Fundamental mode rejection in SOLEIL dipole HOM couplers

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1 Introduction

The SOLEIL superconducting accelerating cavity is a heavily damped two-cell structure. The high order modes damping is provided by superconducting HOM couplers connected to the central tube of the cavity. Monopole and dipole modes are damped by two distinct types of couplers. Two dipole HOM couplers pictured in figure 1 are installed on the SOLEIL cavity.

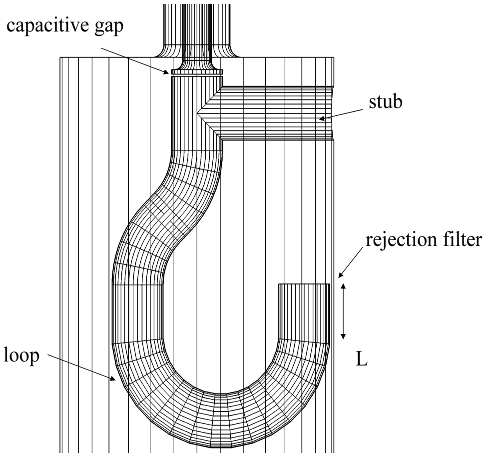

Figure 1: HOM coupler layout

Their design and performance are described in [1, 2]. These dipole couplers should not couple to the fundamental mode of the cavity at 352.2 MHz, which is used for beam acceleration. They would otherwise transmit high power to the ouput lines and possibly go to the normal conducting state, dissipate RF power and becoming a heat source for the cryogenic system. A notch filter was included in the RF design of the coupler to reject the fundamental mode.

Low level measurements on the prototype cryomodule at 4 K exhibit an insufficient rejection of the fundamental mode by the dipole HOM couplers. Typical values of the transmission parameter $S_{FPC,dip}$ between the fundamental power coupler (FPC) and dipole HOM is of the order of -20 dB [3]. The incorrect tuning was confirmed during the test of the SOLEIL module at ESRF with RF power and beam. In this setup, the RF power transmitted by HOM couplers was of the order of 1.6 kW, for a total power of 360 kW transfered to the beam [4]. Power levels of kWs are likely to cause heating and outgasing in the dipole coupler coaxial output lines which may initiate discharge phenomena and damage the lines.

2 Rejection optimization

The rejection filter of the HOM coupler can be tuned by varying the capacitance of the loop termination. This can be achieved either by changing the length L of this termination line or by adjusting the gap g between this termination and the HOM external conductor. The latter adjustment is kept for the fine tuning of the rejection allowed by the mechanical design of the couplers. The rejection line length L on the first HOMs assembled on the SOLEIL prototype is 36.6 mm. This length is obviously not convenient and has to be optimized.

All calculations have been carried out using Ansoft HFSS v8.5. The first model is a cell equipped with 2 coaxial ports on the central tube (port 1) and on the beam tube (port 2), and a dipole HOM coupler (figure 2).

