THE TUNING SYSTEM FOR THE HIE-ISOLDE HIGH-BETA QUARTER WAVE RESONATOR

P. Zhang[1,*], L. Alberty[1], L. Arnaudon[1], K. Artoos[1], S. Calatroni[1], O. Capatina[1],
A. D'Elia[1,2,3], Y. Kadi[1], I. Mondino[1], T. Renaglia[1], D. Valuch[1], W. Venturini Delsolaro[1]
[1]CERN, Geneva, Switzerland
[2]School of Physics and Astronomy, The University of Manchester, Manchester, U.K.
[3]The Cockcroft Institute of Accelerator Science and Technology, Daresbury, U.K.

Abstract

A new linac using superconducting quarter-wave resonators (QWR) is under construction at CERN in the framework of the HIE-ISOLDE project. The QWRs are made of niobium sputtered on a bulk copper substrate. The working frequency at 4.5 K is 101.28 MHz and they will provide 6 MV/m accelerating gradient on the beam axis with a total maximum power dissipation of 10 W on cavity walls. A tuning system is required in order to both minimize the forward power variation in beam operation and to compensate the unavoidable uncertainties in the frequency shift during the cool-down process. The tuning system has to fulfill a complex combination of RF, structural and thermal requirements. The paper presents the functional specifications and details the tuning system RF and mechanical design and simulations. The results of the tests performed on a prototype system are discussed and the industrialization strategy is presented in view of final production.

INTRODUCTION

The HIE-ISOLDE [1] project is a major upgrade of the existing ISOLDE radioactive beam facility at CERN. The main focus is to boost the beam energy from 3 MeV/u to 10 MeV/u by replacing the current normal conducting linac with superconducting quarter wave resonators (QWRs). They will make use of niobium sputtered on copper substrate technology [2]. The QWR will have a working frequency of 101.28 MHz at 4.5 K providing an accelerating gradient of 6 MV/m on beam axis with a maximum of 10 W power dissipation. Two types of QWRs, low-β and high-β, will be installed to cover the entire energy range. Since the linac upgrade will start from the high energy section, the R&D effort has been focused on the high-β QWRs [3–5].

The resonant frequency of each QWR varies inevitably due to mechanical tolerances and uncertainties during the cool-down process. We decoupled these two effects [6–8], thus the tuning system only needs to compensate the variability of the frequency shift during the cool-down process. Due to insufficient statistics on the frequency shift at the beginning, a rather large coarse range for the tuning system was chosen. Measurements from the last two years have pinned down the uncertainty of the frequency shift. Therefore it has been possible to go for a simplified tuning system which will also lower the production cost. In addition, the system must also provide a fine frequency tuning

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[*] pei.zhang@cern.ch

in order to keep the cavity on resonance hence minimizing the forward power variation during beam operations.

This paper first shows the study on the frequency shift during the cool-down process based on previous measurements. Then it reviews the current tuning plate with two different assemblies. Aiming at a lower sensitivity, the study of a simplified tuning plate is described as well as its impact on the main cavity RF parameters. Finally the mechanical implementation and measurement results of two different simplified plates are presented.

FREQUENCY SHIFT DURING THE COOL-DOWN PROCESS

The resonant frequency of the cavity shifts during cool-down process [9], and this shift varies amongst cavities and coatings. Fig. 1 shows the results from our previous measurements on various QWRs using three different couplers. It suggests a peak-to-peak frequency shift uncertainty of 18 kHz. This has to be covered by the coarse range of the tuning system. To stay in a safer limit, we doubled this value to 36 kHz for the coarse range, which is comparable to TRIUMF (33 kHz) [10] and Legnaro (25 kHz) [11].
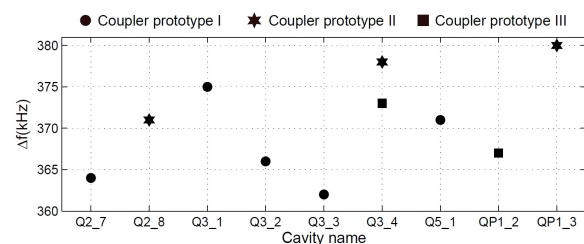

Figure 1: Frequency shift during the cool-down process.

