SRF CAVITY TUNING FOR LOW BEAM LOADING

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Abstract

The design of 5-cell elliptical 650 MHz β=0.92 cavities to accelerate H- beam of 1 mA average current in the range 467-3000 MeV for the Project X Linac is currently under development at Fermilab [1]. The low beam current enables cavities to operate with high loaded Q's and low bandwidth, making them very sensitive to microphonics. Mechanical vibrations and the Lorentz force can drive cavities off resonance during operation; therefore the proper design of the tuning system is very important part of cavity mechanical design. In this paper we review the design, performance, operation, reliability and cost of fast and slow tuners for 1.3 GHz elliptical cavities. We also present a design of the slow and fast tuners for 650 MHz β=0.9 cavities based on this experience. The helium vessel (HV) in the new design is equipped with the tuners located at the end of the cavity instead of the initially proposed blade tuner located in the middle. We will present the results of ANSYS analyses of mechanical properties of tuners.

INTRODUCTION

SC cavities are manufactured from thin sheets of niobium to allow for cooling and are designed to operate with very narrow bandwidths. These two factors combine to make the resonance frequency very sensitive to manufacturing tolerances, to mechanical distortions of cavity walls by the Lorentz force, to fluctuations in the pressure of the surrounding helium bath, and to mechanical vibrations. Cavities are commonly equipped with one or more tuners to compensate for these effects. The tuner is also used to detune the cavities far off resonance in the event of failure.

A variety of tuning methods have been employed, but most fall into one of two broad classes, mechanical or reactive. Many of the methods have been described in more detail in previous surveys of the field [2-4]. Most 1.3GHz elliptical cavities employ mechanical tuners consisting of

- A stepper motor
- A reduction Gearbox
- A rotational-to-Linear Conversion Mechanism
- One or more piezo stack actuators

Each tuner design must be tailored to the features of the specific cavity, e.g. spring constant, sensitivity, df/dP, etc., it will work with but

S1G TUNER COMPARISON

The S1G Global Cryomodule was constructed and tested at KEK using 4 distinctly different cavity/tuner combinations for 1.3 GHz cavity (shown in Figure 1):

- KEK Cavity/KEK Slide Jack-Central Mount
- KEK Cavity/KEK Slide Jack-End Mount
- DESY Cavity/Saclay-DESY Tuner
- FNAL cavity / INFN Blade-tuner

Each of the four cavity/tuner combinations involved different design tradeoffs:

- Saclay-DESY tuner/cavities were based on proven design in use at TTF since 1997 [2, 5];
- KEK cavity/tuners were very stiff in order to minimize dynamic detuning on flattop [4];
- INFN blade tuner/FNAL cavity was designed to be light and low-cost [5, 6].

Table 1 outlines some of the important design considerations.

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Table 1: Tuner Design Considerations

	Static	Dynamic
Range	Sufficient to compensate for variations in resonance frequency following cool-down, ~0.5 MHz. Shift cavity off resonance by many (>20) bandwidths in the event of failure.	Greater than maximum cavity dynamic detuning from all sources (e.g. 1kHz)
Precision	Small fraction of fast actuator range (e.g. 100Hz/1kHz) should be adequate for normal operation.	Small fraction of a bandwidth (e.g. <10 /200 Hz)

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	Small fraction of a BW (e.g. 10Hz/200 Hz) to provide for tuning in event of fast actuator failure	
Stiffness	High Stiffness Bulk of actuator force should be transmitted to the cavity	High Stiffness Bulk of actuator force should be transmitted to the cavity

The S1G test provided a unique opportunity to make back-to-back performance comparisons between the different tuner designs.

The Saclay tuner is based on a compound lever mechanism acting at one end of the cavity. The original Saclay design underwent further development at DESY and is currently use at TTF and XFEL. In contrast the KEK slide tuner is based on a ramp mechanism. The tuner may be mounted centrally or on one end. The INFN blade tuner utilizes a flexure mechanism and is mounted coaxially with the center of the cavity.

