DAΦNE TECHNICAL NOTE

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DAΦNE MAIN RING CAVITY 3D CODE SIMULATIONS

R. Boni, A. Gallo, F. Marcellini

INTRODUCTION

The e.m. behavior of the resonant cavities can be simulated by means of dedicated computer codes which can numerically solve the Maxwell equations in the structure with given boundary conditions. So far, our simulations have been based on 2D computer codes (OSCAR2D[1], URMEL[2]) which can analyze azimuthally symmetric structures. These codes give useful information, like the resonant mode frequencies, impedances and quality factors. However, to obtain better simulations, the 3D perturbations of the basic cavity shape must be taken into account, together with the dissipation of real dielectric and conducting materials and the effect of the coupling ports. This is particularly important in the case of the DAΦNE main ring cavity[3] which has to be simulated as an "open" device due to the presence of many coupling ports (the accelerating mode main coupler, the 3 rectangular ports for HOM damping on the cavity cell, the 2 rectangular ports for high frequency HOM damping on the cavity tapers, ...). The 2D codes can only treat "closed" problems because they compute eigenvectors and eigenvalues of the Helmoltz equation of a free space region completely surrounded by perfect electric or magnetic surfaces.

A new computer simulation code (HP85180A "High Frequency Structure Simulator" HFSS, Hewlett&Packard trademark) recently developed for the Radiofrequency and Microwave CAD-CAE market has been used for 3D simulations of the DAΦNE main ring cavity frequency response. The aim of this work was to gain experience with the code, to find out its limits in describing a narrowband complex structure like the DAΦNE cavity and to check the information that we already got from 2D simulation codes and prototype measurements.

1) The "High Frequency Structure Simulator" code

The HFSS code consists in an e.m. solver based on the finite elements method. It computes the field distribution in the frequency domain inside any passive 3D structure, considering the excitation of a traveling wave entering an input port. The results are presented in the form of a scattering matrix, which relates the wave emerging from any port to the excitation, as a function of frequency. Due to this approach, at least one port must be defined on the model to be analyzed. Hence, the code simulates a Network Analyzer measuring the device under study.

The HFSS code requires a Unix-X Window system to run; its features can be summarized as follows:

- Analysis of 3D passive "open" structure containing an unlimited number of ports and materials;
- Calculation of the scattering matrix with the accuracy defined by the user;
- Capability to take into account losses by defining conductivity, complex permittivity and permeability of each material;
- Powerful postprocessor which allows the visualization of the field evolution with time along any axis or plane intersecting the model.

HFSS does not solve the eingenvalue problem and the resonances can be found only by carefully scanning the device frequency response. Therefore, for the electromagnetic (e.m.) simulation of a resonant cavity, a mode frequency should be approximately known in advance from other codes or measurements in order to scan only the necessary frequency span.

In order to apply the finite elements method, any object included in the model is divided into a number of tetrahedral meshes. The fields in the center of the mesh are given by interpolating the values in the vertices. The code generates and refines the mesh automatically with a step-by-step procedure until the scattering matrix converges below a defined maximum error. Obviously, the finest is the mesh the longer is the CPU time required to solve the problem. In practice, depending on the available computing power, there is a limit on the maximum solvable mesh size. In our case this limit is below 20,000 tetrahedra. Typically, the DAΦNE cavity model requires from 5,000 to 15,000 tetrahedra to reach consistent results, and a single frequency run takes from 10 to 60 minutes.

HFSS code has not been originally developed to deal with very narrowband devices as resonant cavities for particle accelerators. Consequently, the narrower is the bandwidth, the more difficult is to find the resonant frequency and the less precise is the computed frequency response. For high conductivity resonators, the frequency response data must be interpolated in order to get a meaningful resonant curve and to extract the resonant frequency f_r and quality factor Q. An alternative way to get the same information is to reduce the conductivity value, for instance by simulating stainless steel instead of copper devices, and scaling the obtained Q value as the square root of conductivity (see Fig. 2). Moreover, if at least one port is strongly coupled to the resonant mode under study, the computed frequency response is more clearly readable.

