MECHANICAL STABILITY SIMULATIONS ON A QUARTER WAVE RESONATOR FOR THE SPIRAL II PROJECT

H. Saugnac, G. Olry, S. Blivet, J.L. Biarrotte, S. Bousson, T. Junquera, M. Fouaidy, IPN Orsay, CNRS/IN2P3, France

Abstract

In the framework of the SPIRAL II project, IPN Orsay is studying a 88 MHz beta 0.12 super conducting quarter wave resonator prototype. Due to its low RF bandwidth (around 60 Hz) the resonator must have a very high mechanical stability and have small sensitivity to dynamic mechanical loads. To simulate the effects of geometrical deformations on the fundamental RF frequency a three dimensional analysis is required. The simulations were made by coupling mechanical FEM analysis performed in COSMOS/GEOSTAR© with the RF electromagnetic FEM code MICAV© integrated in the COSMOS/GEOSTAR© interface.

Static mechanical loads were first studied to reduce the effects of external pressure on the RF frequency shift and evaluate the tuning sensitivity of the cavity. Then, simulations of the dynamic response of the resonator, using the modal superposition analysis method, with random external pressure variations and harmonic excitation of the cavity were performed.

This paper presents the results of the simulations and mechanical solutions chosen to increase the cavity RF frequency stability.

NUMERICAL CODES AND METHODS

Numerical simulations where performed with the finite element codes COSMOS/GEOSTAR© for the mechanical study and MICAV/EMW© for the RF frequency simulations. MICAV© being integrated in COSMOS© it is possible, after some data treatments on the input and output files, to create a shell mechanical model and a solid RF model with corresponding meshing patterns. RF frequency perturbations are then computed without numerical interpolation [2].

Dynamic simulations are performed using the modal superposition analysis method [3] where the overall response of the structure is the sum of a set of modal responses for specific loading and boundary conditions.

Each mode *i*, considered as a single freedom degree element, has the harmonic stationary relative response :

$$u_i(t) = \frac{1}{2\xi_i\sqrt{1-\xi_i^2}} \cdot X \cdot \sin(\omega_i t + \pi/2)$$

Assuming, for small displacements, proportionality between RF frequency shift, and cavity wall deformation:

$$\Delta f_i \approx \left(\frac{\Delta f}{u}\right)_i \cdot u_i = K_i \cdot u_i$$

K_i is computed with COSMOS/GEOSTAR© and MICAV©.

For a combination of harmonic excitations having the same phase, and amplitude X_j and pulsation Ω_j once have the overall response :

$$\Delta f\ (t) \approx \frac{1}{N}\sum_j\sum_i H(h_{i,j}) \cdot X_{i,j} \cdot K_i \cdot \sin(\Omega_j t + \varphi_{i,j})$$

$$H(h_{i,j}) = \sqrt{\frac{1}{(1-h_{i,j}^2)^2 + 4\cdot\xi_i^2\cdot h_{i,j}^2}} \quad \& \quad \varphi_{i,j} = \arctan(2\xi_i \cdot \frac{h_{i,j}}{1-h_{i,j}^2})$$

$$\xi_i = \frac{1}{2Q_i} \quad \& \quad h_{i,j} = \frac{\Omega_j}{\omega_{0i}}$$

Q_i being the modal mechanical quality factor.

$X_{i,j}$ is the harmonic excitation amplitude.

For harmonic acceleration of amplitude γ_j or harmonic displacement of amplitude Z_{mj} once have:

$$X_{i,j} = \frac{\gamma_j}{\omega_i^2} \quad \text{or} \quad X_{i,j} = h_{i,j}^2 \cdot Z_{mj}$$

STATIC ANALYSIS

Simulations on static changes of cavity geometry were performed to stand cavity and cold tuning system design parameters. The tuning sensitivity was calculated at various positions on the external cavity body in order to optimise the ratio between the tuning sensitivity and the mechanical stiffness.

Static pressure variation effects as well as cool down and chemical etching induced frequency shift are presented in table 1 for two studied models (figure 1).

