

# OVERVIEW OF RECENT TUNER DEVELOPMENT ON ELLIPTICAL AND LOW-BETA CAVITIES

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## Abstract

This paper aims to provide an overview on the latest advances of tuner development for SRF applications. Issues and present approaches on how to resolve them will be emphasized for both TM and TEM cavities and examples from various labs and projects (XFEL, LCLS-II, ESS, SPL, ARIEL, SPIRAL2, FRIB, ANL, IFMIF) will be given in order to better explain issues and solutions.

## TUNERS FOR SRF STRUCTURES

Tuning SRF structures poses peculiar challenges to designers, mainly due to the subject overlapping different disciplines as mechanics, radiofrequency, cryogenics, controls and electronics.

Operating a cavity steadily at its set point within usually strict, project-driven, field amplitude and phase stability limit involves, as of the current state-of-art techniques, an interleaved combination of Low Level RF control on forward power, quasi-static (slow) tuning mechanism and a fast tuning action in the  $\mu$ -meter range. Beforehand, the most effective way to avoid tune disturbances comes from cavity and cryomodule design by either decoupling or damping the contribution of largest resonant modes in the system.

In view of a global overview of various tuning systems for different accelerating machines, some general considerations about the tuner design are here recalled:

- **Deformation vs. Insertion:** a bulk and heavy structure is required to deform an SRF structure but this tuning scheme can preserve cavity RF shape (within its elastic limits). On the other end, light and simple plunger-like solutions directly induce local perturbations in the RF field regions, therefore surface properties become crucial.
- **Continuous Wave (CW) vs. Pulsed RF:** while stochastic background noise or microphonics (MP) will be the main disturbance in the former scenario, synchronized Lorenz Force detuning (LFD) issue will likely be dominating in the latter. A much simpler, feed-forward control scheme is enough to provide a satisfactory compensation in case of LFD.
- **Large loaded Q (Ql) vs. Large bandwidth:** where a large Ql is set by the project, the resonator bandwidth can be easily pushed to tenths of Hz level, a value critically comparable to usual MP operational levels. Lower Ql requirements allow for a spontaneous rejection to background noise.
- **Accessibility vs. Heat load:** the choice of having directly accessible actuators placed outside the vacuum vessel ("warm" actuators) is usually paid in

terms of additional heat loads transferred by the actuating shaft. On the other end, a fully "cold" scenario (XFEL-like) is demanding in terms of component reliability. Nonetheless, a trade-off is still viable, as illustrated later on for LCLS-II case.

- **Active MP compensation, Yes vs. No:** stability of a complex closed control loop involving several resonant RF and mechanical modes is likely the price to pay for an active MP suppression, while extra RF power cost should be budgeted if LLRF controls is asked to drive a noisy cavity. Fortunately, a high stiffness of the cavity constraints helps in both cases: dominant structural modes are pushed up dropping their contribution to phase error and piezo-stroke transfer efficiency is simultaneously maximized.
- **At beam tube vs. Around:** severe spatial constraints usually exist in the inter-cavity area (also related to phasing and beam dynamics) but moving the tuner far from beam ports makes tuner stroke and force transfer crucial.

This review will discuss tuner concepts and recent results by aggregating the different accelerating structures on which they are used.

## QW AND HW CAVITIES

### ATLAS at ANL

In the framework of the ATLAS Efficiency and Intensity Upgrade program, a cryomodule with 7 SC quarter-wave resonators at 72 MHz  $\beta=0.077$  has been recently commissioned [1].

A dual strategy has been developed at ANL, separating the slow tuner mechanism from the fast tuning action for a better individual optimization.

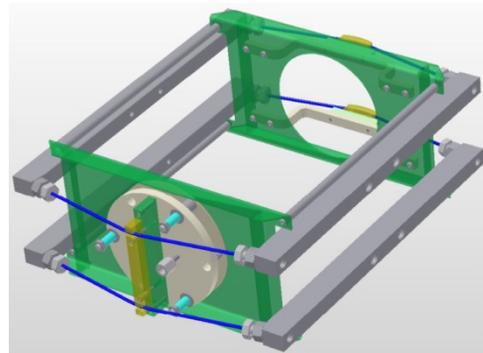


Figure 1: ANL Intensity Upgrade QWR pneumatic tuner.

