RESULTS FROM THE ROOM TEMPERATURE MODEL OF THE LADDER RESONATOR, A VERY LOW BETA CAVITY FOR HIGH CURRENT PROTON LINACS

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Abstract

The 4-gap full Nb Ladder resonator is designed for the 0.1 ÷ 0.2 beta range of high current linacs. The rf design and beam dynamics studies were presented in [1]. A thorough mechanical analysis has been completed. An Al model has been built to check rough tuning sensitivity, mechanical precison tolerances with respect to mode mixing and field flatness along the 4 gaps, reliability of the mechanical vibration studies. Results are given in the paper.

INTRODUCTION

The 4-gap Ladder resonator has been proposed [1] for the very low beta section (β=0.1÷0.2) of high current proton linacs in a variety of applications: production of exotic ion beams, transmutation of nuclear wastes, spallation neutron sources, neutrino factories, and technological neutron irradiation tools.

As a case study, the first section of the EURISOL [2] driver (CW, 5 mA) was considered. Eurisol is a being designed European facility for the production and reacceleration of exotic nuclear species. A total of twelve Ladder resonators (β_{opt} = 0.12 and β_{opt} = 0.17) cover the energy range from 5 to 20 MeV, immediately following the RFQ. The beam dynamics simulations are reported in Ref.1 in detail.

Fig.1 is a photo of the aluminum model of the β=0.12 structure, to which the present paper refers to. Parallel stems allow to obtain a flat profile of the accelerated field on the beam axis in a very short space (the cavity inner length is only 196 mm), thereby providing a very high real estate gradient in the initial part of the superconducting (SC) linac. A 1.2% coupling is given by two holes ($Ø_{in}$ = 70 mm) in the central stem, where the peak magnetic field $B_{s,p}$ is then located. Taking $B_{s,p}$ = 0.065 T as a practical limit, the peak electric field $E_{s,p}$ = 20 MV/m is not critical and provides an accelerating field E_a=5.8 MV/m.

Before building the Nb prototype, a thorough mechanical FEM analysis of the resonator was made. Through a dynamic analysis we designed a stiffening jacket to push the vibration eigen-modes to high frequencies. Through a static analysis we reduced the mechanical deformations under changes of the liquid He bath pressures.

Then we built a full scale Al model to check the following:

- To estimate the error of the mechanical dynamic analysis mentioned above;
- To investigate the methods of frequency rough tuning (changing cavity height and length), with an eye at field flatness and frequency distance of the higher modes;
- To set the tolerances in the mechanical construction of the Nb prototype, with respect to changes of fundamental frequency, mode separation and field flatness.

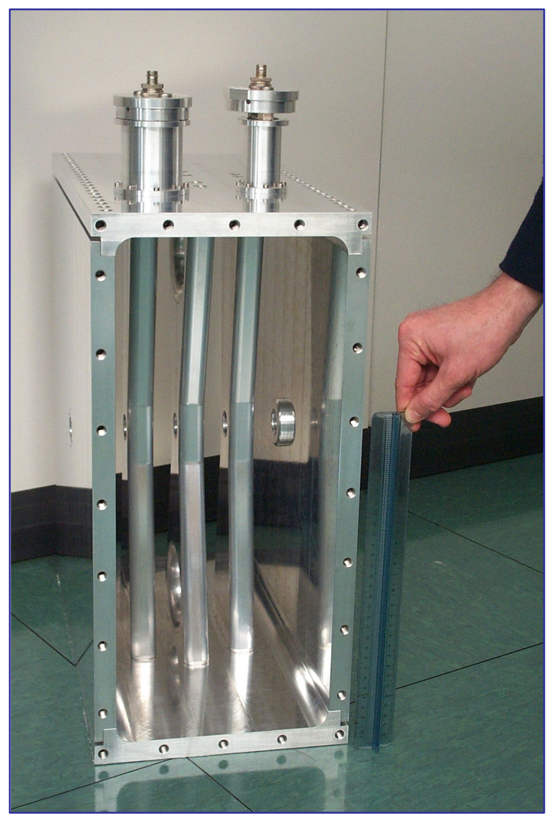

Figure 1: Photo of the aluminium model of the β=0.12 Ladder resonator

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MECHANICAL ANALYSIS

Dynamic and static mechanical analysis were made, by the finite element method, with the code Ansys 6.1. The dynamic analysis aimed at reducing the effect of environmental microphonic noise, by pushing the lowest eigenmodes beyond 200 Hz at least. The static analysis aimed at verifying the material resistance under the following conditions: He bath pressure, cooldown process, force exerted by the slow tuners.

The Slow Tuners

Concerning the latter, the following slow tuning method is proposed: to push and pull the central thin part of both end plates.