Table 1: Static frequency shifts numbers

	Model I	Model II
Tuning. Sens.	~ 15 kHz/mm	~ 15 kHz/mm
Tuning stiffness	~ 15 kN/mm	~ 15 kN/mm
Pressure. Sens.	-5.5 kHz/bar	-4.5 kHz/bar
Chemical etching sens.	~ -5kHz/0.1mm	~ -5kHz/0.1 mm
Therm. sens. @4K	~150 kHz	~150 kHz

These data will give a first evaluation of the design frequency target and the overall tuning range taking into account the manufacturing incertainities that will be measured on a first prototype planed for October 2004.

DYNAMIC ANALYSIS

Mechanical coupling between the helium tank and the cavity is mainly at the helium tank jointing ring (compensating bellows have high compliance).

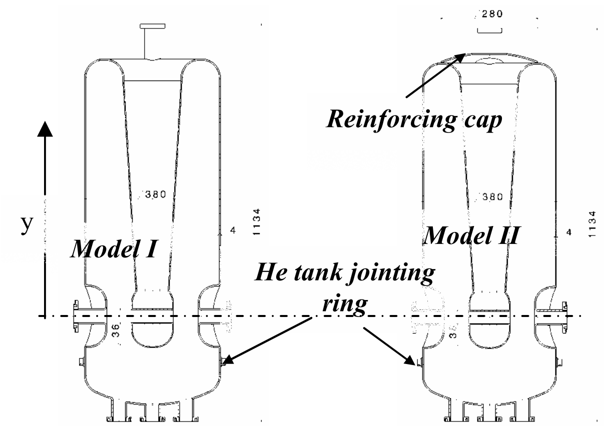


Figure 1: QWR Models.

The displacement boundary conditions (fixing and harmonic base excitation) are then applied only on the helium tank jointing ring.
A number of 60 modes giving a modal mass participation factor of ~80 % in all directions, from 50 Hz to 1100 Hz, where computed to describe the dynamic mechanical response of the cavity. For the base excitation study 10 modes (Model II) were chosen to form the frequency shift modal basis (figure 2). A random dynamic pressure excitation simulation with a white noise PSD shows that only one mode can be used to describe the RF frequency shift due to dynamic pressure loads with a good accuracy. Quality factors values, from 10 to 200, were chosen according to different measured values on bulk niobium super conducting cavities [4].

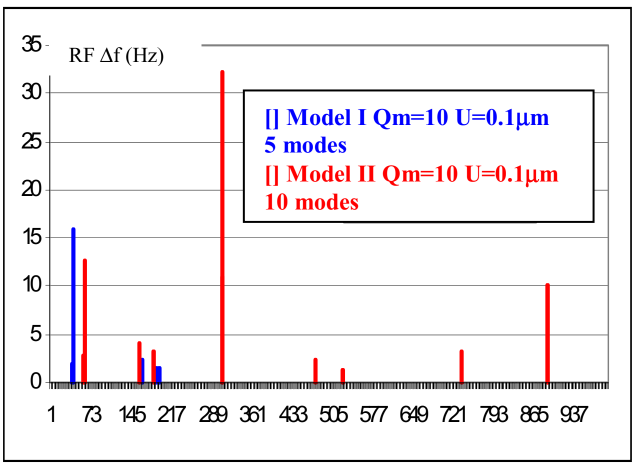


Figure 2: Modal harmonic response for base excitation Model I & Model II.

Base Excitation Analysis

These simulations describe the effects of environmental vibrations transmitted to the cavity from the soil or the cryogenic tubing submitted to rotating machines vibrations (helium compressor, vacuum pumps …).

A comparison for low frequency excitations between the two models is shown figure 3.

