STATUS OF THE HL-LHC CRAB CAVITY TUNER*

K. Artoos†, L. Arnaudon, R. Calaga, E. Cano-Pleite, O. Capatina, T. Capelli,
D. F. Cartaxo dos Santos, M. Garlasché, D. C. Glenat, A. Krawczyk[1], R. Leuxe, P. Minginette,
J. A. Mitchell, B. Prochal[1], J. S. Swieszek, CERN, Geneva, Switzerland
S. Verdu-Andres, BNL, Long Island, New York, USA
T. J. Jones, STFC/DL, Daresbury, UK
[1]also at IFJ-PAN, Krakow, Poland

Abstract

The resonance frequency of the HL-LHC Double Quarter Wave (DQW) and Radio Frequency Dipole (RFD) crab cavities is tuned to the operating frequency of 400.79 MHz. For both types of cavities, the tuning principle foresees a symmetric mechanical deformation of parts of the cavities in vertical direction, with the tuner motor placed outside the vacuum, on top of the vacuum vessel. The tuner design was successfully tested on the DQW prototype cryomodule with two cavities in 2018 in the SPS at CERN. This paper describes the design of DQW and RFD crab tuners. The experience and results of assembly and cold testing are given together with some required improvements.

INTRODUCTION

The High Luminosity upgrade of the CERN Large Hadron Collider (HL-LHC) will be installed in 2024-2025. The upgrade aims at increasing the integrated luminosity [1]. One of the key components that contribute to this increase are the RF compact crab cavities that will be placed on both sides of Interaction Points (IP) 1 (ATLAS) and 5 (CMS). Each cavity will apply a transverse kick of 3.4 MV at 400.79 MHz in order to rotate the bunches for a better overlap when they cross at the IP. This results in a higher number of collisions [2]. There are two crab cavities per beam on each side of the IP. Each pair is mounted in a cryomodule to cool the cavities to 2 K, i.e. four cryomodules per IP. Two compact cavity designs in bulk niobium with unconventional geometries are used for the HL-LHC: the Double Quarter Wave and the RF Dipole [3, 4]. The transverse field is vertical for the DQW (IP5) and horizontal for RFD (IP1).

The fundamental mode RF frequency of the crab cavities shall precisely fit to the operating frequency. The frequency of each cavity will depend on the exact dimensions and shapes of the different cavity parts, carefully managed during the fabrication steps. The cavity parts are formed from niobium plates, trimmed and electron beam (EB) welded together, followed by chemical etching. The cavity is assembled by bolts and welds into the titanium grade 2 helium vessel, forming the “jacketed cavity” [2].

Even with realistic tolerances, careful metrology and intermediate RF measurements, some uncertainties on the RF frequency of the cavity will remain. More uncertainties are introduced during the assembly in the cryomodule, the cool down to the operating temperature of 2 K and other environmental conditions such as helium and atmospheric pressure fluctuations. Mechanical vibrations and Lorentz forces can dynamically alter the frequency of the cavity. Finally, adjustments of the frequency are required when the machine is operated at a different beam energy, i.e. at a different operation frequency. Due to the above, a mechanical tuning system is used for DQW and RFD crab cavities to tune the cavity to the required frequency as precisely as possible to limit the RF power driving the cavity.

CRAB CAVITY TUNER PRINCIPLE

The DQW and RFD cavities are actively tuned during operation by the symmetric deformation of two walls of the cavity, in the vertical direction. The choice of the tuning principle is based on the elastic tuning range available, the required forces, the integration in the cryomodule and the effect on the alignment of the centre of the cavity.

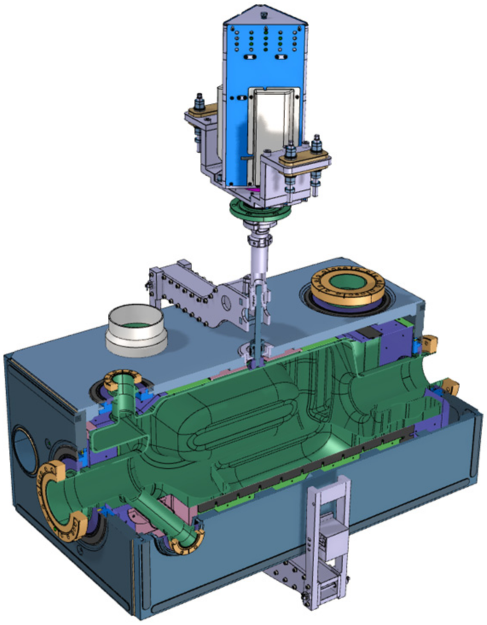

Figure 1: Cut-away view of the RFD tuner.