The mechanical tuning displacement can be as large as ±0.5 mm at T=4 K. The yield stress of Nb (44 MPa at 293 K) limits in principle this excursion up to ±0.15 mm at room temperature: however, a few hundred full tuner cycles up to ±0.5 mm are allowed at room temperature too (which is far more than needed by the typical resonator operation during its lifetime), before fatigue alters the mechanical properties of Nb significantly.

Dynamic Analysis

The high density and the low Young modulus of Nb, together with the limited thickness (3 mm) of the walls, impose a purposely designed stiffening structure in order to reach high modal frequencies. Both the end plates and the stem bases had to be reinforced with a stiffening jacket made out of a set of Ti/Nb ribs (height = 25÷32 mm and width = 7÷8 mm).

The simulation results are shown in figure 2, as far as the lowest modes are concerned.

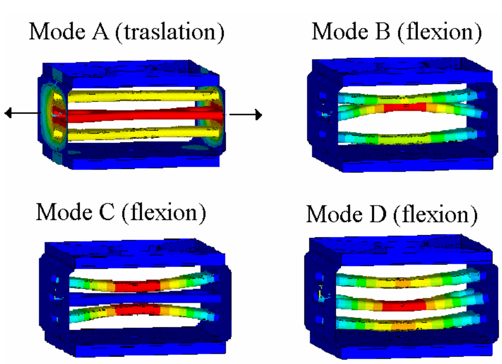

Figure 2: Patterns of the lowest mechanical modes as calculated by ANSYS 6.1 (mode A=429 Hz, mode B=328 Hz, mode C=332 Hz, mode D=343 Hz)

The finite element analysis was remade for the Al model (shown in figure 3), to be able to compare the frequencies generated by the codes with the modes detected, through a few accelerometers, in the laboratory.

The measured values were lower by ~ 13% with respect to the calculated values: this result should be considered when assessing the calculated values of figure 2.

Static Analysis Under He Bath Pressure

Concerning the static response, the numerous flat surfaces tend to be clearly sensitive to the operating value of the liquid He bath pressure (1.2 bar) and to its fluctuations

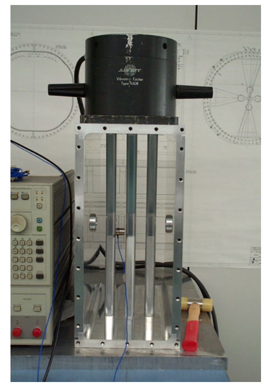

Figure 3: Experimental tests with accelerometers on the Al Model: the modes are excited by a sweepable shaker.

(±50 mbar is assumed here). It was necessary to add a few stiffening bars (in particular on the end plates, see figure 4) and to insert internal pins in the flat regions of the first and third stems, so as to limit the maximum bumps to values comprised between 21 and 85 µm (at ΔP=1.2 bar), depending on the resonator region considered.

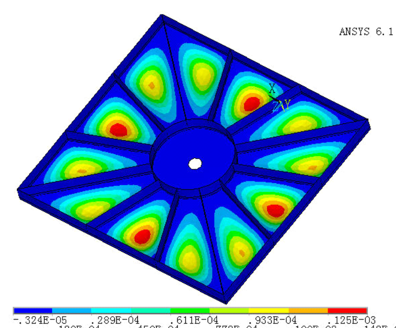

Figure 4: Pattern of the static deformation at the end plates, caused by the liquid He bath pressure. The central region (used for the fine tuner) is cooled by thermal conduction.

Taking into account the distribution and size of the bumps (placed both in regions where they locally increase the capacitance or decrease the inductance), it was analytically estimated that an overall frequency increase of ~ 15 [kHz] has to be expected, when pressurizing the liquid He reservoir at Pa = 1.2 bar, with respect to the resonator vacuum. This effect should be negligible. The obvious hypothesis of a linear response of the material with so small deformations allows to translate these values into deformation changes in operation, where the pressure is assumed to vary within 0.05 bar: the bump will change, for instance, by ± 3.6 µm at the end-plates, where it is largest. Correspondingly, the frequency sensitivity of the resonator to He bath pressure variations was estimated to be ~ 15 Hz/mbar, which is not totally negligible but can be controlled (Legnaro's SRFQs have a sensitivity of ~ 40 Hz/mbar).

Under the hardest conceived loads (i.e. maximum force on the slow tuners, 2 bar He bath pressure, 300 K thermal jump), the maximum Von Mises stress is equal to 243 MPa. This value is acceptable since the yield stress of Nb at 4 K is 444 MPa.

