A Mechanical Tuner for the ISAC-II Quarter Wave Superconducting Cavities

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Abstract

TRIUMF is developing a new mechanical tuner system capable of both coarse (kHz) and fine (Hz) frequency adjustments for maintaining frequency lock on the superconducting quarter wave cavities of the ISAC-II heavy ion linac. A 1 mm thick Niobium plate at the high field end of the cavity is actuated by a vertically mounted permanent magnet linear servo motor, at the top of the cryostat, using a ‘zero backlash’ lever and push rod configuration through a bellows feed-through. The system resolution at the tuner plate center is $\sim 0.055\mu$m (0.3 Hz) with a dynamic range of 8 KHz and a manual coarse tuning range of 33 kHz. In cold tests with a prototype quarter wave cavity the tuning system’s ability to compensate perturbations indicated a bandwidth up to 100 Hz. A large mechanical resonance at 20 Hz should be eliminated in the on-line device. The rf control is based on a self-excited loop with a locking circuit for amplitude and phase regulation. The tuner is fed a position signal integrated from the control loop phase error. Details of the mechanical device and results of open and closed loop cold tests will be given.

1 INTRODUCTION

TRIUMF is installing a superconducting heavy ion linac as part of the ISAC-II upgrade [1] to increase the final energy of the radioactive beam above the Coulomb barrier. A first stage of the project includes the addition of twenty quarter wave, 106.08 MHz, bulk niobium cavities arranged in five cryomodules. A prototype cavity is available for rf testing and development. Four production cavities have recently been delivered to TRIUMF with the remaining sixteen cavities due for delivery in August 2003.

In previous linac installations the tuning of quarter wave cavities has been accomplished with mechanical or pneumatic tuners characterized by slow response, poor resolution and/or large backlash. Detuning by microphonic noise or rapid fluctuations in helium delivery pressure are accomodated by either overcoupling to reduce the loaded Q or with a variable reactive load using a PIN diode network at the cavity. A slow tuner response affects the required Q-loading and may limit the accelerating gradient due to constraints on the stored energy.

The ISAC-II design gradient is 6 MV/m giving a stored energy of $U_o = 3.2$ J. The natural bandwidth of ±0.1 Hz is broadened by overcoupling. The required forward power is given by $P_f(W) \simeq \pi U_o \Delta f_{\frac{1}{2}}$ for overcoupled systems. A rough rule is to use a loaded bandwidth of six times the microphonic noise plus twice the resolution of the mechanical tuner [3]. The ISAC-II medium beta cavities are outfitted with a passive mechanical damper[2]. Test stand measurements show microphonic noise detuning of the cavity frequency at ~ 0.3Hz RMS due to the main mechanical frequency of 72 Hz. Fluctuations in an on-line accelerator can be several times larger but are not expected to be more than a few Hz RMS. The goal for the ISAC-II cavity tuner is to achieve fine (1 Hz) tuning capability with a response time to control fast helium pressure fluctuations allowing stable operation within a bandwidth of $\Delta f_{\frac{1}{2}} = 20$ Hz. Sensitivity to helium pressure fluctuations is 1 Hz/Torr with expected pressure variations of 10 Torr at rates up to 1 Torr/sec. In addition the tuning range must be adequate to compensate for variability in manufacturing and cooldown. A ± 20 kHz coarse range is a comfortable margin. The tuner described here provides both fine and coarse tuning requirements in a single device.

2 MECHANICAL SYSTEM

2.1 Tuning Plate

The tuning plate (see Fig. 1) consists of 1 mm thick RRR Niobium sheet of 240 mm diameter fixed to the bottom Niobium flange by bolts and retaining flange. A flat plate can be used but the deflection force required is parabolic with distance and tends to assume a concave shape upon cooling leading to highly non-linear behaviour. To overcome these problems the ISAC-II tuning plate is spun with a single ‘oil-can’ convolution and milled with eight radial 1 mm slots. The plate is capable of allowing ±20kHz (±3 mm) of tuning range before yielding. Cold tests with the plate give Q and gradient values consistent with the flat plate performance[1].

Figure 1: The tuner plate, lever arm, bottom of push-rod and cavity viewed from below.

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[*] TRIUMF receives funding via a contribution agreement through the National Research Council of Canada

2.2 Tuner

The tuner diaphragm is actuated by a simple lever arm and push rod arrangement as shown in Fig. 2. The top end of the push rod goes from vacuum to air via an edge welded bellows. The push rod is coupled to a linear direct drive ironless coil servomotor. A low stiffness coil is attached to counteract the effects of air pressure on the bellows. The spring compression is manually adjustable in order to set the mechanically self-seeking equilibrium position before servo startup. The lever arm is specially designed to have a high fundamental frequency, ≃200 Hz, so that it remains decoupled from the position loop bandwidth of ≃200 Hz. The push rod consists of a 25 mm diameter 316 stainless steel tubing with a 0.38 mm thick wall giving less than 0.1 W of heat load. The rotary joints are comprised of anti-backlash, high strength and stiffness pivot bearings. They are limited in rotation to about $\pm 8^\circ$, however, the required motions are well within this range.