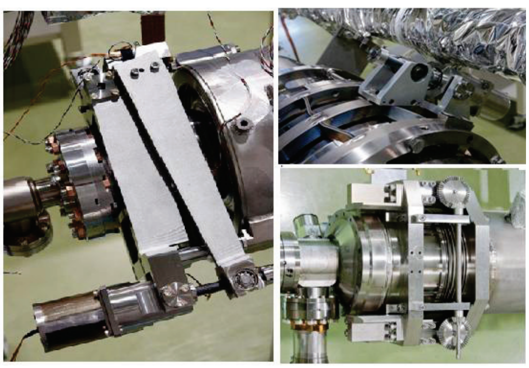

Figure 1: Different Tuner designs: Saclay(left), Blade tuner (top) and KEK Jack-end mount (bottom).

Tuner Operation

During cool-down the static tuner is relaxed tuner to unload cavity. During operation the stepper motor is used to bring the cavity resonance frequency to within a specified tolerance of RF frequency, typically much less than a half-bandwidth.

The piezo actuator may be used to fine tune the static resonance frequency and to compensate for dynamic effects. In the "Standard" approach first demonstrated at DESY [6], the piezo is driven with half sine pulse prior to the arrival of RF pulse. The pulse parameters are tuned to minimize detuning during flattop. Adaptive algorithms, developed at FNAL, have also been employed at FNAL, DESY and elsewhere [7, 8]. Both methods work well for RF pulses short with respect to the period of the dominant cavity mechanical modes but the "Standard" algorithm performance degrades for longer pulses. Adaptive algorithms are able to automatically compensate for He pressure variations and other sources of long term drift.

Adaptive compensation is able to routinely reduce LFD from several hundreds of Hz to 10 Hz or better in FNAL/NML/CM1. During the S1G tests the adaptive compensation was able to achieve comparable performance for all four different designs tested (Fig.2).

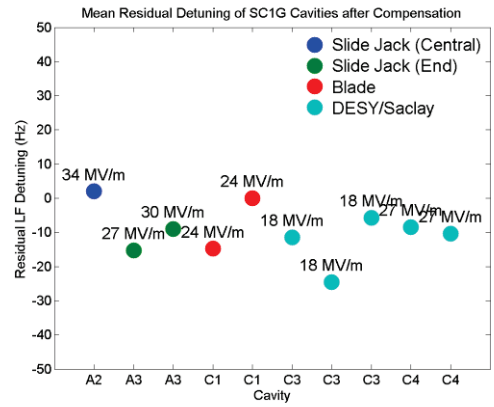

Figure 2: Detuning Performance of the different types of tuners equipped on 1.3 GHz cavity.

Feed-forward Resonance Stabilization in Pulsed Cavities

Cavities are sensitive to changes in He pressure. Tesla style cavities typically have a sensitivity of df/dP ≅ 50 Hz/Torr. This can lead to large shifts in resonance frequency. Adaptive algorithm can adjust piezo bias based on running average of detuning during previous pulses. The resonance can be stabilized to better than 1Hz on average.

Residual pulse-to-pulse detuning (microphonics) was relatively small in FNAL/NML/CM1. It was generally lower in the middle (<2 Hz) and higher at the ends (9 Hz) where vacuum pumps were installed. Microphonics compensation requires feedback. Microphonics has been extensively studied in CW cavities, notably at HoBiCaT using 1.3 GHz CW cavities and 325 MHz spoke cavity. CW detuning is dominated by He pressure variations and can be controlled to 1 Hz RMS or better (see Figure 3)[9]. The same level may not be attainable in pulsed cavities. Accurate detuning measurements are possible only when RF pulse is present.

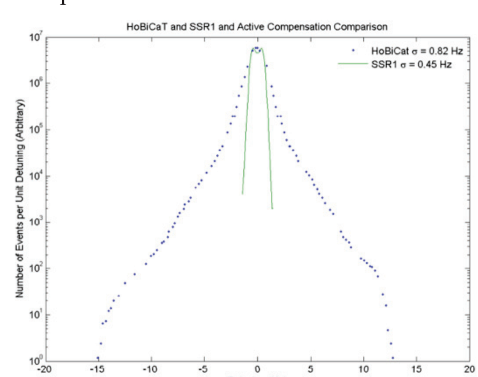

Figure 3: Example of microphonics control by adaptive compensation in CW mode for SSR1 cavity (325 MHz).