The tuner actuator creates a relative motion between two concentric tubes (or tuner tubes), a design inspired by the CEBAF tuner [5]. The top and bottom tuning rods that deform the cavity are mounted to NbTi connection parts that are EB welded to the cavity walls. For RFD cavities, the cavity body perpendicular to the poles are deformed (see Fig. 1), while for DQW the poles are deformed

---

*Research supported by the HL-LHC project
†Kurt.Artoos@cern.ch

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-TUP081

(see Fig. 2). The tuning rods are equipped with edge-welded titanium bellows for a linear motion feedthrough in the helium vessel walls. The inner tuner tube is connected to the top tun-ing rod; the outer tube to the tuning frame surrounding the helium vessel. This tuning frame is connected to the bottom tuning rod. The tuner actuator is floating on load compensation springs, creating a symmetric deformation of the cavity as far as the top and bottom of the cavity have the same stiffness. The tuner design allows working in both push and pull direction.

Finite element (FE) models were made [6-8] to determine the tuning sensitivity, mechanical stiffness, elastic range of the cavity and the required tuning forces (see Table 1). The ± sign indicates the push and pull direction. The deformations are total symmetric cavity deformation, i.e. displacement between the poles or between opposite cavity walls. The thickness of the cavity walls after shaping and chemical polishing is taken into account in the models for completeness. The differences with respect to calculations with the initial thickness of 4 mm was about 5 %.

Table 1: DQW and RFD Tuning Characteristics

	DQW	RFD
Tuning sensitivity (kHz/mm)	318	530
Cavity stiffness (kN/mm)	2.40	3.15
Tuning range at 2 K (mm)	±1.60	±2.45
Tuning range at 2 K (kHz)	±509	±1300
Tuning range force (kN)	±3.8	±7.7

The tuning ranges in Table 1 make use of the full available elastic deformation of the cavity at 2 K to have as much margin as possible to deal with frequency uncertainties. This maximum deformations and required forces are used to design the tuner components. The elastic limit of niobium at 2 K used in the calculations is 333 MPa, including a safety factor of 1.2. The real elastic limit will however depend on the level of work hardening during the shaping process and is higher.

The RFD cavity has a reinforcement on the part that is deformed by the tuner to increase the strength against pressure. An analysis was made to optimise the tuning sensitivity with respect to pressure sensitivity and Lorentz Force Detuning (LFD) [7].

DQW Pre-Tuner

Due to the rather limited tuning range, two (top and bottom of cavity) manual pre-tuning systems are implemented in the DQW cavity design (Fig. 2). This enables the readjustment of the cavity frequency after the helium vessel assembly. The pre-tuner device also reinforces the cavity against the helium pressure. As shown in Fig. 2, four NbTi connectors (1) are EB welded to the cavity wall, in the outer radius region of the bowl part of the cavity (top and bottom). The pre-tuner parts, mounted on the connectors, exit the helium vessel through bellows (2). Finally, M8 push and pull screws (3) between an outer part fixed to the helium vessel wall (4) and the pre-tuner, are used to deform the cavity. The same deformation is applied on the top and bottom pre-tuner in order not to change the centre of the cavity.

The calculated pre-tuner sensitivity [6] is 1046 kHz/mm. An elasto-plastic FE analysis estimates the available pre-tuning range. The base line approach is a fully elastic pre-tuning, but a plastic deformation followed by a release of force is also possible without exceeding a 2 % total plastic strain. The deformation range, required forces and elastic limit depend on the exact cavity wall thickness after shaping, chemical polishing, and the amount of work hardening. The elastic range of the DQW pre-tuner corresponds to around ±400 kHz (push-pull), the plastic range with released force corresponds to maximum ±1 MHz.

