PRECISE 3D GEOMETRICAL CONTROL OF 700 MHZ SC ELLIPTICAL CAVITIES: RF MEASUREMENTS VS THEORETICAL SIMULATIONS

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Abstract

Within the framework of the INFN (Istituto Nazionale di Fisica Nucleare) – CEA (Commissariat à l'Energie Atomique) – CNRS (Centre National de la Recherche Scientifique) collaboration on high power proton accelerators [1], important efforts were made to optimize the design (and also the chemical preparation) of medium-beta elliptical cavities (i.e. 700 MHz, β=0.47 & β=0.65). Despite the excellent results obtained on RF performances (Eacc of about 25 MV/m for both β=0.65 monocell prototype cavities A102 [2] and A105 [3]), some discrepancies were observed between the fundamental mode computed and measured frequencies.

We performed precise 3D geometrical measurements on a couple of cavities in order to explain these discrepancies. The experimental procedure is described and the corresponding data are analysed then compared to 2D & 3D simulations with URMEL and MAFIA codes leading to a good agreement if one considers the real cavity internal shape instead of the design one.

1 INTRODUCTION

The starting point of this study was the RF measurements at room temperature of the fundamental mode on both β=0.65 Saclay-cavities (referred here after as A101 & A102), and on the first β=0.47 Milan-cavity (referred here after as Z101). These results have revealed important differences of several MHz between experimental and computed frequencies [4] as it is detailed in Table 1. Note that the computed frequencies f_c were obtained using the design shape of the corresponding cavity. Moreover, additional measurements of first monopole and dipole modes showed differences of up to several tenths of MHz which may lead to problems from the HOM point of view [5].

Table 1: Differences between the measured and the computed frequencies (with SUPERFISH & URMEL)

Cavity	Measured frequency f_m (MHz)	Calculated frequency f_c(MHz)	Frequency difference f_c-f_m (MHz)
A101	698.5	704.6	6.1
A102	700.3	704.2	3.9
Z101	690.6	699.5	8.6

Taking into account the high sensitivity of these cavities to small deformations (e.g. $\Delta f/\Delta r$=4 MHz/mm and $\Delta f/\Delta z$=3.3 MHz/mm for the A101 equatorial area [6]), it appeared that the observed frequency differences could be attributed to geometrical defects such as misalignment of the beam tubes or the half-cells, bad iris or equatorial welding ... Consequently, the main goal was to find the real internal shape of each cavity in order to perform new 2D simulations with URMEL in a first time and, if it was possible, 3D simulations with MAFIA [7].

We scheduled our study as follows: 1) measurement of the external shape of each cavity, 2) measurement of their thickness, 3) calculation of the internal shape, 4) numerical simulations and 5) analysis of the results.

2 GEOMETRICAL CONTROLS

2.1 External profiles measurements

Geometrical measurements have been done at LAL with a 3D Mitutoyo Euro-C9106 machine (see Fig. 1) on A101, A102 and Z101 cavities. But, the complete study including simulations with URMEL was only performed on the A101 and Z101 cavities. The data-acquisition process of the coordinates of each profile was fully controlled by computer.

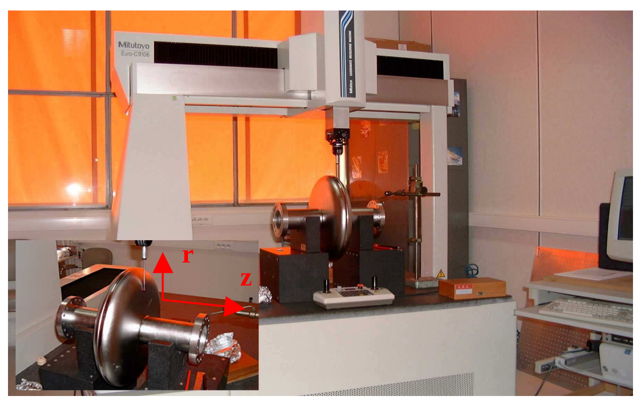

Figure 1: 3D machine & a cavity profile being measured

Each cavity has been divided into 18 azimuthal profiles (i.e. every 20°) along z axis (see zoom in Fig. 1) taking the first one measured as a reference. At the end of the process, direct comparisons between the resulting 17 profiles with the reference one were performed. It gave us an overall about the cavity profile shape deformations from design value (see Fig. 2) as well as the minimum and maximum deviations (deviations higher than ± 1 mm are notified in red in Fig. 2). These preliminary data allowed us to notice a misalignment of the half-cells from 1 to more than 2 mm on a quarter of the A101 and A102 monocell prototypes, both fabricated by CERCA [8]. At the opposite, the Z101 cavity, fabricated by ZANON [9],

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did not show such large deviations. Concerning the measurements, as the cavity was rotated by hand, the origin has been recalculated every time before performing each profile measurement in order to have the same reference for the 18 profiles.

