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DESIGN, CHARACTERISTICS AND DYNAMIC PROPERTIES OF MOBILE PLUNGER-BASED FREQUENCY TUNING SYSTEM FOR COAXIAL HALF WAVE RESONATORS

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Abstract

The practical realization of a prototype of the frequency tuning system (FTS) for coaxial half-wave cavities (HWR) for the Nuclotron-based Ion Collider fAcility (NICA) injector is presented. The impact of FTS on electromagnetic parameters of copper HWR prototype is experimentally studied and discussed. The most important parameters like tuning range, tuning sensitivity, the dependence of the resonant frequency on the position of the plungers are estimated. The effective operation algorithms of the proposed FTS are discussed and analyzed. The dynamic characteristics of FTS are investigated and showed the ability to adjust the frequency with an accuracy of about 70 Hz.

INTRODUCTION

The present work is focussed on the estimation of experimental characteristics of Frequency tuning system (FTS) for half-wave coaxial superconductive cavities[1], which are developed for the Nuclotron-based Ion Collider fAcility (NICA) injector. The model of the half-wave coaxial resonator (HWR) and fabricated copper prototype operating at the frequency near 325 MHz are presented in Figs. 1(a) and (b).

The proposed FTS is based on mobile plungers placed inside the holes in the HWR end cups (Fig. 2). Similar systems were discussed in [2-4]. By varying of plungers' penetration depth inside the cavity volume it is possible to change the effective distance between HWR end caps and tune the frequency. The plunger is driven by a linear actuator based on a stepper motor. Frequency tuning accuracy is generally determined by the minimum one-step movement δx of the actuator (typical values for δx are a few microns). Analysis shows that such a stepper motor-based system can be potentially used as a slow FTS with an adjustment accuracy of the order of 100 Hz.

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FTS OPERATION ALGORITHMS

The experimental realization of the FTS concept is based on a vector network analyzer (VNA) Micran R4M used for resonance frequency control. In a dynamic regime, the FTS should automatically compensate for the variations of HWR resonant frequency. In the present work, we will discuss two different dynamic operation algorithms for considered plunger-based FTS.

The previous investigations [1, 2] demonstrated, that the penetration depth of the plunger placed in the hole in the end caps of the resonator is monotonically related to the resonant frequency shift of HWR. In Fig. 3(a) is presented typical spectra of reflected from the cavity signal S_{11} for plunger positions with minimal, middle, and maximal penetration depth ΔL in the cavity. This frequency dependence of S_{11} spectra may be used for dynamic frequency tuning and realized within the first algorithm A.

Algorithm A is based on scanning using VNA a narrow frequency range near goal value f_0 and searching for actual resonance frequency. Within this strategy, the resonant frequency value is continuously measured by the VNA and processed by the Arduino controller. If the deviation of the measured value of the frequency differs from f_0 more than threshold value Δf_0, then the stepper-motor actuator changes the plunger position to compensate for the frequency difference. The speed of the stepper motor is dependent on the deviation of resonant frequency from the goal value.

This algorithm is simple, clear, and intuitive but has some disadvantages. First, the need for frequency scanning leads to a rather slow operation of this algorithm. Second, the minimum threshold value for stable FTS operation using Algorithm A is about $\Delta f_0 = 1$ kHz. This is much higher than the minimal plunger movement step defines the frequency adjustment limit df. In the presented FTS configuration, the minimum possible plunger movement was $\delta x = 5$ μm. This value gives the value for $df = 65$ Hz.

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The accuracy and efficiency of frequency control can be significantly increased using **Algorithm B**, based on phase measurements. FTS in this case operates as follows.

In Fig. 3(b) is presented typical phase spectra of reflected from the cavity signal S_{11} for plunger positions with minimal, middle, and maximal penetration depth ΔL in the cavity. Important to note that the phase values at the resonant frequency in all cases lie in a narrow range of values near a certain average (about 154 degrees). One can see the phase ambiguity, (i.e. two frequency values correspond to one phase value). Phase spectra have two extrema, which can be used to divide them into three regions: A, B, C. The regions A, C are characterized by a negative derivative $d\arg(S_{11})/df$. The middle region B is characterized by a positive derivative and including the resonance point. This frequency dependence of the phase allows organizing an algorithm for frequency tuning by 3 points (see Fig. 3(c)). The VNA operates much faster when it is used for phase measurements only in three

