# OPERATIONAL EXPERIENCE WITH THE MECHANICAL TUNER SYSTEMS IN THE SUPERCONDUCTING LINAC AT IUAC

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## *Abstract*

The phase locking of the QWRs by dynamic phase control method in the superconducting linac at IUAC is done in a fast time scale. The slow frequency drifts (few hundreds of ms) are corrected using a niobium bellows tuner attached at the open end of the cavity. Initially, the tuners in the cavities were operated using helium gas. This system had the limitation of non-linearity, hysteresis and slow response due to which the cavities could not be phase locked at higher fields. To address this, piezo based tuning system was implemented in the cavities of the 2nd and 3rd linac modules. But due to space constraints, the same could not be used in the 1st linac module and the buncher modules. For them, the helium gas based system was continued, albeit with suitable modifications. The old flow control valves which operated with DC voltages were replaced with valves operating in pulsed mode and controlled by varying the duty cycle of the input pulses. The above mentioned limitations were overcome by using this PWM based technique and this enabled phase locking at higher gradients. This paper presents our operational experience with all the different tuning systems and their comparison.

## INTRODUCTION

The superconducting (SC) heavy ion linear accelerator (linac) [1-3] of Inter University Accelerator Centre (IUAC) augments the energy of the heavy ion beams coming out of the Pelletron accelerator [4]. The linac consists of five cryostats housing 27 identical quarter wave resonators (QWR) [5] optimized for a normalized velocity (β=v/c) = 0.08, operating at 97MHz (Fig. 1). The superbuncher (SB) cryostat has a single QWR used to bunch the ion beams from ~ 1.5ns FWHM to 150ps FWHM beams. The next three cryostats, which are the accelerating modules, have twenty four QWRs for accelerating the ion beams. The last cryostat, namely rebuncher (RB), has two QWRs which are used to rebunch the accelerated ion beam either in time or in energy on to the experimental target.

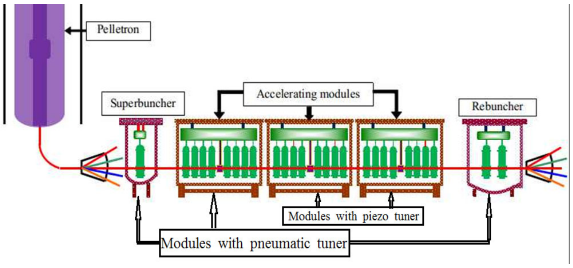

Figure 1: Schematic of Pelletron – Linac System.

In order to accelerate the heavy ion beams through the linac, the amplitudes and phases of the accelerating electric fields in the QWRs must be locked. The phase is locked using the dynamic phase control method [6, 7] and with the help of mechanical tuners operating parallelly. The IUAC-QWR and frequency tuner bellow is shown in Fig. 2. To maximize the phase locked fields in the cavities at a given input RF power, different techniques have been developed, e.g. modification of the power coupler design [5], damping of vibration of the central conductor of the QWR [3], improvements in the mechanical tuner design [8-12], surface treatment of the cavities [13], etc. This paper will focus only on the mechanical tuner systems used and modified from time to time till date.

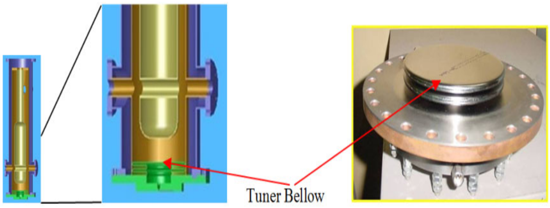

Figure 2: IUAC QWR (left) and frequency tuner bellows (right).

## QUARTER WAVE RESONATOR

SC QWRs in the IUAC linac operate at 97MHz hence the operating temperature is 4.2K. The loaded quality factor ($Q_L$) [14] in the IUAC QWR is typically set around $10^6$–$10^7$. Therefore the resulting narrow bandwidth makes these cavities quite sensitive to the surrounding mechanical microphonic vibrations. The QWRs are independently powered and phase locked [6, 7]. In the free running self-excited loop (SEL) [6, 7] (Fig. 3), the resonance frequency of the IUAC-QWR drifts in two time scales (Fig. 4). Therefore the phase locking scheme adopted, consists of two level of control. One acts in fast time scale (electronic) and

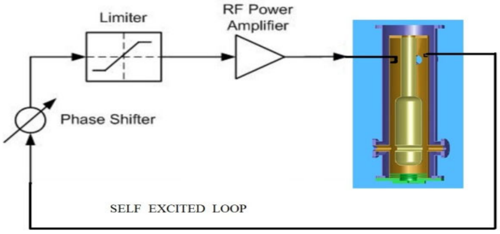

Figure 3: Cavity running in self excited loop.