THE ORIGINAL TUNING PLATE

The original tuning system is conceptually similar to TRIUMF's and has been described in [6]. An oilcan-shaped diaphragm of copper-beryllium (CuBe) was hydroformed and then coated with niobium. Fig. 2(b) shows schematically the tuning plate in mid-range position "pos0". This plate was designed to be assembled upwards on the bottom of the baseline QWR (Fig. 2(a)) as shown in Fig. 2(c). The tuning range is 20 mm consisting 5 mm upward and 15 mm downward movement from "pos0". The coarse range is calculated to be 220 kHz giving an average tuning sensitivity of 11 kHz/mm. During beam operations,

microphonics, helium pressure variation and Lorentz force will constantly change the cavity resonant frequency which need to be tuned in a "fine" manner. The LLRF requires 0.5 Hz per tuning step [12], which can be translated into a mechanical step of 45 nm. This makes the mechanical control very challenging.
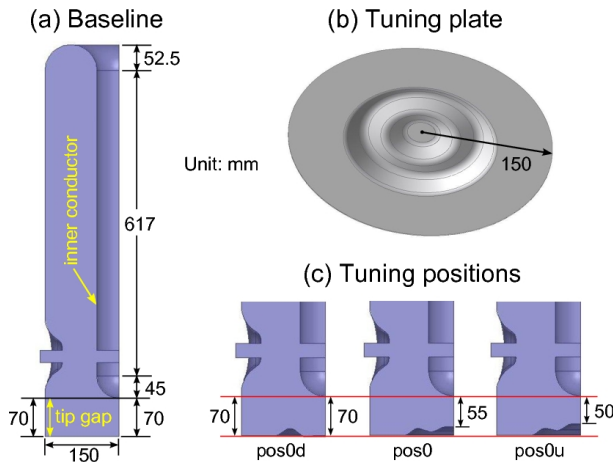

Figure 2: Baseline QWR with tuning plate assembled upwards.

A possible solution is to flip the existing tuning plate to assemble it downwards as shown in Fig. 3. By doing that, the effective tip gap is enlarged from 55 mm to 83.1 mm for "pos0". The inner conductor of the cavity has been elongated by 1.9 mm from the baseline (Fig. 2(a)) in order to tune back the nominal frequency. The simulation results for three tuning positions are listed in Table 1. Simulations suggest a reduced sensitivity of 6.85 kHz/mm and a smaller coarse range of 137 kHz accordingly. In this case, a mechanical step of 73 nm would be sufficient to fulfil the 0.5 Hz/step LLRF requirement, making the mechanical control less challenging. However this tuning plate is highly costly and the 137 kHz coarse range is not really necessary. A simplified, low-cost tuning plate is therefore preferable.
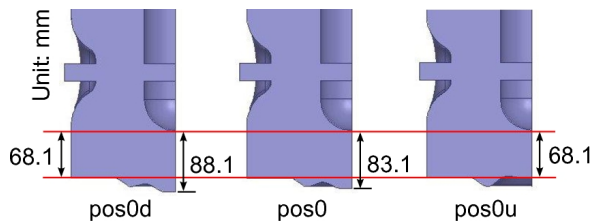

Figure 3: Baseline QWR with tuning plate assembled downwards. The inner conductor has been elongated by 1.9 mm to tune back the nominal frequency.

THE NEW SIMPLIFIED TUNING PLATE

Starting from a simple flat plate, the tuning is made by deforming the plate from the center. Fig. 4 shows the sim-

Table 1: Tuning Sensitivity and Coarse Range of the Original Plate Assembled on the Baseline QWR both Upwards and Downwards. The results are from simulations at room temperature in air.

