STRUCTURAL ANALYSES OF MSU QUARTER-WAVE RESONATORS

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Abstract

A superconducting linac for re-acceleration of exotic ions is under development at Michigan State University. Two types of superconducting quarter-wave resonators (80.5 MHz, optimum $\beta = 0.041$ and 0.085) will be used for reacceleration to energies of up to 3 MeV per nucleon initially, with a subsequent upgrade path to 12 MeV per nucleon. Structural design is an important aspect of the overall cavity and cryomodule implementation. The structural design must include stiffening elements, the tuning mechanism, and the helium vessel. The main mechanical design optimization goal is to minimize the shift in the cavity's resonant frequency due to the Lorentz force, bath pressure fluctuations, and microphonic excitation. Structural analyses of the MSU quarter-wave resonators are presented in this paper; stiffening measures are explored. The numerical predictions are compared to test results on prototype cavities.

INTRODUCTION

The re-accelerator requires one cryomodule containing six $\beta = 0.041$ quarter wave resonators (QWRs), one cryomodule containing eight $\beta = 0.085$ QWRs, and additional QWRs for matching [1, 2]. Unstiffened first prototypes of both the $\beta = 0.041$ QWR [3] and the $\beta =$ 0.085 QWR [4] have been fabricated and tested. Stiffened versions of the $\beta = 0.041$ QWR [5] are presently being produced; several have been tested in a Dewar and one of them is being tested in a cryomodule [6]. The unstiffened $\beta = 0.085$ QWR has been tested in a prototype cryomodule [5]; a stiffened version is presently being fabricated.

A stable resonant frequency for the QWRs is desired, since excessive frequency fluctuations require additional RF power to control the RF amplitude and phase. Sources of frequency fluctuations include microphonic excitations, fluctuations in the helium bath pressure and Lorentz force detuning. Since the operating temperature is 4.5 K, the helium bath pressure stability will likely be determined by the extent to which the return pressure of the cryogenic plant can be controlled. The stiffening measures were intended primarily to reduce the pressure sensitivity.

The pressure sensitivity and Lorentz force detuning coefficient were predicted and measured for both the $\beta = 0.041$ and $\beta = 0.085$ QWRs.

MODELLING

A sequential coupled field analysis RF/Structural/RF is used to predict the frequency shift due to cavity shape

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deformation from changes in the bath pressure or the Lorentz forces on the cavity walls caused by the electromagnetic field. In order to predict the frequency change, a structural analysis is required to find the deformation of the cavity walls. A subsequent highfrequency analysis determines the frequency shift for the deformed cavity. The same simulation technique is also used to calculate the range of the tuning system.

The prediction of the resonant frequency change depends on the accuracy of the calculated electromagnetic fields as well as the calculated mechanical deformation.

For the sequential coupled field analysis, two model parts are used: the "RF model" (Fig. 1) that describes the inner RF volume of the cavity and the "mechanical model" (Fig. 2) that represents the mechanical structure of the cavity. Both models are generated within ANSYS/Multiphysics [7].

The geometrical symmetry allows the simulation of only one quarter of the cavity. Since the inner niobium walls of the cavity are relatively thin Nb sheets, shell elements are used to model the walls and some of the thin stiffening elements. This simplifies the whole modelling procedure.

To determine the free resonant frequency shift and the range of the tuning system, the following steps are necessary:

- Step 1 A high frequency modal analysis is used to calculate the resonant frequency and the magnetic field distribution (Fig. 1) of the undeformed cavity, using the RF model.
- Step 2 Calculation of the Lorentz force distribution on the surface of RF model (Fig. 3). The resulting Lorentz force distribution on the cavity surface is scaled to a peak magnetic field of 100 mT as an input for the next step.



Figure 1: Electromagnetic fields (RF model) for the β = 0.041 QWR: (a) electric field and (b) magnetic field.

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Figure 2: Mechanical model for the $\beta = 0.041$ QWR.



Figure 3: Lorentz force distribution for the β =0.041 QWR.

- Step 3 Calculation of the deformation of the mechanical model (Fig. 4) by applying atmospheric pressure and the Lorentz force distribution from Step 2 as input loads.
- Step 4 Calculation of the resonant frequency of the deformed RF structure by applying the deformations from Step 3 to the RF model. The RF model has to be treated as an elastic structure. A mechanical calculation for the RF model computes the deformation (Fig. 4). Additionally, the elements/nodes have to be "frozen" at their deformed location. The element type is then switched back to the RF element and the resonant frequency of the deformed structure is calculated.
- Step 5 Calculation of the tuning range. Additional forces from the tuner are applied to the mechanical model and the simulation is repeated following Steps 3 and 4.



Figure 4: Deformation of the $\beta = 0.041$ QWR: (a) external pressure and (b) Lorentz force.