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the other acts in slow time scale (mechanical). The fast time scale frequency jitter is taken care by dynamic phase control using complex phasor modulator [6, 7] (or I-Q modulator). On the other hand, the slow frequency drift is arrested by using mechanical tuner [8-12, 15] system to flex the niobium bellows attached at the high voltage end of the QWR. The two tuning mechanisms work simultaneously and are able to lock the phase of the accelerating electric fields in the QWRs. This scheme helps in reducing the overall power requirement of the fast tuner to control the frequency jitter.

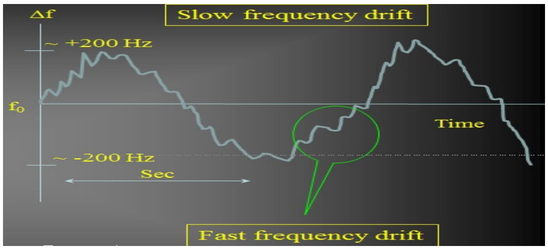
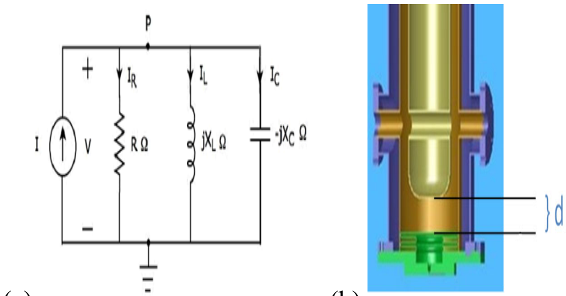


Figure 4: Resonance frequency drift of IUAC QWR set under SEL, in two time scales.

## OPERATION OF FREQUENCY TUNERS

During phase locked condition, the frequency tuners correct for slow changes in the cavity frequency due to changes in the liquid Helium bath pressure. Tuners are an active part of a complete RF control system which fulfils several functions. A tuner stabilizes the frequency, amplitude and phase variations induced by sources such as the RF drive, beam current variations, Lorentz force detuning and microphonics. Different types of frequency tuners are being used for different cavity designs across the world. Few of them are tuners based on change of length of cavities by stepping motor + piezoelectric (e.g. $e^- e^+$ collider at KEK) [14-16], mechanical tuners based on change of length of cavities by thermal expansion + magnetostrictive (e.g. $e^- e^+$ collider at CERN / LEP) [14-16], VCX tuner for ATLAS at ANL [15], mechanical tuners based on deformation of flat bellows in high electric field region (by piezoelectric actuator and by using helium gas) (e.g. heavy ion linac at IUAC ) [8-12, 15]. The electrical analogue of QWR is a parallel LCR circuit as shown in the Fig. 5(a). The gap between the open end of the central conductor and the frequency tuner bellows forms a parallel plate capacitor as shown in the Fig. 5(b).



(a) (b)

Figure 5: (a). LCR circuit, (b) QWR open end as parallel plate capacitor.

The resonance frequency of the LCR circuit is given by

$$f_o = \frac{1}{2\pi\sqrt{\left\{L\left(\frac{\varepsilon A}{d}\right)\right\}}} = \frac{\sqrt{d}}{2\pi\sqrt{\varepsilon L A}} \quad (1)$$

$$\Rightarrow \quad f_o \propto \sqrt{d} \quad (2)$$

where, d is the gap between the drift tube and the tuner bellows. It is clear that the resonance frequency depends on ‘d’. So, for frequency tuning, this gap has to be varied.

## FREQUENCY TUNERS USED IN QWR OF IUAC LINAC

When the SC linac at IUAC initially started accelerating the ion beams, the mechanical tuner system used helium gas to flex the bellows (pressurized and evacuated), to change the resonance frequency of the cavity. To maintain the mean resonance frequency of the resonator equal to the reference frequency, the fast component of frequency variation was handled by the dynamic phase controller [6, 7], and the slow frequency drift was taken care by the helium gas based slow tuner system. However, the response of this mechanical tuner was slow (of the order of seconds) [8, 9] as shown in Fig. 6, because it was dependent on the mechanical response of the helium gas flexing the niobium bellows.