Slow tuning action is provided by a well-known pneumatic type tuner (Fig. 1): a cold, Hegas-filled bellows expands and pushes outward on the wire ropes

that finally pull in on bars bolted to the cavity beam port flanges, thus squeezing the cavity [2].

An independent, side mounted on cavity wall, fast tuner with cold piezo actuators has been also developed [3] but the current strategy chosen to keep MP level in operation acceptable is fully passive. It features:

- Reduced cavity pressure sensitivity by a combined RF-mechanical design.
- Centering of cavity central conductor during fabrication. Alignment accuracy of about 100  $\mu\text{m}$  allowed a virtual elimination of the pendulum-mode contribution to MP level.
- Mechanical damper to lower mechanical Q of modes specific to pendulum effect.

As of today, MP level in the upgrade cryomodule are characterized in between experimental runs on ATLAS, exploiting the possibility to unlock RF control loop [4].

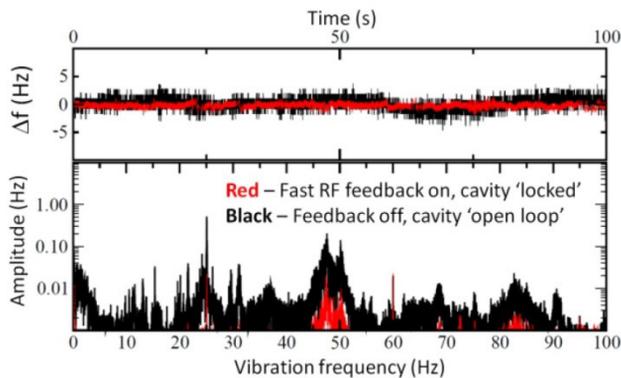


Figure 2: MP levels in ATLAS Upgrade cryomodule, known pendulum peak at 48Hz is broadened by damper.

Peak-to-peak MP was measured to be excellent and steadily within  $\pm 2$  Hz closed loop ( $\pm 4$  Hz open loop) range (Fig. 2), corresponding to only about 5% of foreseen fast tuning range.

### FRIB at MSU

A full family of QWR at 80 MHz and HWR at 322 MHz have been designed for the FRIB linac, spanning from beta 0,041 to 0,53.

QWRs exploit a simple tuning scheme where the lower moving plate position is directly determined without levers by an external and warm linear actuator driven by a stepper motor. Possibility of a fast tuning action by means of an in-series piezoelectric actuator is foreseen in the design but not installed as baseline [5].

Cold test performed on ReA3 cryomodule for  $\beta=0.041$  and  $\beta=0.085$  QW cavities confirmed speed, force and resolution of the tuner to be fully adequate to the FRIB requirements. An additional 24 hours locked run on ReA6 at 4 K with FRIB specifications also confirmed the required RF stability with no active compensations of the current microphonic disturbance level (Fig. 3), fast tuning capability will be anyhow preserved as an additional risk mitigation.

For HWRs, the initial choice of a scissor-type tuner, inspired by the model introduced for CEBAF cavities at

JLAB [6], had then to be discarded, also due to the unacceptable level of residual magnetization generated by the use of AISI420 steel for pivot plates and leading to Q0 degradation [7]. The definitive solution has been then changed to an ANL type [8] pneumatic tuner.

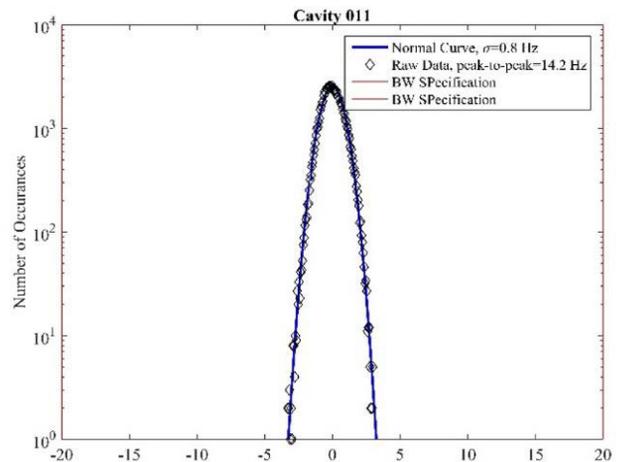


Figure 3: Detuning on QWR at 6.2 MV/m (110 % of goal) confirmed within specs,  $\sigma < 2.25$  and  $p < 20$  deg.