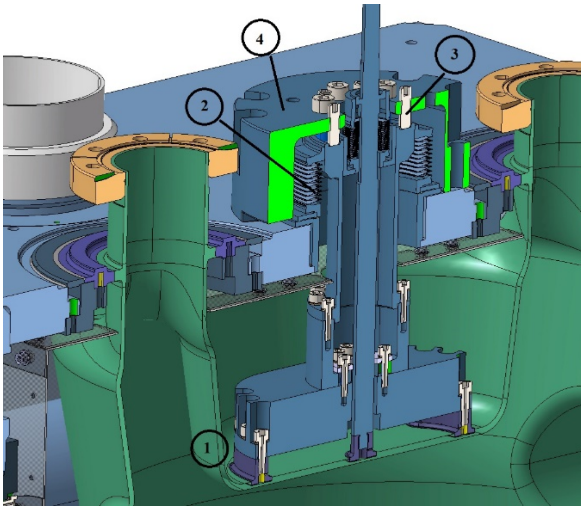

Figure 2: Cut-away view of the DQW cavity with pre-tuning device.

The practical approach for the pre-tuning of the two DQW cavities for the SPS test was based on torque and RF measurements. The frequencies of SPS test DQW1 and DQW2 cavities were increased respectively by 300 and 400 kHz, with a pre-tuning precision of about 20 kHz.

Tuner Linear Actuator

The tuner linear actuator (see Fig. 3) that creates a relative motion between the two concentric tubes is placed on top of the cryomodule, at room temperature and atmospheric pressure. It is thus accessible for maintenance in situ. A 1.3 Nm hold torque bi-phase stepper motor (1) with 1.8°/ motor step, is coupled with a frictional Oldham coupling (2) to an elliptical type gear (3) with a 100:1 ratio. The gear contains a bearing that holds the longitudinal tuning force. A planetary roller screw (4) with a 1 mm lead transforms the rotation in a linear motion. The motion is guided by linear roller bearings (5) mounted on precision guides to protect the roller screw and gear against bending moments and lateral forces. The relative motion is transmitted to the two tuning tubes by a vacuum feedthrough with two concentric bellows.

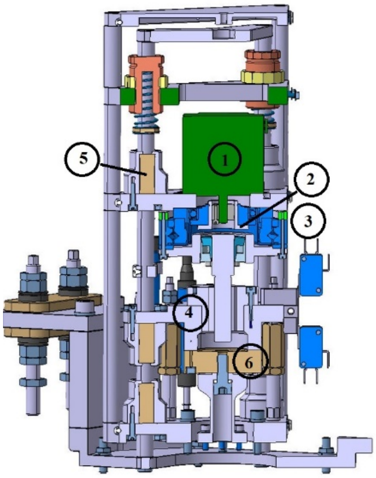

Figure 3: Cut-away view of the linear actuator.

The motor is operated in micro stepping mode with 8000 steps/turn (theoretic 1.25 nm at the exit of the actuator). The precision is however limited by the repeatability of the gear and the roller screw, as well as by the friction present in the linear bearings. The required motor torque M at constant speed for the maximum RFD required force F without gear would be 1.6 Nm, for the DQW 0.8 Nm. With the gear, the required motor torque is 0.016 Nm for RFD, 0.008 Nm for DQW (efficiency η gear 0.95, roller screw 0.79). This is smaller than the motor detent torque of 0.04 Nm, meaning that with the gear, the tuner is self-locking and the current can be lowered when the position is reached.

$$M = \frac{F_{max} ScrewLead}{2\pi \eta_{Screw} \eta_{gear} Gear\ ratio}$$

The torque calculated above is at constant speed. A significant additional torque is required to accelerate motor and gear with their inertia. The motor steps are sent at a certain number of steps per second, without ramp. From standstill, this requires a certain acceleration to reach the wanted motor position in time. A smaller motor would limit the available tuning speed. A piezo tuner to compensate fast changes was not implemented for the first DQW SPS tests, as it was not expected to be required.

The cables to the stepper motors are long, even well over 100 m in the SPS test stand. This can create overvoltage and transmission problems [9]. Low capacitance cables, low motor speed and micro stepping mitigate this problem.

In the prototype linear actuators, a potentiometer was installed to measure the relative displacement of the actuator. Two electromechanical limit switches and mechanical stops are present to protect the cavity. A force sensor (Fig. 3 (6)) in the linear actuator measures the tuning force applied to the cavity. With the stiffness of the cavity and the tuning frame, the force sensor has a better displacement resolution than the potentiometer. In addition, trigger levels on the load cell conditioner are used to implement an overload interlock on the cavity tuner. The replacement of the potentiometer by an encoder is being examined.