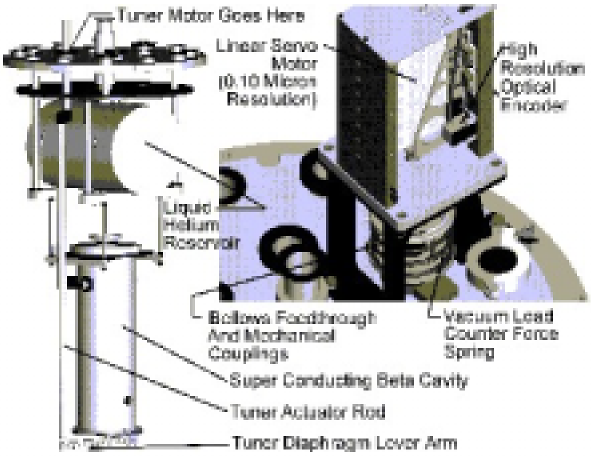

Figure 2: Tuner drive assembly layout.

3 CONTROLS

3.1 Tuner Drive

The heart of the supervisory control is the PCI bus digital servo controller. The feedback position of the motor is sent to the controller by the servo amplifier in phase quadrature form. The return command drive error signal is analog in the range ± 10 V but with the “impress” of the previous 12 bit signal.

The position of the motor is sensed by a high resolution sine encoder and fed through special subdividing electronics with an effective control resolution inside the servo amplifier of 0.01μm. The actual system resolution at the plate is about 0.055μm limited only by the analog command signal from the digital servo controller to the amplifier as well as the phase quadrature position signal from the amplifier which can be adjusted to suit. The bandwidth of the current control loop is 600 Hz while the velocity loop can be tuned to better than 200 Hz. The design target for the position loop is 100 Hz to handle possible microphonic control. Fast, precise tuner response is made possible by a stiff high bandwidth velocity loop compensation called PDFF that is immune to overshoot and load disturbances like friction.

3.2 RF Controls

The ISAC-II rf control[4] is based on a self-excited loop with a locking circuit for amplitude and phase regulation. The tuner is fed a position signal integrated from the control loop phase error. When a resonant cavity with a natural frequency ω_c and time constant τ is excited at a frequency ω, the phase shift between the input and output is given by $\tan\phi = \tau(\omega - \omega_c)$. This phase shift is measured by an edge-triggered JK flip-flop phase detector. This detector is well suited since it lacks memory when a cycle is skipped and exhibits no reversal behaviour in its output at all phase ranges. The phase shift is processed by a DSP to drive the mechanical tuner and keep the cavity in tune with the external master frequency.

The system response equation is given by

$$\frac{\delta\phi}{\delta x} = \frac{s^2 G_u}{s^3 + s^2\Phi_p(1+T_p) + s(\Phi_i(1+T_p) + \Phi_p T_i) + \Phi_i T_i}.$$

Here $\Phi_{p,i}$ and $T_{p,i}$ are the quadrature loop and tuner loop feedback parameters respectively and G_u is the detuning of the cavity resonance due to deformation of the cavity where $\delta\omega_c = G_u \delta x$. The expression ignores the amplitude loop. An analysis of the equation[4] shows that the tuner response must be slower than the response of the phase quadrature loop in order for the system to remain stable. This fundamental limitation could be avoided if the tuner control was configured to respond to a velocity signal. If the mechanical resonance at 20 Hz is removed (see below) it may be possible to use the tuner to combat detuning from 72 Hz microphonics. However as the results below confirm the present configuration is certainly sufficient to provide accurate compensation for slow (few Hz/sec) frequency fluctuations.

4 COLD TEST RESULTS

The mechanical tuner performance has been characterized over several cold tests from Oct. 2002 to present. Since the tuner plate is linked to the cryostat by the tuner shaft we had concern that tuner or environment noise would feedback to the cavity. Low frequency (0-10 Hz) dithering of the tuner produced no significant coupling to the cavity microphonics. The transfer function from the mechanical tuner modulation signal to the amplitude and phase of the cavity self-excited frequency was recorded. The amplitude is given in Fig. 3. Except for a mechanical resonance at 20 Hz there is good response out to at least 100 Hz. Present thinking is that the mechanical resonance is due to a dogleg in the push-rod that is necessary in the test cryostat but can be eliminated in the on-line system.