A prototype was initially realized, test benched at room temperature and then crosschecked at cold by means of a partially integrated cavity in a vertical dewar at 2 K [7]

Following these positive prototyping activity, tuner design has been finalized for  $\beta=0.53$  cavities in collaboration with ANL (Fig. 4).

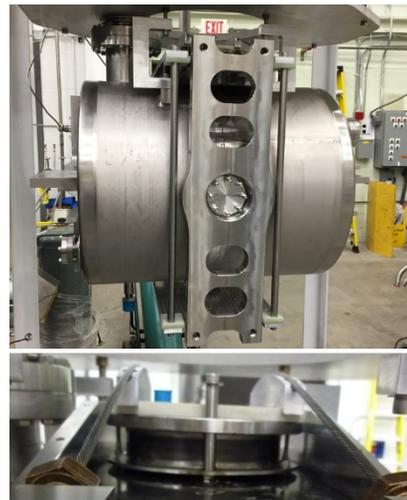


Figure 4: First prototype done at FRIB with final design and close-up of actuating bellow without sliding elements.

Tuner details have been optimized and parts are now manufactured in FRIB:

- Top/bottom aluminium plates and lateral tuner bars are now split to allow for side mounting with the power coupler (FPC) already in place.
- Actuator is now a simpler bellow without sliding elements operated with helium gas up to 4.8 barg.

A first warm test of this finalized tuner has been already done, a second one is already planned in ANL. Cold test

with an integrated cavity will then follow but preliminary cold result on development model are satisfactory: 54 kHz coarse range with 20 Hz/mbar sensitivity, tuning speed between 250 and 600 Hz/s.

*IFMIF-LIPAc at Rokkasho*

For the IFMIF prototype accelerator (LIPAc) a 175 MHz  $\beta=0.097$  HWR is under development (Fig. 5). Cavity design has been recently updated in the central ports region to host a revised tuning system based on a deformation type tuner inspired by CTS/Saclay-II [9].

This tuner design features two lever arms with eccentric joints to transform rotation of a cold motor unit into the displacement required to deform the cavity [10]. It has then further finalized with addition of specialized details:

- The displacement generated by the lever mechanism, initially designed to drive a vertical tuning membrane, is now transformed to a squeezing action at the beam port location by titanium arms with flexible hinges. The bulk coupler port on the bottom induces anyway an uneven and asymmetric deformation.
- A disengagement mechanism has been introduced in order to free the cavity from the tuner constraint and thus avoid plastic deformation during thermal transients.

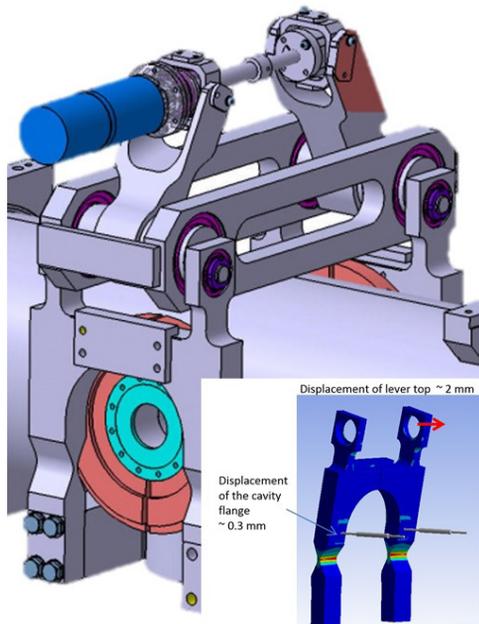


Figure 5: Deformation tuner for IFMIF HWR, close-up on FEM analyses of Ti lever with flexible hinges.

Procurements of parts is in progress hence experimental results on complete prototype will soon follow.

*SPIRAL2 at GANIL*

Cryomodules type A, developed by CEA/IRFU, at the lower beta section host a single 88 MHz  $\beta=0.07$  QWR per vacuum vessel [11]. Tuning system for these cavities is also a special revision of the CTS/Saclay-II tuner [10].

The CTS model specifically developed for Spiral2 CMA is actually a transverse tuner (Fig. 6): in order to minimize longitudinal (beam direction) footprint the tuner “squeezes” the cavity cylindrical wall and this corresponds to a stretching at beam ports.

