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A FAST MECHANICAL TUNER FOR SRF CAVITIES

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Abstract

There is a particular need for fast tuners and phase shifters for advanced superconducting accelerator RF systems. The tuners based on ferrite, ferroelectric and piezo materials are commonly used. However, those methods suffer from one or another issue of high power loss, slow response, and narrow tuning range. We propose a robust, fast (up to ~5 MHz/sec), high efficient mechanical tuner for SRF cavities operating at the frequency 50 MHz. We develop an external mechanical tuner that is strongly coupled to the cavity. The tuner design represents a trade-off of high efficiency (low RF losses and low heat flux) and frequency tunability range. Our approach solves this trade-off issue. We propose RF design which exploits two coupled resonators so that a main high-field cavity is controlled with a small tunable resonator with a flexible metallic wall operating in a relatively low RF field. Simulations, carried out for a 7.5 MV/m 50 MHz SRF Quarter Wave Resonator (QWR), show that frequency tunability at level 10-3 is obtainable.

INTRODUCTION

High-energy cyclic accelerators of relativistic heavy ions, like PIP III, RHIC, and JLEIC, which have extensive roles in both fundamental and applied research, as well as in industrial applications, require fast tunable superconducting RF cavities providing high acceleration gradients. In PIP III new RF stations and new cavities will be required to accelerate a large amount of beam using a faster ramp [1]. The energy changes from 8 GeV to 120 GeV, and the RF frequency should change by 5×10^{-3}. This requires new tunable cavities with broad tuning range. The minimum acceleration voltage in this upgrade is planned to be 6.75 MV, and, assuming a maximum bucket area of 0.65 eV-sec after the transition, an RF voltage of 7.5 MV will be required [2]. The necessary RF voltage would require more normal conducting RF stations (between 31 and 33). The use of fast tunable superconducting cavities, operating at much higher gradients, can significantly reduce the impedance and decrease the number of the necessary cavities, and, therefore, can considerably reduce the overall power cost.

There are major efforts worldwide to develop high-gradient tunable SRF cavities. At the moment, the best devices provide ~2 MV acceleration per cavity and relatively small tuning range [3]. In particular, the RHIC 56 MHz cavity does not have a sufficient tuning range to follow a large change in frequency during the RHIC energy ramp. The RHIC cavity has a mechanical tuner located in a cryomodule. This represents a challenge for a tuner to provide fast tuning speed in large frequency range at cryogenic temperature. That is why, an external warm tuner strongly coupled with an accelerating SRF cavity seems appealing one.

There is also a particular need for fast tuners and phase shifters for advanced superconducting accelerator RF systems operating in the 0.05-1.3 GHz frequency range, and intended for ERL (Energy Recovery Linac) and ILC, etc. Specific features of ERL accelerator technology, and the challenges of ERL designs for X-ray light sources, are the high amplitude and phase stability requirements for their operation, in the range of 3×10^{-4} and 0.06 degree, respectively [4]. At the same time, mechanical vibrations (microphonics) contaminate the resonator frequency with characteristic frequencies in the range of ~100 Hz.

Fast tuners can be based on several concepts. In particular, ferrite tuners are widely used for boosters and proton cyclic accelerators, and provide acceptable tuning speeds [2], where the use of the orthogonally biased garnet tuner has been described. The major problem is to minimize the losses, which can limit the acceleration gradient. A simple estimate for a 50 MHz cavity that can provide energy gain of particles up to 8 MeV (R/Q~200 Ohm), with frequency tuning range 10^{-3}, shows that power loss can be as high as 15 kW (duty cycle is ~50%). Thus, the cooling of the tuner materials is still a severe issue. Note that ferrites have very low thermal conductivity, with a magnetic loss tangent of $\sim10^{-4}$.

Ferroelectrics can provide extremely high tuning speeds, as has been experimentally demonstrated [5]. More importantly, there are still many problems with the ferroelectric material quality and with metallization techniques, which results in high RF losses, which, again, may limit the gradient. In the example given in the last paragraph, if one substituted ferroelectric for ferrite, the power loss would still exceed 7.5 kW, taking into account the typical $\sim10^{-4}$ loss tangent for ferroelectrics. In addition, ferroelectrics have low thermal conductivity.

The use of piezoelectric deformation tuning is another approach for SRF cavity tuning [6]. However, there is only limited experience with the reliable long-term operation of piezoelectric actuators, especially in the CW regime. At DESY, piezoelectric actuators operate at a small duty factor (0.5%) without significant problems.