Tuner during Thermal Cycles

An important aspect is the much lower elastic limit of niobium at 300 K (65 MPa), compared to 2 K. At 300 K, the elastic tuning range is reduced to 0.3 mm (DQW) and 0.5 mm (RFD). It is for this reason important to return the tuner to the neutral position before warm-up. The available range at room temperature will be further reduced by deformations created by the tightening of the tuner last coupling and the setting of mass compensating springs during the tuner assembly. The connection of the last component will close rigidly the tuner around the two cavity sides. A conical coupling connects gear and roller screw in order to limit the deformation of the cavity at this last step.

The differential pressure between the outside and inside of the vacuum vessel creates a force on the tuner vacuum feedthrough bellows. Due to the floating tuner actuator, the cavity supports this force. In the first prototype, a pressure compensation bellow was applied [10]. With the bellow effective surface reduced to the minimum, the force acting on the cavity is 258 N. This results in a sufficiently low stress in the cavity (11 MPa for DQW and 5 MPa for RFD) and pressure compensation is no longer needed. This made available more space for the actuator.

Large temperature differences between tuner components at the start of a cool down could also lead to forces on the cavity. Both inner and outer tuner tubes are however thermalized by copper heat interceptors to the cryomodule thermal screen. The tuning frame is thermalized to the helium vessel by the tuning rod and flexural guides (see next section). Moreover, the elastic limit of the cavity will quickly increase when it cools down.

TUNER DESIGN

Several parameters such as modal behaviour, buckling, pressure sensitivity, Lorentz Force Detuning (LFD) and thermal factors determine the design of the tuner components. To avoid detuning of the cavity and misalignments during cool down, the materials selected minimize differential contraction. The tuning frame and helium vessel tank surrounding the cavity are in titanium grade 2 because of the similar thermal contraction as niobium between room temperature and 2 K. The concentric tuning tubes are in stainless steel EN 1.4429, the same material as the cavity support.

Mechanical modes in the structures surrounding the cavity can be excited and generate displacements transmitted to the cavity, resulting in dynamic detuning or so called micro phonics. This is particularly a concern for the tuner device, directly connected to the cavity. In general, the displacements will be smaller at higher frequencies. Therefore, the tuner design focussed on increasing the frequency of the vibration modes by increasing stiffness and decreasing mass. The safety factor for linear buckling of the tuner is another factor acting on the stiffness of the tuner components. A parametric optimisation with Catia™, CadNexus™ and Ansys™ was performed for the design of the tuning frame. The main dimensions of the components were parametrised to minimise the mass, while maximising stiffness and buckling load multiplier.

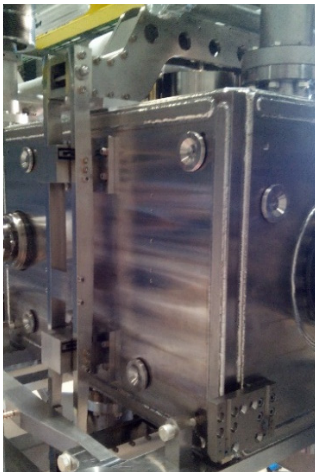

Figure 4: Tuning frame and flexural guides on the DQW helium tank.

Two lateral and longitudinal (with respect to the beam axis) vibration modes of the tuner frame were initially the lowest modes with frequencies around 10 Hz [11]. Flexural guides were therefore added between the tuner frame and the helium tank (see Fig. 4). The flexures were designed to have a low stiffness in the tuning direction and a high stiffness in longitudinal and lateral directions. They were produced by electro discharge wire cutting in titanium grade 5, with a flexure thickness of 0.7 mm. Figure 5 shows the flexure used for the DQW in the SPS test (left), on the right is the improved design with lower stresses: 335 MPa for 4 mm deformation in the tuning direction. The stiffness is hundred times higher in longitudinal and twenty times in lateral direction. The addition of four flexural guides increased the frequency of the frame-on-cavity modes to above 40 Hz. The guides also increased the linear buckling safety factor.

