3D computation of dipole mode impedance and damping in SOLEIL cryomodule

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1 Introduction

During the design phase of the SOLEIL RF structure, only 2D evaluations of HOM damping had been carried out [1, 2]. We recall the first two dipole modes characteristics in table 1.

mode	frequency [MHz]	r/Q [Ω/m]	Q_{ext}
1	403	4.8	800
2	404	51.6	900

Table 1: Computed (2D) characteristics of the first two dipole modes

During RF measurements with a network analyser on the prototype cryomodule at 4 K, these modes could not be observed. Two explanations are possible : either they are extremely well damped or they can not be excited from the available ports. In 2002, the module was inserted in the ESRF ring [3]. In november 2002, a beam experiment was carried out using a single bunch in the ring, which could be ran through the module with an offset with respect to the cavity axis. The observation of one dipole HOM coupler output signal with a spectrum analyser allows one to probe the cavity transverse impedance. Since the excitation spectrum is comb-like with a spacing corresponding to the revolution frequency of 355 kHz, is it difficult to resolve resonances in the 400 MHz region with a loaded Q greater than 1000. Two resonant superimposed resonant peaks have been observed on the cavity spectrum around 400 MHz (figure 1)

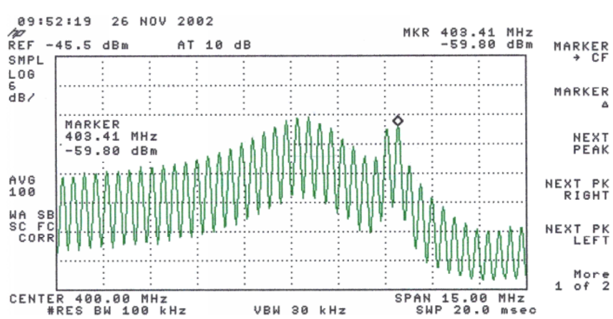


Figure 1: dipole HOM signal spectrum in single bunch operation at I= 4.5 mA

We can only derive estimates of the quality factors of these resonances. The first peak at 400.15 MHz is asociated with a Q of 100 while the sharpest resonance which occurs at 403.155 MHz has a quality factor between 1000 and 4000. The first peak corresponds to a strongly damped mode, which frequency can not be directly compared to those in table 1 corresponding to the undamped case. Therefore, mode identification is hazardous ; two scenarii can be considered :

- the second peak could be assigned to the first dipole mode, with a low r/Q of 4.8 Ω/m, resulting in a transverse impedance ranging from 5 to 19 kΩ/m to be compared to the coupled bunch instability harmful threshold impedance of 125 kΩ/m . The first peak is assigned to the second dipole mode which impedance is thus about 5 kΩ/m. This is the favorable scenario.
- The alternative is less favorable : the sharp peak corresponds to the second dipole mode, the impedance of which would be between 52 and 210 kΩ/m thus potentially exceeding the threshold for coupled bunch instabilities. In this case, additionnal damping would be required. In the case of the SUPER-3HC harmonic cavities, which RF design is based on a scaling of the SOLEIL structure, higher requirements in terms of tranverse impedance and the complexity of first dipole mode identification have lead to insert two additional dipole HOM couplers in the structure [4].

In the present situation, the interpretation of measurements alone is difficult. Would bead-pull measurements provide more information on field profile? In this specific case, the 3 dB width of one of the modes is greater than 1 MHz, which is about the same as the frequency separation between the two modes. As a consequence, they are co-excited during RF measurements, and measured field profiles would be difficult to interpret due to this mixing. 3D simulations of the whole structure are now tractable with current EM codes and workstations, and can give a much better insight of the situation, and help to evaluate the need for additional damping. One can notice that 2D formerly predicted and measured Q_{ext} do not match, 3D effects are thus expected. The general picture of heavy damping in an non-axisymmetric structure itself is worth being looked at in details.

2 Numerical Model

All field calculations have been carried out using Ansoft HFSS v8.0 [5]. Since we are mainly interested in dipole modes impedance, the model includes the two cells and the dipole couplers. No symmetry exists, since one dipole coupler can be transformed into the second one by the combination of a translation along z axis and a rotation around z axis also. The monopolar couplers and the power couplers are left out in order to keep the mesh size compatible with the memory available. Figure 2 show the full RF model of the structure.

