Physics Faculty Publications

Physics

2015

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DEVELOPMENT OF SRF CAVITY TUNERS FOR CERN*

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Abstract

Superconducting RF cavity developments are currently on-going for new accelerator projects at CERN such as HIE ISOLDE and HL-LHC. Mechanical RF tuning systems are required to compensate cavity frequency shifts of the cavities due to temperature, mechanical, pressure and RF effects on the cavity geometry. A rich history and experience is available for such mechanical tuners developed for existing RF cavities. Design constraints in the context of HIE ISOLDE and HL-LHC such as required resolution, space limitation, reliability and maintainability have led to new concepts in the tuning mechanisms. This paper will discuss such new approaches, their performances and planned developments.

INTRODUCTION

A new linear accelerator for the HIE ISOLDE project is currently under construction with the first cryomodule installed and being commissioned. Each cryomodule is composed of five superconducting quarter wave resonators (QWR), accelerating radio frequency (RF) cavities. Only the high-β cavities are described in this paper. The QWR are niobium sputtered, bulk copper substrate cavities, operated at 4.5 K. The operating frequency is 101.28 MHz for a 6 MV/m accelerating gradient with a power dissipation of 10 W on each cavity [1,2].

The HL-LHC upgrade requires crab cavities providing the deflecting field of 12-13 MV on the particle bunches at a frequency of 400.79 MHz. The bulk niobium cavities are operated at 2 K with a heat load of about 30 W. Two compact cavity designs with unconventional geometry are currently being developed: double quarter wave (DQW) and RF Dipole (RFD) [3,4].

The resonant RF frequency of a SRF cavity shall fit precisely to the operating frequency in order to limit the RF power required to drive it. The obtained resonant frequency will depend mainly on the dimensions and shape of the cavity and their changes during cool down. Material properties such as the RRR will have a much smaller influence on the frequency [5].

Geometrical variations due to the forming, welding and surface treatments made during the fabrication will result in a first frequency uncertainty. Stringent but realistic tolerances can be defined on the fabrication of the cavity to reduce the uncertainties. A well mastered chemical polishing combined with metrology and RF frequency measurements can improve the obtained tolerances. The precision of such measurements is however limited at room temperature due to temperature and air humidity variations.

The cool-down to the operating temperature will shift the frequency due to the thermal contraction of the components. Other environmental conditions [6] such as the vacuum conditions, helium pressure, constraints created by the support system in the cryostat and presence of mechanical vibrations can also introduce uncertainty on the resonant RF frequency.

Finally, during RF operation, Lorentz forces detune the cavity (Lorentz Force Detuning, LFD).

Facing realistic fabrication tolerances and added uncertainties, especially at the start of the production, a mechanical tuning system is required for both projects with a tuning range as large as possible. For the HL-LHC cavities, the tuner might also be required to tune the cavity away from the operating frequency when the cavities are not used during presence of beam. The cavities in both projects are operated in CW mode and require no fast pulsed tuning.

The technical solutions, status and performance of the mechanical tuners will be discussed in the next two sections for both projects.

HIE ISOLDE TUNER

During operation, the RF frequency of the QWR cavities of the HIE ISOLDE project should be within 0.5 Hz from the 101.28 MHz operation frequency. The frequency shifts from the copper substrate to the chemically polished and Nb-deposited cavity, cooled down to 4.5 K were well managed. From analytical predictions and experience during the start of the production it was possible to set a target frequency at room temperature, obtained by trimming the cavity length, changing the tip gap between inner conductor and the bottom plate, well described in [5]. To cover for the uncertainties on the production and cool-down, a tuning range of 36 kHz was aimed for by deformation of the bottom (tuning) plate. An optimisation was made on the nominal tip gap to have the best combination of tuning range, sensitivity and cost of the tuning plate design [7]. The tuning plate is machined from a 15 mm thick cold rolled Cu OFE UNS C10100 plate machined down to 0.3 mm thickness. The flat Nb-deposited plate is deformed up to 5 mm by pulling it down centrally. With an additional 0.6 mm pushing range this

