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MODELING OF SUPERCONDUCTING SPOKE CAVITY WITH ITS CONTROL LOOPS SYSTEMS FOR THE MYRRHA LINAC PROJECT

Maguy Dominiczak*, Accelerators and Cryogenic Systems, Orsay, France
Nicolas Gandolfo, Christophe Joly, IPN, Orsay, France
Frédéric Bouly, LPSC, Grenoble, France

Abstract

In the construction framework of a future 600MeV/4mA CW Superconducting Linac accelerator for the MYRRHA project at SCK•CEN (Mol, Belgium), modeling works under Matlab/Simulink® are carried out upstream to understand the behaviour of 352.2MHz single Spoke cavity with its environment and its associated feedback control loops (LLRF and Cold Tuning System). One of the main goal is to assess the feasibility of cavity failure compensation in the Superconducting Linac. Indeed, stringent reliability requirements must be fulfilled to ensure an efficient operation of the MYRRHA Accelerator Driven System: unexpected beam interruptions, due to failures, must be compensated in less than 3 seconds. Our preliminary study focuses on the fast frequency re-tuning of the cavity and the power balances. Our goal is to prepare the R&D tests foreseen at IPN Orsay on a prototype cryomodule including two SC Spoke cavities equipped with couplers, tuners with feedback loop and connected to dedicate LLRF.

INTRODUCTION

In the transmutation framework of highly radioactive wastes, the MYRRHA ("Multi-purpose Hybrid Research Reactor for High-tech Applications") is an ADS project initiated by SCK•CEN (Belgium), to study the reduction of nuclear wastes radio-toxicity. A subcritical nuclear reactor of 65-100MWth will be driven by a continuous protons Linac (Linear Accelerator) of 600MeV and 4mA. This accelerator fires protons at a spallation target, creating the neutrons that will maintain the fission chain reactions in the reactor. MYRRHA Phase 1 [1] (MINERVA project) is composed of a Linac of 100MeV, 4mA that will allow to prove the technical feasibility of a high reliable Linac. It will install, at the high energy beam line, a radioactive ion beam facility (ISOL type) for fundamental physics experiments, and a new facility for radioisotopes production. SCK•CEN's BR2-reactor – is already producing for at least 25% of the worldwide radioisotopes. MYRRHA will expand this radioisotope production, while also developing a new generation of isotopes in the fight against cancer. MYRRHA will also be used to expose materials to extreme conditions that approach those in nuclear fusion reactors. The construction of MYRRHA Phase 1 (100MeV) started in 2018 and, the construction of MYRRHA Phase 2 (subcritical reactor and 600 MeV proton accelerator) will start in 2027. In the initial phase (MINERVA), our objective is to analyze the feasibility of the "Fault Tolerance strategy" in the case of an accelerator failure. In the ADS systems, the accelerator failures producing beam stops need to be carefully handled. The "fault recovery" procedure proposed for MYRRHA, requires a beam stop of less than 3 seconds in order to limit the thermal stresses in the reactor, the mechanical fatigue of the spallation target, fuel and assemblies, and the long start procedures in the reactor. To ensure a good reactor performance over long periods, it was estimated to be below 10 beam stops per 3-month cycle equivalent to a mean time between two breakdowns must exceed 250 hours. The full Linac consists of an ion source, an injector, a section of copper cavities and a section of SC cavities. The 17-100MeV section, concerned by our study, is composed of 30 SPOKE cryomodules. Each cryomodule (Figure 1) contains two superconducting cavities that are cooled down to 2K under ultra-vacuum conditions. The cryomodule assembly contains thermal and magnetic shieldings which is connected to a Valve Box needed to control and distribute cryogenic fluids.

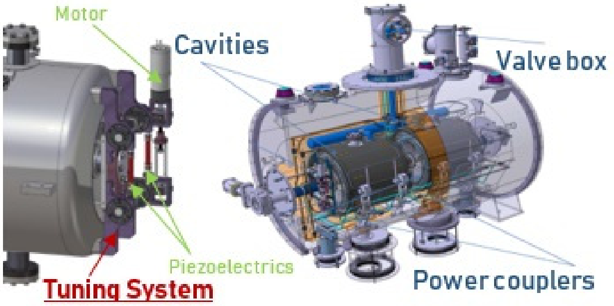

Figure 1: Schematic view of the Tuning System [2] installed on a single SPOKE on the left, and the SPOKE cryomodule containing two cavities on the right.