Both the RF and mechanical meshed models were generated before beginning the simulations. During the calculations, models were switched off when they were not needed. Such a procedure produces the highest simulation accuracy. Because of the non-homogeneous electromagnetic field distribution, the most convenient meshing method is an automatic meshing with a manually-corrected local mesh density. The criterion for mesh optimisation was the minimization of the peak surface magnetic and electric field [8].

For an optimisation of the mechanical design, Steps 3-5 have to be done for each stiffening scheme.

RESULTS

A series of different options for QWR stiffening were investigated. As indicated above, the main goal was to minimize the frequency shift due to helium bath pressure fluctuations. Another objective of QWR stiffening was to minimize the dependence of cavity behaviour on the cryomodule environment. When making the choice between different stiffening schemes, the cavity fabrication procedures had to be taken into account as well.

The results of cavity stiffening are shown in Fig. 5. The chosen QWR stiffening structure includes a dome ring (Fig. 6), a central electrode plate (Fig. 7), and a beam port buttress (Fig. 8). All results are for completely unconstrained cavity beam pipes.

The dome ring connects the top of the cavity to the helium vessel, which reduces the vertical displacement of the central electrode (Fig. 5, curve "top.ring").

The plate in the lower part of the central electrode joins the two opposite plane surfaces that are mainly affected by the bath pressure (Fig. 5a, curve "ce.plate_top.ring").

The conical shape of the beam ports simplifies cavity fabrication, but represents a flexible element. A connection to the helium vessel was made via a buttress to minimize the displacement of the beam ports (Fig. 5b, curve "bp.buttress_top.ring").



Figure 5: Results of QWR stiffening: (a) predicted frequency shift with bath pressure; (b) predicted Lorentz force detuning, $K_{\rm L} = df/dE_{\rm acc}^2$.



Figure 6: Stiffening ring for the $\beta = 0.041$ QWR: (a) model showing the ring in blue; (b) photograph of the stiffening ring prior to welding of the helium vessel.



Figure 7: Central electrode stiffening plate for the β = 0.041 QWR:.(a) model with the plate shown in blue; (b) photograph of the plate; (c) photograph of the central electrode with the plate welded into it.

The results of simulations and measurements for the β = 0.041 and 0.085 QWRs are compared in Table 1. The results correspond to a cavity wall thickness of 2 mm except for the top dome, which is 3 mm thick. The location of tests "Dewar" and "module" slightly differ by different cavity support. (Dewar testing with a helium vessel was done under realistic conditions, with liquid in the vessel and vacuum outside the vessel.) Note that, in Table 1, $K_{\rm LP} = df/dE_{\rm pk}^2$ is defined using the peak surface electric field, but in Fig. 5, $K_{\rm L} = df/dE_{\rm acc}^2$ uses the accelerating field (in our case $E_{\rm pk}/E_{\rm acc} = 4.1$). We assumed the same mechanical properties for the cavity walls and stiffening elements (Young modulus = 105000 N/mm² and Poisson ratio v = 0.38).

The agreement between predicted and measured values of df/dp in Table 1 is relatively close. The measurements confirm the prediction that the stiffening elements produce a significant reduction in the absolute value of df/dp for the $\beta = 0.041$ QWR.

The predicted values of the Lorentz detuning coefficient are generally larger in magnitude than the measured values. This level of agreement is not unexpected, considering that the simulations are rather complicated and that simplifying assumptions are needed in the numerical models. Both the simulations and the measurements indicate a reduction in the absolute value of the Lorentz detuning coefficient with stiffening.

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Figure 8: Beam port buttress for the $\beta = 0.041$ QWR: (a) model with the buttress shown in blue; (b) drawing of buttress; (c) photograph of buttress; (d) beam port with buttresses welded to cavity.

Table 1: Simulation and test results for QWR stiffening. The Lorentz detuning coefficient is defined as $K_{LP} = df/dE_{pk}^{2}$.

$\beta = v/c = 0.041$						
	He		df/dp		K _{LP}	
stiffened	vessel	location	(Hz/mbar)		$[Hz/(MV/m)^2]$	
			calc.	exp.	calc.	exp.
no	no	Dewar	-18.25	-18.5		-0.1
no	no	module	-18.7		-0.19	
no	yes	Dewar	-11.1		-0.15	
yes	no	Dewar	-12.21	-12.8	-0.18	-0.08
yes	yes	Dewar	-2.5	-2.0	-0.1	-0.04
yes	yes	module	-2.7		-0.12	-0.07
$\beta = v/c = 0.085$						
no	no	Dewar		-19.7		-0.19
no	no	module	-19.3		-0.2	
no	yes	Dewar		-7.8		-0.12
no	yes	module	-6.6	-7.3	-0.16	-0.13
yes	no	module	-10.96		-0.16	
yes	yes	module	-6.86		-0.12	

CONCLUSION

Numerical models have been used to predict the stiffness of quarter-wave resonators for the MSU re-accelerator linac and to design stiffening elements for the resonators. The stiffening efficacy has been verified experimentally on the $\beta = 0.041$ resonators. Fabrication of stiffened $\beta = 0.085$ resonators is in progress.

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