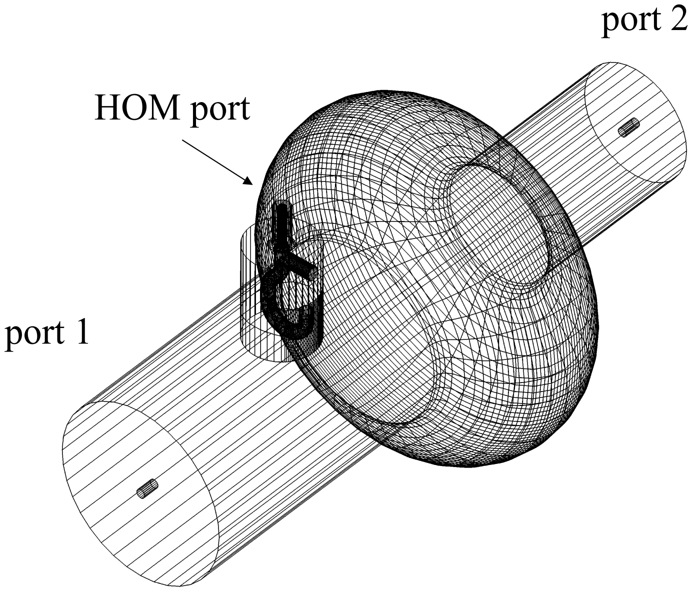

Figure 2: HFSS model

Calculations include several adaptive passes and a fast frequency sweep (FFS) typically in a span of 800 kHz around the frequency of the fundamental mode. In order to compute the external Q of the HOM coupler, the 3 dB width method on the S_{21} curve would be inaccurate since Q_{ext} is expected to reach values greater than 10^9. Q_{ext} can be computed using the field distribution in the structure at resonance from the stored energy U and the power P radiated through the HOM coupler. The S_{21} curve is used to locate the resonance accurately. Without port 2, it would be difficult to determine the resonant frequency of the structure when the rejection filter is relatively well tuned!

Using the field distribution at resonance, the stored energy in the cell is obtained and the power flowing out from the dipole coupler P_d is computed:

$$P_d = \frac{1}{2}\int_{\mathcal{S}_{\mathcal{D}}} (\mathbf{E} \times \mathbf{H}^*) \cdot \mathbf{dS}$$

where $\mathcal{S}_{\mathcal{D}}$ is a section of the output coaxial line of the coupler and $d\mathbf{S}$ a surface element carried by its normal. The external Q of the coupler is then $\frac{\omega U}{P_d}$

All the HFSS calculations have been performed using a manually optimized mesh which is highly refined in the region of the rejection gap. Each time a new model is generated the mesh is different. This induces variations of the resonant frequency of several tens of kHz which is smaller than the expected width of the rejection.

The variation of Q_{ext} with respect to L is shown in figure 3. In this case the cell frequency was 353.2 MHz, 1 MHz above the nominal frequency. The optimum L is 26 mm which is very far from the prototype value of 36.6 mm. For all these runs, the resonant frequency of the cavity was extremely stable, within ±5 kHz.

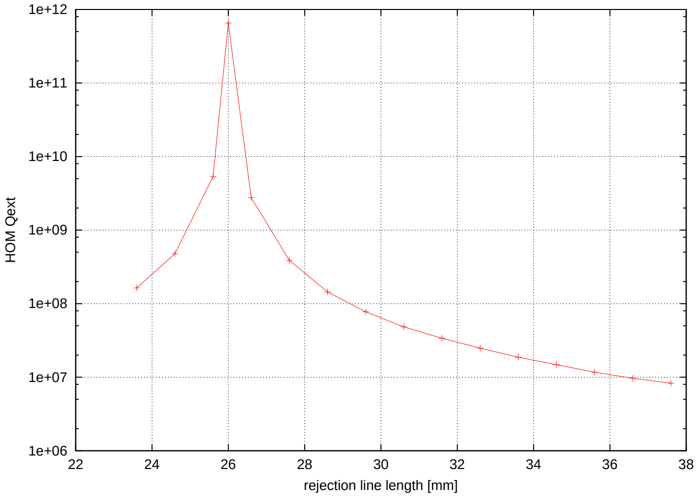

Figure 3: L optimization

One could resort to a symmetrized model (two HOMs) and use the symmetry to reduce the model and increase the mesh density in the cell. The observation of the EM field in the central tube on a full model reveals that the distribution is far from being symmetric with respect to the horizontal plane (the HOM is set vertically). This gives a hint that the rejection optimization with a symmetrized model would be inaccurate. It has been verified on a halved model for which L_{opt} was found at 23.8 mm instead of 26 mm.

In order to obtain a more accurate resonant frequency, the process has been repeated on a model with a better description of the cell profile. The dependence of Q_{ext} with respect to L is shown in figure 4. For these calculations, $f_0 = 352.3 \pm 0.1$ MHz.