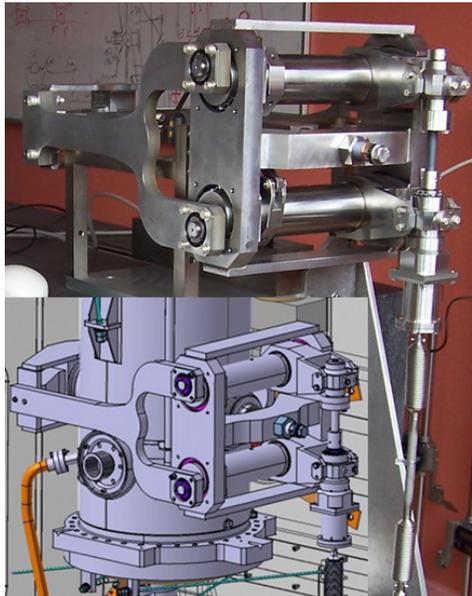


Figure 6: Spiral2 CMA “transversal” tuner mechanics.

No fast action is required thanks to the viable MP level and a “warm” stepper motor drive unit is outside the vacuum vessel.

Cavity plastic onset limit, set at only 0,1 mm deformation at warm, has been extended to more than 25 kHz at cold by optimizing shape and position of the tuner to cavity wall connection. Furthermore a disengagement system is introduced (similar to IFMIF HWR) to free the cavity from tuner constraint and, moreover, tuner body is equipped with heater to warm it up faster than the cavity. Both procedures have been successfully proved during CM cold tests.

Cryomodule “B”, developed at IN2P3/IPNO, are used in the  $\beta=0.12$  section and host two 88 MHz QWRs in each vessel. For these cavities an hollow, liquid helium cooled SC plunger tuner solution has been developed and optimized along these past years [12].

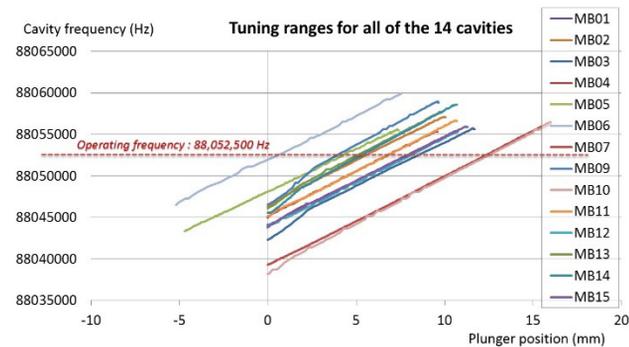


Figure 7: Tuning range comparison among installed units.

Plunger is installed at the high magnetic field region at upper plate and it is driven by a warm drive unit based on a brushless motor transferring the linear action through a cold shaft. Assembly and cold test of all modules has been successfully concluded at December 2014: no negative impacts on cavity performances have been detected and all plunger systems are up to specs (1 kHz/mm, 10 mm range) (Fig. 7).

Both Spiral2 tuner models have been already extensively demonstrated during single CM cold tests [13] and as of today cavity string is ready for cooldown, further tuner results are expected soon with Spiral2 linac commissioning.

### ESS SPOKE CAVITIES

Beta 0.50 section of ESS linac makes use of double-spoke cavities. Tuning system is operating by deformation at beam port, it has been derived from CTS/Saclay-II [10] and developed at IPN.

Challenges come from design of cavity itself: with its about 100 kHz/mm and 20 kN/mm in the tuning direction, such resonator is rather stiff and in the same time poorly sensitive to chosen detuning action.

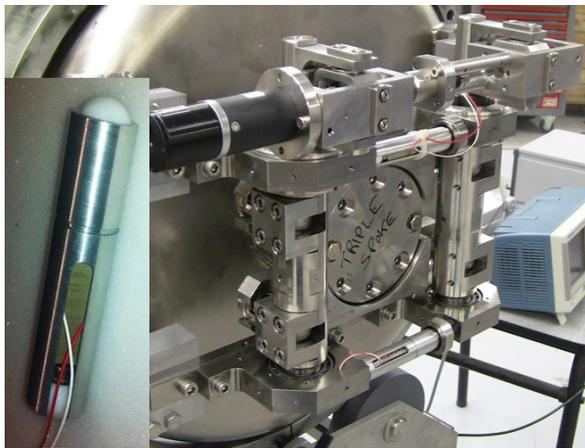


Figure 8: ESS spoke tuner and piezo capsule.

Tuning system design (Fig. 8) has been already presented [14] and features a cold motor unit and two piezo fast actuators hosted by special capsule and installed in between lever arm joints (different choice than, for instance, on CTS for ESS elliptical).