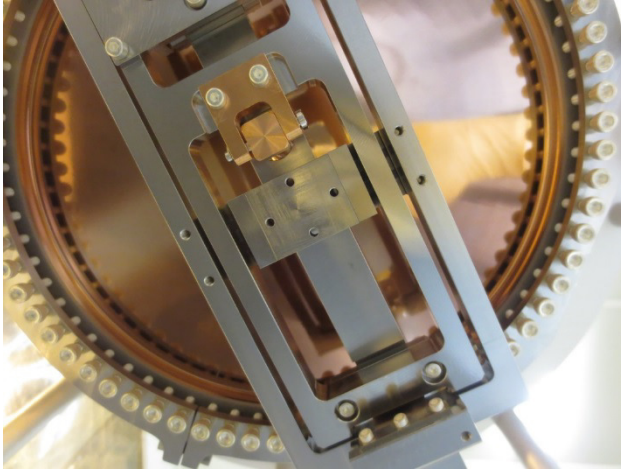results in a 39 kHz tuning range. The force required to deform the tuning plate by 5 mm is about 400 N.

Figure 1: The HIE ISOLDE tuning plate with lever mechanism.

The mechanical deformation of the tuning plate is created by an actuator placed outside of the cryostat. The actuator can be removed and exchanged without opening the cryomodule. A stepper motor creates a rotation that is transformed to a linear motion in a greased, steel (1.2210) single thread metric M6 lead screw with a 1 mm pitch. The nut is in bronze (C52100) and serves also as a linear bushing. The use of such a simple lead screw seems less adapted for the required frequency resolution. Tests with a first prototype, extensively used in the tests station showed however a 0.2 µm resolution and a 2 µm precision for small displacements, measured with an optical ruler sensor. Because of the low cost compared to a ball screw, the design adopted a lead screw.

This linear motion is transferred by a vacuum tight passage to a hinged rod connected to a lever system fixed at the bottom of the cavity (Fig. 1), attached to the clamping ring that clamps the tuning plate on the cavity. The lever mechanism inverses the upward motion of the pulling rod to a downwards pulling on the centre of the tuning plate. In addition, the mechanism reduces the motion by a factor of about 10 in order to lower the external force required to deform the plate to 40 N. The alignment system of the cavities limits the accepted external force to 100 N per cavity. The levers also increased the resolution of the motorisation.

The available space inside the cryomodule under the cavity demanded a very compact design of the lever system. The final design has only a maximum height below the cavity of 80 mm for a 56 mm motor excursion. The mechanism consists of two lever arms mounted each on an axis (Fig. 2). Both axes are mounted on the same support. A flexible connection transmits the motion of the first lever to the second lever in a frictionless way. The layout of axis position and lever arm length was chosen such that the displacement between the two levers at the connection is as small as possible, representing a so called virtual pivot. A flexible connection is placed at this position that

transmits the motion of the first lever arm to the second lever. The connection between the two levers is hence frictionless. A ridge on the outer lever is mounted inside a groove on the inner lever with a small clearance. In case of failure of the flexural connection, the ridge will make contact in the groove and the lever system will continue to work in a frictional way.
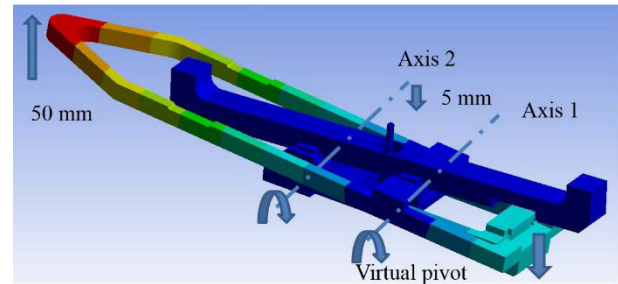

Figure 2: Lever mechanism with virtual pivot.

Because of the vacuum and its effect on friction, mechanisms with sliding friction would not be compatible with the required resolution. For the nominal deformation of 5 mm of the tuning plate, the first axis will turn over 8.5 °, the second axis over 4.2 °. The angles are rather high in order to find a solution with flexural guides. In addition, the reaction forces acting on the axis are 178 N on axis 1, 261 N on axis 2 for a 400 N tuning plate load. The first condition of a large angle would require a highly flexible flexural guide, the second condition would require a stiff flexural guide. The so-called "butterfly" pivot [8] with the largest range of angular stroke is not perfect to adapt in the available space with a certain position stability of the rotation axis under the reaction forces, but still possible. The cost, lack of robustness during transport and reliability issues made the butterfly pivot less attractive. Such considerations are described in [9].