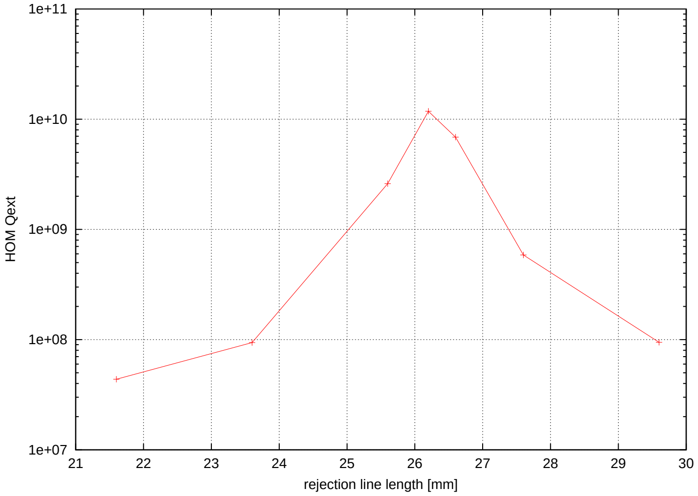

Figure 4: L optimization

Since f_0 is less stable than in the former set of calculations, the extremely high Q_{ext} of 10^{12} could not be reached, but one can conclude that the optimal value for L, L_{opt} is unchanged.

3 Influence of power couplers

The distance between dipole HOM couplers and FPC is less than 200 mm, that is, comparable to their size. Moreover, the new SOLEIL parameters will lead to increase the FPC coupling: since Q_{ext} which is 2 10^5 on the prototype module will have to be changed to 1 10^5, the FPC antenna has to be lengthened [5]. We are concerned about a possible perturbation of the field distribution in the region of the HOM loop by the fundamental coupler, which would result in a less effective fundamental mode rejection. Calculations have been carried out using a half structure model including the FPC lower part.

First, the FPC antenna length was set to the original position for an FPC Q_{ext} of 2 10^5. The relative positions of the HOM and FPC for the two cells are different (see figure 5), therefore, two sets of simulations, labeled 'left' and 'right', have been run.

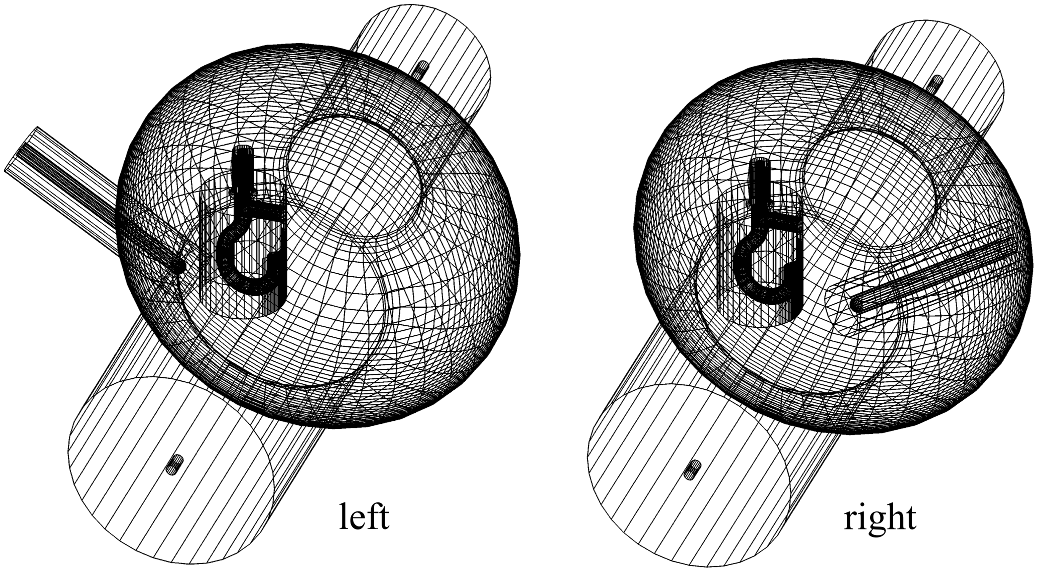

Figure 5: FPC/HOM relative positions

The optimum L is changed symmetrically by 0.2 mm around the L_{opt} without FPC. This indicates an influence of the FPC on the rejection. In order to confirm this proximity effect, another set of calculations has been done for a longer FPC antenna, corresponding to a fictive Q_{ext} of 5 10^4, for which L_{opt} is changed by 2.4 mm for the 'left' case. Two informations can be drawn from these two Q_{ext} setups : first, the coupler antenna position modifies the field in the region of the loop termination, and second, simulation are capable to resolve the influence on rejection of a modification of the filter termination of the order of 0.1 mm.