Cold tests have been recently performed with three different prototype cavities and hosting two different type of piezoelectric actuators.

Results were successful for both coarse and fine tuning range (Fig. 9); also custom piezo encapsulation developed at IPN proved to be effective at cold while ensuring a simplified handling during installation.

Plunger design is also planned to be explored as an option, aiming to an higher coarse tuning range on these resonators compared to deformation type tuner. Some analyses and simulations on this have been already done [15] and group at IPN has already scheduled to extend such research in the next years.

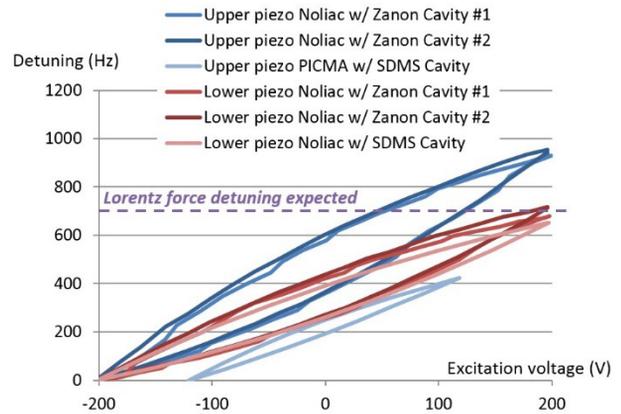


Figure 9: Piezo DC stroke comparison among different piezo models, successful full bipolar operations.

### ELLIPTICAL CAVITIES

#### ARIEL e-linac at TRIUMF

The new photo-fission driver project at TRIUMF is currently housing two cryomodules hosting three 1.3 GHz nine-cell TESLA type cavities, final layout will be using 5 cavities up to 50 MeV electrons. Resonators have been partially re-designed to sustain intense CW operations [16].

Tuning system is a scissor-type (Fig. 10) with external motor exploiting the well experienced JLAB CEBAF flexible leverage [6] as cold part and then adapted to the custom TESLA cavity type in use. Mechanics makes use of titanium flex joints connecting pivot plates in place of axial/rotating axis in order to null backlash generation along the strain transfer chain. A first tuner prototype has been initially loaned from JLAB and it has then been successfully characterized on a room temperature test bench [17].

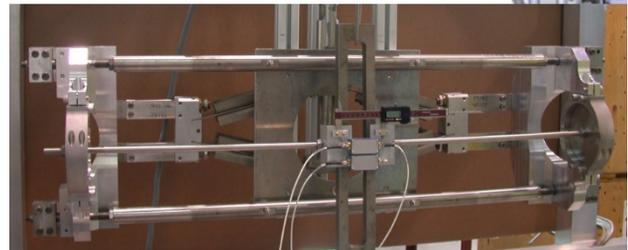
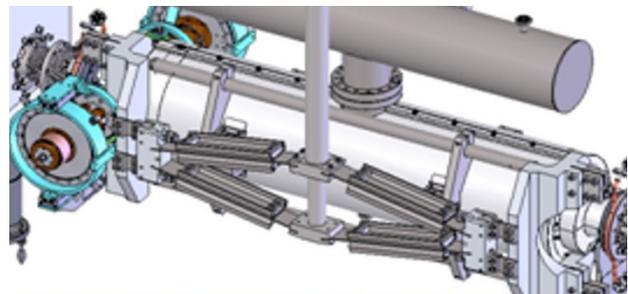


Figure 10: ARIEL scissor tuner CAD model and the first unit test bench at room temperature.

This is making use of a cavity spring mock-up, capable of reproducing the cavity stiffness constraint and equipped with force and displacement readouts. Linearity and accuracy of force transfer through tuner kinematics has been proved up to micrometer strain level.

Driving motor has been updated to a cost-efficient rotary servo-motor with ball screw coming from the positive experience within TRIUMF with ISAC-II SC linac (leverage + tuning plate on a QWR) [18].

Thanks to the broad cavity bandwidth at 1 kHz and to the compact cryogenic system (only 2 cavities per vessel, one for the injector module) in stable operations at 2 K an active compensation of microphonics is not required.

This tuner prototype then equipped the first linac cavity into the injector cryomodule and cryogenic measurements performed along 2014 confirmed excellent frequency stability, contained microphonics disturbance and robust cavity phase lock (Fig. 11). The choice of not having any fast actuators installed is then confirmed experimentally.