Each cavity operating at 352.2 MHz is equipped with a power coupler adapted for transfer the RF power coming through a coaxial transmission line 50Ω needed by the beam acceleration. Thus, 18kW of power are transported from the RF amplifier to the cavity. In nominal operation, the RF power is 10kW. A cavity model based on theoretical equations and its two feedback control loops (LLRF & Tuning System) was developed under Matlab/Simulink® [3,4], in order to study the stability and transient behaviour of the whole system. New input parameters (Table 1) and adjustments were made in this simulation model (RF SSA amplifier based on a similar amplifier operating at 176.1MHz, coaxial line (L=40m)…).

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*maguy.dominiczak@acsfrance.com

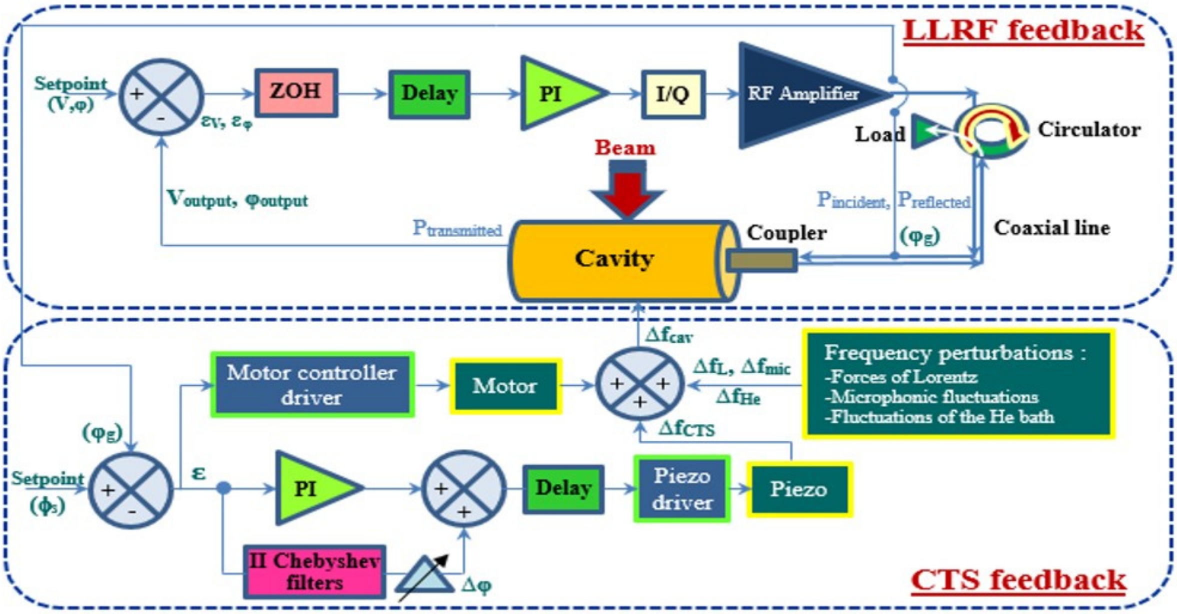

Figure 2: Cavity control system with its two feedback loops.

In this paper, numerical simulations from the model are launched to study different failure scenarii : **1) with beam**, we use a generic case for the fault compensation by adjacent cavities to the one that is defective, with an accelerator gradient (E_{acc}) ranging from 7 to 9.1MV/m and a synchronous phase (ϕ_s) from -25° to -15°. **2) without beam**, to treat the case of the initial prototype tests of the SPOKE cryomodule.

Table 1: Simulation Input Parameters

Parameters	Values
Number of cavities	60 (30 cryomodules)
Frequency (MHz)	352.2
I0 (mA)	4
r/Q (Ω) [βopt=βgeom]	217
G (Ω)	109
T(He) (K)	1.9
Rs (nW)	20
Lorentz coeff. (Hz/MV/m²)	-5.5
Vcav (MV)	1.7
Qo	5.2 10^9
Qt	10^12
Qi(~QL)	1.5 10^6
Eacc (MV/m)	7
ϕs(°)	-25
PMax RF (kW)	18

Experimental tests on the SPOKE cryomodule will take place at the end of 2020 - beginning 2021 at the IPN Orsay with full equipment (circulator, power coupler, RF amplifier, LLRF, Cold Tuning System (CTS), cryogenics systems and all interfaces). In this context, the powers and couplings are different from those in Linac real operation mode.