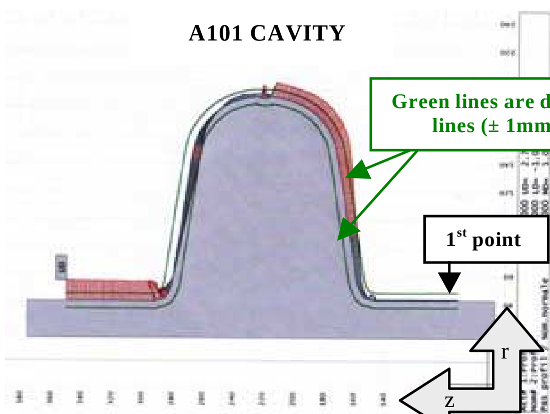

Figure 2: A101 cavity profile n°15 compared with the reference one.

We have measured one point every 0.5 mm with an accuracy of ± 3 µm for the coordinates. Each profile was constituted of about 1000 points. All coordinates were saved into DXF files.

At this point of the study, we had the external shape of the cavities. The next step was to measure the thickness of the cavity along these measured profiles in order to deduce the internal coordinates.

2.2 Thickness measurements

To perform these measurements, we have used an handily ultrasonic apparatus which accuracy was ± 0.01 mm. Instead of measuring the thickness along the 18 profiles of the A101 and Z101 cavities, we made it, respectively on 6 and 9 profiles. We measured only one point every 2 cm: the step was limited to this value due to the width of the probe. Note that the data was taken at the same abscissa on each profile in order to calculate an average thickness for each cavity (see Fig. 3).

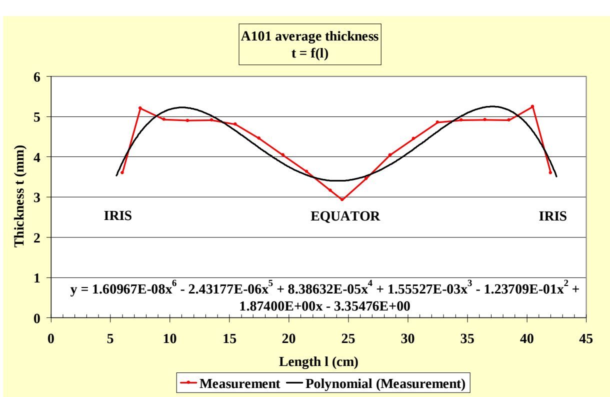

Figure 3: The average thickness (red curve) of the A101 cavity from iris to iris and the associated polynomial function (black curve).

Such data curve with about thirty points could not be directly used to recalculate the internal coordinates. Consequently we used the best polynomial function to fit experimental data. Polynomial functions of 6th degree have been used. A test has been done with polynomial functions of higher degrees but finally, it brought no important improvements for the simulations.

As a conclusion, these are the main points that we could have noticed:

For the A101 cavity

- The thickness of the beam tubes was very constant, about 3.6 mm. Mean value of the difference between the average thickness of both beam tubes (i.e. less than 1 µm) was lower than the accuracy of the measurements.
- The thickness of the half-cells was rather similar as shown by the symmetry of the curve in Fig.3, but it presented important variations from 5.2 mm near iris to 2.9 mm at the equator.

For the Z101 cavity

- There was a more noticeable difference between the average thicknesses of both beam tubes (mean value of about 0.07 mm).
- The thickness of the half-cells was more constant as compared to the A101, between 3.5 and 3.65 mm.

About this last point, significative difference can be explained by the two different techniques of production used: deep-drawing for the Z101 & spinning for the A101.