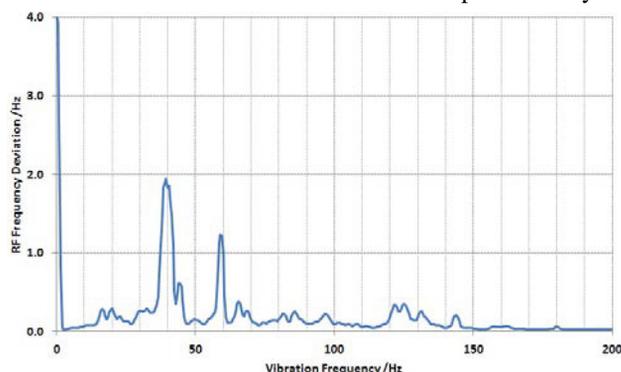


Figure 11: MP disturbance spectrum at ICM cold test.

As a first result, tuner exceeded tuning range expectations with about 400 kHz at cold compared to the 240 kHz deduced from test bench analysis [19].

Further tuner-related experimental data are going to be collected later in 2015 in the framework ICM injector & ACM linac first module commissioning.

### European-XFEL at DESY, Main Linac

XFEL tuning system is a well-known double leverage mechanism with asymmetric levers and makes use of cold actuators, a stepper motor based drive unit with harmonic drive and two piezo-electric stacks hosted by a single frame [20].

Being the main linac in an advanced production stage, no further R&D on tuner design has been done since the procurement phase in 2012. Nonetheless the ongoing large-scale assembly is worth having a brief review since in the framework of the module series production at CEA [21] and cold test at DESY AMTF [22], a tuner assembly and validation procedure has been as well properly established.

As of today, about 60% of the XFEL module production has been completed (Module 61, or XM61, is leaving CEA) and this implies about 500 tuning systems already mounted.

Summing up the results so far, the quality control strategy developed for tuning system installation [23] is globally successful and the strongest contribution to the final quality level is probably coming from pre-assembly controls and resources:

- Robust agreements with producers of sub-components: partial assembly, test at factory (including cold test for motor units at LN2), delivery strategy etc.
- Detailed, thoroughly reviewed and jointly approved step-by-step instructions.

It can be considered, for instance, that among the first 352 tuning systems installed, only 2 mechanics sets, 2 piezo frames and 4 motor units had to be returned to manufacturer. Besides, the amount of non-conformities at installation is so far largely dominated by recurrent small machining and temporary inventory shortage.

Once modules are delivered at DESY, tuners additionally undergo a room temperature acceptance test where remaining and undetected non-conformities are identified and repaired. These were so far mostly related to cabling and curing was always possible through a re-soldering of feed-through connectors at the vessel ports.

As of today, while XM59 is going to be cold tested at AMTF, every cryomodule processed at DESY exhibited a fully functional tuning system.

### European-XFEL at DESY, 3H Injector Module

Cold tuning system for the third harmonic (3H) cavities of the XFEL injector [24] has been developed at INFN and its design is inspired by the Coaxial Blade tuner already qualified for the 1.3 GHz ILC cavities [25].

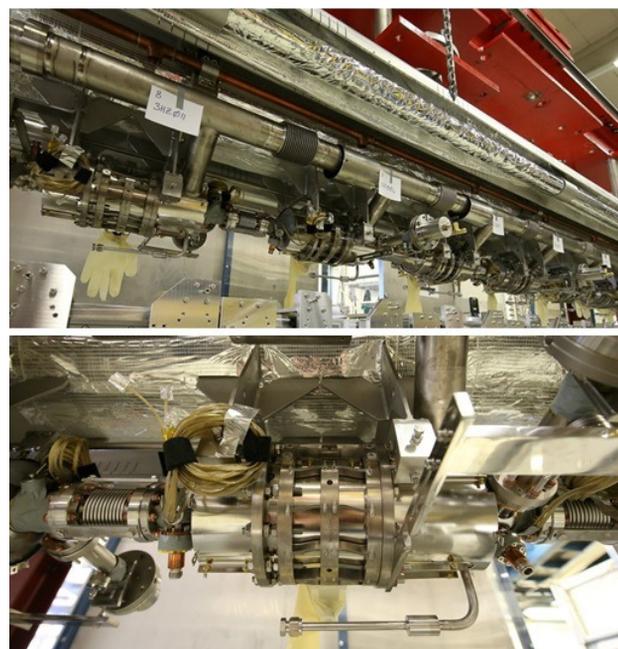


Figure 12: 3H tuners during assembly of X3M1 module.

