# WIDE-RANGE FREQUENCY COMPENSATION BY COAXIAL BALL-SCREW TUNER

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*Abstract*

Low-loss 9-cell 1.3GHz cavities have been developed at KEK aiming at a high-gradient operation for the International Linear Collider. One of the most important issues to realize such a high gradient in a pulsed operation of super-conducting cavities is how to compensate the Lorentz detuning. The Lorentz detuning of the cavity amounts to 3kHz at our goal of 45MV/m acceleration field. None of the tuners to date have achieved this range. A coaxial ball-screw tuner was designed and proved to reach this level in the room temperature operation. The performance at liquid nitrogen temperature was also studied and the feasibility to reach the high dynamic range needed for 45MV/m operation was proven. In the present paper we describe these studies and evaluate the feasibility of the operation at 2K.

## INTRODUCTION

To operate the ILC cavity at the nominal operation field of 31.5MV/m in its initial stage, a fast tuning of more than 2kHz is needed, which is written in BCD, basic configuration document[1]. However, none of the tuners in the world to date established this large dynamic range. On the other hand, our group, the ILC Asia WG5, has been aiming at an operation of even higher field, 45MV/m. Through the development toward this goal, we obtain all of the essential features for realizing ILC BCD performance, especially on the tuner development. Recently a compensation of Lorentz detuning up to 20MV/m in TESLA cavity was proved using mechanical resonance[2]. Further study for larger dynamic range with the blade tuner is planned[3].

As our trial to realized the large dynamic range, an idea of the coaxial ball-screw tuner was presented[1,4]. A series of model tests of this tuner mounted on our "ICHIRO" cavity with its design field of 45MV/m were performed and proved the feasibility of compensation of more than 3kHz. The design and experimental tests at the room temperature and at the liquid nitrogen temperature were presented in the present paper.

## LORENTZ DETUNING

The Maxwell's stress amounts to 25kN/m$^2$ at iris region and 6kN/m$^2$ in equator region in the ILC cavity operated at 35MV/m. Since this stress makes the thin cavity to be frequency-detuned by ~2kHz, which is much larger than the band width of 100Hz or so with Qex~3x10$^6$, the tuning is needed. The amount of the detuning largely depends on the rigidity of the cavity system with tuner system comprising of the tuner itself and the helium vessel connected to the cavity via end plates. In Table 1 are listed the relevant mechanical parameters.

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Table 1: Static mechanical parameters of ICHIRO cavity at 45MV/m

| Item | Values | Units |
|---|---|---|
| Total axial force | 103 | N |
| Shrinkage of bare cavity | 56 | microns |
| Shrinkage of cavity system | 1.73 | micron |

### *Static Detuning*

The Lorentz detuning of 9-cell cavity was estimated as follows. Firstly the electromagnetic field was calculated by 2D code and the deformation of the cavity due to Maxwell's stress was estimated by ANSYS. Then the Slater's perturbation formula was applied on each mesh to deduce the frequency shift on each mesh. The effect on each mesh was integrated in all over a cell to obtain the frequency change of the cell. The result of ICHIRO cavity is plotted in Fig. 1. The detuning of the cavity is the sum of the frequency changes of all of the cells. This became

$$\Delta F/E_{acc}^2 = -1.49\ [Hz/(MV/m)^2]\ ,$$

resulting in 3 kHz at 45MV/m as shown in Table 2.

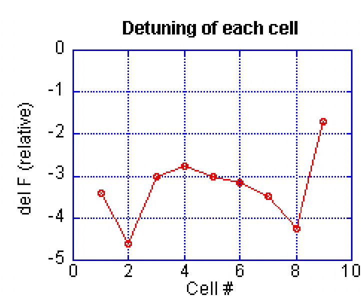


Figure 1: Static Lorentz detuning of each cell.

Table 2: Static Lorentz detuning

| Frequency shift | $\Delta F_{LD}$ | $k_{LD}$ |
|---|---|---|
| | 45 MV/m | Sensitivity |
| Units | kHz | Hz / (MV/m)$^2$ |
| Single cell with both ends fixed | - 1.73 | - 0.85 |
| Cavity with two ends fixed | - 2.38 | - 1.18 |
| Actual cavity with tuner and jacket | - 3.02 | - 1.49 |

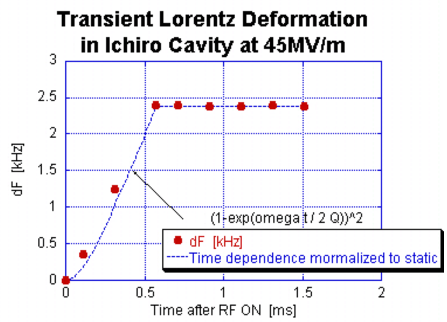


Figure 2: Dynamic Lorentz detuning.