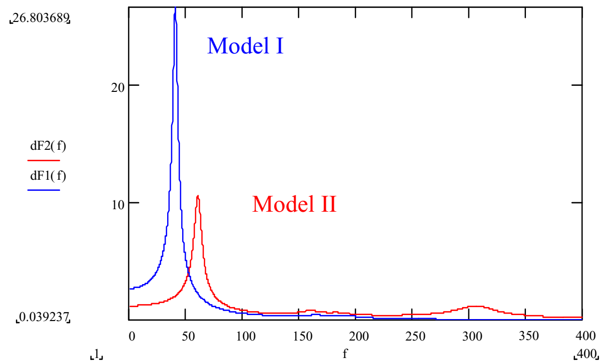


Figure 3: RF frequency Shift (Hz) for 0.01 m/s^2 constant acceleration amplitude.

The reinforcing cap on the model II, increases the first mode frequency from 40 Hz to 60 Hz, and lead to a better RF frequency stability for low frequency mechanical excitations.

Pressure Excitation Analysis

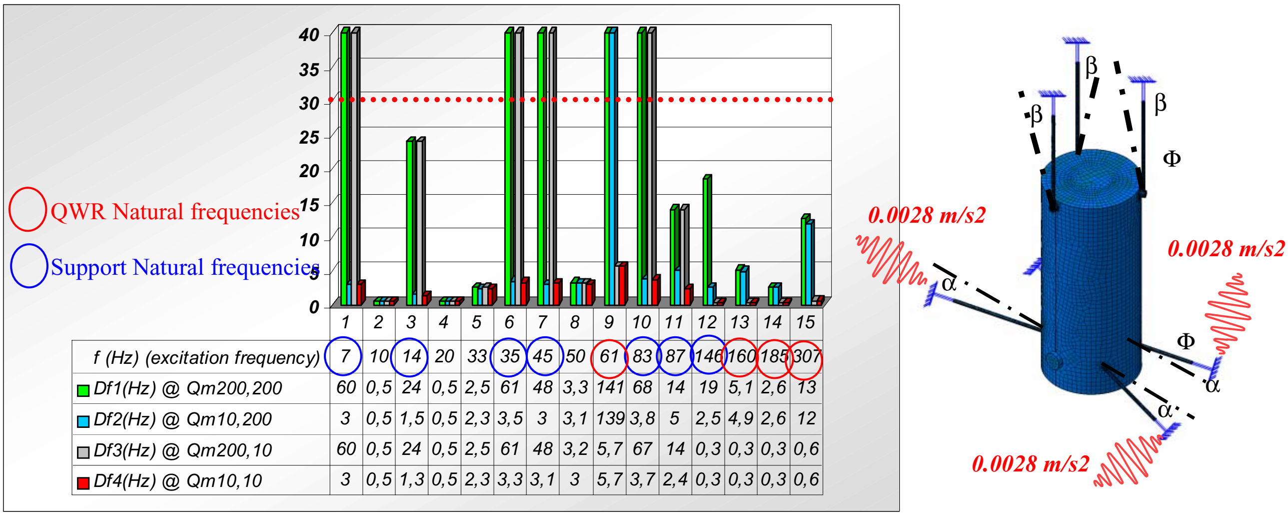
Spiral II resonators are to be cooled with liquid He I at 4.2 K. Bubbles, created during pool boiling, have random characteristics (diameters, formation frequency, distribution on the surface…) which depend on various parameters: surface history, roughness … The pressure forces can be roughly (predictions are not well established) evaluated from mathematical correlation [5]. Assuming a number of nucleation sites of 10^6/m^2, a maximum 150 µm bubble diameter, a homogenous distribution on the surface and a formation frequency at the most sensitive QWR resonant mode, we can make a conservative evaluation (Table 2) that shows that this effect should be small compare to other mechanical perturbations.