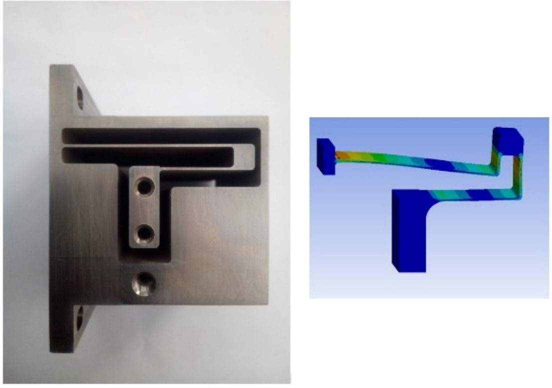

Figure 5: Flexure guide design.

Further increasing the buckling safety factor would require a reinforcement of the tuner tubes, especially the inner one. The design of the two tubes must however minimize the heat transport from room temperature to the 2 K bath. Thermal links are placed between the inner and outer tube and the thermal screen at 70-80 K (Fig. 6).

Figure 6: The concentric tuning tubes with thermalisation.

The tolerances on the cavity and the tuner components combined with long lever arms result in misalignments and possible assembly offsets in the range of millimetres. To avoid large frequency changes during assembly, a design with spherical in conical jointed connections was made that allows offsets and misalignments. The frequency shift after full installation of the SPS DQW tuners was smaller than 20 kHz.

DQW SPS TESTS

A first prototype cryomodule assembled in 2017 with two DQW cavities was successfully tested with a proton beam in the SPS in 2018 [12]. Before the installation in the SPS, the cryomodule was cooled down in the SM18 facility to test the mechanical and cryogenic performance. The tuner operation was verified on both cavities. Due to the difference between injection and maximum beam energy, a frequency span of 300 kHz is required for the crab cavity frequency in the SPS test. The target frequency after cool down at the neutral position (without tuner displacement) was set at 400.65 MHz to split the frequency span in ±150 kHz (push and pull). At 2 K, DQW1 and DQW2 reached respectively 400.6 and 400.65 MHz.

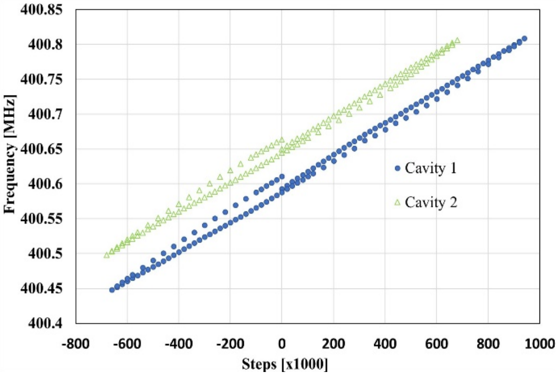

Figure 7: Tuner 300 kHz cycle at 2 K.

Figure 7 shows the complete tuning range of 300 kHz (even 360 kHz for DQW1). The hysteresis of around 20 kHz on a 300 kHz cycle is sufficiently small. Linear interpolation of the 300 kHz cycle and a small 200 Hz cycle with steps of 20 Hz, indicate a resolution of 0.21 Hz/step with a standard deviation of 0.07 Hz. The calculated tuning sensitivity is 0.27 Hz/step (taking into account the calculated stiffness and frequency sensitivity). No clear backlash is observed when going through the neutral position but this was done in rather large steps. The backlash in the roller screw used is given to be about 10 µm corresponding to 3 kHz for DQW. For operation in the HL-LHC, where the frequency change due to beam energy increase is smaller, it is more advised to set the target frequency such that the tuner operation will only work in push or pull direction.

The cryomodule installation in the new SPS RF test facility, beginning 2018, was followed by commissioning of the technical infrastructure. The testing with beam started at the end of May with successful crabbing of the SPS beam. The two tuners performed in the same way like during the tests in SM18 and the frequency of both cavities could be precisely set. Beginning of October, the force cell of cavity DQW1 started to indicate a much higher load increase when tuning and would trigger the overload protection. After stopping the tuner, the force would then gradually decrease again. The frequency change per number of steps corresponded however still to 0.21 Hz/step and the tuner could still be used. After some weeks, the conical coupling between motor and gear started to slip because of the higher forces and the tuner went out of service. In the same period, cavity 2 started to show the same problem but with a smaller load increase and no slipping. The possible causes were examined such as possible ice formation in the tuner bellows on the vacuum vessel due to the failing of a heater. Clearances with surrounding thermal screen components are small and a component might have shifted. A bearing in the motor might block when lateral forces are too high. The reason of the problem is not yet confirmed. The possible causes are being studied and are taken into account in the update of the design.

