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HOM COUPLER DESIGN AND OPTIMIZATION FOR THE FCC-ee W WORKING POINT

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Abstract

A 2-cell 400 MHz superconducting radio-frequency cavity with improved damping has been designed as an alternative to the baseline 4-cell cavity for the **W** working point of the future circular lepton collider (FCC-ee). For this cavity, the longitudinal higher-order modes' (HOMs) impedance stay under the beam stability threshold value. This paper, therefore, focuses on the design of the HOM couplers for the purpose of damping the high-impedance transverse HOMs. The resulting impedance of the HOM-damped cavity is then calculated and compared with the impedance limit set by synchrotron radiation.

INTRODUCTION

The Future Circular electron-positron Collider (FCC-ee) is planned to operate with beam energies from 45.6 to 182.5 GeV and beam currents from 5.4 to 1390 mA [1]. The purpose is to study the properties of the **Z**-, **W**- and **H**iggs boson and the top and anti-top (**t$\bar{\mathbf{t}}$**) quarks. The beam current of 147 mA of the **W** working point requires particular care to strongly damp the HOMs excited by the beam. A 2-cell superconducting radiofrequency (SRF) elliptical cavity has been designed for the **W** working point of the FCC-ee [2]. The geometric dimensions of the cavity are given in Table 1. Figure 1 shows the longitudinal and transverse impedance plots of the cavity. It can be seen that the frequency of two high impedance modes, the TE_{111} and TM_{110} modes, 487 MHz and 520 MHz, respectively, are below the TE_{11} cut-off frequency of the beampipe to which they can couple. The $R/Q_\perp$ of the modes are 15.46 Ω and 26.35 Ω, respectively. The LHC hook-type HOM coupler design is thus adopted [3] for the damping of these two modes. This coupler is particularly designed for the strong damping of the modes in the first dipole passband. The general requirements of such HOM couplers are to extract as much energy as possible from the potentially parasitic modes while rejecting the fundamental mode (FM).

Table 1: Geometric Dimensions of the Designed Cavity (C_{3794}), The Parameters Correspond to the Common Definition used for Parametrizing an Elliptical Cavity [2]

All dimensions in mm except stated otherwise.

A	B	a	b	R_i	L	R_eq	α [°]
73.52	131.75	106.25	118.7	150	187	369.63	107.23

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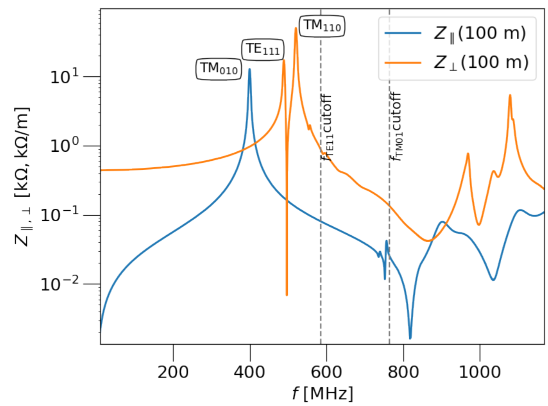

Figure 1: Longitudinal and transverse wakefield impedance plot for the designed cavity (simulated wakelength = 100 m).

HOOK-TYPE HOM COUPLER

The design methodology of the hook coupler in [3] follows the analysis of an approximate lumped element circuit model followed by a conversion to a 3D geometric model. This type of coupler has been developed from such a circuit model first and then translated to a 3D equivalent geometry as shown in Fig. 2 [3,4].

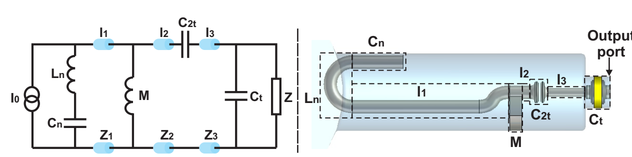

Figure 2: Lumped element circuit model and CST Studio Suite® 3D model.

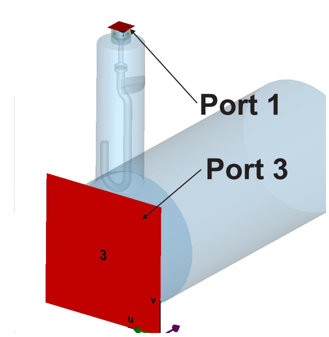

Figure 3: The excited ports (red) of the hook-type coupler.

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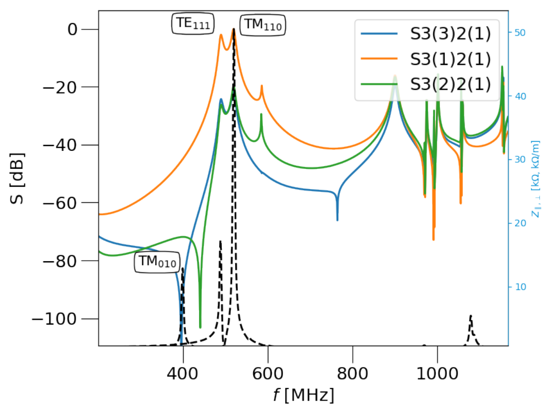

Figure 4: The hook-type coupler transmission curves.

