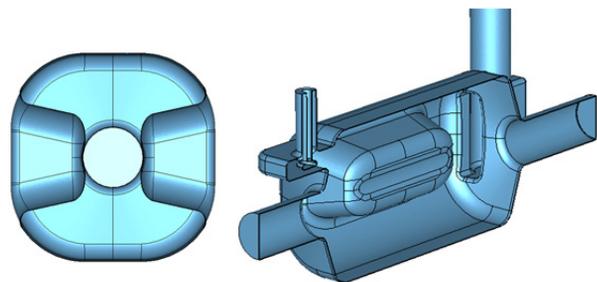


Figure 4: RF-dipole cavity with curved loading elements.

Table 3: Higher Order Multipole Components at 1.0 MV

Component	Bare Cavity	Full Cavity	Units
b_1	3.3	3.3	mT/m
b_3	39	47	mT/m ²
b_5	2.0×10^5	2.0×10^5	mT/m ⁴

Cavity Tuning Mechanism

The tuning system was developed jointly by ODU and CERN. The main design features are from Jefferson Lab's tuner [10]. The tuner frame is floating around the cryostat and it applies equal force on top and bottom of the cavity. The actuator is outside the cryomodule which makes the service convenient. The actuator is connected to the tuner frame by the telescope tubes.

HELIUM VESSEL AND CRYOMODULE

Dressed Cavity

The dressed cavity consists of the bare cavity, beam tube, HOM, fundamental power coupler, and pickup flanges, tuner interface, and the helium vessel. The preliminary design of the dressed cavity is shown in Fig. 5. The tube shown at the side of the vessel is a secondary beam tube needed to allow the un-crabbed beam in the LHC to pass through the cryomodule assembly. The pressure requirement for testing in the SPS at CERN is 1.8 bar pressure inside the helium vessel with atmospheric pressure inside the cavity with a maximum allowed stress in the niobium cavity of 50 MPa. This results in an internal pressure on the helium vessel and external pressure on the cavity. The direct connection of the cavity to the helium vessel through all the cavity ports means that any deflection of the helium vessel due to the applied pressure results in forces acting on the cavity structure. For this reason, the helium vessel design incorporates external stiffeners to limit these forces on the cavity. The extra plates shown on the top and bottom surfaces of the helium vessel serve the purpose of these external stiffeners. The helium vessel and stiffeners are both 9.5 mm-thick grade 2 titanium plate. Titanium is used for this and nearly all superconducting rf cavity helium vessels because it nearly exactly matches the thermal contraction properties of the niobium cavity, minimizing stress during cooldown. The interface material between the cavity and helium vessel is niobium/titanium.

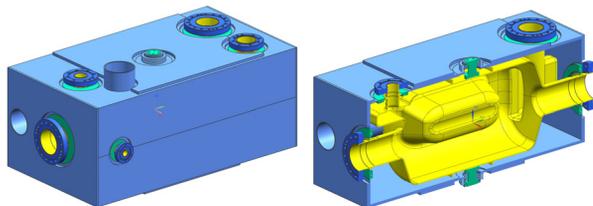


Figure 5: RF-dipole dressed cavity assembly (left) with cross section (right).

The cavity and helium stresses due to the 1.8 bar test pressure are shown in Fig. 6. In the cavity, stress areas that are over the allowed 50 MPa, are localized stresses only. Linearization through the thickness of the material in those areas has shown the combined bending and membrane stress values in those areas to be less than 1.5 time the allowed 50 MPa as required by the ASME Code.

Cryomodule

For testing in the SPS, two cavities will be mounted in a single cryomodule. Connections to the cryogenic distribution, rf, and tuning systems will all be integrated into the cryomodule design. A thermal shield operating nominally at 80 K reduces the heat load to the 2 K system. An integral magnetic shield reduces the effect of the earth's field and of surrounding equipment on the superconducting cavities. Figure 7 shows a preliminary cryomodule design for the RF dipole [11]. Eventually,

when fully implemented in the LHC there may be as many as eight crab cavities in one cryomodule.

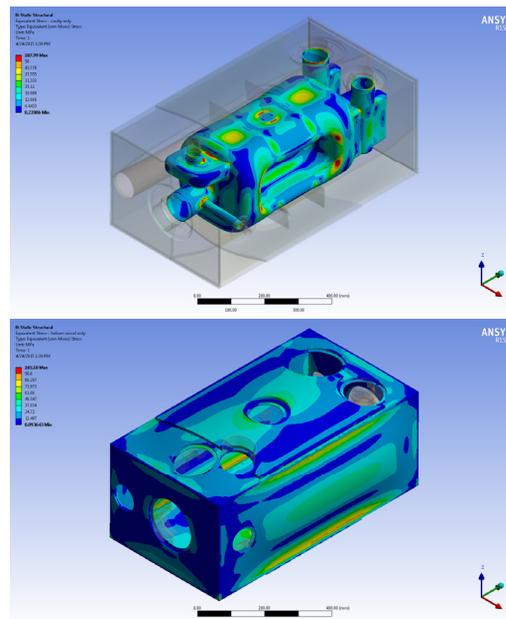


Figure 6: RF-dipole cavity helium vessel stress due to 1.8 bar external test pressure (top) and internal test pressure (bottom).

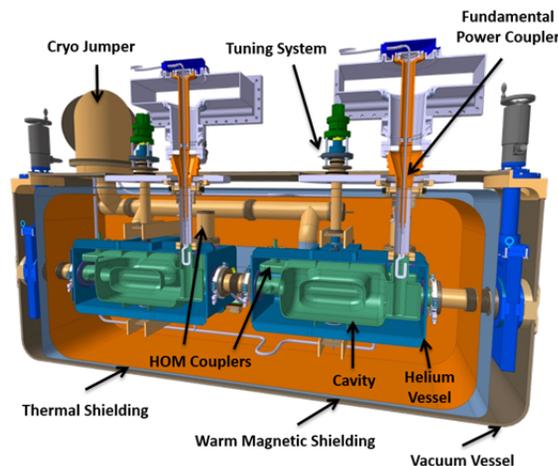


Figure 7: RF dipole preliminary cryomodule design.

CONCLUSION

The 400 MHz rf-dipole crabbing cavity has been designed to meet the requirements for the LHC high luminosity upgrade. The preliminary analysis on the dressed cavity is completed and the helium vessel design is being integrated into a 2-cavity Cryomodule design for SPS test. Two rf-dipole cavities are currently being fabricated by Niowave Inc. and scheduled to undergo rf tests this year.

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