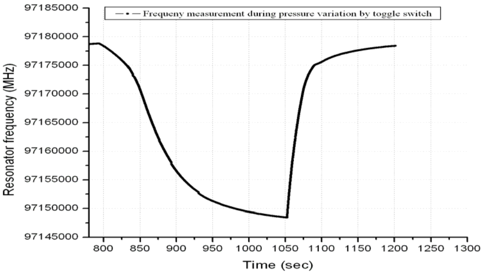


Figure 6: Slow response of old pneumatic tuner.

Other limitations were, non-linearity and hysteresis behaviour (Fig. 7). So, before the slow tuner control could completely correct the phase error, the resonance frequency used to deviate from the clock frequency and this had to be taken care of by the dynamic phase controller which demanded large amounts of RF power (200-250 W). This high RF power operation invited problems such as cable melting, heating of drive coupler, increased cryogenics load, etc. In order to keep the operation trouble free, the loaded bandwidth had to be increased (keeping the RF power at the safe limit of 100W) to nearly equal the peak-to-peak frequency deviation due to both slow and fast frequency fluctuations, thereby further decreasing the value of $Q_L$. This resulted in the cavities operating at reduced accelerating gradients even though these QWRs were capable of operating at higher field gradients. The large control power restricted their operation to low gradients only.

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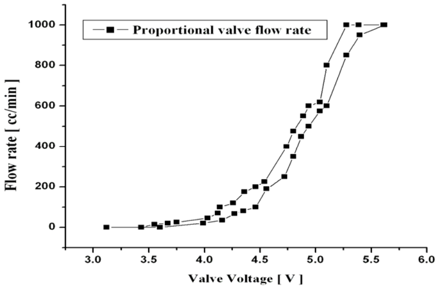

Figure 7: Hysteresis behaviour of proportional valves.

In 2007, the first accelerating module was ready and in the beam acceleration test, the average accelerating gradient achieved was 2.78MV/m. As more and more cavities got produced [17], they were installed in the second accelerating module after having been tested in the test cryostat.

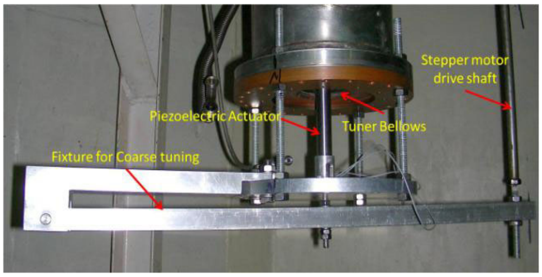

Figure 8: Piezo-electric tuner.

In 2011, sixteen QWRs were installed in the first two accelerating modules and tested. The average phase locked fields of the first and the second accelerating modules were 2.90MV/m and 2.47MV/m respectively although the cavities were capable of operating at comparatively higher field gradients. There were other issues as well. The third cavity of the second accelerating module (i.e. R23) was operating at higher gradients and was phase locked at field gradient 2.72MV/m. However during phase locking, it was found that with R23 under phase locked condition, the locks of the cavities R25, R26, R27 and R28 became very unstable. So, R23 was deliberately phase locked at a very low field 0.22 MV/m.

To address the problems in the pneumatic tuner, a new piezoelectric actuator based mechanical tuner was tested and implemented in the QWRs of the second accelerating module. The piezo actuator flexed the tuner bellows and thus the frequency was tuned. The schematic diagram of the piezoelectric tuner [8] system is shown in Fig. 8.

To control the resonance frequency excursion, an electronic controller was developed, tested and implemented with the piezoelectric tuner (Fig. 9). In the piezoelectric tuner controller [8, 12], two simultaneously working feedback loops were incorporated to improve the dynamics of the phase control. The first one is the Proportional-Integral (PI) based control, that corrected the slow frequency drift and the second one is the Positive Position Feedback (PPF) loop that suppressed the microphonics. The piezoelectric integral control was optimized to correct the slow drifts caused by liquid helium system at an optimised rate (~ 80 Hz in 12 ms) without exciting any of the higher resonant modes of the cavity. This improvement in the phase correction rate has enabled the control scheme to phase lock the resonators at higher field gradient with forward power less than 100 W. In the subsequent linac test, there was improvement in the locking fields (Table 1). Before piezo tuners were installed, R22, R23, R24, R26 and R28 were given High Pressure Rinsing treatment. During test, these cavities were given Helium Pulse conditioning treatment also.

Figure 9: Piezo-electric tuner controller.