The code postprocessor does not compute directly the shunt impedances that have to be worked out by the user from integration of the fields contained in the code output files.

2) The Accelerating Mode

The accelerating mode of the DAΦNE cavity has been studied first. Three different models, shown in Fig. 1, have been investigated; geometrical and e.m. symmetries of each model have been carefully analyzed with the aim to reduce the size of the problem to be solved. The results are reported in Table I in comparison to the simulations of other codes and the experimental measurements of a copper prototype.

The results of the code OSCAR2D and a new 3D code especially developed at Pavia University[4,5] for particle accelerator cavity design have been compared in Table I. The low quality of the cavity prototype available for the test, is probably responsible for the slight disagreement between theoretical and experimental results.

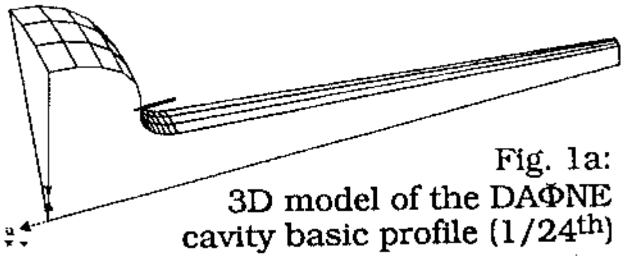

Fig. 1a:
3D model of the DAΦNE
cavity basic profile (1/24th)

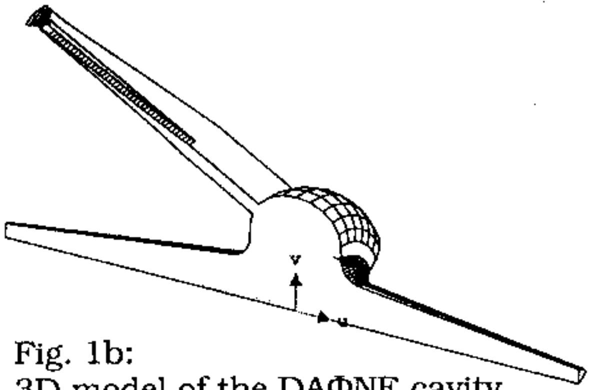

Fig. 1b:
3D model of the DAΦNE cavity
including the 3 BTHDs (1/6th)