Up to the present date, a RF tuner with a rapid response, large tuning range, low RF loss, and high reliability is still lacking. That is why, we propose an approach to use a simple normal conducting metallic tuner, which incorporates an actuator with light flexible metallic wall that is electrically controlled by magnetic fields coils (similar to the function of piezo-elements), in order to produce a much lower RF power loss, which will increase the convenience of the cooling design. The main innovation of the proposed approach lies in the use of an external fast mechanical tuner

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strongly coupled to the cavity. The tuner design represents a trade-off between high efficiency (low RF losses and low heat flux) and good tunability (range of frequency tuning). We propose an RF design that exploits two coupled resonators, so that the main higher energy resonator is controlled by a tunable resonator that operates at a low accumulated energy.

A CONCEPT FOR FAST TUNER

We consider a cavity of the classical Quarter-Wave Resonator (QWR) design, which supplemented with an external tuner. In particular, a 53 MHz cavity of the PIP-II main injector is assumed to be developed. As was shown in [7], an external tuner (Fig. 1) has the greatest likelihood to be robust in the CW regime. However, instead of the ferrite tuner version, considered in [7], we plan to develop a mechanically controlled tuner, the idea of strongly coupling two resonators, where one of them is tunable, will be developed below.

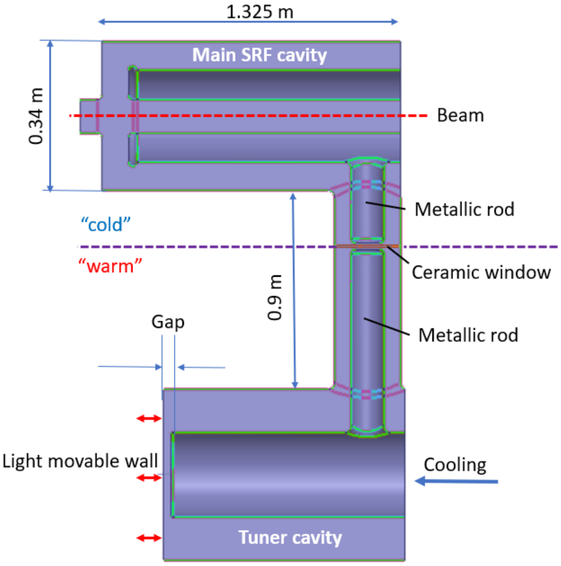


Figure 1: Over all conceptual drawing of the 53 MHz SRF cavity equipped with warm external mechanical tuner.

Let us consider a so-called quarter wave resonator (QWR) cavity. The main QWR cavity operates at a resonant frequency close to $\omega=2\pi c/4l$, where l is the length of the cavity. The proposed tuner design assumes that most of the tuner parts are located outside of the cryomodule, and that the tuner has a flexible metal coated (normal conducting) wall section for fast tuning. The metallic rod in the tuner must be produced of thin wall pipe, in order to reduce thermal flux to SRF cavity and to simplify cooling of the warm tuner. In Fig. 1, the main SRF cavity is coupled to the external tuner cavity. We assume that fast tuning speeds can be provided by means of a fast mechanical actuator based on two coils, one attached to the flexible wall, and the second attached to an external support. The mentioned principle was successfully demonstrated at Fermilab [8]. In both cases, we assume a small amplitude of motion (up to 20 mm). The main cavity and the tuning cavity in Fig. 1 are separated by a coupler.

The coupling must have a defined value, with an eigenmode that limits the fields in the tuner cavity to a stored energy of no more than ~10^{-3} of the energy accumulated in the main cavity. This condition is necessary to obtain two goals simultaneously. In accordance with the perturbation theory, the required frequency shift of $\Delta f/f$ ~10^{-3} in a high-Q resonator requires an energy change caused by tuning at level $\Delta E/E$ ~10^{-3}, where E is the total energy stored in the resonator that consists of the two coupled cavities. On the other hand, the stored energy in the tuner should also be small to keep a reasonable heat flux at the tuner. These considerations determine the trade-offs that arise between tuning range and power absorption in the tuner.

SIMULATIONS FOR 53 MHz CAVITY

The ultimate goal of the design is to build, and commission a fast, tunable 53 MHz SRF cavity that can provide up to 8 MV gap acceleration (Table 1).

Table 1: Targeted 53 MHz QWR Performance

Parameters	**Values**
Frequency	53 MHz
Acceleration gain	8 MV/m
Duty Cycle	50%
Stored energy in the main cavity	10^3 J
Stored energy in tuner cavity	1 J
Tuning range	~50 kHz
Tuning speed	5 MHz/sec
Power loss in tuner	~10 kW

The scheme, shown in Fig. 1, is based on the use of a tuner with QWR resonator having variable capacitor. The capacitor helps to reduce the necessary cavity length by a factor Δl=cZ_0C (C – a capacitance, Z_0 – the impedance of the coaxial waveguide), as well as to increase the sensitivity to a shift of the flexible wall.