The selected solution are rolling rotary couplings, also known as knife edge pivots [10], often used in high precision balances. In such pivots (Fig. 3) a part with a sharp edge is in contact with a concave surface.
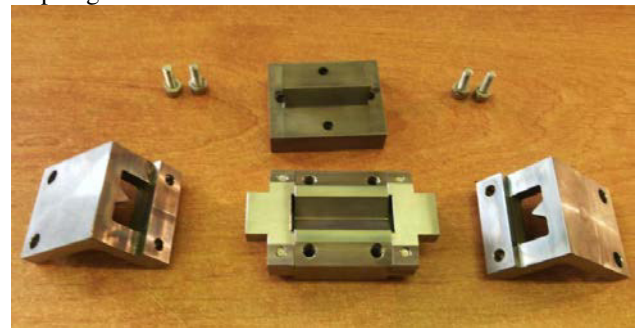
Figure 3: HIE ISOLDE knife edge pivot.

With a sufficient friction coefficient, a torque around the edge will result in rolling around the edge without sliding and hence with no frictional or stick slip effects to deteriorate the precision. Such pivots have a very low rotational stiffness but a very high stiffness perpendicular to the axis. The absence of lubricants and wear created particles make them well adapted for UHV and cryogenic

temperatures [11]. The pivots are in Titanium grade 5 because of the moderate Young modulus (compared to steel or sapphire) and thus lower Hertz pressure but high yield stress.

Obtained Results

The tuner was extensively tested in a test station on each separate cavity during the production for cryomodule 1. A resolution of 0.1 Hz/step was reached with 8000 micro-steps in a full range of 39 kHz. Figure 4 shows 100 small cycles of about 4 Hz. A drift of about 3 Hz occurred during the cycles due to pressure variations. The hysteresis was better than 20 Hz.step, surface normalised to a 1 Hz cycle or 2 Hz corresponding to 0.3 µm maximum difference between the curves up and down for 60 steps. For all tested cavities it was possible to tune to the exact frequency. In the first cryomodule, each cavity is brought to the right frequency and operated with a 3 Hz bandwidth (~ 30 steps). The low level RF control keeps the cavity on tune by making continuously fine adjustments of a few steps.
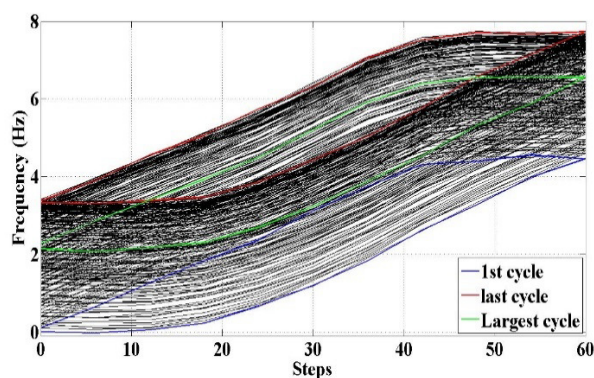

Figure 4: Small frequency cycles on a HIE ISOLDE cavity.

HL-LHC CRAB TUNER

The resonant RF frequency of the DQW and RFD HL-LHC crab cavities should precisely fit to the operating frequency of 400.79 MHz with a resolution better than 0.5 kHz. In order to determine the tuning principle, the different frequency sensitivities to dimensions or shapes of different parts of the cavities were calculated. The elastic deformation of each dimension gives the reachable tuning range. The final choice of the tuning principle is based on the range, the space in and around the cryomodule, required forces and their effect on the alignment of the centre of the cavity. Coincidentally, for both DQW and RFD, the selected tuning principle is the symmetrical displacement between two plates of the cavity, in the vertical direction.

For the RFD (Fig. 5), the tuner deforms, symmetrically around the centre, the outside horizontal plates with a calculated sensitivity of 345 kHz/mm for a distance change measured between the plates. For the DQW, the distance between the central plates is symmetrically changed with a sensitivity of 186 kHz/mm.