### *Dynamic Detuning*

The power is fed to a cavity at 5Hz with 0.56ms ramping and 1ms constant power for beam acceleration. The cavity mechanical dynamics may change the static detuning amount estimated in the above section. Firstly we estimated the dynamic response with both ends of the cavity fixed[6]. The result is shown in Fig. 2. In this case, the detuning is simply proportional to $E_{acc}^2$, which is shown with blue dashed line.

In reality, the finite stiffness *k* of the tuner system makes the Lorentz detuning larger than that shown in the previous section. The stiffness of the tuner system composed of tuner, helium vessel and end plates is 60MegaN/m. If we assume the mass of the system to be *m* ~20kg, the characteristic resonance frequency becomes $\omega/2\pi=\mathrm{Sqrt}(k/m)/2\pi\sim100$Hz. Therefore, the dynamic Lorentz detuning behaves slower and smoother than that shown in Fig. 2.

## TUNER DESIGN

### *Tuning Characteristics of Cavity*

Firstly the static tuning characteristics of the Ichiro cavity was estimated to be 368kHz/mm. Secondly, the dynamic response of the cavity frequency due to the fast tuning action with 1μm/1ms linear ramping was estimated. The result is shown in Fig. 3, where the case of the cavity beam tube flanges fixed (red curve) and the case of the cavity with a realistic helium vessel mounted (blue dots). It was found that the reduction of the tuning amount is about 20% in this time regime.

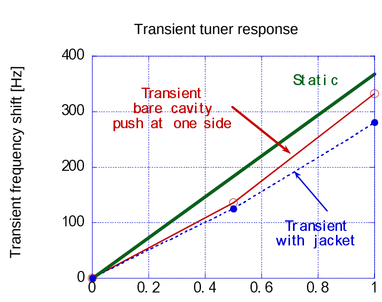


Figure 3: Dynamic tuning characteristics.

### *Tuner Design*

In order to obtain a large dynamic range with keeping a large stiffness of the tuner system in a longitudinal direction, a coaxial ball-screw type tuner was designed. The ratio lead / diameter of the ball-screw is 1:7. The longitudinal movement of the cavity is realized by circumferential movement on a large wheel attached on a male screw. The slow tuning is performed by a worm gear driven by a pulse motor. This slow tuning part is mounted on a ring loosely coupled to helium vessel via 12 thin blades so that the slow tuner as a whole can be pushed fast by Piezo device mounted on a helium vessel. The schematic view is shown in Fig. 4.

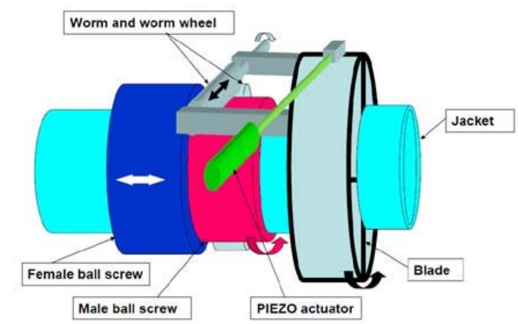


Figure 4: Tuner schematic.

## MECHANICAL CHARACTERISTICS

Cavity frequency change responded to the tuner actions were measured in a realistic setup. The tuner was set on a helium vessel which was mounted on both end plates by bolts. Inside was a cavity with mechanical movement sensors attached together with the RF antenna at beam pipe flange so that the resonant frequency of the cavity could be measured.

### *Pulse Response*

Fig. 5 shows the transient frequency response of cavity in room temperature test (Green marks) driven by the tuner action with 2ms square-pulse drive voltage (Blue). More than 10ms later, there appeared a slope with large amplitude. One of the main frequency components was 250Hz. With an applied voltage of 800V, frequency compensation of 1.5kHz was realized. It is to be noted that the frequency was well reproduced by the measured mechanical length of the cavity (Red marks).

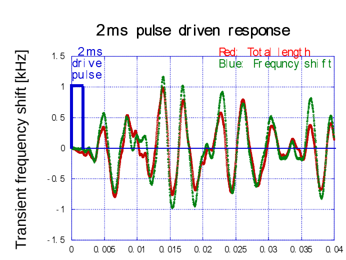


Figure 5: Pulse response of cavity frequency.