Fast tuning action via piezo actuators is not required in this case due to the stiffer cavity and the moderate gradient. Design analyses and experimental validation has

been conducted [26] and this scaled coaxial blade tuner unit has been cleared for series production in 2013. By the end of 2014, 20 units have been delivered for the injector and spare module series.

An horizontal cold test on a fully dressed third harmonic cavity has been performed on Jan. 2015 in a special single cavity adapter in AMTF cave #1 [27].

The 3H coaxial tuning system performed as expected:

- Tuning range at cold confirmed to be reached with large margin the expected plastic onset limit at 1 MHz, showing about 1.5 MHz maximum stroke with sensitivity not higher than 2.4 Hz/step.
- A “standard” (1.3 GHz cavities) stepper motor unit and its driving electronics is to be used in the linac also for the 3H section: full compatibility has been then confirmed by this cold test. Current configuration has 70400 steps/turn and about 240 ksteps to frequency goal.

Finally, starting from June 2015, 3H cavity string and cold mass assembly started [24] (Fig. 12). All eight 3H tuning systems have been installed and functionalities have been cross-checked by measuring cavity frequency shift in a back-and-forth motor few turns.

Third harmonic module X3M1 is expected to reach its position in the tunnel by October 2015 and tuning systems final commissioning is expected to come with the XFEL injector commissioning starting at the end of 2015.

### LCLS-II at SLAC

LCLS-II will feature 1.3 GHz resonators technically identical to XFEL cavities. A new tuning system has been designed at FNAL [28] from scratch in order to benefit from the large amount of experience available for TESLA type cavity tuners by overcoming any known weak point while gathering good technical solutions already available.

Baseline is still the XFEL double leverage kinematics installed at the PU end of the cavity [20] but has now a 21.5 mechanical ratio and about 450 kHz tuning range. “Push” tuning action is chosen in place of “pull” (Fig. 13).

A first relevant design update is generated by a reliability strategy choice: all actuators are designed to be directly accessible through a dedicated port on the cryomodule vessel in order to be replaced if needed without rolling out the cavity string. This is made possible by introducing an adjusting screw to allow releasing of cavity elastic reaction forces acting on the tuner of a tuned cavity that would prevent such an operation.

Two “soft” limit switches avoid the intervention of the “hard” stop used for instance by XFEL motor assembly. Additionally a set of safety rods are installed to preserve basic tuning capabilities in case of a piezo breakdown as already introduced on INFN Blade Tuner [25]. Two encapsulated piezo actuators (two 18 mm stacks in each capsule) are directly coupled to the cavity ring therefore the fast tuning action is not transferred through the tuner levers. This solution boosts the transferred stroke to a value of about 3 kHz at maximum voltage. A conical-to-

spherical open joint is used to transfer piezo action safely shielding the stack from shear forces.

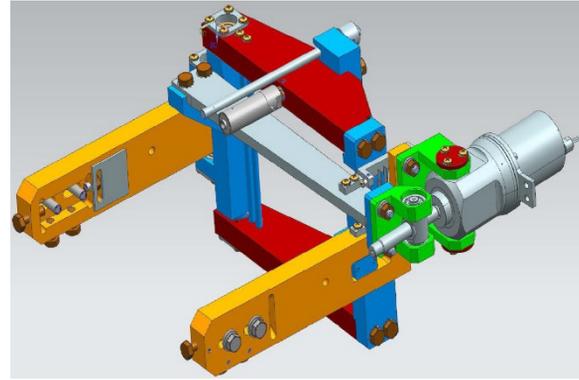


Figure 13: LCLS-II tuner CAD model.

The motor drive unit, already designed in the framework of ProjectX at FNAL, makes use of a planetary gearbox with titanium rod in place of harmonic drive and copper-beryllium (restricted material for US safety regulations). Final resolution is aligned to other TESLA type cavity tuner, about 1.4 Hz/step but life-time is expected to increase by avoiding surface coatings on shaft and nut (DESY recipe) [29].

In view of LCLS-II tuner developments, the HTS facility at FNAL has been recently updated in order to perform a CW cavity test. Cold test with tuner prototypes have been performed in 2014 and 2015 and both static and dynamic performances were met [30] (Fig. 14).