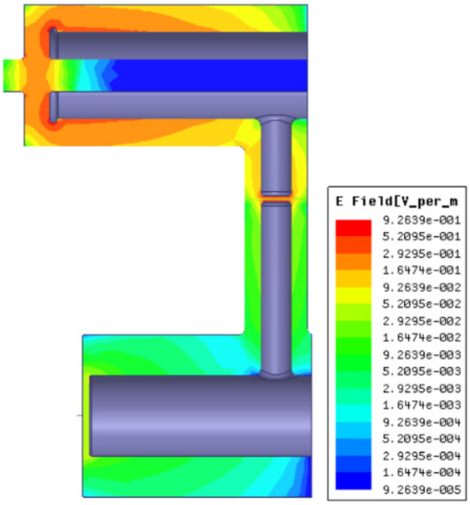


Figure 2: E-field distribution for tuner gap 30 mm (logarithmic scale).

The main SRF cavity is coupled to a warm tuner cavity employing a flexible wall. Let us consider the QWR with parameters corresponded to those that were proposed for PIP-II [1]. This 53 MHz QWR is based on a 1.3 m long coaxial waveguide with outer diameter 68 cm and aperture 7.62 cm.

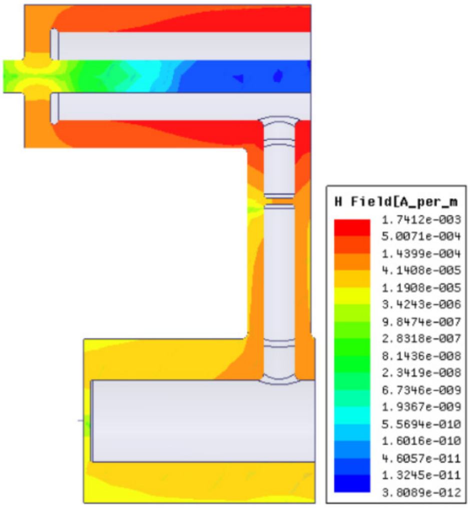
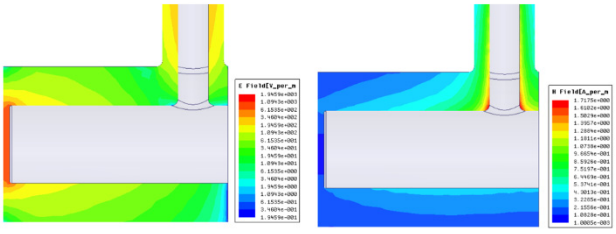
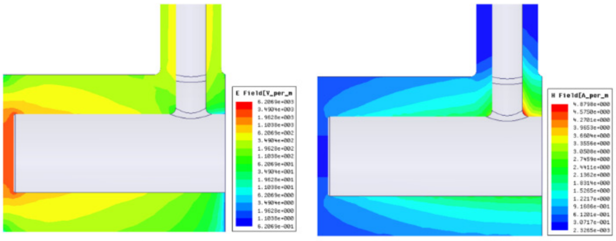


Figure 3: B-field distribution for tuner gap 30 mm (logarithmic scale).



(a) (b)

Figure 4: E-field (a) and B-field (b) in the tuner resonator for the gap 30 mm (logarithmic scale).



(a) (b)

Figure 5: E-field (c) and B-field (d) in the tuner resonator for the gap 50 mm (logarithmic scale).

We propose to add fast normal conducting tuner according to the scheme shown in Fig. 1, in order to control the frequency of the main cavity. The stored electromagnetic energy in the tuner cavity is to be by $\sim10^3$ less than the energy stored in the main accelerating resonator. That is why, in a linear scale all fields in the tuner are not seen in comparison with strong ones of the main SRF resonator. Note that mounting a coupler antenna of the tuner does not make an asymmetry of the electromagnetic field in the SRF cavity. In Figs. 2 and 3 E- and B- fields correspondingly are shown in the logarithmic scale.

The coupler consists of two coaxial waveguide sections with capacitive coupling between them. The coupler has also Al_2O_3 window ($\tan\delta=3\times10^{-5}$). This window is necessary because vacuum condition between cavity and tuner should be separated to avoid particle contaminations. Tuner mechanics can produce duct particle, and in case of window absence the cavity performance would degrade due to field emission by contaminants. The coupling factor was selected with reflection by window taken into account to provide a ratio of 10^{-3} of the stored energy in the tuner to the energy in the main cavity.

