COUPLING SLOTS MEASUREMENTS AGAINST SIMULATION FOR TRISPAL ACCELERATING CAVITIES

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Abstract

At the LINAC96 conference, we presented a new coupling scheme for the Trispal CCL accelerating cavities: the “4-petal” slots [1]. It resulted from a MAFIA optimization in which we tried to maximize the shunt impedance. Since that time, we designed and built a mock-up for an accurate measurement of the Q-drop. Indeed, we achieved a good accuracy and reliability in Q-drop measurements, but the value was rather disappointing: -22.5% (+/-0.5), instead of 5% as predicted. As a consequence, the “4-petal” coupling scheme was abandoned, and we learned that local power losses computed by cavity simulation codes can be widely underestimated. Further simulation showed that improving the mesh resolution could give better results though we felt that only a more subtle meshing method (like triangular cells or partially filled cells) could lead to realistic values.

1 INTRODUCTION

The TRISPAL linac [2] will deliver a 40 mA CW beam of 600 MeV protons. Above 100 MeV, it will be made of 352-MHz π-mode coupled cavities. Their coupling slots had been optimized with MAFIA in a way to minimize the shunt impedance drop that they induce [1]. Starting from a "2-bean" configuration of slots inspired by LEP cavities [3], the optimization resulted in a new "4-petal" scheme, for which MAFIA predicted a -6 % Q-drop (about half that of the "2-bean" slots), with the same coupling coefficient. Moreover, this Q-drop was found to be approximately canceled by an improvement of R/Q, resulting in a quasi-negligible loss in shunt impedance.

These characteristics were weakly dependent on the resolution, and variations versus various geometrical parameters were rather coherent. For verification, the optimized geometry was also computed by other codes: Soprano [4] and Antigone [5]. Roughly, all the codes agreed about coupling factor and R/Q improvement. The Q-drop values were rather close too, except for the one computed with Antigone-H (-17 %) which seemed very pessimistic.

To settle the point of the Q-drop, a 1/3 scale aluminum alloy cold model has been build (fig. 1). The central part, which contains the coupling slots, can be removed for single-cell measurements. A major issue is to get a reliable Q value in spite of successive assembling and dismantling. The electrical seal is made of a 0.8-mm solder wire squeezed to 0.4 mm with a mechanical limitation that makes the contact quality independent of the tightening strength.

Coupling antennas were made of N connectors screwed outside each end plate (fig. 2) and did not need to be dismantled at changes of configuration (single or double-cell). The central stem of the connector was extended somewhat toward the cavity to make an on-axis electrical antenna, but the coupling remained low enough (<-25 dB) to neglect the external Q.

Fig. 1. The 2-cell cold model

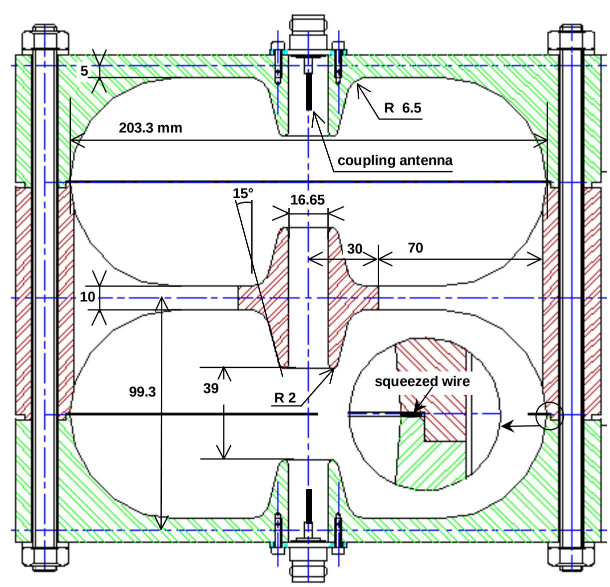


Fig. 2. Longitudinal section (transverse view on fig.4)

2 MEASUREMENTS VS. SIMULATIONS

In the MAFIA computation of the cold model, no symmetry is assumed in the center of the cell. So it represents a true double cell cavity, rather than infinitely long structure. We computed the coupling coefficient γ and the slot frequency drift α with the following formulas:

$$\gamma = 2\frac{f_0 - f_\pi}{f} \quad , \quad \alpha = 2\frac{f_1 - f_0}{f},$$

in which f is the goal frequency (3×352 MHz). Indices π, 0 and 1 indicate the pi-mode, 0-mode and single cell cavity mode (i.e., a cell without any coupling slots), respectively. The factor two is to extrapolate the data to the case of an infinitely long structure with coupling slots on both sides of the cell as computed in [1]. The mesh used was exactly the same for the three modes, but in the case of a single-cell cavity, slots were filled with metal instead of vacuum. We used about 60000 points for a quarter of a cell, resulting in a 2.5 mm resolution in the vicinity of the slots.