	freq. (upwards)	freq. (downwards)
pos0d	100.933 MHz	100.937 MHz
pos0	100.804 MHz	100.911 MHz
pos0u	100.713 MHz	100.800 MHz
Coarse range	**220 kHz**	**137 kHz**
Sensitivity	**11 kHz/mm**	**6.85 kHz/mm**

plified plate along with the cavity at different tuning positions. The tuning is realized by pushing/pulling the plate by a maximum of 2.5 mm. Fig. 5 shows the frequency tuning varies with the radius of the deformable area. It can be clearly seen that R=95 mm at tg=80 mm (the green hexagram in Fig. 5) would give a reasonable choice with a coarse range of 34 kHz and a sensitivity of 6.8 kHz/mm.
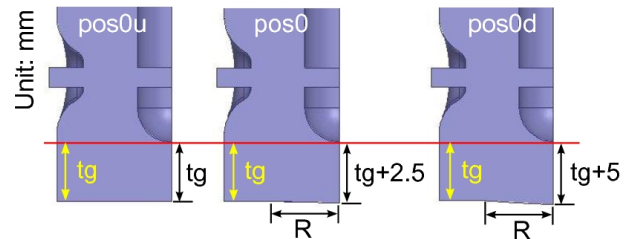

Figure 4: Simplified tuning plate; tg stands for tip gap and R is the radius of the deformation region.
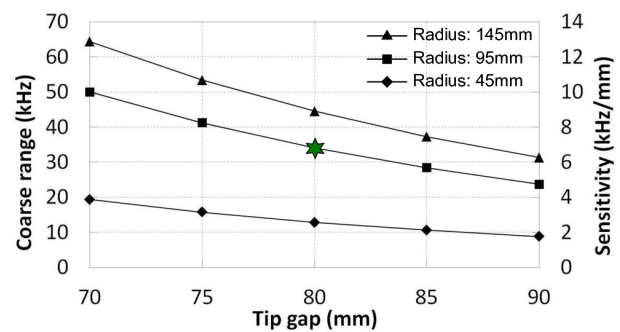

Figure 5: Coarse range and tuning sensitivity of the simplified plates with different deformation radius.

Compared to the baseline design in Fig. 2, the tip gap has been increased by 10 mm. This will inevitably increase the cavity frequency by several hundred kHz, thus the cavity needs to be retuned. We assume [9] a frequency shift of +365 kHz to characterize the changes from room temperature in air to 4.5 K in vacuum. Thus

$$f_{\text{simulation}}^{eigenmode} = 101.28 - 0.365 = 100.915 \text{ MHz.} \quad (1)$$

As the cavity frequency is very sensitive to the change of

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the inner conductor length, we decided to modify this parameter to tune back the frequency in order to minimize the changes on the overall cavity design. Fig. 6 shows how the frequency varies with the inner conductor length. After a linear fit of the simulation results, the fitted line intersects with the target frequency line giving the required inner conductor length. It suggests an elongation of the inner conductor by 2.5 mm.
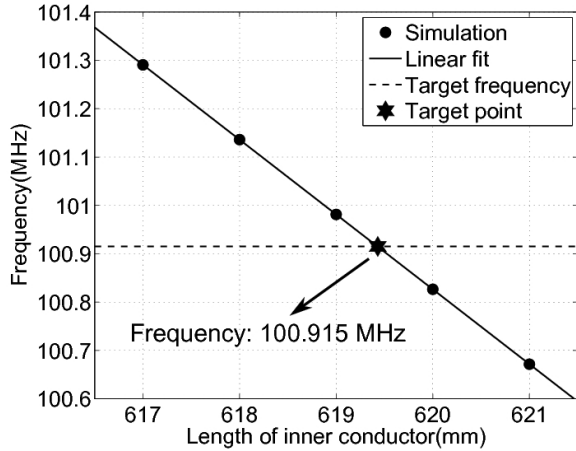

Figure 6: The tuning of the cavity frequency by changing the inner conductor length.

The simplified tuning plate will have a deformable area with a radius of 100 mm, a mid-range position at 2.5 mm deformed downwards with a total movable range of 5 mm (±2.5 mm around the mid-range position). Finally a fine cavity tuning gave a tip gap of 78.1 mm. Fig. 7 shows the final cavity geometry.
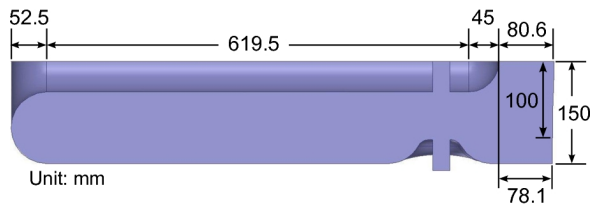

Figure 7: Current cavity with the simplified tuning plate at mid-range position.