### *Mechanical Resonance in Warm and Cold*

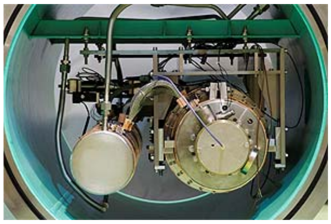

Figure 6: Tuner test setup.

The tuner mechanism was evaluated at cold temperature as shown in Fig. 6. Cavity in a helium vessel (right cylinder) was cooled by liquid Nitrogen (stored in left cylinder) through blade wires. The temperatures at various places are shown in Fig. 7. The characteristics of tuner system at cold temperature was performed at 130K. The cavity RF frequency response was measured at room temperature and at liquid nitrogen temperature. The result was shown in Fig. 8. When cooled, resonances around 330Hz disappeared. The resonances at around 270Hz remained and became high Q. The resonance at

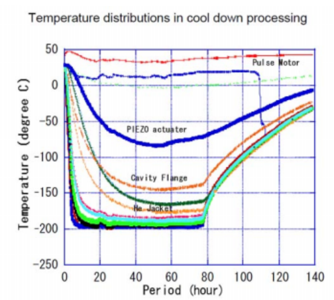


Figure 7: Temperature trend.

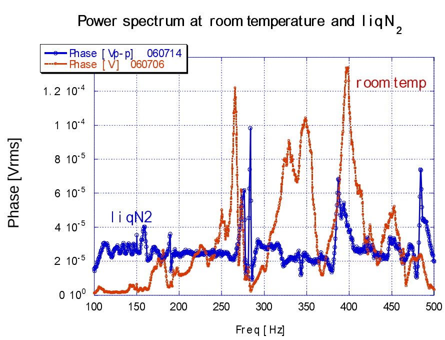


Figure 8: Frequency response of cavity in warm (red) and in cold (blue).

276Hz became the main component of the oscillation remaining between 5Hz pulse driving. The movement of cell #2 and #8 were measured in addition to monitoring frequency change. The result is shown in Fig. 9. The both ends of the cavity oscillate in breething mode so that the total length of the cavity changes which makes frequency change. This is probablly assinged to the resonant mode shown in Fig. 10, where the caluclation was performed with two ends fixed so that the resonant frequency was larger than that measured.

The tuning range using the resonance mode at 276Hz was evaluated in cold as show in Fig. 11. Full range of 2kHz was established with 150V. We speculated that above this voltge, the power supply gradually became saturation. If the power suppply is improved to generate higher voltage toward the Piezo specification of 1kV or any mechanical booster to amplify the mechanical driving range, we think this range becomes larger and the tuner can realize even higher dynamic range than 3kHz needed for 45MV/m operation.

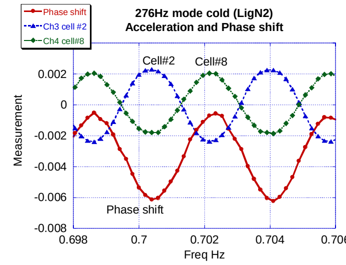


Figure 9: Frequency shift and cell movement.

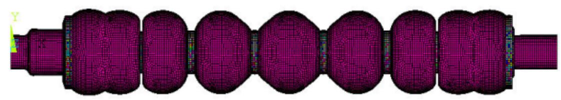

Figure 10: Resonant mode with two ends fixed at 317Hz calculated by ANSYS.

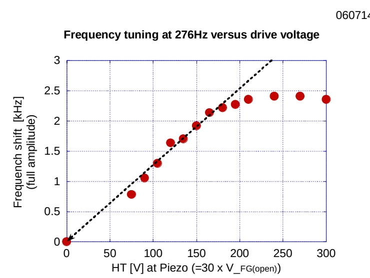


Figure 11: Full range of tuning versus voltage applied to Piezo.

## SUMMARY

A coaxial ball-screw tuner was designed and studied in warm and in cold. The feasibility to reach the high dynamic range of 3kHz needed for 45MV/m operation was proven by using mechanical resonance at 276Hz. This mode is with high Q so that it remains between 5Hz pulses. Cavity system changes its mechanical properties from room temperature to liquid nitrogen temperature. This change should be taken into account for designing the tuner in operation at 2K.

## REFERENCES


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