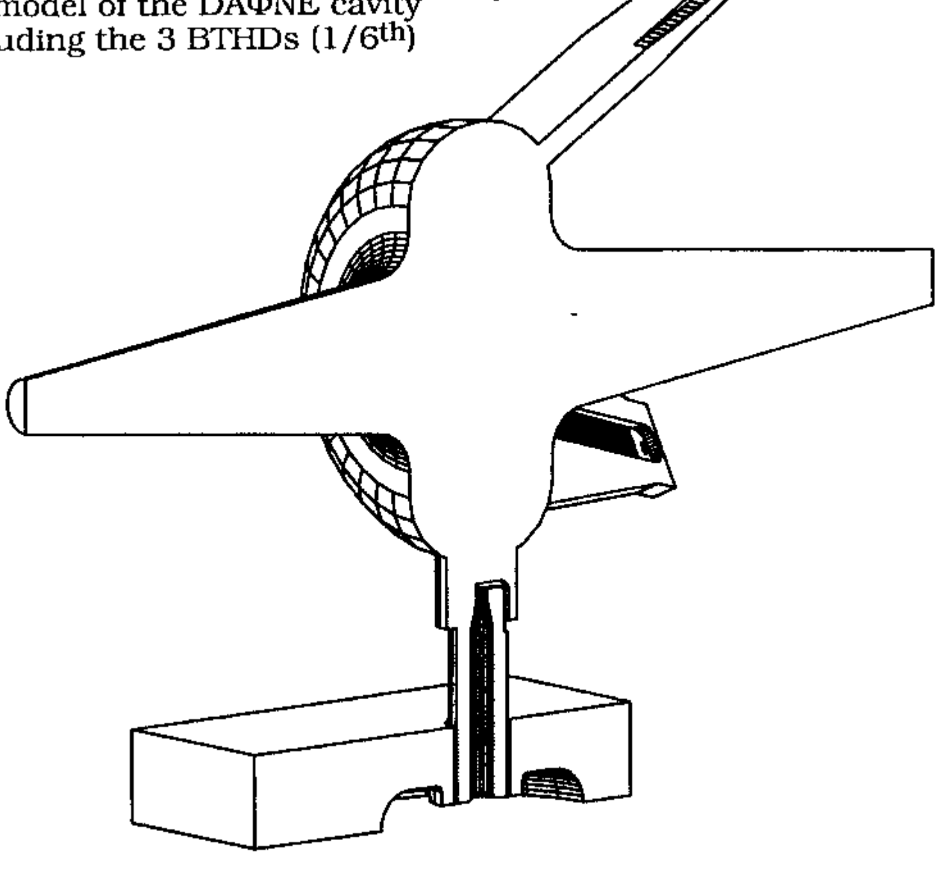

Fig. 1c: 3D model of the DAΦNE cavity including 3 BTHDs
and the Fundamental Mode Coupler (1/2)

The first model (Fig. 1a) represents the 2D basic half-cell profile rotated by 30° and excited with a probe on the cell side. The boundary conditions are the finite conductivity for the metallic surfaces, the perfect magnetic wall on the two 30° apart radial planes and the perfect electric wall on the central transverse plane; the model volume is therefore reduced to 1/24 of the total.

	Unperturbed cell				Cell + 3 BTHDs			Cell + 3 BTHDs + Main Coupler
	OSCAR-2D	Pavia University Code	HFSS	Prototype Measurements	Pavia University Code	HFSS	Prototype Measurements	HFSS
f[MHz]	377.66	385	379.85	357	376.7	372.8	349.5	372.3
Q	52770	52730	52764	25000	39910	40700	22000	39607
R/Q [Ω]	59.456	57.25	59.17	61	57.93	59.426	____	59.29

Tab. 1: Accelerating Mode.

The solution of this model gives a direct comparison between the results of HFSS and those obtained from 2D codes. The agreement for the main RF parameter, as shown in Table I, is well satisfactory. The only significant difference is the resonant frequency value which, in the HFSS evaluation is about 1% higher than that computed by OSCAR2D, whose frequency precision, accordingly to our experience, is within few ‰. This small disagreement is due to the smaller accuracy of the 3D discrete model of the real cavity geometry respect to the accuracy of the 2D discrete model of the cavity cross section; in any case HFSS seems to have a frequency computation accuracy comparable (or even better) to the 3D Pavia Univ. code.

The second model (Fig. 1b) corresponds to a 60° slice (i.e. 1/6) of the entire DAΦNE cavity cell equipped with three Broadband Transitions for High order mode Damping (BTHD)[6] placed on one side 120° apart, and excited with three small probes from the other side of the cell. The frequency response of this model is shown in Fig. 2 for both high and low conductivities ($\sigma_l = 1\cdot10^{6}\ \Omega^{-1}m^{-1}$, $\sigma_h = 59\cdot10^{6}\ \Omega^{-1}m^{-1}$) corresponding approximately to stainless steel and copper metallic conditions. The real cavity will be made of OFHC copper but, as already mentioned, assuming the conductivity of stainless steel for the metallic boundaries, the code produces a smoother frequency response; the actual quality factor can be easily derived by scaling the computed value as the square root of the conductivity. However, the interpolation of the high conductivity model frequency response gives a Q value equal to that obtained by scaling the low conductivity Q as the square root of 59.

The resonant frequency computed by HFSS is slightly affected by the mesh configuration and by the exciting probe length; it is also sensitive to the skin depth of the metallic wall. For this reason, the two frequency responses of Fig. 2 show a slightly different resonant frequency. The results obtained with the copper conductivity are compared in Table I with those obtained from the Pavia Univ. 3D code and the measurements on prototype. A reduction of about 7 MHz of the resonant frequency, due to evanescent field penetration in the HOM dampers, very well matches the experimental data and is in good agreement with the prediction of the Pavia Univ. code (-8.3 MHz). A good agreement between the two 3D codes also exists for Q which decreases from 52,700 to about 40,000 (-24%) after the applications of the 3 BTHDs, while the experimental measurements give a reduction from 25,000 to 22,000 (i.e. about -12%). The normalized impedance R/Q is about 60 Ω in all cases.