Since our goal is to minimize the changes to the overall cavity design, we examined the main RF parameters of each design. These results are listed in Table 2. Due to an increased tip gap in the new design, the E_p/E_{acc} decreases by 10% from the baseline, which may reduce the occurrence of field emission. The magnetic field on the plate is also lowered, which cuts down the power dissipation on the plate by 49% from the baseline. In particular, the magnetic field at the contact between the plate and the cavity outer wall is lowered by 10%. This would reduce the loss due to contact resistance. The changes to other RF parameters are negligible.

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Table 2: The Main Cavity RF Parameters with Different Tuning Plate from Simulations at Room Temperature in Air.

	Up.	Down.	New
$f^{eigenmode}_{simulation}$ [MHz]	100.804	100.911	100.914
$\beta_{optimum}$ [%]	10.86	10.87	10.88
TTF at $\beta_{optimum}$	0.90	0.90	0.90
R/Q [Ω] (incl. TTF)	554	556	556
E_p/E_{acc}	**5.5**	**5.0**	**5.0**
H_p/E_{acc} [G/(MV/m)]	95.4	95.3	95.3
U/E^2_{acc} [mJ/(MV/m)^2]	208	207	207
$G=R_sQ$ [Ω]	30.7	30.8	30.8
P_{diss} [W] in the cavity	7.7	7.7	7.7
P_{diss} [W] on the plate	**0.0035**	**0.0021**	**0.0018**
Conductor L [mm]	617	618.9	619.5
Tip gap [mm]	70	68.1	78.1
Coarse range [kHz]	220	137	37
Sensitivity [kHz/mm]	11.0	6.9	7.4

Allowing for mechanical tolerances of 0.1 mm, a detuning of 28 kHz from the nominal cavity frequency can be expected in the worst case. For this reason, the tip gap value has been chosen to be a free parameter in order to compensate the mechanical-tolerance induced frequency detuning [7]. Simulations suggest that a change of approximately ±1.5 mm to the tip gap is necessary to recover the ∓28 kHz frequency detuning. The impact of this possible tip gap variations on the coarse range and tuning sensitivity has been studied by simulations and listed in Table 3. The 1.5 mm variation of the tip gap will shift the coarse range by 2 kHz and the sensitivity by 0.2 kHz/mm. These are small and tolerable.

Table 3: The Coarse Range and Tuning Sensitivity at Different Tip Gap with R=100 mm Simplified Plate.

	Tip gap (mm)		
	78.1-1.5	78.1	78.1+1.5
Coarse range (kHz)	38	37	35
Sensitivity (kHz/mm)	7.6	7.4	7.0

THE MECHANICAL DESIGN OF THE SIMPLIFIED TUNING SYSTEM

The mechanical deformation of the tuning plate is created by a stepper motor in microstep mode. It has 8000 steps per turn which is transformed to a linear motion by a screw at room temperature with 1 mm advance per turn. The theoretical smallest motor step of 0.125 μm was confirmed by measurements. The precision is however reduced to the micron range by friction, depending on the motion range and load. The hysteresis is 1–2 μm when changing moving directions.

The linear motion is transmitted by a pulling rod with two hinges to a mechanical lever changing the motion direction at the bottom of the cavity. The lever further divides the mechanical motion by a factor of 3 in order to reach a theoretical resolution of 40 nm.

As mentioned above, the total deformation range of the tuning plate is 5 mm, pulling down from the flat position. Given the space available for the mechanical lever, this range results in a lever angle up to 10°. This linear and angular range along with the force required to deform the tuning plate complicates the use of a precise flexural and hence frictionless guidance. For the first test an adjusted frictional guidance was used with material combination of copper on stainless steel in order to reduce the risk of stick slip and cold welds at 4.5 K in vacuum. A knife edge pivot can also be considered to further reduce the friction.