2.3 Internal profiles calculation

We calculated the coordinates of the 18 internal profiles of both cavities by subtracting their average thickness from each external profile. To do this, we used simple trigonometric relations. An example of the corresponding result is illustrated in Fig. 4.

Difficulties came from the iris and equatorial areas because of the irregular shape of the weldings.

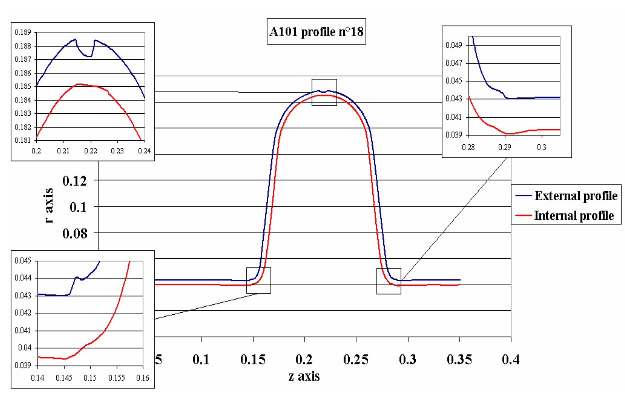

Figure 4: A101 internal (red curve) and external (blue curve) profiles n°18.

3 2D & 3D SIMULATION

3.1 Simulation with URMEL in 2D

As we measured the first monopole and dipole modes frequencies of each cavity, we had to use URMEL software instead of SUPERFISH to compare them with the computed frequencies (SUPERFISH does not allow dipole modes calculations). We performed 18 numerical runs per cavity with, respectively, their 18 internal profiles. Due to the limited number of mesh points available (i.e. 150000), we used only 1 coordinate over 3 of the internal profiles in the input data files.

At the end, we calculated the average of the 18 frequencies of each mode ($<f_{mode}>$). The standard deviation σ gave us the minimum ($Fmin=<f_{mode}>-\sigma$) and the maximum ($Fmax=<f_{mode}>+\sigma$) values of the frequencies (see Table 2).

Table 2: Results of the simulation (in red) compared with the theoretical frequencies (in italic) and the measured ones.

Cavity A101		Monopole modes (MHz)					Dipole modes (MHz)					
Initial design		*704.2*	*1520*	*1822*	*2320*	*2328*	*1035*	*1408*	*1827*	*1940*	*2085*	*2184*
RF measurements		698.5	1516	1810	2310	2318	1031	1409	1826	1920	2069	2177
Geometric	Fmin	696.2	1515	1808	2297	2313	1026	1406	1822	1917	2065	2169
	Fmax	699.5	1523	1814	2306	2328	1032	1417	1835	1927	2074	2201

Cavity Z101		Monopole modes (MHz)					Dipole modes (MHz)					
Initial design		*699.2*	*1526*	*2265*	*2331*		*1029*	*1707*	*1827*	*2276*	*2283*	*2414*
Measurements		690.6	1522	2217	2328		NO	1711	1819	2230	2245	2334
Geometric	Fmin	687.7	1516	2206	2318		1023	1709	1813	2224	2255	2350
	Fmax	691.4	1521	2225	2326		1026	1717	1819	2242	2274	2370

As illustrated in Table 2, the results of the simulations are in good agreement with the measurements data.
Detailed information has to be mentioned concerning these results. The Z101 cavity results are not as accurate as those obtained with the A101 cavity.

These differences have certainly two origins: a) the polynomial function used to fit the data of the average thickness, b) the number of mesh points. Indeed, despite that the average thickness profile shows lower variations, it is more irregular than for the A101 cavity. Consequently, the fitting curve was not as precise as that presented in Figure 3. Secondly, we had to adjust (i.e. to decrease) the number of mesh points in z direction for several profiles because of problems during mesh generation. Actually, the mesh size on r axis Δr was quite the same for both cavities (i.e. Z101: Δr=1.40 mm & A101: Δr=1.33 mm) but in z direction, the mesh size Δz used was different (i.e. Z101: Δz ~2 mm & A101: Δz=0.45 mm). These differences could explain the standard deviation values obtained (especially for the last dipole modes): there are two times higher than A101 cavity simulation.

3.2 3D SIMULATION

To confirm the results obtained with URMEL, we tried to perform the simulation directly with the 3D internal shape of the cavities using MAFIA. As a test-run, we computed the eingenvalues only for the A101 cavity. The internal surface has been imported into MAFIA using CAD software Pro/engineer [10].