Table 2: Nucleate boiling induced frequency shift

	Model I (197 Hz)	Model II (277 Hz)
ΔP = 10-3 mbar Qm=200	1.53 Hz	0.68 Hz

CRYOMODULE DESIGN CRITERIA

Dynamic simulations on the cavity support rods (figure 4) has been done with a constant acceleration amplitude harmonic excitation roughly established from measured values on an accelerator environment [6]. These simulations show that risks to have RF frequency shifts greater than our QWR bandwidth are possible for excited mechanical eigen modes with high quality factors.
For small quality factors the frequency shift remains low even when resonant modes are excited. Lowering the mechanical quality factors of the QWR [7], the cavity support and the cryostat/soil interface[8] is then an issue for the cryomodule design.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
f (Hz) (excitation frequency)	7	10	14	20	33	35	45	50	61	83	87	146	160	185	307
Df1(Hz) @ Qm200,200	60	0,5	24	0,5	2,5	61	48	3,3	141	68	14	19	5,1	2,6	13
Df2(Hz) @ Qm10,200	3	0,5	1,5	0,5	2,3	3,5	3	3,1	139	3,8	5	2,5	4,9	2,6	12
Df3(Hz) @ Qm200,10	60	0,5	24	0,5	2,5	61	48	3,2	5,7	67	14	0,3	0,3	0,3	0,6
Df4(Hz) @ Qm10,10	3	0,5	1,3	0,5	2,3	3,3	3,1	3	5,7	3,7	2,4	0,3	0,3	0,3	0,6

Frequency shift response for a harm. acceleration excitation amplitude 0.0028 m/s2. Qm i,j : mechanical quality factor of the support rods (i) and the QWR (j). *For* ***QWR Model II & Tank Model*** $\alpha=0$, $\beta=0$, $\Phi= 10$

Figure 4: Frequency shift for cavity support / QWR integrated model.

An other direction, aiming to avoid excitation of the natural frequencies of the cavity support rods, is to allow an adjustment of the rods geometrical parameters α, β or Φ (figure 4) which have a sufficient effect on the eigen frequencies values. Qualitative solutions to decrease the influence of the vacuum pumps, cryogenic tubing and cold tuning system stepping motor lead to reduce the vibration transmission to the QWR (bellows, distance, working conditions…). First design numbers and qualitative goals are presented table 3.

Table 3: Design numbers

Soil vibration intensity	U < 20 nm f >5 Hz
Cryostat / soil transmission	T < 0.5
1 st QWR mode Quality factor	Qmj < 20
Cavity support Quality factors	Qmi < 20
First cavity support Mode	f > 15 Hz
No excitation of the natural modes by the tuning system stepping motor → effect on the working speed	
No common resonant frequency between : Cryostat, Cavity support, QWR	
Vac. Pumps, cryo. tubing, tuner.	To be evaluated
He bath pressure stability	+/- 1 mbar
QWR RF frequency Fab. Incertainities	Δf < +/-10 kHz

CONCLUSION

Despite the incertainities on the boundary conditions values (acceleration and displacement intensities, mechanical Q factors…), these simulations give a basis for the construction choices and the design concepts of the beta 0.12 SPIRAL II cryomodule. From vibration tests on a first QWR prototype, planed for 2005, the numerical model validity will be checked and the QWR mechanical modal quality factors will be evaluated.

The next step is to manufacture a prototype cryomodule and measure the dynamic response of the whole mechanical structure.

REFERENCES

[1] T. Junquera & al., "High Intensity Linac Driver for the SPIRAL-2 Project : Design of Superconducting 88 MHz Quarter Wave Resonators (beta 0.12), power couplers and cryomodules", EPAC'04, Luzern, July 2004.

[2] F. Krawczyk & al., " An integrated design for a beta=0.175 spoke resonator and associated power coupler", EPAC'02, Paris, June 2002.

[3] N. Ouchi & al., "Pulsed SC proton LINAC"," LINAC 2000, Monterey, August 2000.

[4] L. Lilje & al., "Characteristics of a fast piezo-tuning mechanism for superconducting cavities" EPAC'02, Paris, June 2002.

[5] W.B. Bald "Cryogenic heat transfer research at Oxford", CRYOGENICS, August 1973, p 457.

[6] J. Welch, "Ground vibration and siting of the Cryogenics Facility for Cornell ERL Prototype", ERL reports 2002.

[7] A. Facco & al. "On-line performance of the LNL mechanically damped superconducting low beta resonator", EPAC'00, Stockholm, June 2000.

[8] R. Assmann & al. "The CLIC stability study - Stabilizing Accelerator Magnets to the Sub-nm Level", ELAN Workshop Frascati, Italy, May 2004.