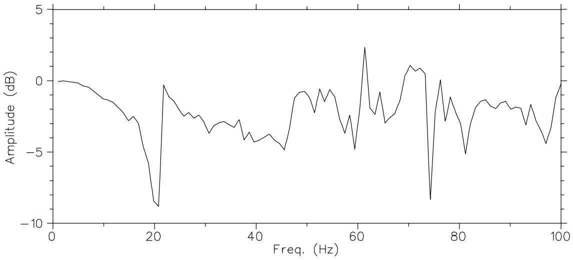

Figure 3: Tuner transfer function.

The tuner on-line performance is measured by altering the cavity frequency by forced variations of the helium pressure with a valve on the vent gas line. The pressure is measured with a transducer located on a flange on the helium space. In general the pressure variations are more extreme than we expect for the on-line system but they allow us to optimize the PID parameters for the control and tuner loops. Data is taken for a variety of cavity field and coupling strength settings. Results for both a low field and a high field case are shown in Fig. 4 and Fig. 5 respectively. The bandwidth for the high field case is limited by the maximum power of the test amplifier. The plots give the pressure change and the associated position drive signal for the tuner. The voltage and phase error are given for each case. Note that the phase error resolution is limited to 1° by the 12 bit ADC. The plots show that the tuner responds accurately to the pressure variation with a resolution better than 0.1μm (0.6 Hz). The regulation in amplitude and phase is within the limits of ±1% and ±1° for the low field case. In the high field case due to the limited bandwidth the phase stability goes out of the regulation tolerance during moments of rapid pressure change.

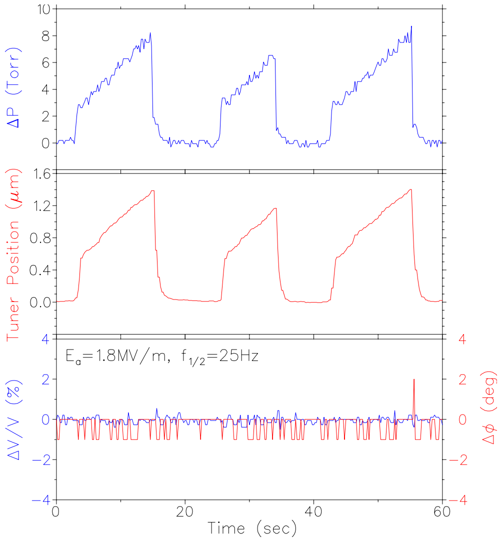

Figure 4: Tuner response to forced helium pressure fluctuation ($\frac{\Delta f}{\Delta P}$ = 1Hz/Torr) and corresponding voltage (blue) and phase (red) errors for low field (E_a=1.8 MV/m) and a bandwidth of ±25 Hz.

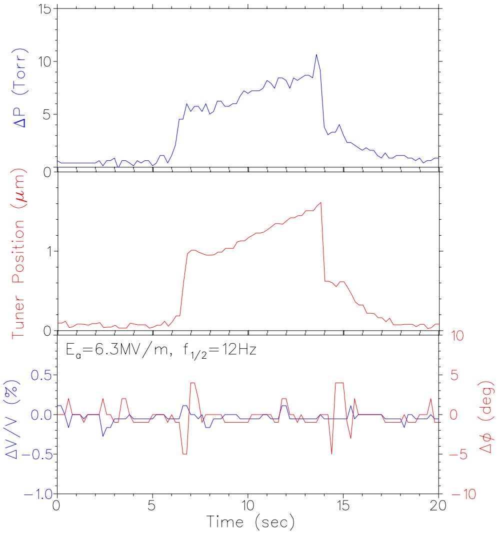

Figure 5: Tuner response to forced helium pressure fluctuation ($\frac{\Delta f}{\Delta P}$ = 1Hz/Torr) and corresponding voltage (blue) and phase (red) errors for high field (E_a=6.3 MV/m) and a bandwidth of ±12 Hz.

The dynamic range of the tuner is limited by the motor strength to ±4 kHz. A threaded position platform for the spring tensioner is used to provide manual coarse frequency adjustments. A tuning range of 33 KHz has been demonstrated and was limited only by mechanical stops on the platform that will be altered to give the full 40 kHz design range.

5 CONCLUSION

The tuner is a significant advance on mechanical tuners presently used on quarter wave structures due to its high precision (0.3 Hz), and response bandwidth (presently limited to 20 Hz). The demonstrated coarse tuning range is 32 kHz. In addition the convoluted lower tuning plate and robust tuner mechanical design allow cold plastic deformation of the plate reducing the tolerance on cavity geometry necessary during cavity fabrication. Assuming that the mechanical resonance at 20 Hz can be eliminated future developments could see the rf controls configured to provide a velocity signal removing the fundamental limit on the tuner speed due to loop stability.

6 REFERENCES

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