The actuator induces a relative motion between the two thin walled concentric tubes, a design previously used in CEBAF [12]. The inner tube is connected through a helium tight bellow on the helium vessel and a rod to the top part of the cavity, the outer one is connected to a frame surrounding the dressed cavity. The bottom part of the cavity is connected to this frame. The actuator displacing the two tubes is floating on load compensating springs. A relative displacement between the two tubes will hence create a symmetric deformation of the cavity.
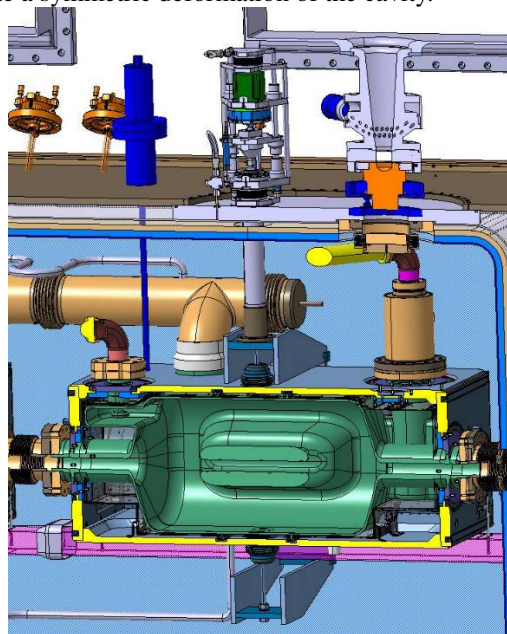

Figure 5: The HL-LHC RFD crab cavity with tuner.

Finite Element (FE) analysis was made to evaluate the tuning stiffness of the cavity with helium tank and the stresses induced, to estimate the possible tuning ranges for DQW and RFD. With the elastic limit of Nb at 2 K (400 MPa) and a safety factor of 1.2, a range of ± 0.31 MHz (± for push and pull) for a displacement of 1.7 mm between the plates was calculated for the DQW and ± 0.980 MHz for a displacement of 2.8 mm for the RFD. The tuner has to provide a tuning force of 2.2 kN/mm for the DQW cavity and 2.5 kN/mm for the RFD. Such numbers shall still be - given the number of parameters not yet measured- confirmed on the first prototypes. The range could be further limited by the final implementation of the electron beam welded connections between the cavity and the push-pull rods. Because of the rather small tuning range, a manual pre-tuning system was foreseen in the design with an additional elastic tuning range of ±0.150 MHz (at room temperature) on the DQW cavity by acting on the central plates.

The actuating system that displaces the tubes is placed on top of the cryomodule, at room temperature, under atmospheric pressure and accessible for maintenance. A stepper motor with a high resolution (1.8 °/motor step) is coupled with a frictional Oldham coupling to a harmonic gear with a 100:1 ratio. A planetary roller screw, allowing a smaller lead (1 mm) compared to a ball screw, transforms the rotation in a linear motion, guided by linear roller

bearings on precision guides. The roller screws were selected instead of ball screws because of a longer life cycle (for the same load and duty cycle) due to a linear instead of a punctual contact. This could be beneficial under degraded lubrication due to radiation. The absence of recirculation failure modes is another advantage.

One motor step results in a theoretic displacement resolution of 0.1 µm or a frequency resolution of 20 Hz for the DQW and 35 Hz for the RFD. Micro-stepping can further increase the resolution but this will be at some point limited by the angular precision of the harmonic gear corresponding to 10 nm and friction in the roller guides.

A first prototype (Fig. 6) was built for testing the frequency tuning on a first proof-of-principle cavity in a test station.

Figure 6: Prototype tuner actuator.

With the motor components in this first design, the limit actuator force capacity is determined by the harmonic gear box at 7.7 kN dynamic force, compatible with the values mentioned above. The stepper motor has sufficient torque (1.3 Nm) and the detent torque makes the motorisation self-locking when the stepper motor is not powered.

Two potentiometers with a resolution of 10 µm measure the position of the two concentric tubes and the position of the floating motor with respect to the vacuum vessel. In addition, two limit switches and two mechanical stops are present to protect the cavity. Finally, a force sensor is added to measure the tuning force as an additional information. With the tuning stiffness of the cavity, this force sensor can measure the tuning displacement with about 1 µm resolution and should give useful information on backlash and hysteresis.

A pressure compensation feature was added to the motorisation. The vacuum in the cryomodule exerts a non-negligible force on the section of the tuner motorisation. As the motorisation should be floating in order to produce a symmetric cavity deformation, the vacuum force is not transferred to the vacuum tank. The load compensating springs visible on Fig. 6 are much less stiff compared to the cavity and the vacuum force is transferred to the cavity. Without pressure compensation, the vacuum force would pull down the motorisation, creating a force on the cavity, changing its frequency and alignment. With the bellow section of the prototype, there would even be a risk of locally plastifying the cavity at room temperature. A pressure compensating bellow with the same section as the tuner vacuum passage bellow (Fig. 6) was therefore added in the motorisation, connected to a vacuum port to make the design less sensitive to vacuum or atmospheric pressure changes.