DESCRIPTION OF THE LLRF AND TUNING SYSTEM FEEDBACK LOOPS ASSOCIED TO THE CAVITY

The cavity model and all the elements surrounding it for its operation are shown in Figure 2. In the LLRF (Low Level Radio Frequency) loop that controls E_{acc} in amplitude and phase, a ZOH (Zero Order Hold) discretizes the signal and blocks it during Ts=1µs to which we add a delay function Td=2.5µs, then this signal is corrected before being rebuilt by the I/Q modulator. The cavity response time (step=1MV/m), at 5% in LLRF closed loop (Ibeam=0), is estimated at t_R~460µs and signal stability of ±1% at t=440µs, lower than the natural response time of the cavity (τcav=1.4ms). In the CTS loop, ϕ_s is the input setpoint and ϕ_g (generator phase) is measured at the coupler input. Phase shift, ε (between ϕ_g & ϕ_s) must be minimized to regulate the Tuning System. The signal proportional to ε drives the motor to approximately control fcav (resonance frequency of the cavity) and the piezo system gives a more precise and fast adjustment of the accelerator frequency around fcav. The Tuning System allows to compensate for rapid variations due to Lorentz forces, microphonics and slow variations due to H_e bath. These perturbations must be corrected adjusting Δf_{cav}. The Tuning System mechanism effectively transmits deformations induced by the piezoelectric actuators. Chebyshev filters in the CTS model compensate microphonics perturbations and are associated

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to a PI corrector, to compensate low frequency variations due to H_e bath pressure fluctuations. Delay block corresponds to a delay constant (τm=1ms [3]).

SCENARII STUDIES FOR LINAC FAULT TOLERANCE SIMULATION

A fault tolerance analysis of the linear accelerator was developed. We study using the model, the feasibility of procedures for fast re-adjustment of the accelerating cavities when a failure occurs and the adjacent cavities have to be adjusted. The re-adjustment procedure must be performed in less than 3 seconds (Figure 3).

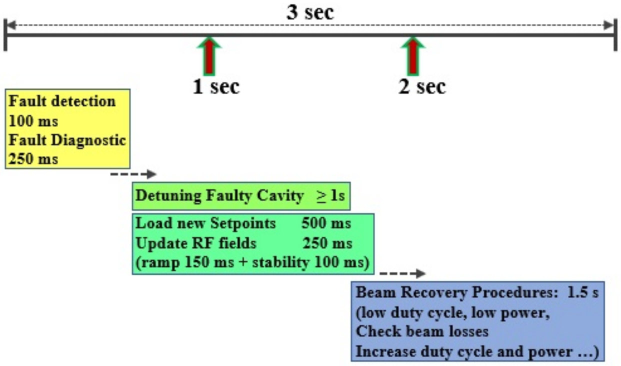

Figure 3: Fault tolerance tests (specification for MYRRHA ≤3s).

A new Linac design has been developed to obtain the right RF powers. We impose a field rise time of 500ms. We study the E_{acc} behavior as well as ϕ_s for each considered procedure as a function of the RF powers, piezos voltage, motor control and cavity detuning (δf_{cav}). Our objective is to study different scenarii: case for the fault RF compensation in beam condition (Ib) with a) detuning of faulty cavity after beam stop (Figure 4) and b) adjacent cavity compensation (cavity adjustment and beam ON) (Figure 5). Then case of the prototype cryomodule tests without beam with c) adjacent cavity compensation (cavity adjustment and beam ON) (Figure 6) and d) detuning of faulty cavity (Figure 7). The motor detuning capability must be of 14kHz achievable within 1s (condition required for the MYRRHA project). Figure 4 (Ib≠0), the case of a faulty cavity in the Linac is investigated (E_{acc}=7MV/m, ϕ_s=-25°). The striped rectangle corresponds to E_{acc} increases. We stop the RF source. E_{acc} start decreasing to zero at t=1s and Pg (generator power) switches to zero as well as Pb (beam power). Beam losses are observed and we have a beam stop. The new setpoint for the cavity frequency driving of the CTS is Δf_{CTS} =+100kHz (ideal case) to detune the cavity as faster as possible [4]. On the δf_{cav} plot (Figure 4), we can see the piezos effect and motor being pushed to the maximum capability to compensate the Lorentz Forces (FLs). When the nominal frequency of the beam (f0) is far from the cavity (fcav), the piezos are assisted by the motor to increase fcav which detuned the cavity of 14kHz in 1s. The electric actuators are drived to a maximum voltage of 120V to detune the cavity to a max. value and to minimize the beam induced effects. Thanks to the fast Tuning System, we have detuned in less than 3s. CTS has detuned quickly of 14kHz on one second and we have observed the motor detuning capability of +100kHz. The beam is turned on before the motor has finished its action at t=2.9s (Figure 4). Thus, we can say that beam could be restart after 1.9s from fault detection. Problem: the beam induces a field in the detuned cavity, its value must therefore not exceed 0.5% of $E_{acc\ nom.\ (7MV/m)}$ = 350kV to minimize perturbations in the beam dynamics. Knowing that L_{acc}=0.32m, the maximum energy perturbation of the proton beam is of 112keV on 600MeV ($\Delta E/E$=5.10^{-4}). The LLRF loop control can be completed by a feedforward to avoid any perturbation of the « beam loading » during the beam injection into the accelerator line and any loss in the beam.