The change from an oilcan-shaped diaphragm to a flat tuning plate introduced difficulties for mechanical and thermal design. A flat plate design implies a non-linear stiff behavior. In addition, stresses and the force required for a 5 mm moving range increase significantly. The first prototype was produced in 0.3 mm thick CuBe C17140, which has high elastic limit and acceptable thermal conductivity at 4.5 K. This thin plate was clamped against the cavity between 300 mm and 320 mm in diameter. The radius of the deformable area was limited to 100 mm by a limiting Cu OFE ring under the plate. This ring might also help to conduct the dissipated RF power on the plate. The second prototype was produced in Cu OFE. Starting from a 5 mm thick Cu OFE disk, the deformable area with a radius of 100 mm was machined to 0.3 mm. This plate will be plastified locally before reaching the maximum 5 mm deformation. This requires higher forces but have a significantly better thermal behavior compared to the CuBe plate. It therefore has sufficient thermal margin to keep the coated niobium layer to remain superconducting during beam operations.

Both plates have been coated with niobium in order to minimize losses. Surface treatment prior to coating was performed in the same way as for the cavities [3], which removed approximately 20 μm. However the assessment of our surface treatment as optimal method for CuBe surface preparation has still to be performed. The final preparation step is a low pressure, dust-free, demineralized water rinsing. The plates are then packed in dust-free polymer bags for transfer to the coating laboratory. Niobium coating was performed by sputtering in a dual planar magnetron system, different from the one used for cavities [3,4]. Niobium layers of approximately 1.5 μm thick were coated on both plates with the RRR exceeding 15. Final production step was again the dust-free water rinsing prior to assembling on the cavity. The quality factors Q_0 in excess of 2×10^9 ($R_s<15$ $n\Omega$) at low field have been measured for the same reference baseline cavity using both tuning plates, indicating that the coating of the plate is not an intrinsic limiting factor of the performance. Adhesion of the coating is generally satisfactory, except sometimes peel-off at the edges

of the plate was observed. This is irrelevant from the RF point of view, and could be traced to contaminations by the polymer bags which must be used for packaging to prevent surface contamination from dust.

MEASUREMENT RESULTS OF THE SIMPLIFIED TUNING SYSTEM

The tuning plate was installed on a coated baseline cavity with 80 mm tip gap and mechanically controlled by the above stated stepper motor. Fig. 8 shows the measurement setup. Measurements of coarse range and sensitivity were subsequently conducted at 4.5 K for both CuBe and Cu OFE plate.
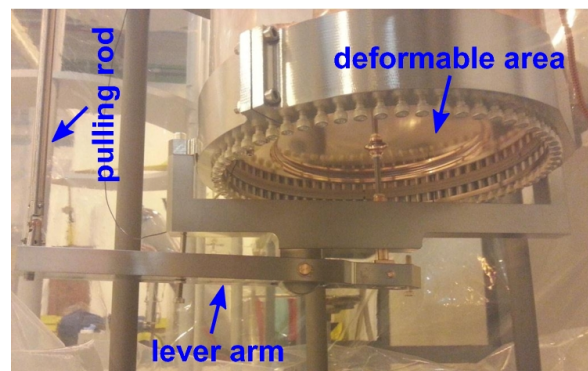

Figure 8: Measurement setup for the tuning system test (photo taken outside the cryostat).

Fig. 9(a) shows an example of the measurement results for the CuBe plate. A total frequency tuning of 130 Hz was tested in 390 motor steps with 3 steps per movement. The frequency tuning followed the motor step changes linearly with a resolution of 0.32 Hz/step. Stick slip were observed several times during the tuning. This results in deviations in the order of 5 Hz between the measured frequency and the linear fit as shown in Fig. 9(b). Such frequency errors correspond mechanically to the micron level as can be expected in the best case for a frictional system. The coarse range for the CuBe plate was measured to be 27 kHz at 4.5 K.

One example of the measurement results for the Cu OFE plate are shown in Fig. 10(a). The motor was moved in both directions in 40 steps each time to test both positive and negative tuning. A similar stick slip behavior was observed and a resolution of 0.27 Hz/step was measured. As shown in Fig. 10(b), frequency errors are in the same order with the CuBe plate. The coarse range of the Cu OFE plate was measured to be 24 kHz, smaller than that of the CuBe plate. For both plates, backlash was observed when changing moving directions as shown in Fig. 5(b) for the Cu OFE plate.