Table 1 shows a +8 MHz systematic frequency error in simulation versus the cold-model that probably results from gap length and nose shape changes due to discretization. But this bias is constant, and should not alter relative differences. Indeed, α and γ computed values are close to the measured ones: the agreement is pretty good, from the coupling-factor and slot-frequency-drift points of view.

Table 1. Frequency and quality factor (4-petal).

	MAFIA	cold model
pi-mode (MHz)	1073.912	1064.415
zero-mode (MHz)	1081.556	1072.412
single-cell (MHz)	1088.948	1080.841
coupling γ (%)	1.45 (1.40*)	1.51
fq. drift α (%)	1.40 (1.42*)	1.60
Q pi-mode	11924	11340
Q zero-mode	12922	12938
Q single-cell	12236	12880
δQ_π (%)	-5.0 (-5.9*) (-16.9**)	-22.5
δQ_0 (%)	+11.5 (+11.3*) (+4.7**)	+0.9

(*MAFIA and **Antigone-H simulations in [1])

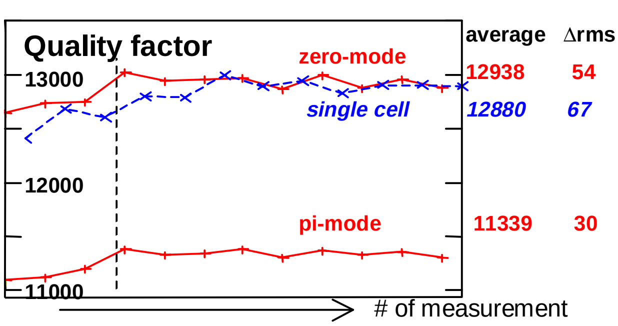


Fig. 3. Statistical variation of the measured Q.

The resistivity of the alloy (Al: 96%, Cu: 4%) was 51 nΩ.m, and the measured single-cell cavity Q was 12880, slightly above the computed value (12236). But, because of surface imperfection and seal losses, we should expect the measured Q to be 10% to 15% lower. We conclude that the MAFIA Q-value is probably underestimated, an effect that had already been established [1]. Anyway, as this bias is rather small and should be identical for the three modes computed here, the relative differences should not be significantly altered.

To estimate the quality factor reliability, we made a series of measurements alternating both configurations (single or double-cell) and changing the seal each time. The gradual Q improvement in the left-hand part of the curves (fig. 3) shows the improvement of the operator's skillfulness during the first measurements. Disregarding the first three points in each curve, the statistical variation on the measured Q is about 0.4 % r.m.s.. The accuracy on the mean value is then 0.15 %, leading to a 0.5 % absolute accuracy on δQ (see definition below).

Table 1 also gives measured quality factors against predicted ones. Here, relative variations versus single-cell mode (δQ) have been doubled by squaring the ratios to represent the case of an infinitely long structure with coupling slots at both sides of each cell:

$$\delta Q_\pi = \left(\frac{Q_\pi}{Q_1}\right)^2 - 1 \qquad \delta Q_0 = \left(\frac{Q_0}{Q_1}\right)^2 - 1.$$

We can see that MAFIA prediction of δQ_π is widely underestimated: -5 % instead of -22.5 %. Furthermore, we measured a very small δQ_0: +0.9 %, instead of +11.5 % as predicted. Other codes used in [1] gave results close to MAFIA ones, except for Antigone-H. This code predicts δQ values closer to measurements but still not very satisfactory.

3 BACK TO "2-BEAN" SLOTS

Previous measurements showed that the 4-petal slots did not yield the performance we expected from them. So, we built a new central-part for the cold model, with two classical bean-shaped slots. A single measurement (i.e., no statistics) in each configuration was performed this time. According to measured results (fig.4), the 2-bean slots are definitely preferable to 4-petal ones.