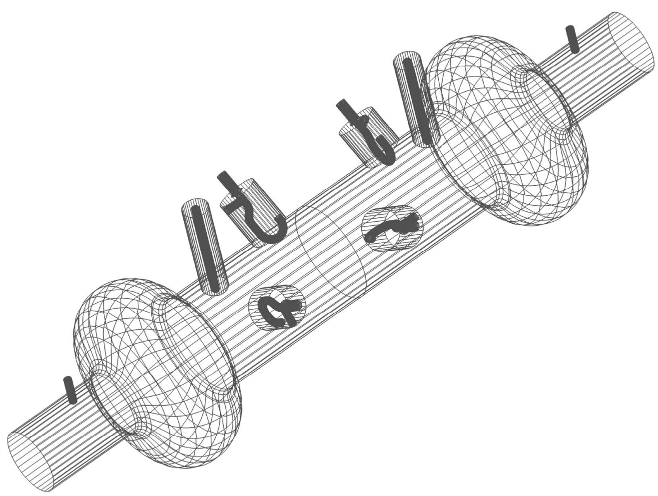


Figure 2: HFSS full model

2.1 Transmission calculations

The goal is to obtain the electromagnetic field of each of the first dipole modes, then to process it in order to derive the r/Q and Q_{ext} for each of them. A first set of calculations was carried out using the transmission module of HFSS. The same interpretation problem occurs as for the RF measurements : S parameters do not provide enough informations. A single transmission peak was found in the frequency span between 390 and 410 MHz. For a driven problem, the HFSS post-processor is able to display the EM field at any frequency provided the Fast Frequency Sweep (FFS) method has been employed for the S parameter calculation. Due to the heavy damping, the field in the cavity is a mix of several polarizations of several modes. This calculation method is not adapted to determine RF parameters of single mode and polarizations. This observation confirms that bead-pull measurements would have lead to non-usable results.

2.2 Eigenmode calculations

The solution is to compute the eigenmodes of the structure. But in this case, no adapted ports can be included in the model. Since we expect a strong damping, a large portion of the electromagnetic energy should flow out of the structure through HOM couplers. This is not compatible with a standard setup for eigenmode calculation where E-plane or H-plane boundary conditions are available. A specific model was set up including adapted loads connected to the coaxial output of dipole couplers. Here we take advantage of HFSS ability to carry eigenmode calculations in a lossy structure. This coaxial loads are filled with a high loss factor material in order to damp the incoming TEM wave efficiently, and have a low reflection factor for a length of several tens of centimeters. Their reflection coefficient have been computed separately with HFSS transmission module : S_{11} is -55 dB, for a 12000 element mesh. The contribution of the loads to model will be around 24000 elements, compared to the typical value of 100000 elements for the full structure. The first 6 dipole modes have been computed using this method, calculating the two polarizations of each mode at a time. We will focus on the first two modes for which a detailed understanding is needed.

2.3 benchmarking

Test calculations have been performed in order to check the accuracy of r/Q calculations for a large 3D model. The accuracy of r/Q calculation is directly related to the quality of the computed field. The test case is simply the SOLEIL 2-cell cavity without couplers, fully modeled (no symmetries are assumed) so it can be compared to Urmel calculations. This test allows one to define the mesh requirements for a given accuracy level on the r/Q.

mode	frequency [MHz]	3D r/Q [Ω/m]	2D r/Q [Ω/m]
1a	404.014	8.5	4.8
1b	404.023	8.3	-
2a	404.665	48.4	51.6
2b	404.673	48.8	-
3a	456.052	0.1	0.01
3b	456.056	0.1	-
4a	484.698	57.6	61.6
4b	484.722	57.2	-
5a	495.44	10.8	6.7
5b	495.49	10.5	-
6a	506.89	97.2	100
6b	506.94	96.7	-

Table 2: Comparison of 2D and 3D r/Q calculations for the first dipole modes (no HOM couplers)

A good agreement between 2D and 3D calculations is found for the six first dipole modes (tab. 2). One can notice that a larger discrepancy occurs between 2D and 3D calculations for the small r/Q values. The reason is that errors in the 3D field calculation are not completely symmetrical in the two cells since the mesh is not completely uniform in the structure. In the case where low impedance results from almost canceling terms in the two cells, numerical errors of 3D increase artificially the r/Q value. For instance, computing the 6^{th} mode in 3D for an halved structure and assuming a perfect field symmetry provides a more accurate value of 99.4 Ω/m for r/Q.