Table 2: S-parameters of the Hook-type Coupler at Parasitic HOM Frequencies

[MHz]	$S_{\mathrm{TE}_{11}}$ (0° Pol) [dB]	$S_{\mathrm{TE}_{11}}$ (90° Pol) [dB]	$S_{\mathrm{TM}_{01}}$ [dB]
400.79	na	na	-110.99
488	-3.32	-28.03	na
520	-0.03	-19.76	na

The design of this coupler begins from the geometric variables in [4, p. 87]. Starting from this model, the geometric variables are optimized for the designed cavity by performing a sweep over the variables which control the maximum transmission amplitude and frequencies as given in Table 3.3 in [3]. Since the TM_{010} mode of the cavity couples to the TM_{01} mode of the beampipe, and the TE_{111} and TM_{110} modes couple to the TE_{11} mode, it could be avoided to simulate the complete cavity-coupler assembly. Instead, Port 3 shown in Fig. 3 was excited with the TE_{11} and TM_{01} modes to mimic the transmission of the TM_{010}, TE_{111} and TM_{110} modes from the cavity to Port 1 of the coupler.

Figure 4 shows the transmission curves of the optimized coupler. The longitudinal and transverse impedance plots of the cavity are also shown in dashed lines in Fig. 4. This is to show that the max transmission points correspond to the impedance peaks. The rejection of the FM is also seen at 400.79 MHz. The transmission of the first peak of the TE_{11} mode S-parameter curve can be lower than that of the second peak because the $R/Q_{\perp}$ of the TE_{111} mode is lower than that of the TM_{110} mode. The S-parameters of the designed coupler at the frequencies of the TM_{010}, TE_{111} and TM_{110} modes of the cavity are given in Table 2. The dimensions of the designed coupler are shown in Fig. 5.

MULTIPACTING

The regions labelled $\mathrm{C_n}$ and $\mathrm{C_{2t}}$ in Fig. 2 were suspected to potentially support multipacting. Multipacting simulations were carried out with CST Spark3D [5] for field values up to the cavity operation field value of 10 MV/m. Multipacting

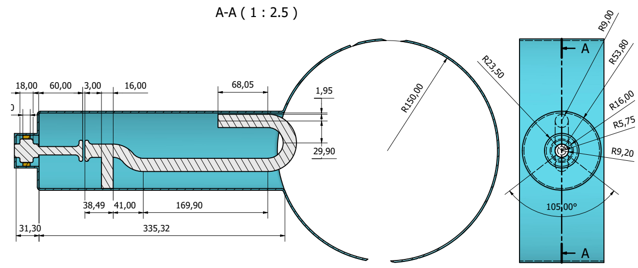

Figure 5: HOM coupler orthographic view and dimensions.

was not observed in any of the analysed regions. Figures 6 and 7 show the plots of the electron evolution with time for different accelerating electric field values.

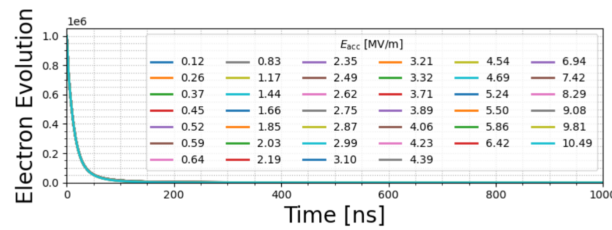

Figure 6: Electron evolution vs time in region $\mathrm{C_n}$.

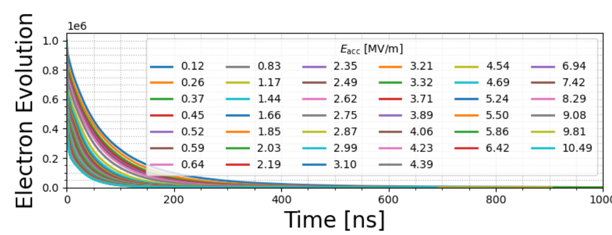

Figure 7: Electron evolution vs time in region $\mathrm{C_{2t}}$.

To get an idea of the electric field values for which multipacting could occur in $\mathrm{C_n}$, the region was approximated as a parallel plate capacitor and the field value and impact energy at which multipacting would likely occur were estimated analytically as in [6]. For a gap distance of 3 mm and frequency of 400.79 MHz, the field value and impact energy at which multipacting occurs were calculated to be 3.44×10^4 V/m and 65.8 eV, respectively. This corresponds to an accelerating field of about 230 MV/m of the FM. A 3D simulation was performed and multipacting was observed between 219 MV/m and 332 MV/m assuming a first cross-over energy K_1 of 60 eV for the secondary emission yield. This indicated that multipacting only occurs at extremely high field values compared to the working E_{acc} and therefore does not cause problems for cavity operation.