RF TESTS ON THE ALUMINUM MODEL

One goal of the bead pulling campaign (and associated simulations) was to meet the resonant frequency of 352 MHz within the expected range of the slow tuner (around ±500 kHz, by pushing/pulling the central part of both end-plates by ±0.5 mm). Another goal was not to exceed a deviation from full field flatness larger than ± 5 % along the four gaps: this specification was calculated to be perfectly acceptable for the beam dynamics of the linac, as far as transit time factor curve of the six β=0.12 resonators is concerned.

The simulations reported in [1] were made with the code M.A.F.I.A. [3]. For practical reasons, the use of the code HFSS [4] was later found more convenient, when comparing results and simulations on the Al model. For the sake of comparison, the same geometry was initially given as an input to the two codes and the results of the simulations compared. The agreement was judged to be very satisfactory: fig. 5 shows, as an example, the comparison of the first three eigen-modes as calculated by MAFIA and HFSS, where the corresponding experimental results are also shown.

From there onwards, comparison was made only between experimental results and HFSS.

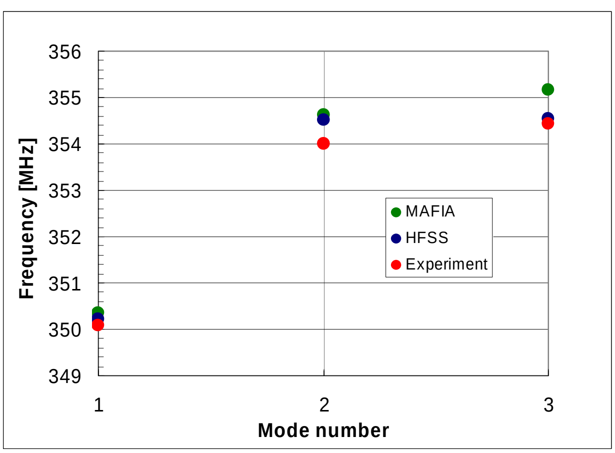

Figure 5: The first three eigen-modes of the ladder cavity, as measured experimentally and calculated by M.A.F.I.A. and HFSS.

Frequency Tuning by Varying the Cavity Height

Frequency tuning by stepwise reducing the stem length is shown in fig.6. The result is -650 kHz/mm, with excellent agreement between calculations and results.

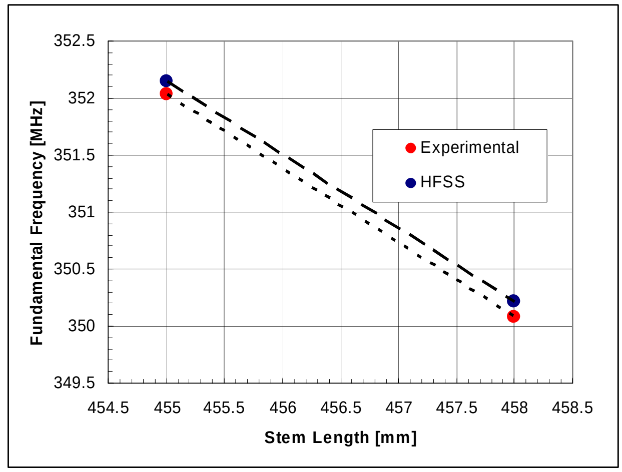

Figure 6: Result of rough frequency tuning by reducing the stem length (and cavity height).

Construction Tolerances

How will mechanical construction errors affect the field flatness, the separation of the next higher mode and the fundamental frequency itself? To check this with the Al model, we introduced on purpose a misplacement of the first stem, by ±0.2 mm in the longitudinal direction, where the effect of a positioning error is expected to be highest.

The deviation from the 100% field flatness is reported in fig.7. It must be noted that the deviation of ~1% of the central point should be regarded as a residual error of the code HFSS. The result is encouraging: in fact at INFN-Legnaro, for the more complicated SRFQ resonators, we achieved a positioning error smaller than ± 0.1 mm, on each electrode and on each Cartesian axis [5].

The distance of the next mode (+3.9 MHz in the nominal case) was both simulated and measured to increase, although by only around 1%, as a consequence of the misplacement of one stem: therefore it is not a problem.

The sensitivity of the fundamental frequency to the misplacement was measured to be ~50 kHz per 0.1 mm (HFSS: 35 kHz/mm). This result advises to consider a second step of rough frequency tuning after welding the stems to their base plates (see next paragraph).

From Round to Sharp Corner at End Plates

The uncertainty on the final frequency linked to construction tolerances, as discussed in the previous section, suggested to consider a second and final rough frequency tuning, to be performed after welding the three stems to their base plates: we decided to stepwise reduce the cavity length at this purpose.

Before doing this, however, the construction sequence was revised. The round corners between the end-plates (carrying the beam ports) and the stem base plates were replaced by sharp corners, for the ease of both varying the cavity length (by simply milling the resonator length) and of the subsequent electron-beam welding of the end plates themselves.