2.4 External Q computations

Eigenvalue calculation including losses provide the stored energy U and the power radiated outside the cavity P, from which the external Q is computed as $Q_{ext} = \frac{\omega U}{P}$. The external Q values for the six first modes of the damped structure have been computed (table 3).

mode	frequency [MHz]	Q_{ext}
1a	400.705	74
1b	401.191	72
2a	403.942	1850
2b	404.225	1890
3a	455.895	150
3b	456.550	71
4a	483.876	92
4b	484.642	50
5a	495.207	1443
5b	495.279	953
6a	505.314	162
6b	505.993	94

Table 3: Q_{ext} calculations on the loaded structure

3 First two dipole modes

Let us consider the values in table 3 for the first pair of modes. The computations show clearly that the damping is less efficient for the second mode, which gives a hint as to assign the sharp peak in the measurements to the second mode. Moreover, the Q_{ext} estimations derived from the ESRF experiment and the computed values are now compatible. The first mode frequency is shifted towards 401 MHz due to the high damping. In the undamped case, the mode separation was of the order of 600 kHz, while the high damping of the first mode raises this value to about 3.1 MHz in the 3D simulations. The later matches fairly well the 3 MHz mode separation derived from the ESRF measurements. Let us recall the field distribution for the first two dipole modes in the simple case of the axisymmetric structure. The electric field $\mathbf{E}$ in the (yz) plane is shown in figure 3 and 4 for the first two modes.

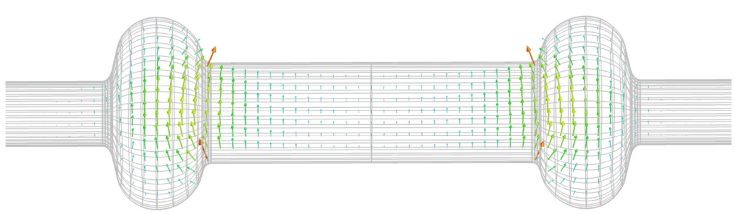


Figure 3: Electric field (yz) plane, first dipole mode

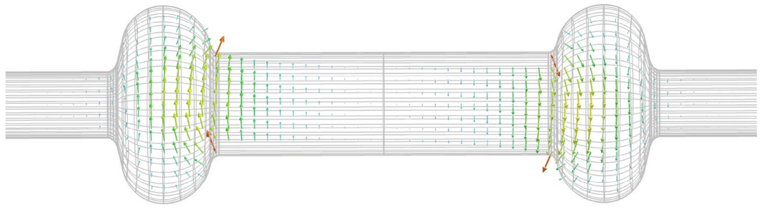
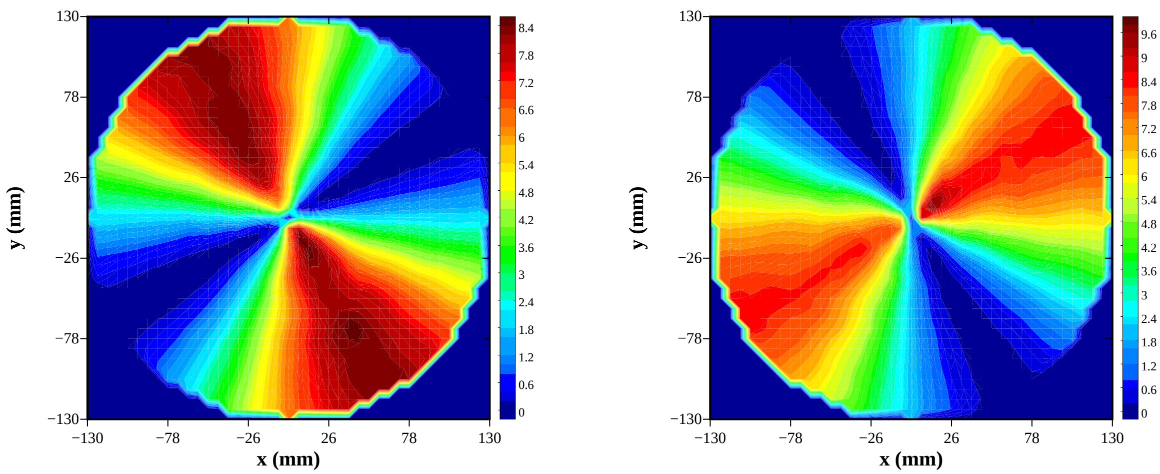


Figure 4: Electric field (yz) plane, second dipole mode

For the second mode, **E** cancels at the center of the inner tube and changes its sign between the two cells, whereas its sign is kept unchanged along the structure for the first mode.

3.1 Discussion on polarization

The excitation of a dipole mode polarization by the beam depends on beam position (r, θ). The energy lost by the beam on this mode is proportional to $r^2 cos^2(\theta - \theta_0)$, where θ_0 is the polarization angle of the mode. For illustration purposes, the r/Q has been computed on the simplified structure (no couplers) for beam trajectories parallel to the cavity axis, but for a beam entrance position (x,y) scanning the whole transverse plane.