The results corresponding to the new coupling parameters of SOLEIL ($Q_{ext}=10^5$) are shown in figure 6. The two optimal values for the length L are 25.4 and 27 mm for right and left case respectively. The mid value is 26.2 mm, which is still very close to the 26 mm optimum found without FPC. Computed Q_{ext} values for tuned dipole couplers are above 10^9 which would maintain the power at 352.2 MHz flowing through the dipole output lines in the order of 100 W in operation. The comparison between a tuned and a detuned ($Q_{ext} \approx 10^8$) filter can be made looking at S parameters represented on figure 7 and 8 respectively. In the tuned case, $S_{FPC,dip}$ = -70 dB whereas $S_{FPC,dip}$ = -23 dB in the other case (red

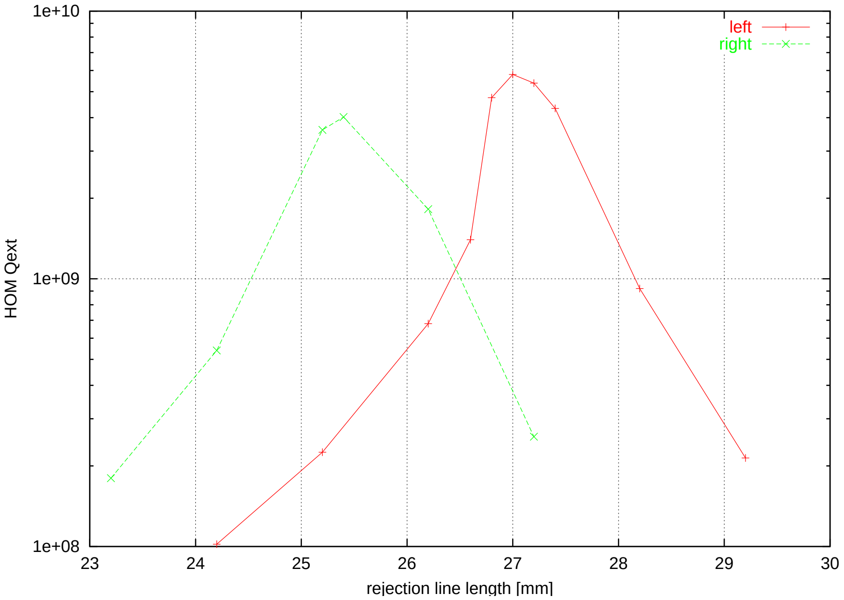

Figure 6: Q_{ext} optimization varying L with FPC in left and right configurations, for $Q_{ext}=10^5$

curves), at the resonant frequency of the cell, which is compatible with the previously reported values. The base level $S_{FPC,dip}$ is -40 dB in both cases.