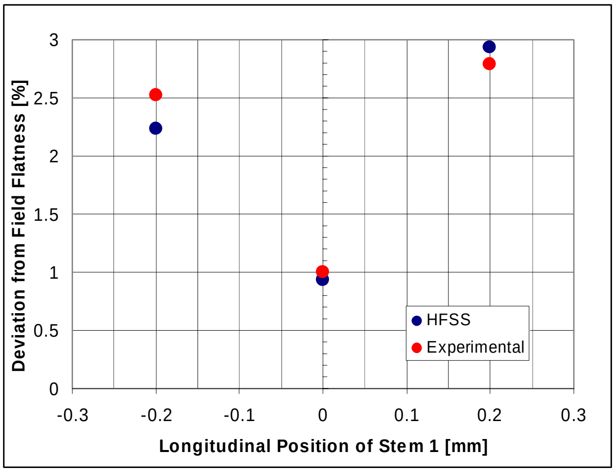

Figure 7: A deviation from the field flatness of the order of 1% per a misplacement of a tenth of a mm is to be expected.

The removal of the round corner at this stage causes the inductance of the end cells to increase: as a consequence, both the fundamental frequency and the field flatness drop.
While the frequency changed by -1.114 MHz (HFSS: -0.948 MHz), the relevant worsening of the field profile is shown in figure 8.

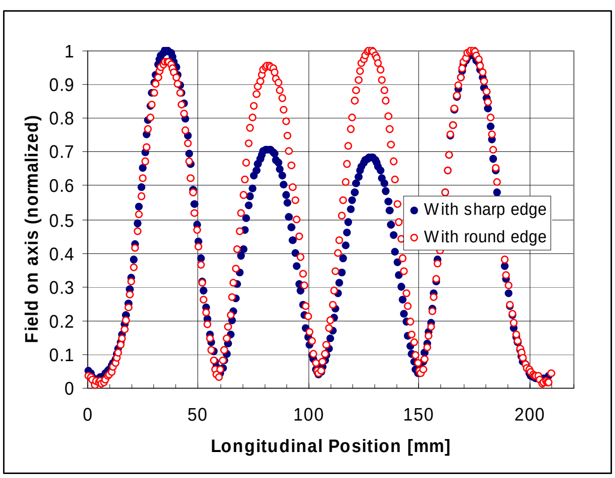

Figure 8: Milling a sharp corner at the end-plates worsens the field profile: the deviation from the full field flatness increases from ±2.3 % to ±16% (measured data).

Frequency Tuning by Varying the Cavity Length

To recover both the frequency drop and the worsen field profile, we stepwise shortened the cavity length, while keeping the length of all gaps unchanged (i.e. the beam ports were not moved). By doing this, as expected, we had a larger impact on L drop rather than on C increase: consequently, both the fundamental frequency and the field profile flatness changed in the desired direction. Only the amount of shortening had to be calculated and measured, so as to get a reasonable compromise between the final values of field flatness (not too far from 100%) and fundamental frequency (352 MHz ± Δf, Δf being the slow tuner range).

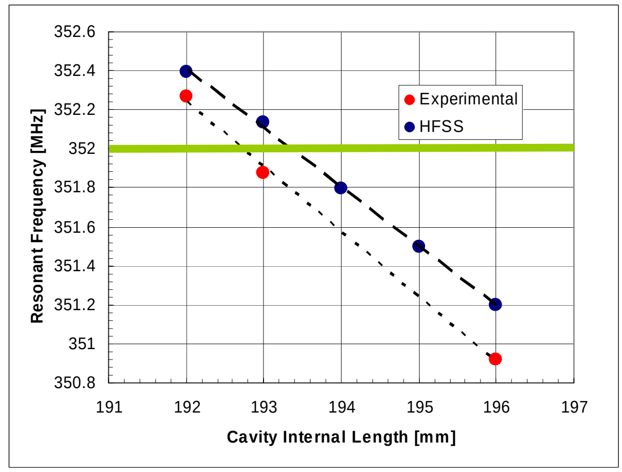

Figure 9: The working frequency and the flat field profile are recovered by stepwise reducing the cavity length.

Experimental results and related HFSS simulations are shown in fig.9. Linear fits of the experimental data show that a reduction of the cavity length by ~ 3.3 mm would meet both requirements very nicely.
It should be incidentally noted that, in all the text described in this chapter, the separation of the second mode from the fundamental one fluctuates between 3.7 and 3.9 MHz : therefore it is not a construction issue.

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[5] G. Bisoffi et al., Proc. of the 8th Int. Conf. on Heavy Ion Accelerators, Argonne (IL, USA), 173-184