(a) r/Q 404.014 MHz

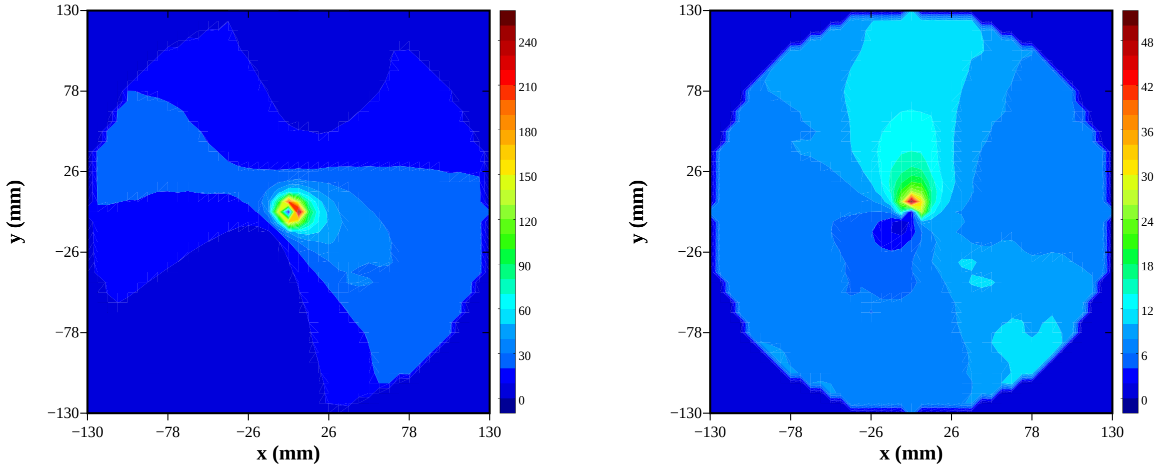
(b) r/Q 404.014 MHz

Figure 5: r/Q mapping in the transverse plane, undamped structure

The figure 5 shows the results for the two polarizations of the first dipole mode. One can notice the orthogonality of the polarization planes.When couplers are included in the model, the same mapping of r/Q is carried out, leading to much less simple diagrams (fig 6) for the 2 polarizations of the damped first dipole mode.

The maximum value of r/Q for the first polarization is increased by a factor 2.5 with respect to the undamped case. This indicates that a 3D computation of all dipole modes impedances is needed since modes which had been considered as harmless refering to the 2D study could become dangerous if their maximum r/Q is increased by too large a factor.

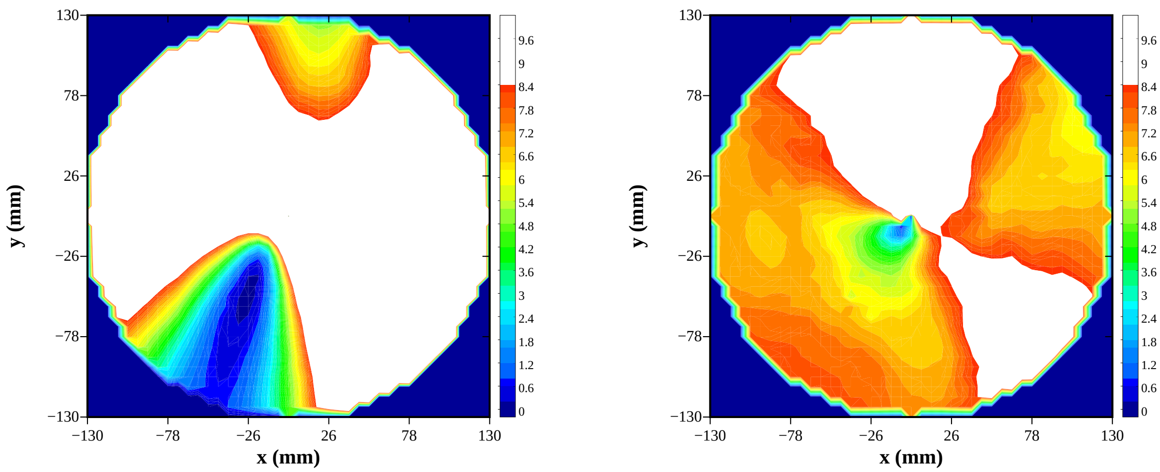
The diagram on figure 7 is the same as the previous one but the r/Q values has been clipped at 8.5 Ω/m, which is the r/Q of the first mode of the undamped structure computed in 3D.