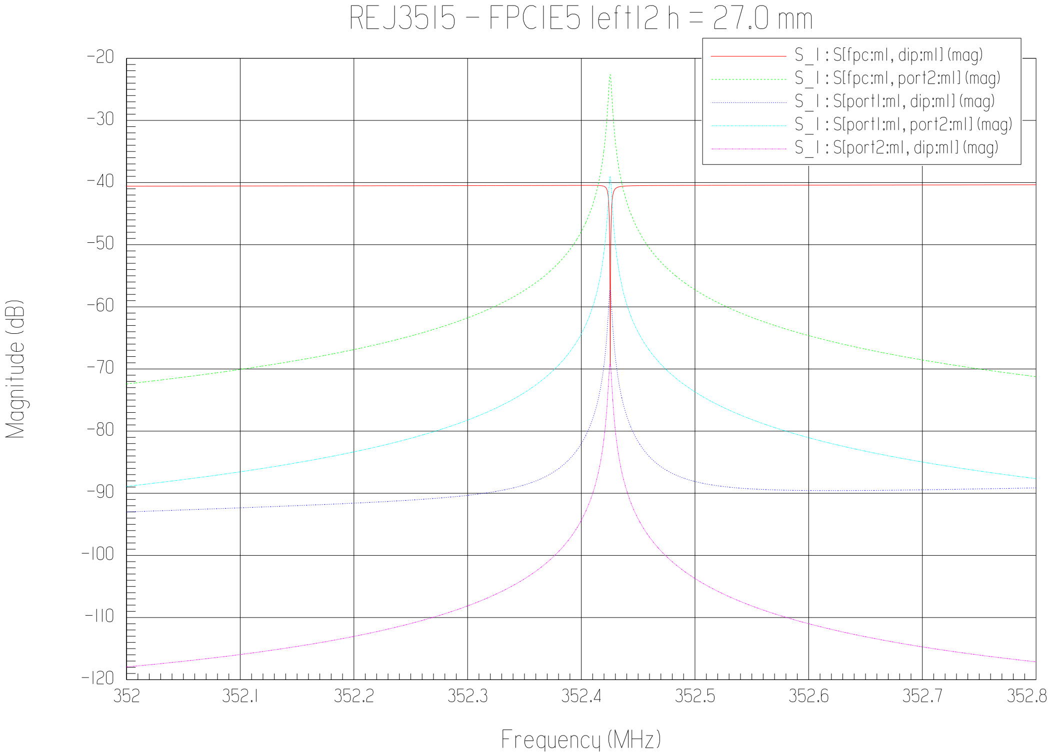

Figure 7: S parameters for a left configuration, with a tuned rejection filter

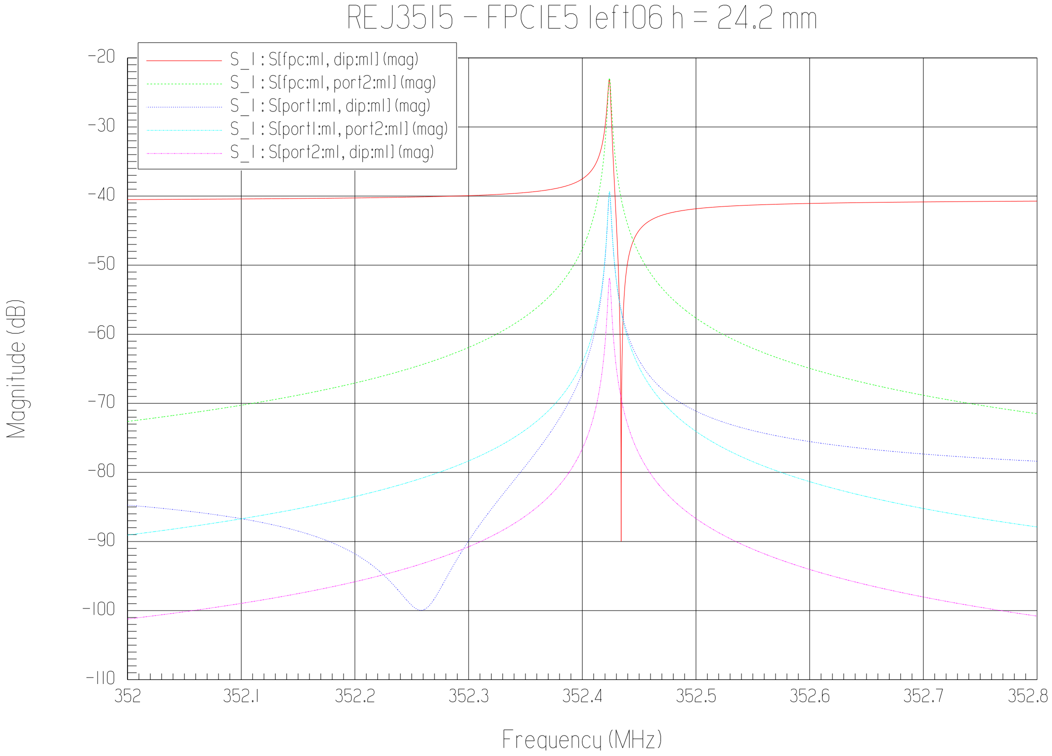

Figure 8: S parameters for a left configuration, with a detuned rejection filter

4 Width of the rejection band

The tuning process is carried out at room temperature. The cell frequency is adjusted at 351 MHz to anticipate the +1.2 MHz shift that occurs during cooldown. Let us assume we can tune the rejection filter perfectly. If the cell and the notch filter are detuned by the same amount during cooldown, a tuned filter at 300 K should remain perfectly tuned at 4 K. During cooldown, the difference in expansion coefficients of materials composing the HOM could result in a 4K geometry which deviates from the simple scaled geometry that would occur if it was built from a single material. During the engineering design of the module, materials have been carefully chosen so as to reduce this difference. Nevertheless, we have to compare the rejection width to this typical 1 MHz frequency shift, since it gives an information on how accurate the tuning has to be carried out at room temperature.