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Narrow Bandwidths and Long Pulses

For some applications longer pulses and narrower bandwidths may be useful. During 2011 tests using 9ms pulses for the proposed Project X, adaptive LFD control was able to limit detuning for 25 MV/m to better than 50 Hz across the flattop and most of the fill as Q_L ranged between $3x10^6$ and $1x10^7$ [10]. Figure 4 shows results obtained for cavity #5 in cryomodule CM1 installed at NLM at Fermilab. This cavity was equipped with Saclay type tuner and tested in 9 ms pulses at accelerating gradient 25 MV/m and QL=1.10^7.

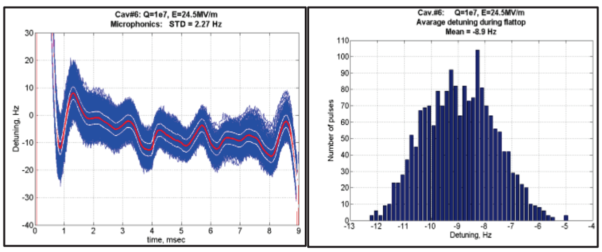

Figure 4: Residual cavity detuning in 9ms pulses after Adaptive compensation (statistic for 1800 pulses).

TUNER RELIABILITY

Slow and fast tuners must operate reliably over the lifetime of the machine. Failure prone components should be located outside vacuum vessel if possible. In some cases this may not be possible because of

- Excessive heat loads
- Linkage spring constant and inertia may limit dynamic performance.

Internal components (Stepper motor, Gearbox, Linkage, Piezo, etc.) must have a high MTBF. In some cases access ports may be provided for repair or replacement.

Experience varies widely from laboratory to laboratory. There have been notable large scale "Piezo" failures at SNS, but only a handful of tuner failures at DESY/FLASH. Experience at FNAL shows there can be a long learning curve even with a "proven" design [7]. It may be necessary to treat tuner design more like "Rocket Science". Many of the same components used by space flight community and many of the environmental and reliability requirements are similar.

Piezo Actuator Reliability

Piezo actuators can be extremely reliable if treated properly. High piezo cryogenic lifetime have been demonstrated in several tests

- INFN – $1.5x10^9$ cycles ≅ 10 yr operation [11]
- NASA – 10^{10} cycles [12]

At the same time, piezo actuators can fail quickly if they are not treated properly. Piezo lifetime is strongly affected by humidity, temperature, voltage and shear forces. Cryogenic vacuum should be close to ideal environment but shear forces can lead to rapid failure. Careful actuator encapsulation (piezo holder to avoid shearing forces and non-uniform pressure on the end-plates of the piezo-stack) is critical to reliable operation.

In many of the "Piezo" failures at SNS, 1 bar pressure transients damaged the piezo capsule. One of piezo at the tuner installed on the S1G cryomodule failed (Figure.5).

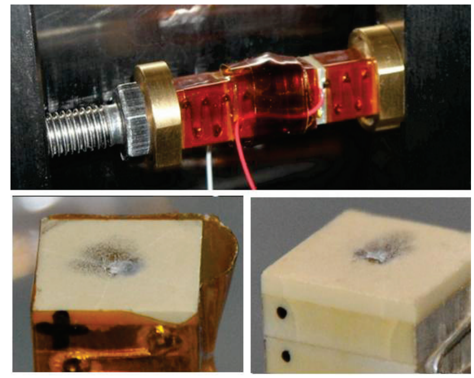

Figure 5: top: Piezo holder at original design of slim blade tuner (S1G cryomodule). bottom: Piezo-stack damaged during operation of fast tuner (cracks on the end-plate and piezo-ceramics).

Post-mortem examination reviled this piezo-stack developed crack on the endplate and active part of piezo. Modified for CM2 piezo holder presented on Figure 6. Any shearing forces absorbed by stainless steel cylinder. The similar techniques have been used for design of piezo tuner for SSR1 [13]. Special G10 cylinder protects piezo from HV breakdown between piezo electrodes and metal parts of the fixture as shown in Figure 6.

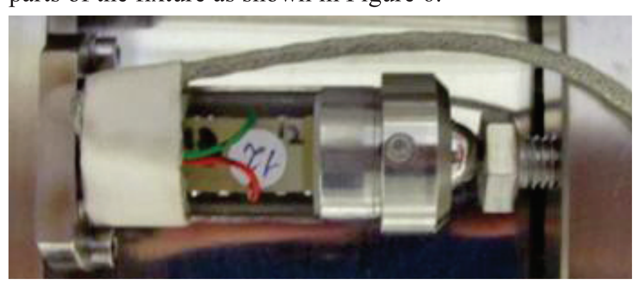

Figure 6: Modified design of piezo holder for CM2.