Coarse range was measured to be smaller than that of the design value for both prototypes. This was because we set some restrictions on the lever arm to limit the deformation. Later measurements at warm have confirmed
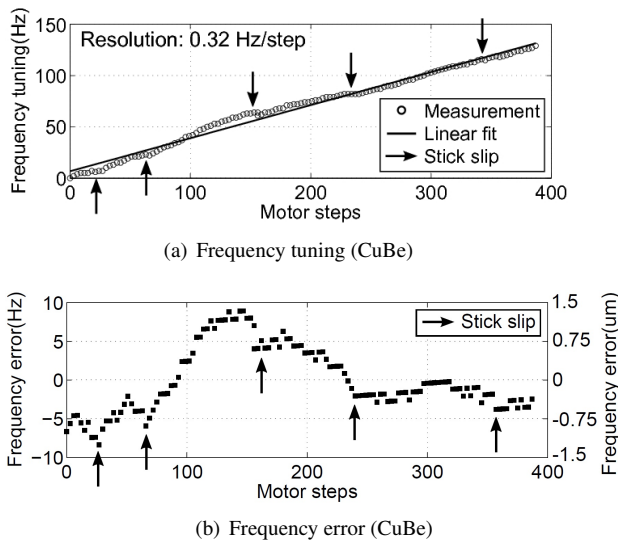
(a) Frequency tuning (CuBe)

(b) Frequency error (CuBe)

Figure 9: Measurement results of the CuBe plate.

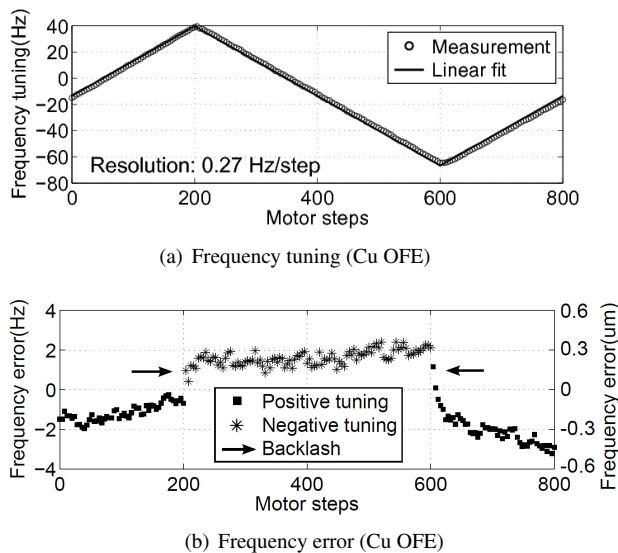(a) Frequency tuning (Cu OFE)

(b) Frequency error (Cu OFE)

Figure 10: Measurement results of the Cu OFE plate.

the desired coarse range of 37 kHz for the Cu OFE plate. This is perfect consistency between simulations and measurements. Compared to CuBe plate, the Cu OFE plate exhibited a more stable behavior during the test.

FINAL REMARKS

The frequency shift during the cool-down process of the HIE-ISOLDE high-β quarter-wave resonators has been characterized based-on measurements from the last two years. A much smaller coarse range of 36 kHz along with less sensitivity was then proposed. Therefore a simplification of the original tuning system was favored in order to reduce the production cost. Two prototypes of the simplified tuning plates have been designed, manufactured and coated with niobium at CERN. They were subsequently installed on the cavity and tested at 4.5 K. Both plates

were able to tune the cavity frequency linearly with the stepper motor control. The field and power requirements for HIE-ISOLDE were reached for both plates. The resolutions of both plates were measured to be much better than 0.5 Hz/step required by LLRF. However the measured coarse ranges at cold were lower than the design value for both plates which was due to restrictions set on the lever arm. The measurement results fit simulations perfectly for both coarse range and sensitivity. Given the large margin left for the resolution, we plan to enlarge the deformable area of the plate to increase the coarse range and lower the forces applied on the plate.

ACKNOWLEDGEMENTS

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