A set of calculations with a fixed value L= 27 mm (optimum value for a 'left' configuration) was performed while varying the cell resonant frequency by successive deformations of its equatorial region. The results are displayed in figure 9.

The ability to reach Q_{ext} values above 10^9 is limited to a [-1.5,+2.5] MHz range around the cell frequency, which is very demanding on the tuning accuracy.

5 Conclusion

Using a detailed 3D model of the SOLEIL accelerating structure, we have been able to study the fundamental mode rejection by the dipole HOM couplers. The length of the rejection line L which is equal to 36.6 mm on the prototype is not convenient, and should be reduced. The rejection properties of the HOM couplers are modified by the presence of the fundamental coupler in two ways: first, full rejection can not be obtained by a tuned rejection filter. Instead is typical values for Q_{ext} are in the 10^9 to 5 10^9 range. Second, the rejection filter center frequency is modified when the FPC antena penetration changes. For

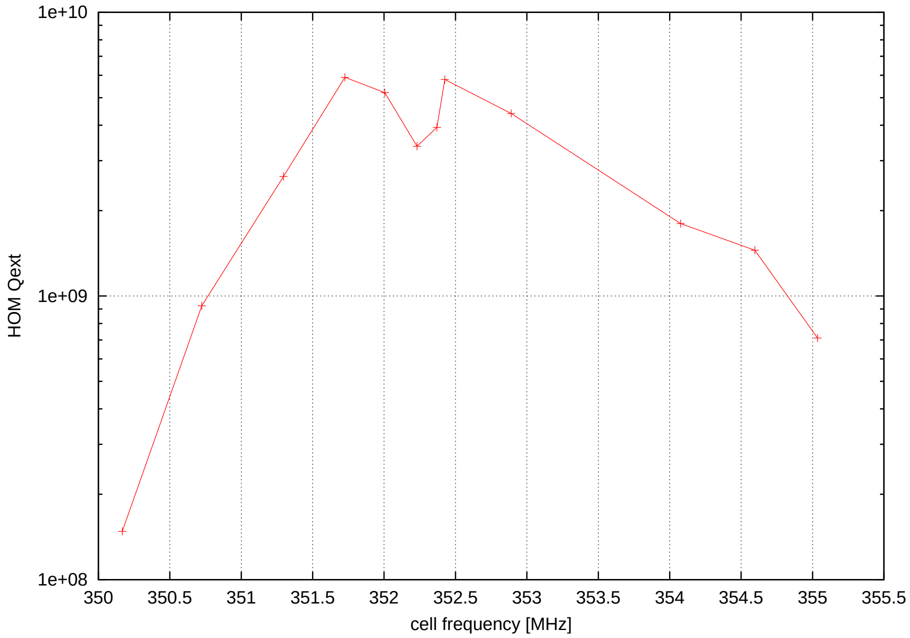

Figure 9: Q_{ext} versus frequency for L$_{opt}$ = 27 mm , 'left' case

the nominal coupling of the FPC which corresponds to a Q_{ext} of 10^5, the optimal rejection filter length is different for the two dipole couplers. However it is much simpler to keep both loops identical. Since fine tuning of the filter capacitance can be achieved through a mechanical adjustment of the filter gap, a single value of L=26.2 mm can be chosen.

References

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[2] Mosnier et al., HOM damping in SOLEIL superconducting cavity, EPAC'98,Stockholm, 1988.

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[4] J. Jacob et al., Test of the SOLEIL Cryomodule Prototype with beam at ESRF, proceedings of the 11^{th} workshop on RF-Superconductivity, Travemünde, 2003

[5] Coupler de puissance:reprise du Qext, CEA/DSM/DAPNIA/SACM Technical note SC/SOLEIL/03_06_18