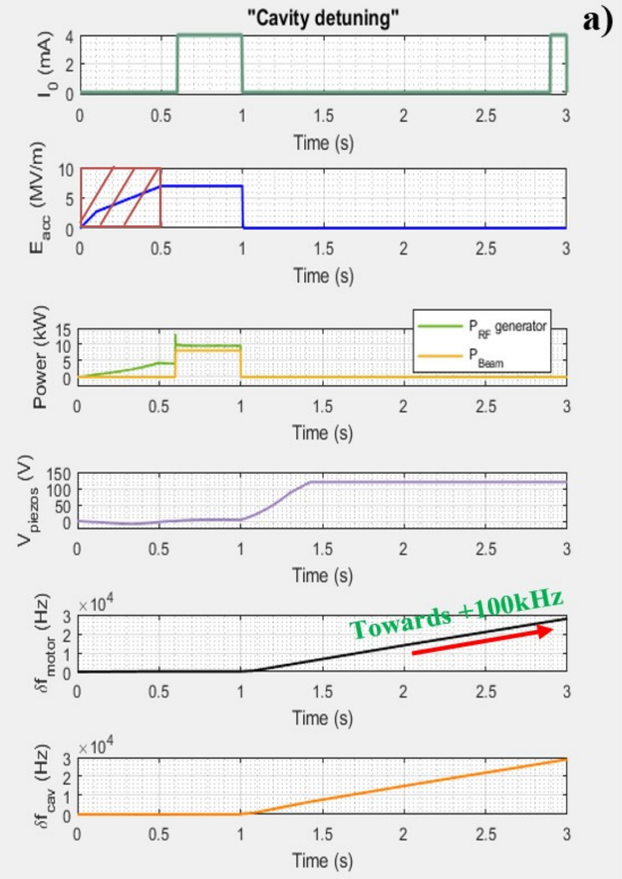

Figure 4: Evolution versus time for the faulty cavity with beam.

It has been shown that in presence of a faulty cavity, the Linac can be re-configurated within time constraints and beam operation can be continued delivering a 600mMeV beam. Figure 5 (Ib≠0), when a fault detection occurs, it is necessary to re-adjust quickly an adjacent cavity. We adjust E_{acc} (7 to 9.1MV/m) and ϕ_s (-25° to -15°) for an adjacent cavity. We start beam at 600ms and stop the beam for simulation after 300ms, because we simulate a failure detection. After the beam is interrupted, it is considered that 100ms are usefull to identify the faulty element and initiate the fast adjustment procedure. When E_{acc} is increased (Figure 5), it is decided to apply a setpoint to fix the phase to -15°. The E_{acc} increase leads to a power increase of Pg to compensate the FLs. A sudden change in the phase leads to an overshoot on E_{acc} and Pg. Cavity compensation can be easily retuned in 200ms. The beam is reconnected 435ms after failure detection to adjust the adjacent cavity of the failed cavity. The piezos react to each Pg variation then the piezos voltage decreases thanks to the motor detuning which takes over to compensate the FLs. On the δf_{cav} plot, we can observe a transient of 500ms due to the response time of the piezos and the feedback system, then the frequency tuning of the cavity was re-adjusted as the supply voltage of the piezos decreased to zero. The voltage decreases as the motor increases the strain force on the cavity.