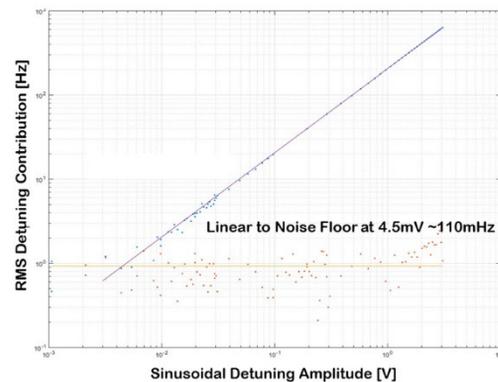


Figure 14: Piezo dynamic resolution at cold compared to background noise at HTS.

Tuning systems for LCLS-II is now finalized, production and procurements of actuators for the first series has already started.

### ESS and SPL

Different projects currently benefit from the intense design activity jointly conducted at CEA, IN2P3, CERN, INFN and others on the design of a high-beta elliptical multicell cavity for protons, exploiting the large knowledge gained on this technology e- linac activity worldwide.

Among these, large R&D drivers are currently the ESS project [31] and the SPL program at CERN [32].

Resonator designs are slightly different, ESS foresees a lower beta section with  $\beta=0.67$  6-cells cavity followed by an higher beta section with a  $\beta=0.86$  5-cell while at SPL a 5-cell  $\beta=1$  cavity is initially under development.

Nonetheless, current tuner design developed at CEA is indeed very similar for both projects and it is once more a revised version of the original CTS/Saclay-II (later evolved into Saclay-V). As of today their design can be both considered as finalized and going into procurement phase. In both cases, cold stepper motor drive unit with planetary gearbox reduction stage (1:100) is chosen. For SPL project tuner, one piezo frame with a single stack is installed and allows actuator preloading to be independent from cavity spring-back force (piezo frame stiffness is about 10 x higher than cavity one). A first series of tuner units has been already produced and characterized through devoted test bench at CERN [33]. The first niobium  $\beta=1$  cavity with final design and integrated in its helium tank is now available and realistic tuning system validation is therefore expected in the near future.

For the ESS cavities a robust tuner design has been already developed as well [34] (Fig. 15). Minor changes to SPL lever design are due to the different geometry of the beam tube region and the clearance required for the installation of the cold magnetic shield.

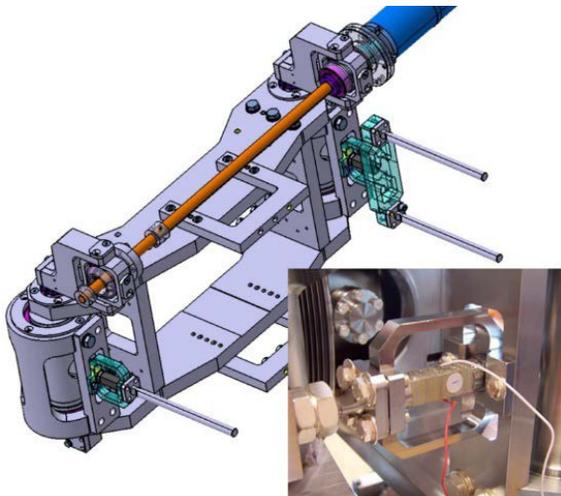


Figure 15: CTS/Saclay-V tuner developed for ESS with a close-up view of actual piezo frame.

Additionally, for the ESS cavity, two piezo stacks in their individual frame are installed for redundancy, one on each side of the beam tube.

## CONCLUSION

Looking through the excellent R&D activity described, a general attitude seems to stand in favour of the safest use of consolidated tuning designs in place of totally novel schemes.

The quality of initial tuner design development is indeed as good as the ability in introducing workaround solutions to unexpected and specific issues, a reaction that may even extend up to a radical tuning system change.

Installations of cold actuators are quickly growing in number, thus moving the spotlight onto reliability for the next years. Moreover, larger projects are going to be crucial to prove that such a complex system as a cold tuner is able to withstand the challenge of mass-scale production foreseen for next-gen projects as the International Linear Collider [25][35].

## ACKNOWLEDGMENT

The author would like to thank all those that have been involved in the completion of these review paper for having promptly provided information, pictures and results from each of the mentioned project and laboratory.

This paper was not meant to be a comprehensive listing of all existing tuning systems, just few topical examples have been highlighted.

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