In Figs. 4 and 5 fields are shown in the tuner fed at 53 MHz by 1 W power source for two positions of the tuning end wall, with 30 mm and 50 mm gap respectively. In both cases, the E-field maxima are located at the capacitor which we tune. The B-field maxima occur near the opposite wall of the tuner. Simulations of steady-state regimes shows that a tuning range of about 50 kHz has been provided when the gap in the tuner is variated in-between 30 and 50 mm (Fig. 6). This frequency difference corresponds to the different eigen modes corresponding to the Figs. 4 and 5.

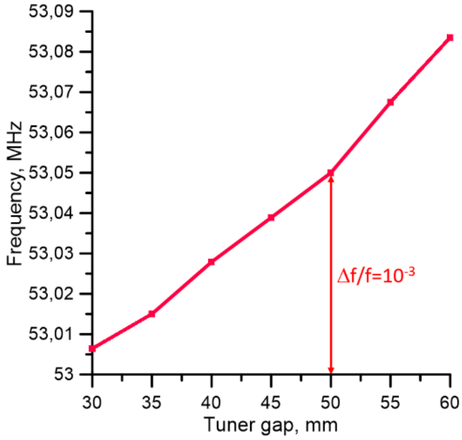


Figure 6: Eigen-frequency of the whole RF system (main cavity plus tuner).

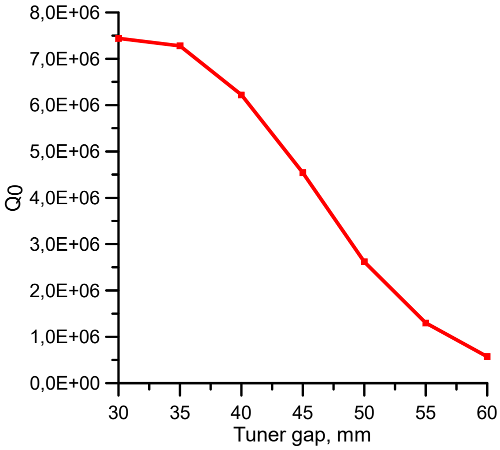


Figure 7: Q_0 of the whole RF system.

The quality factor of the eigen mode in the whole system depends on tuner gap and decreases when tuning gap expands (Fig. 7). The reason is that an eigen frequency of a partial mode of the tuner itself approaches to the frequency of the main cavity when the gap becomes wider. This leads to field increase in the gap (Fig. 8) as well as in all volume of the tuner (compare fields in Figs. 4 and 5). Eventually, if one changes gap in the range 30 mm - 50 mm, E-fields grows up from 5 MV/m to 10 MV/m. Correspondingly, a full power loss in the tuner and coupler (including ceramic window) is as small as 20 kW for the gap 30 mm and is as large as 60 kW for the gap 50 mm (Fig. 9). The mentioned power loss is still small comparing to full consumed power of the main resonator (550 kW). Nevertheless, it is reasonable to restrict tuning range within 30 mm – 50 mm. In this range the necessary tuning has successfully been provided (Fig. 6).

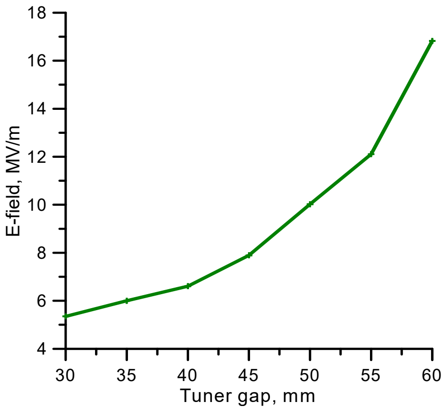


Figure 8: Field in tuner gap between coaxial rod and movable wall.

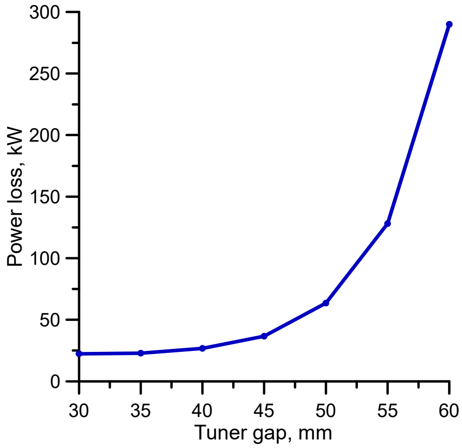


Figure 9: Power loss in tuner and in transmission line for duty factor 50%.

CONCLUSION

We have proposed to develop, fabricate, and demonstrate a robust, fast (up to ~5 MHz/sec), highly efficient tuner for SRF cavities operating at a frequency of 53 MHz and an accelerating voltage up to ~8 MV. Our simulations show that this goal is feasible.

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