MOUNTING OF HOM COUPLERS

A single HOM coupler is not sufficient to achieve the required damping of the HOMs below the transversal stability threshold of the **W**. Two, three and four couplers were

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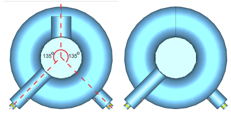
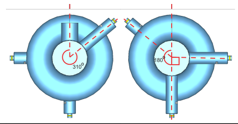
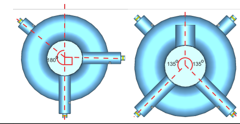
Table 3: Quantities of Interest for Parasitic HOMs

		2HC1FPC		3HC1FPC			4HC1FPC			
										
	α_i	[135°, 135°]		[90°, 180°, 310°]			[45°, 135°, 225°, 315°]			
TE_{111}	f [MHz]	487.63		487.49			486.19			
	$R/Q_\perp$ []	5.64		5.18			4.45			
	Q_{ext}	698.22		545.32			424.50			
	$Z_\perp$ [k/m]	40.25		28.87			19.22			
TM_{110}/TM^*_{111}	f [MHz]	520.96		520.29			516.36/555.88*			
	$R/Q_\perp$ []	9.125		10.42			8.41/0.16*			
	Q_{ext}	3693.35		1219.91			120.13/1115.09*			
	$Z_\perp$ [k/m]	368.05		138.63			10.93/13.04*			
Hook Coupler Mode	f [MHz]	149.38	149.40	148.83	149.075	149.259	149.18	149.24	149.33	149.40
	R/Q []	0.078	0.0068	0.104	0.040	0.072	0.125	0.118	0.017	0.024
	Q_{ext}	2.9e3	1.24e4	7.41e4	7.37e4	7.35e4	8.1e4	7.5e4	1.0e5	7.4e4

*The TM_{110} mode has the second-highest impedance value for the 2- and 3-hook couplers systems. The TM_{111} mode has the second-highest impedance value for the 4-hook couplers system. $Z_\perp = (2\pi f/c) \cdot R/Q_\perp \cdot Q_{ext}$ [4].

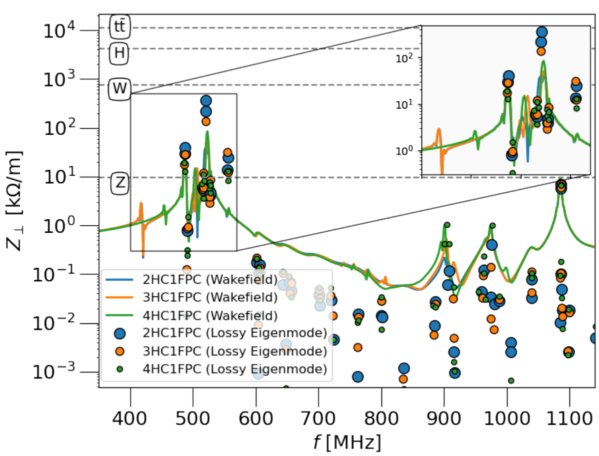


Figure 8: Wakefield and lossy eigenmode transverse impedance values for 2-, 3-, and 4-hook coupler systems.

connected to the cavity and the entire system was simulated. The fundamental power coupler (FPC) was placed vertically upward and different configurations of the couplers relative to the FPC were simulated by varying the angle of the couplers on either side of the cavity relative to the FPC. The optimal configuration for each system is shown in Table 3. The mounting angle α_i for each coupler i, moving anticlockwise from the positive vertical axis on the FPC side, is also shown in the table.

The transverse impedance values for the optimal configurations of the 2-, 3-, and 4-hook coupler systems, calculated from lossy eigenmode analysis, are shown in Fig. 8. The 4-hook coupler system achieved the highest damping of the modes below the threshold value. The results for the 2-, 3- and 4-hook coupler systems are summarized in Table 3.

In the 2-, 3- and 4-hook coupler systems, a lower order mode with a frequency of 149 MHz is trapped in either of the designed hook couplers. This mode is one of the eigenmodes of the hook-type coupler that is determined by the shape of the coupler. The relevant quantities of interest of these modes are recorded in Table 3. These modes were also reported in [7]. They are to be studied to ascertain if they are potentially parasitic.

CONCLUSION

A HOM coupler has been designed to dampen the parasitic HOMs of the proposed cavity design for the **W** operating point of the FCC-ee. For sufficient damping of the dipole modes below the transversal impedance stability threshold of the **W** working point, four of the designed couplers were used. It was also shown that the HOM coupler does not multipact up to the operating field value.

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