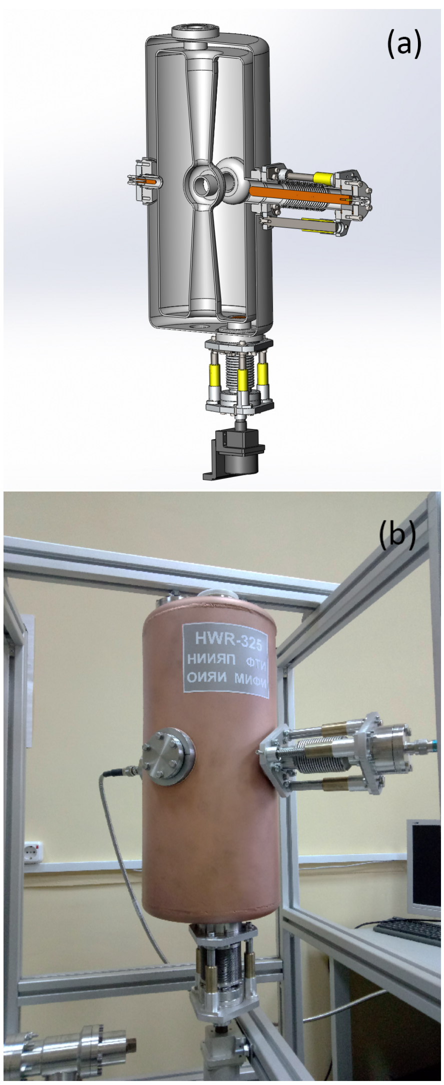

Figure 1: (a) 3D model of the coaxial half-wave resonator with field probe, power input antennas, and plunger-based FTS; (b) manufactured copper prototype.

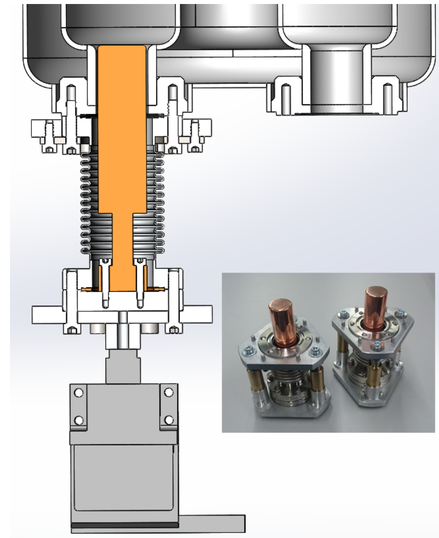

Figure 2: FTS in the one plunger configuration, (inset: fabricated copper plunger units).

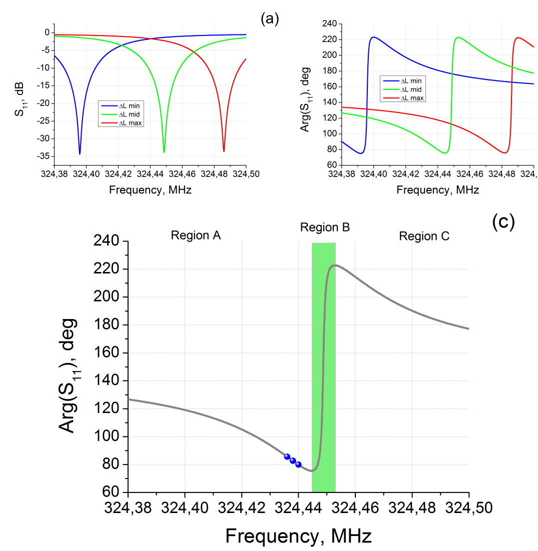

Figure 3: (a) Frequency dependencies of reflected from the cavity signal S_{11} for plunger positions with minimal, middle, and maximal penetration depth ΔL; (b) the same for S_{11} phase; (c) 3 points positions in Algorithm B.

fixed frequencies. The central point is corresponding to the goal frequency. The lateral points are distanced from goal frequency by ± 1 kHz.

If the current frequency is far from the goal (i.e. points are locating in regions A or C), synchronous comparison of the phase of central point with the goal value, as well as the phases of the lateral points with each other, allows determining the direction of plunger movement with a maximal velocity of stepper motor. With such a movement, all three points move to region B, where the phase difference between the lateral points changes sign. After this event it is possible to directly compare the phase of the central point with the phase at the goal frequency, avoiding ambiguity. The speed

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of the stepper motor is also may be ranged depending on deviation from the goal phase.

In practice, it was possible to implement stable tuning with a phase threshold value of about 5 deg. This noise value corresponds to the deviation from the goal frequency of less than 70 Hz. This value is close to the frequency adjustment limit *df* caused by minimum possible plunger movement $\delta x = 5\,\mu$m for the proposed configuration.