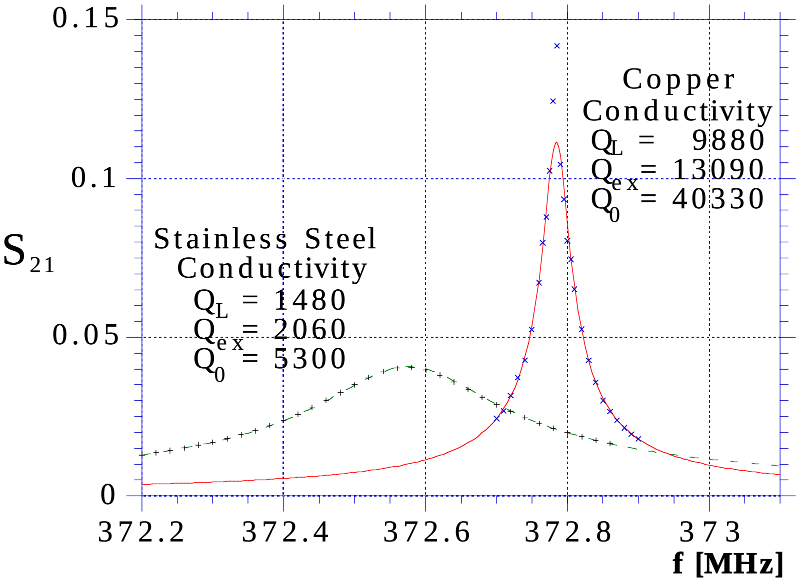

Fig. 2: Transmission Response of the Accelerating Mode

Due to the HFSS capability of running "open" problems, the study of the whole cavity-main coupler system is straightforward.

A model including half cavity with three BTHDs and the main coupler is sketched in Fig. 1c. In order to maintain the symmetry condition, the coupling loop has been placed in the radial plane corresponding, for a given penetration, to the maximum cavity loading. Any rotation of the loop from the radial position reduces the coupling. A plot of the frequency response of the reflection parameter s_{11}, as seen from the main coupler, is shown in Fig. 3. The coupling loop length has been adjusted in order to set the coupling coefficient β at about 9.3; the resulting loaded quality factor is $Q_L \approx 3850$. Since the unloaded quality factor Q_0 is given by:

$$Q_0 = Q_L\,(1+\beta)$$

the cavity-main coupler system shows a Q_0 value slightly lower than that computed for the previous model ($Q_0 \approx 39600$). The possibility of varying the coupling loop length, including the main coupler frequency response in the model analysis is a HFSS feature.

As a final test on the cavity fundamental mode, a cylindrical tuning plunger of 143 mm diameter and 45 mm length has been incorporated to the model, opposite to the main coupler. The cavity resonant frequency increases by 1.6 MHz,; the result is in good agreement with the cavity prototype measurements.