For that purpose, the cavity has been cut into 16 sections at fixed abscissa on z axis. Each section was of course composed of the 18 associated internal coordinates. A smoothing function was used to generate the surface between each section. An external surface was automatically generated in parallel with the internal one in order to model the cavity as a solid in MAFIA. Thus, once it was done, the cavity has been imported into MAFIA using the STL file type (see Fig. 5).

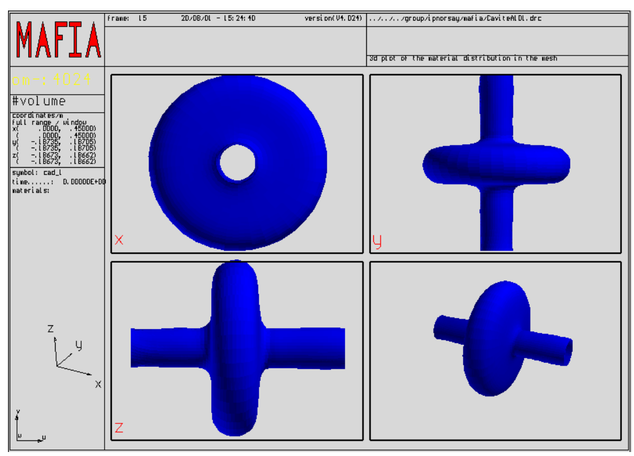

Figure 5: 3D plots of the cavity

However, a problem appeared during the importation of the STL file (problem which is not yet solved). Indeed, it was impossible to model the cavity as a solid piece. Hence, we imported it using the sheets option (i.e. the cavity is identified as composed of two infinite thin layers, see Fig.6).

This modeling definition caused problems to perform the eigenmodes calculation because solver calculated all modes (monopoles, dipoles …) inside and outside the cavity. Problems occurred within the mesh solver too. We were limited to use 1 millions of mesh points at most to compute the fundamental mode. The corresponding mesh size was large (about 4 mm). However this coarse mesh led to a preliminary value of the fundamental mode frequency: 689.5 MHz.

Work is going on to solve these problems and we hope to present new results in the near future.

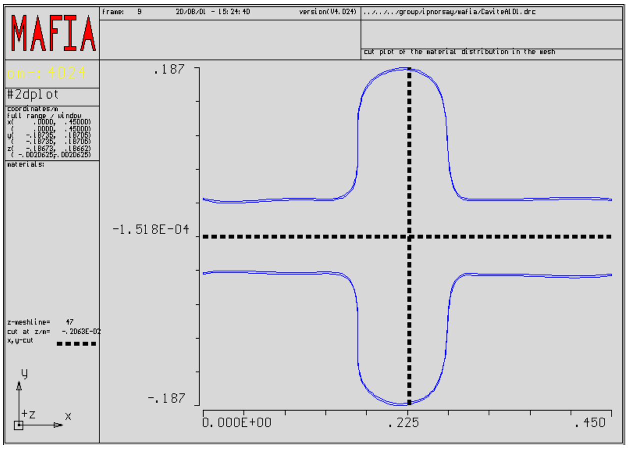

Figure 6: 2D plot of the cavity (normal to z axis)

4 CONCLUSION

The geometrical profile measurements using a 3D machine and an ultrasonic probe allowed us to get a precise description of the real internal shape of two 700 MHz prototype monocell cavities. It is a powerful technique to detect and characterize the geometrical defects due to cavity fabrication process especially to show up misalignments. Moreover, an intermediate 3D control could also be performed before fabrication of cavities in order to check precisely geometrical deviations between the half-cells and the dies (for instance for deep drawing technique) [11]. Finally, we plan to perform such measurements on the next cavity to be built jointly by the CEA and the IPN (i.e. a 700 MHz, β=0.65, 5-cells cavity).

In general, it might be stressed that our device is easier to set up as compared to the apparatus used at DESY for TESLA cavities [12].

Regarding the thickness measurements, improvements may be done on a few points to refine the results of the simulation: a more precise ultrasonic apparatus, use of spline functions instead of polynomial ones for a better fit, calculation of the internal coordinates of each profile using their individual thickness and not an average for every single one.

5 ACKNOWLEDGMENTS

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