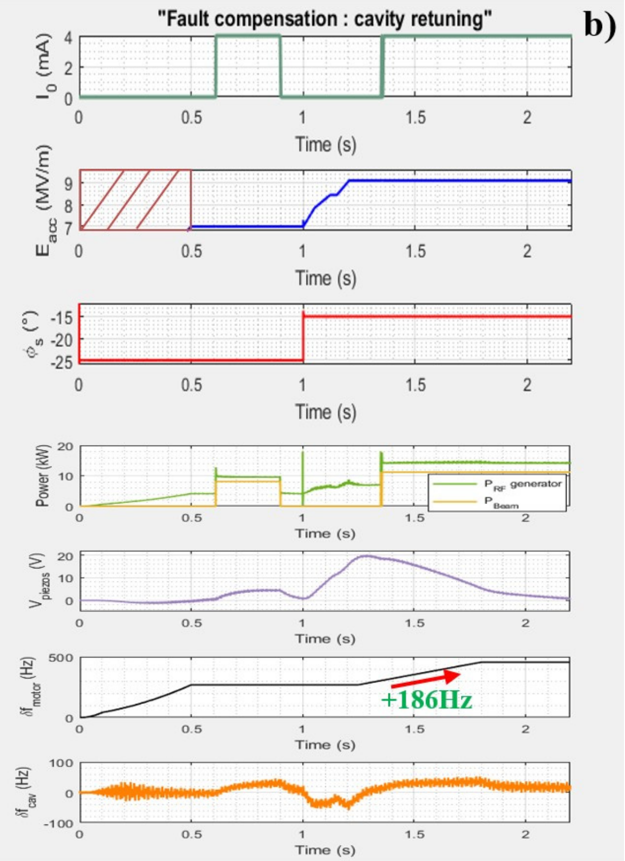

Figure 5: Evolution versus time for the compensated adjacent cavity with beam.

Note that the voltage on the piezos was only 20V while the max. supply voltage fixed is 100V for simulation. After reaching the nominal operation point (Figure 5) concerning the increase of E_{acc}, the Tuning System has time to compensate the FLs and thus avoid saturation of the RF amplifier. In fault tolerance phases, Pg and Pb are stronger than in nominal mode because the faulty cavity needs to be compensated. Figure 6 (Ib=0), the modeling study permits to check the procedures for fast adjustment of the cavities in the case of a cryomodule without beam. We set the nominal mode with E_{acc}=7MV/m and ϕ_s=0. Pg max is 4kW before CTS can really compensate the FLs. Here, we can observe a transient of 300ms on the δf_{cav} plot during the E_{acc} increase. Variations of Pg function of E_{acc} show that feedback system is effective in LLRF closed loop. If we increase E_{acc} to 9.1MV/m, Pg must supply 7kW. Figure 7 (Ib=0), in the case of a failed cavity, what changes without beam is ϕ_s= 0° and the piezos contribution for detuning is weak even null, it is the motor that essentially acts to detune the cavity.

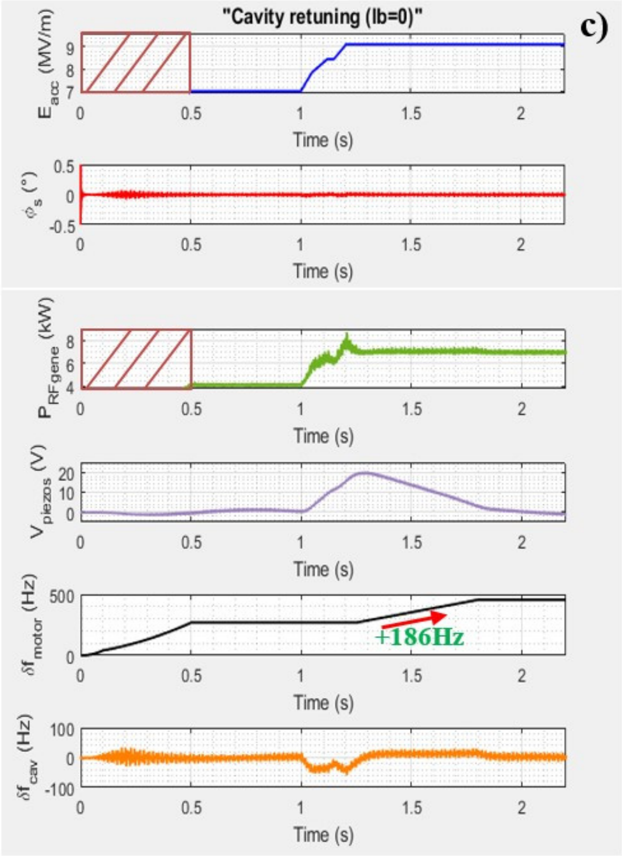

Figure 6: Evolution versus time for the compensated adjacent cavity without beam.