Table. 1: Comparison of locking fields of the QWRs with old pneumatic frequency tuner and with piezoelectric based frequency tuner in the second accelerating module.

| | **QWRs with old pneumatic tuner** | | | **QWRs with piezo actuator based tuner** | | |
|---|---|---|---|---|---|---|
| **QWR #** | **Electric Field @ 4 Watt [ MV/m ]** | **Electric Field @ 6 Watt [ MV/m ]** | **Phase Locked Field [ MV/m ]** | **Electric Field @ 4 Watt [ MV/m ]** | **Electric Field @ 6 Watt [ MV/m ]** | **Phase Locked Field [ MV/m ]** |
| **R21** | 1.75 | 2.06 | 1.10 | 2.84 | 3.42 | 2.48 |
| **R22** | 4.55 | 5.26 | 2.95 | 4.68 | 5.18 | 3.98 |
| **R23** | 3.78 | 4.36 | 0.22 | 5.06 | 5.55 | 4.39 |
| **R24** | 5.08 | 5.35 | 2.75 | 4.35 | 4.70 | 4.00 |
| **R25** | 4.13 | 4.32 | 3.52 | 2.33 | 2.75 | 2.61 |
| **R26** | 2.99 | ------ | 3.01 | 5.46 | 5.94 | 3.05 |
| **R27** | 4.12 | ------ | 2.28 | 4.89 | 5.05 | 4.06 |
| **R28** | 4.58 | 4.68 | 3.95 | 2.25 | 1.86 | 1.88 |
| **Avg. Field** | | | **2.47** | | | **3.31** |

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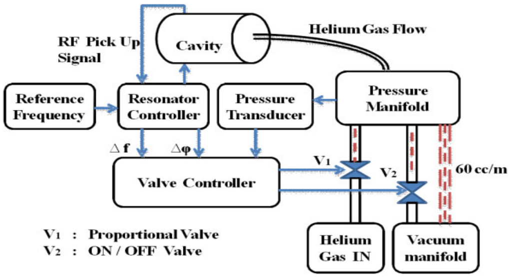
In the recent linac test, R23 was phase locked at the field gradient 4.39 MV/m. In the same test, during Q-measurement of R25, the field was not stable and it fell down to a lower value after the RF power was increased beyond 6W. Field gradient of 2.75 MV/m could be achieved @ 6W and thus this cavity was phase locked at the field gradient 2.61MV/m. During Q-measurements of R28, it was found that the field became unstable after 4W. Field gradient 1.86MV/m was achieved @ 6W. So, this cavity was phase locked at the field gradient 1.88 MV/m.



In the new system, dashed lines are not present and V1 , V2 both are pulse operated Proportional Valves

Figure 10: Schematic diagram of helium gas based pneumatic tuner (old and new).

The piezoelectric tuner system was also implemented in the cavities of the third accelerating module. However, due to space limitation at the bottom of the cryostat, this system could not be implemented in the QWRs of the Super-buncher, first accelerating module and the Re-buncher. For these cavities, helium gas based tuner system was continued with the above mentioned limitations while other options were evaluated and tested. The Pulse Width Modulation (PWM) based pneumatic frequency tuner [9-11] appeared to provide a good alternative. It was successfully tested in a QWR in the test cryostat. In this system, the valves in the pneumatic frequency tuner system were replaced by two identical valves operating in pulsed mode and the valve openings controlled by varying the duty cycle of the input pulses. The phase error signal generated by resonator controller was processed by the PWM controller and thus the duty cycles of the pulses going to the valves were modulated thereby correcting the phase error. Flow restrictors were also removed as shown in the Fig. 10.

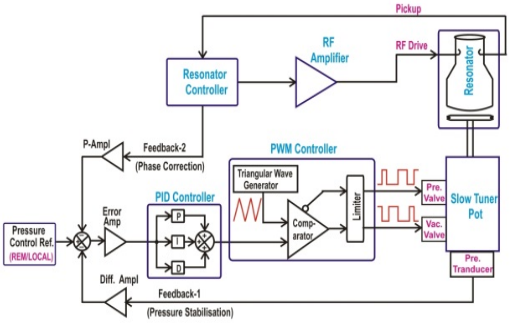


Figure 11: Schematic diagram of PWM based pneumatic tuner controller.

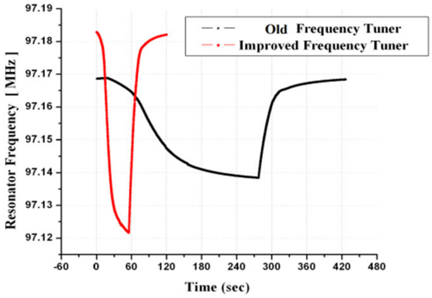


Figure 12: Fast response of PWM based tuner.