The size of the prototype is vertically too large for integration in the cryomodule. A smaller motorisation was therefore designed for crab cavity testing in the SPS, as can be seen in Fig. 5. This design is also dismountable without having to open the cryomodule.

First measurements on the tuner motorisation without load were made with 400 micro-steps per motor turn on the prototype. The tuning displacement between the two concentric tubes was measured with a LVDT. The resolution estimated from linear interpolation is 0.03 µm/step, measured over a range of 1 mm. The hysteresis as a difference between the push and pull direction at the same position on a 1 mm cycle is about 60 µm. Frictional effects and backlash were observed on cycles of 2.5 µm and 25 µm. The measured steps were systematically smaller than expected from the resolution and with irregular size. The actuator performed better in the push direction although there was no load. In this direction the actuator was pushing inwards the LVDT, against the spring suggesting a possible influence of the sensor. The noise level and drift of the sensor was between 0.1 and 0.2 µm. With some sensor averaging, the measurements show that for the first measurements, the smallest effective actuator step or actuator resolution is about 0.1 µm and the precision in small adjustment cycles is about 0.5 µm (100 Hz for DQW and 175 Hz for RFD). Although this should be sufficient to tune the crab cavities (< 500 Hz), a better precision would give an overhead to changing requirements and would result in an easier RF frequency control. More measurements are required to distinguish actuator and sensor effects and to identify the performance of each component. Especially the over-determined three ball bearings on precision guides and the load compensating springs will be looked at as they introduce friction after the roller screw and harmonic gear. They should possibly be replaced by flexural guides. The design of a more elaborate test bench has started, including the possibility to test the tuner against a spring load corresponding to the stiffness of the cavity. The test bench shall also allow to make fatigue tests and calibrations and

the results should lead to an improved design of the smaller tuner motorisation mentioned above.

In the prototype and the design with reduced size for the tests in the SPS, there is for the moment no piezo for precise and fast frequency changes. The LFD at the nominal field is kept small in the design of the cavity ($\leq$ 0.6 kHz) but the cavity shall remain sufficiently on resonance when the power is increased. If such changes are made during a sufficiently slow ramp, the tuner actuation can follow, if not a piezo shall be implemented. A fast change could also be required for machine protection, during the failure of a cavity e.g. during a quench.

The implementation of a piezo might improve the precision of the motorisation unless the observed friction and hysteresis is created by the ball bearings. Available space, cost and reliability could be parameters against the use of a piezo. Finally, even a preloaded piezo should be used under compression, in the push direction, i.e. that the mechanically available tuning range would be divided by a factor 2.

CONCLUSION

Mechanical RF tuners are used on the HIE ISOLDE and HL-LHC crab cavities. For both projects it was preferred to place the motorisation outside of the cryomodule, at room temperature and at atmospheric pressure in order to avoid frictional problems at low temperature, under vacuum and to increase the reliability. In addition, the actuator is designed to be dismountable for a full exchange without necessity to open or transport the cryomodule. Any breakdown requiring repairs would mean a lengthy and costly disassembly and transport to the clean room (for HIE ISOLDE) with significant machine downtime. Therefore features are also added on the tuners inside the cryomodule to ensure reliable operation and possible operation under degraded conditions.

The HIE ISOLDE RF cavity tuner was designed with a lever system mounted on the cavity with minimal friction based on knife edge pivots and a flexural connection, dividing the motion but also the resolution and precision of the motorisation by 10. The tuning precision of 0.1 Hz per tuner step was largely sufficient to tune all the cavities to the right frequency and allowed the RF tuner to be used in the LLRF control for the first cryomodule that is currently being commissioned.

The motorisation components for the HL-LHC crab cavities, such as harmonic drive, roller screws and roller bearings on precision guides are more advanced compared to the HIE ISOLDE motor components, in the first place due to the higher required tuning forces. First resolution and precision measurements without load were made on a prototype and gave reasonably good results for an actuator with ball bearings. Additional testing and a more elaborated test bench are planned in order to further improve the performance. The use of flexural guides will be studied. Such an upgrade would also be required to fully benefit from the implementation of a more precise piezo actuator, an implementation in the first place for fast cavity tuning. First tuning tests at 2 K on a proof-of-principle DQW crab cavity in a test station are planned for November 2015.

ACKNOWLEDGMENT

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