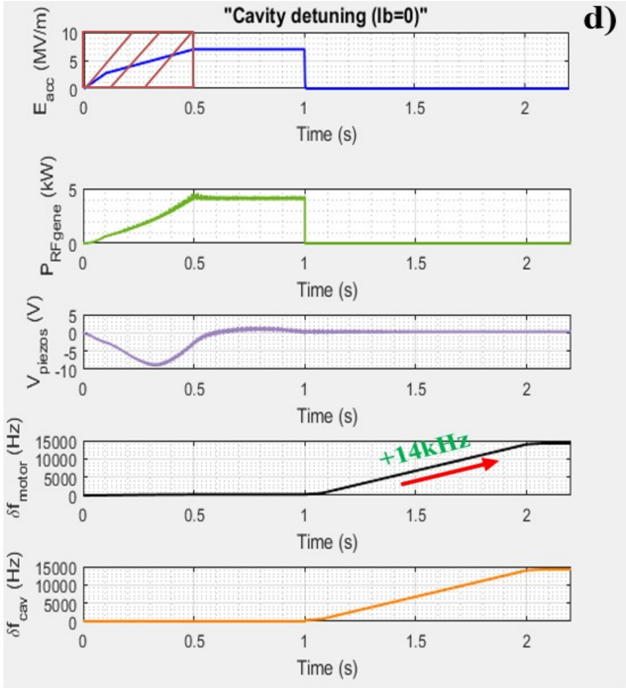

Figure 7: Evolution versus time for the faulty cavity without beam.

From simulation, we tested some phases of the procedures and time diagram don't correspond strictly to the fault tolerance. To conclude this part, we showed the feasability of the fault recovery procedures in less than 3s and CTS fast detuning for 14kHz/s is checked too.

SOME TYPICAL TUNING SYSTEM EXPERIMENTAL MEASUREMENTS

In this study, a particular attention was carried out to measure and characterize the mechanical behaviour of the Tuning System. We invite you to refer to the paper id "*TUP087*" which specifically develops a study on the Tuning System. The recent vibration spectrum measurement of the cavity allows to identify the mechanical vibrational modes under cold conditions see Figure 8. It will be used to optimize the simulation model under Simulink in the Tuning System feedback loop. Presently this spectrum is implemented through 40 Band pass filters [5]. At room T, CTS fast detuning is possible for 15kHz/s. Tests are in progress for low T.

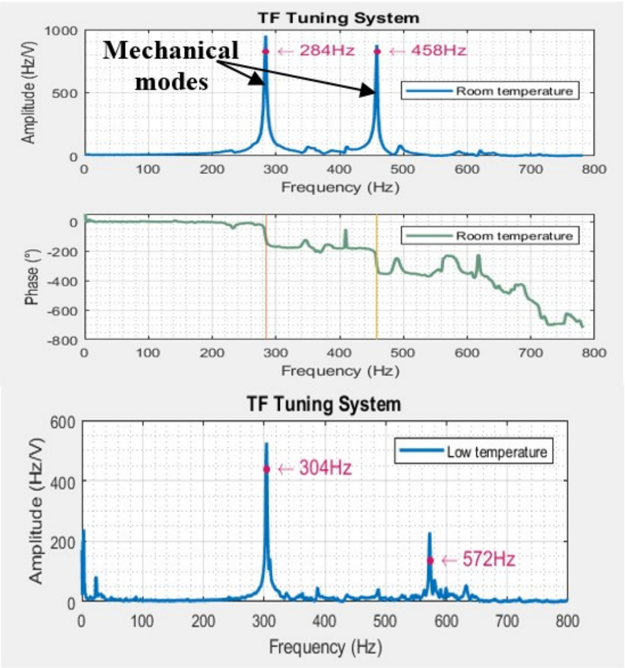

Figure 8: TF of the Tuning System at room T (up, MYRRHA single Spoke cavity « Virginia ») and low T, T_{He}=2K (down, cavity « Amelia »): detuning on the RF frequency of the cavity according to the low frequency excitation of one of the piezoelectric actuators.

CONCLUSIONS

This study analyzed the RF power and Tuning System requirements to meet the conditions for MYRRHA and demonstrated the feasibility of cavity fast adjustment in less than 3 seconds (analysis of the fault tolerance by the Simulink modeling with and without beam) in respect to operation conditions of the fast neutron reactor. All these results must be experimentally confirmed by the good performance and speed of the LLRF digital system and the Tuning System with a short response time of the order of few ms.

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