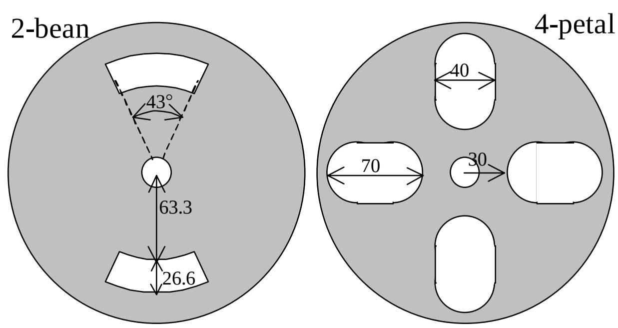
Unfortunately, we did not have time and material to make R/Q measurements with the bead-pull technique. Anyway, even if MAFIA predictions were right (the pi-mode R/Q variation versus single-cell is +5.2 % for 4-petal, and -0.2 % for 2-bean), the net result in shunt impedance would still be in favor of conventional slots.

For 2-bean slots, the simulated frequency is also 8MHz higher than measured, and a rather good agreement is obtained for relative frequency differences (table 2). The slot frequency drift α is pretty well predicted. The actual coupling factor is a little bit smaller than computed (1.27 % instead of 1.51 %). Perhaps the actual 5 mm radius due to the machining method, instead of right angles (at the slot corners), explains a part of this discrepancy. For linac designing, such a discrepancy is non-negligible and the slot width should be slightly increased in order to reach the desired 1.4 % coupling factor.

About Q-variations, this time the agreement between measurement and simulation is not bad. Apparently, losses are inaccurate in the case of composite coupling (like 4-petal), and not in case of pure magnetic coupling (like 2-bean), but we have no explanation. This is a possible track for further investigations.

Table 2. The 2-bean coupling.

	cold model	MAFIA
pi-mode (MHz)	1069.976	1076.629
zero-mode (MHz)	1076.702	1084.604
single-cell (MHz)	1080.922	1088.554
coupling γ (%)	1.27	1.51
fq. drift α (%)	0.80	0.75
Q pi-mode	12083	13269
Q zero-mode	12959	14118
Q single-cell	12825	13928
δQ_π (%)	-9.2	-11.3
δQ_0 (%)	+2.8	+2.1



1.27%	coupling	1.51%
-9.2%	Q-drop	-22.5%

Fig.4. “2-bean” vs. “4-petal” slots (actual performances).

4 CONCLUSIONS

About the cold model: we managed to get a reliable quality factor in a cold model cavity, despite successive assembling and dismantling. Thus, we can estimate the percentage Q-drop induced by the coupling slots in an infinitely long structure, with an accuracy of $\pm$ 0.5. This accurate experimental data can be a benchmark for future codes.

About simulation: cavity code accuracy has been widely discussed until today (see, for example [6]). But most of the time, only the frequency or the on-axis field has been taken care of. The present study gives accurate experimental data involving the quality factor. We conclude that, at the present time, 3D codes tested here are not suitable for minimizing cavity losses.

In a closed vacuum-filled cavity, the quality factor is the ratio between two integrals: a volume integral (field energy) and a surface integral (losses). The first integral should be good, because if there were a bias in the whole volume, the resonant frequencies could not be predicted accurately. Thus, we probably should suspect the surface losses to be inaccurate. For a given field in the center of the cell, losses should be identical between a single-cell cavity and a multi-cell one, as long as walls are identical. Thus, only small areas in which surface currents are deviated by coupling slots (i.e., nearby the slot edges) should yield different losses. The discrepancy between computed and measured Q-drop is rather important though only small areas of the cavity walls may cause this difference. So, we suspect the local power dissipation to be very inaccurately computed in some cases, particularly in areas where the fields are strongly non-uniform.

Further analyses have been carried out at CST to explain the discrepancy between MAFIA results and measured ones. It appeared that the computed Q-drop would depend on the resolution, and be a little closer to experimental values with a much larger number of points. Anyway, no clear convergence was found, and the conclusion was that one should not try to get this kind of information from MAFIA at the present time. The future “Partially Filled Cells” algorithm, should lead to more accurate Q-drop values.

About Trispal: the 4-petal coupling slots must be abandoned. As we have no reliable way to optimize the slots, we will use the more classic 2-bean ones, which have proved to be not so bad.

Right now, we should take a great care when designing cooling circuits. If possible hot spots are suspected, a more important margin should be used. This remark is also valid for the Trispal RFQ design.

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