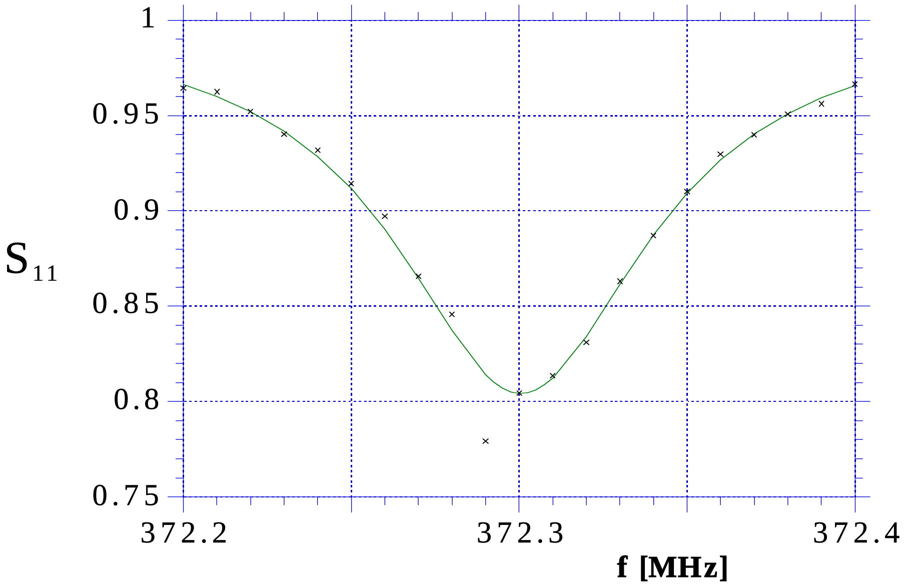

Fig. 3: Reflection Response of the Accelerating Mode with FM Coupler

In conclusion, the HFSS analysis of the DAΦNE cavity accelerating mode has substantially confirmed the results that we already got from other codes and prototype measurements, and has given us the possibility to tune the coupling loop length in order to set the desired coupling between cavity and power source. Moreover, HFSS can also evaluate the frequency shift due to the tuning plunger penetration. The time required to carry out the accelerating mode analysis with HFSS is however much longer than that needed by the other mentioned codes.

3) The High Order Modes

Three monopole HOMs (0MM1, 0EM2, 0MM2) have been analyzed for the unloaded (Fig. 1a) and loaded (Fig. 1b) models, and the results, together with those of OSCAR2D and prototype measurements, are shown in Table II. We want to point out that none of the standard codes can directly calculate the HOM damping once the waveguides are applied to the cavity main body. So far, this kind of information could be obtained only by means of numerical or semi-analytical methods based on postprocessing the code outputs [3,7,8,9]. On the contrary, HFSS can solve directly the problem of the loaded cavity; furthermore, the presence of strongly coupled ports in the model (the damping waveguides) produces smooth and easily readable frequency response curves (see Fig. 3).

A comparison between the loaded cavity HFSS results and those obtained by a semi-analytical method applied on the OSCAR2D output[3,9] is also included in Table II.

		Unperturbed Cell			Cell + 3 BTHDs		
		OSCAR-2D	HFSS	Prototype Measure-ments	Semi-analytical Method	HFSS	Prototype Measure-ments
0MM1	f [MHz]	700.63	703.3	747.5	—	704	745.7
	Q	52491	54336	24000	75	28	70
	R/Q[Ω]	16.18	16,02	16	—	16.24	—
0EM2	f [MHz]	814.76	817.5	796.8	—	818.24	796.5
	Q	92009	89780	40000	550	1136	230
	R/Q[Ω]	$2.9 \cdot 10^{-6}$	0.1195	0.5	—	0.1784	—
0MM2	f [MHz]	996.45	998.27	1023.6	—	1001	1024.9
	Q	73158	70384	28000	190	59	150
	R/Q[Ω]	$4.7 \cdot 10^{-3}$	0.0198	0.9	—	0.057	—

Tab.2: High Order Modes.

3.1 The first longitudinal High Order Mode (0MM1)

Due to its high impedance, 0MM1 is the most dangerous HOM for the beam longitudinal dynamics and therefore it must be heavily damped. As for the accelerating mode, the unloaded 0MM1 basic parameters (f_r, Q_0, R/Q) computed by HFSS and those computed by the other codes are in good agreement.

Because of the strong waveguide damping, the 0MM1 frequency response for the loaded cavity is not a pure resonance anymore, as shown in Fig. 4. Thus, the loaded quality factor cannot be deduced from the mode bandwidth but must be computed accordingly to the definition:

$$\frac{1}{Q_L} = \frac{P_{Cav} + P_{Wg}}{\omega_r U} = \frac{1}{Q_0} + \frac{P_{Wg}}{\omega_r U}$$

where ω_r is the mode angular frequency, U is the energy stored in the mode, P_{Cav} is the power loss on the cavity walls and P_{Wg} is the power flowing through the waveguides.