Lessons Learnt

The assembly of the SPS DQW cryomodule gave valuable input for the design of the tuner. Some connections will be reworked and the clearances between parts will be increased. The most important design input came from the SPS tests. The access to the linear actuator situated under the RF wave-guide is too difficult and only possible from the tunnel side. The tuner instrumentation needs to be dismounted to give access to the connections to the tuner tubes and the connecting screws at the back of the tuner are very hard to reach. The conical coupling between motor and gear was weaker than the catalogue value due to an intermediate part with insufficient stiffness. More reliable, non-frictional couplings that still respect the required alignment tolerances are under study.

Finally, the necessity of an additional piezo tuner was questioned after the observation of a possible excitation of a vibration mode of the cavity. This will be studied in the next months.

CONCLUSION

The paper describes the tuning principle selected for the DQW and RFD HL-LHC crab cavities and the components involved. The available tuning ranges are calculated in FE models for the elastic range of the deformed cavity walls. The smaller DQW tuning range is enhanced with a manual pre-tuning device used at room temperature after the assembly of the cavity with helium vessel. The design of the linear actuator and tuner components is explained with respect to resolution, stiffness, assembly precision, vibration modes and buckling. The successful tests of the first DQW cryomodule in the SPS with precise frequency control confirms the tuner design principle. The target frequencies after cool down were reached precisely. A problem of blockage and slipping of a coupling observed at the end of the tests triggered design modifications to improve reliability and access for maintenance of the crab tuner.

REFERENCES

[1] HL-LHC Technical design report, CERN Yellow Reports Volume 4/2017.

[2] R. Calaga, “Crab Cavities for the High-luminosity LHC”, in *Proc. 18th Int. Conf. RF Superconductivity (SRF'17)*, Lanzhou, China, Jul. 2017, pp. 695-699. `doi:10.18429/JACoW-SRF2017-THXA03`

[3] S. Verdú-Andrés *et al.*, “Design and Prototyping of HL-LHC Double Quarter Wave Crab Cavities for SPS Test”, in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 64-66. `doi:10.18429/JACoW-IPAC2015-MOBD2`

[4] S. U. De Silva, J. R. Delayen, H. Park, Z. Li, and T. H. Nicol, “Design and Prototyping of a 400 MHz RF-dipole Crabbing Cavity for the LHC High-Luminosity Upgrade”, in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 3568-3571. `doi:10.18429/JACoW-IPAC2015-WEPWI036`

[5] V. Nguyen *et al.*, “Frequency tuning of the CBAF upgrade cavities”, in *Proc. PAC’99*, New York, USA, 1999, pp. 928-930, paper MOP114.

[6] S. Verdú-Andrés, ACE3P calculation DQW tuning sensitivity, private communication.

[7] E. Cano Pleite *et al.*, “Numerical evaluation of the tuning, pressure sensitivity and Lorentz force detuning of RF superconducting crab cavities”, in *Proc. COMSOL conference*, Lausanne, Switzerland, 2018.

[8] E. Cano-Pleite *et al.*, “An Insight on the Thermal and Mechanical Numerical Evaluations for the High-Luminosity LHC Crab Cavities”, presented at the 19th Int. Conf. RF Superconductivity (SRF'19), Dresden, Germany, Jun.-Jul. 2019, paper THP036.

[9] R. Picatoste Ruilope, “Modelling and control of stepper motors for high accuracy positioning systems used in radioactive environments”, PhD Thesis CERN, Politécnica de Madrid, 2014.

[10] K. Artoos *et al.*, “Development of SRF Cavity Tuners for CERN”, in *Proc. 17th Int. Conf. RF Superconductivity (SRF'15)*, Whistler, Canada, Sep. 2015, paper THPB060, pp. 1247-1251.

[11] T. J. Jones *et al.*, “Development of a Novel Supporting System for High Luminosity LHC SRF Crab Cavities”, in *Proc. 18th Int. Conf. RF Superconductivity (SRF'17)*, Lanzhou, China, Jul. 2017, pp. 304-308. `doi:10.18429/JACoW-SRF2017-MOPB104`

[12] R. Calaga, O. Capatina, and G. Vandoni, “The SPS Tests of the HL-LHC Crab Cavities”, in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 846-849. `doi:10.18429/JACoW-IPAC2018-TUPAF057`