(a) r/Q 400.705 MHz

(b) r/Q 401.191 MHz

Figure 6: r/Q mapping in the transverse plane, damped structure



(a) r/Q 400.705 MHz

(b) r/Q 401.191 MHz

Figure 7: r/Q mapping in the transverse plane, damped structure, clipped at 9 Ω/m

The white areas represent the locations for which the r/Q has been raised by the introduction of couplers. The footprint of the polarization plane on the loss factor is no longer clearly visible as it was in the undamped case. This can be explained by the field distribution along the trajectories (fig. 8). A polarization plane can still be defined inside the cell, but it is meaningless when considering the whole structure. The orientation of the electric field is obviously locally influenced by HOM couplers. It is also different in the two cells.

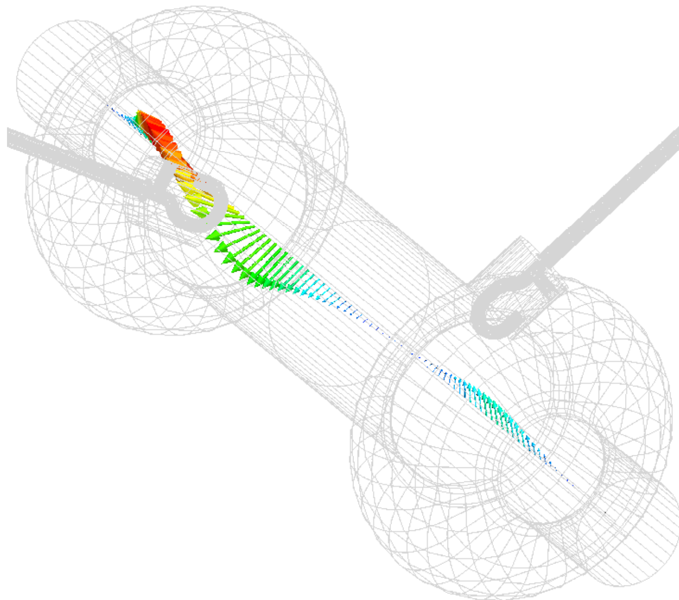


Figure 8: Electric field along beam axis

3.2 Impedance and instability thresholds

In order to compare the impedance of the dipole modes and the instability threshold of CBI, we have to consider the maximum values $(r/Q)_{max}$ of r/Q in the transverse maps discussed above, and multiply by the corresponding mode Q_{ext}. The results are summarized in table 4.

mode	frequency [MHz]	Z [Ω/m]
1a	400.705	2140
1b	401.191	829
2a	403.942	39920
2b	404.225	64405
3a	455.895	153
3b	456.550	121
4a	483.876	4242
4b	484.642	2133
5a	495.207	10556
5b	495.279	11298
6a	505.314	15011
6b	505.993	8591

Table 4: First dipole modes impedances of the loaded structure

These impedances have to be compared to the 125kΩ/m threshold. The second mode impedance is only a factor two below this threshold, which leaves only a small safety factor.

Since the beginning of the construction phase of SOLEIL, several machine parameters have been upgraded. Since the nominal beam energy was raised to 2.75 GeV, HOM impedance requirements are now relaxed with respect to the original specifications. The computed threshold on impedances are now 493 kΩ/m for the dipole modes and 53 kΩ.GHz for the longitudinal HOMs. Taking into account these new SOLEIL parameters, the safety factor is about 7.7 for transverse mode impedance.

4 Conclusion

These RF simulations showed that for this type of heavily damped structures, one should expect

- strong distortions of the field distribution of dipole modes due to the large size of HOM couplers, the electrical center of the cavity no longer being the physical axis of the cavity.
- as a consequence, the impedance seen by a beam traveling parallel to beam axis can no longer be a simple sinusoidal function of the azimuthal position
- whereas a geometrical relation of orthogonality exist between the electric field of the two polarizations of a dipole mode in the axisymmetric case, no such relation holds for a strongly damped mode in the SOLEIL structure.

The 3D computations and beam experiments on the first two dipole modes are in good agreement. It confirms that complex RF structure analysis is now within the reach of 3D electromagnetic codes such as HFSS.

With the initial parameters of the SOLEIL ring, the two dipole couplers configuration would have provided a small safety margin on the transverse impedance with respect to the CBI threshold. With the present ring parameters, the impedance requirements are met for the most dangerous dipole modes and consequently the 4 HOM couplers configuration (2 dipole and 2 monopole) need not be modified.

References

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[3] J. Jacob et al., Successful beam test of the HOM free superconducting SOLEIL cavity prototype at the ESRF, PAC'03, Portland, 2003.

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