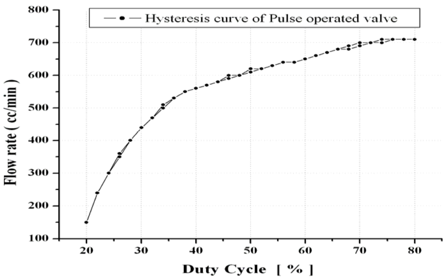


Figure 13: Hysteresis free behaviour of pulse operated valve.

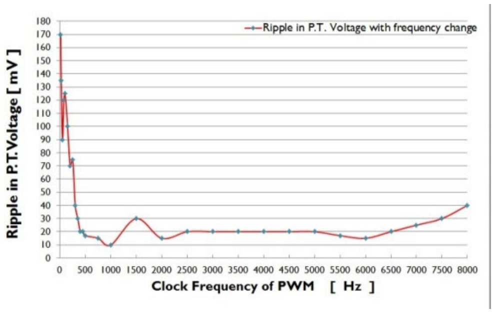


Figure 14: Ripple in the Pressure Transducer voltage as a function of clock frequency of PWM.

The schematic diagram of the PWM based pneumatic tuner controller is shown in the Fig. 11. In this test, encouraging results were found as shown in the Fig. 12 and Fig. 13. A test to study the jitter in the pressure transducer voltage as a function of clock frequency of PWM pulse was performed. The result is shown in the Fig. 14. It was found that the ripple measured in the pressure transducer voltage was minimum at the clock frequency of 1kHz, so the clock frequencies of the pulses of all the PWM based tuner controller was set at 1kHz.

After that, the stability of the phase lock was further improved. The PWM based pneumatic frequency tuner was installed in the first accelerating module. The helium mass flow system is shown in Fig. 15(a) and the controller is shown in the Fig. 15(b). In the linac test, substantial improvement was observed as shown in Table 2.

Table 2: Comparison of locking fields of the QWRs with old pneumatic frequency tuner and with PWM based pneumatic frequency tuner in the first accelerating module.

| | **QWRs with old pneumatic tuner** | | | **QWRs with PWM based pneumatic tuner** | | |
|---|---|---|---|---|---|---|
| **QWR #** | **Electric Field @ 4 Watt [ MV/m ]** | **Electric Field @ 6 Watt [ MV/m ]** | **Phase Locked Field [ MV/m ]** | **Electric Field @ 4 Watt [ MV/m ]** | **Electric Field @ 6 Watt [ MV/m ]** | **Phase Locked Field [ MV/m ]** |
| **R11** | 3.03 | 3.20 | 2.58 | 3.30 | 3.51 | 2.91 |
| **R12** | 4.15 | 4.56 | 3.83 | 4.26 | 4.63 | 3.84 |
| **R13** | 3.85 | 4.09 | 3.03 | 3.75 | 4.19 | 2.87 |
| **R14** | 3.60 | 4.00 | 2.80 | 3.64 | 4.07 | 3.28 |
| **R15** | 4.75 | 5.20 | 2.52 | 3.93 | 4.37 | 3.14 |
| **R16** | 4.40 | 4.72 | 3.26 | 4.11 | 4.06 | 3.55 |
| **R17** | 4.57 | 4.85 | 1.80 | 4.78 | 5.11 | 3.60 |
| **R18** | 3.50 | 3.63 | 3.40 | 4.06 | 4.27 | 3.64 |
| **Avg. Field** | | | **2.90** | | | **3.35** |

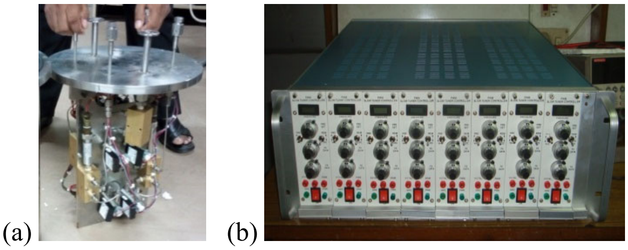


Figure 15: (a) Helium mass flow system; (b) PWM based tuner controller.

This improvement was due to fast response (Fig. 12) and hysteresis free behaviour of pulse operated valves (Fig. 13). Later the PWM based pneumatic frequency tuner was implemented in the QWRs of Super-buncher and Re-buncher.

## CONCLUSION

After implementation of piezo-electric actuator based tuning mechanism in the 2nd and 3rd accelerating modules and PWM based pneumatic tuning mechanism in the 1st accelerating module and buncher cryostats, the control scheme in the IUAC Linac is improved.

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