EXPERIMENTAL FTS STATIC AND DYNAMIC PROPERTIES

Results of typical measurements of the resonant frequency of the cavity for various penetration depths ΔL are presented in Fig. 4.

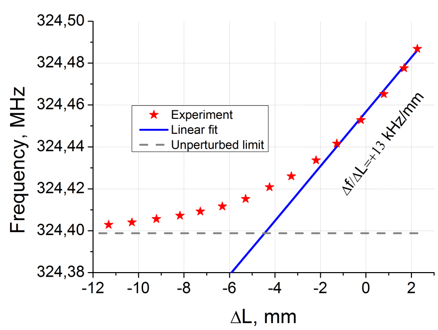

Figure 4: Experimentally measured resonant frequency vs plunger penetration depth ΔL.

From Fig. 4 one can see the monotonic dependence of resonant frequency on plunger penetration depth. The maximal frequency sensitivity is equal to $\Delta f/\Delta L = +13$ kHz/mm when the plunger is inside the cavity volume.

The typical dynamic behavior of FTS when the initial frequency deviation is close to the full tuning range (about 70 kHz) is presented in Figs. 5(a), (b) and (c). Due to the nonlinearity of sensitivity $\Delta f/\Delta L = +13$ kHz/mm, the response is depending on the frequency deviation sign.

The stabilization time of full tuning range perturbation (70 kHz) in all cases is about 1.3 s. Using Algorithm A the minimum threshold value Δf_0 for stable FTS operating is about 1 kHz. A much better tuning level is possible when the FTS is operating using Algorithm B. The minimum threshold value, in this case, is $\Delta f_0 = 70$ Hz, which is close to the frequency adjustment limit *df* caused by minimum possible plunger movement $\delta x = 5\,\mu$m for the proposed slow frequency tuning system.

Important to note, that for further practical applications the frequency oscillations below $df = 70$ Hz should be tuned by a fast sub-system based on piezoactuators. The penetration of rf power into the gap between the plunger and

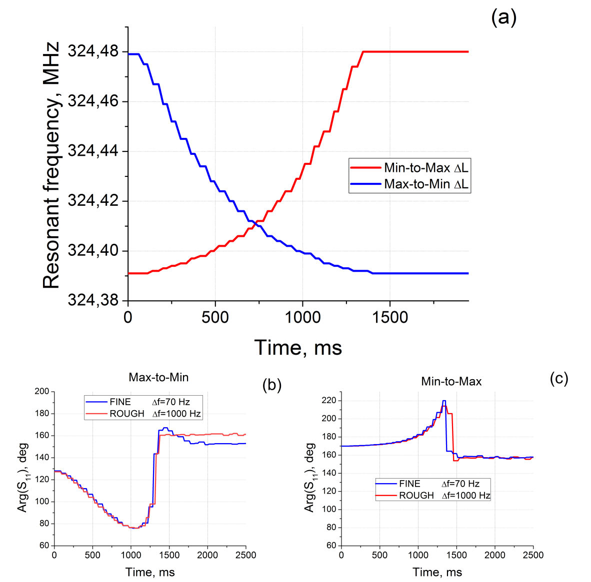

Figure 5: (a) The FTS dynamic response depending on the frequency deviation sign for Algorithm A, and (b-c) for Algorithm B.

the polishing port as well as plunger cooling should be also taken into account for further tests at high rf power.

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REFERENCES

[1] D. Bychanok *et al.*, "Control of electromagnetic properties during prototyping, fabrication and operation of low-β 325 MHz half-wave resonators", *Journal of Physics D: Applied Physics*, vol. 54, p. 255502, Apr. 2021. doi:10.1088/1361-6463/abf168

[2] D. Bychanok *et al.*, "Frequency Tuning System Based on Mobile Plungers For Superconductive Coaxial Half Wave Resonators", in *Proc. 19th Int. Conf. on RF Superconductivity (SRF'19)*, Dresden, Germany, Jul. 2019, pp. 664-666. doi:10.18429/JACoW-SRF2019-TUP086

[3] N. Bazin *et al.*, "Thermo-mechanical simulations of the frequency tuning plunger for the IFMIF half-wave resonator", in *Proc. 26th Int. Linear Accelerator Conf. (LINAC'12)*, Tel-Aviv, Israel, Sept. 2012, paper MOPB074, pp. 351-353.

[4] D. Longuevergne *et al.*, "A cold tuner system with mobile plunger", in *Proc. 16th Int. Conf. on RF Superconductivity (SRF'13)*, Paris, France, Sept. 2013, paper THIOD04, pp. 884-888.