The 0MM1 loaded quality factor given by HFSS for the model of Fig. 1b is $Q_L \approx 30$. The values measured on the prototype and computed with the semi-analytical method are higher (i.e. $Q_L \approx 70$ and 75 respectively). This might be due to the different position of the waveguide slots that has been optimized in the HFSS cavity model. The 0MM1 R/Q is about 16 Ω for both loaded and unloaded models and therefore the shunt impedance is reduced by a factor 1900 to 450 Ω.

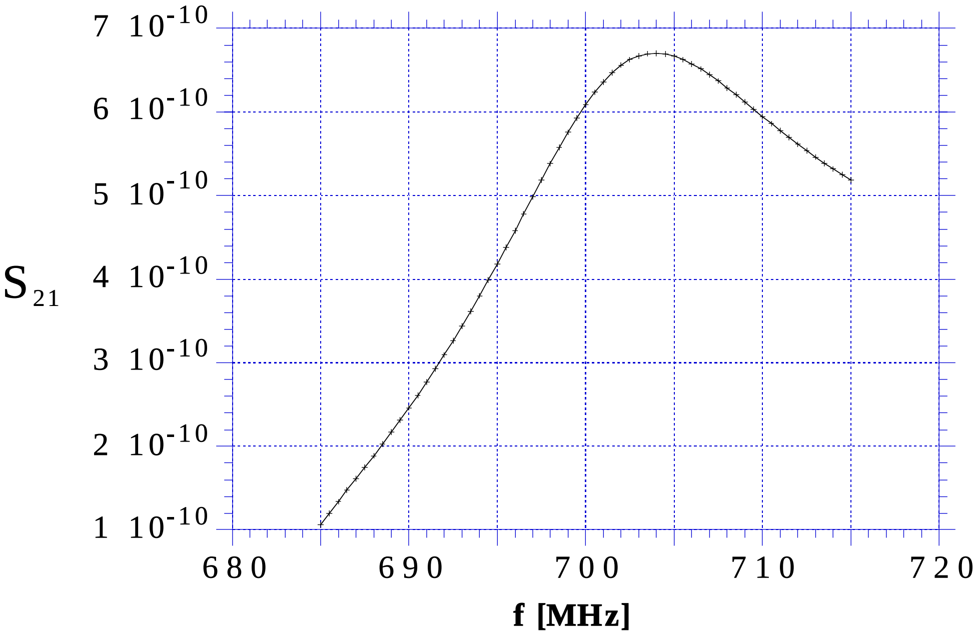

Fig. 4: Transmission Response of the Loaded Cavity
0MM1 Mode

3.2 The High Order Modes 0EM2 and 0MM2.

The HOMs 0EM2 and 0MM2 have a quite low impedance and should not affect very much the longitudinal beam dynamics. Nevertheless the HFSS analysis of these two modes has been carried out to test the code features further. The unloaded cavity simulations made with HFSS and OSCAR2D are in very good agreement for the mode 0MM2 and are acceptable for the mode 0EM2. The Q value computed by OSCAR2D in this last case ($Q_0 \approx 92000$) seems somewhat unrealistic and the R/Q is so low that the contribution of the numeric noise to the E-field integral is relevant.

The loaded cavity Q values for the two last modes computed by HFSS, measured on the prototype and estimated with the postprocessing method do not perfectly agree, although they are of the same order of magnitude. The small variation in the slot position between the prototype and the final model of Fig. 1b can partially explain this difference. In any case, the various results are all compatible with the damping requirements of the DAΦNE beam dynamics[3]. The accuracy of the HFSS results for this two last modes will be definitely checked with the final cavity measurements.

CONCLUSIONS

The High Frequency Structure Simulator is a powerful tool for cavity and other RF devices design, although the user needs to gain experience to get meaningful results. Since the HFSS complete mode analysis of a resonant structure is very time consuming, a pre-analysis based on other simpler and faster codes is required. On the other hand, once the mode resonant frequencies are approximately known, the study of the fundamental mode coupler and the HOM damping is straightforward. Simulations carried out on a model of the DAΦNE main ring cavity confirmed the information that we already got from other codes and measurements on a low quality prototype. Moreover, by means of HFSS we had the possibility of tuning the design length of the coupling loop in order to have a maximum coupling coefficient $\beta \approx 9$ between the cavity accelerating mode and the power source.

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