Slow Tuner Actuator Reliability

Slow tuner actuator consist from stepper motor, gear box and shaft, translated rotation to linear displacement. To preserve long lifetime of the actuator it is important to select actuator which will accommodate to the stiffness of the cavity and tuner. Operation in cold vacuum requires specially coated bearing and other modifications, but vacuum and space qualified motors are commercially available. In the frame of the S1G&CM2 projects FNAL conducted "lifetime cold tests" of the blade tuners. From several failures it is important to emphasize failure events when the harmonic drive gear stripped and the wave generator got stuck in the spline gear after system reached 31 Msteps (Figure 7) [14]. This seizure contributed to mismatch between the blade tuner required forces (~600 N) and selected actuator's maximum specification

(~ 200 N). As reported by SNS, several failures of their actuator were also caused by stripped gear inside harmonics drive [15]. There is on-going project (joint Phytron/Fermilab) to develop slow tuner actuator which can satisfy requirements for several new tuners for SRF cavities for Project X (SSR1, 650 MHz) and CM3. Major technical specifications for actuators under development are:

- Maximum forces (push/pull) applied to actuator are 1300 N;
- Lifetime of the actuator is 20 years of operation (30 Msteps);

Figure 7: Harmonics drive gear failure.

Limits to Tuner Reliability

Cold vacuum is difficult environment for electromechanical systems. Every component is a potential point of failure, piezo, stepper, gearbox, linkage, etc. Reliable tuner design requires careful component selection and extensive warm and cold testing of individual components and of assembled tuners A Tuner reliability program should be initiated and completed well prior to commencement of procurement and production. Once production begins schedule will take priority over everything else.

Tuner Cost

An AES ILC Cost Study commissioned by Fermilab 2007/2011 set the cost of tuning at 4% of overall cryomodule cost.

CHOISE OF TUNER FOR 650 MHZ CAVITY

In Project X currently under development at Fermilab H^-beam with average current1mA will be accelerated from 0.47GeV to 3 GeV using 5-cell 650 MHz β_G =0.92 SC cavity working at CW mode. The design of a dressed cavity has been mechanically optimized by minimizing df/dP, the sensitivity to microphonics detuning due to fluctuations in helium pressure. The result of optimization has been presented at [16]. General view of the cavity in helium vessel is shown in Figure 8.

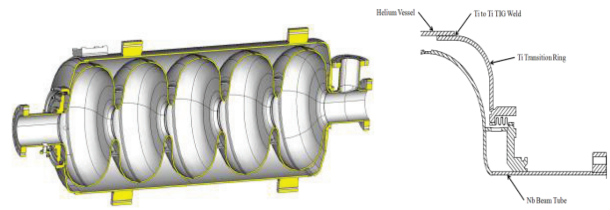

Figure 8: Design of the 5-cell 650 MHz β=0.92 cavity and helium vessel. On the right plot details of end for Lever tuner installation are shown.

Based on Fermilab experience the first proposed design for 650 MHz cavity tuner was scaled version of 1.3 GHz blade-tuner, but preliminary studies shown disadvantages of such a design:

- High stiffness of the cavity requires stiffer tuner and motor able to provide much larger forces than for ILC cavity.
- Large diameter Ti bellow in the middle of helium vessel is expensive.
- Blade tuner increase transverse size of the cavity assembly. It leads increase size of cryostat.

Second design the Lever Tuner shown, mounted on short end of the cavity in Figure 9 has better characteristics than blade-tuner [17]. This compact fast/slow tuner will work for both versions of cavities (β=0.9 and 0.92-baseline) has been developed for final tuning of the resonance frequency of the cavity after cooling down and to compensate frequency detuning due to the microphonics. This design with minor modification will be used for low beta 650 MHz cavity (β 0.6) designed for beam acceleration in range 170-470 MeV in Project X.

The lever tuner was designed

- to tune cavity in the range of 200 kHz
- able to deliver up to 20 kN forces on the cavity
- fast tuning range 1 kHz

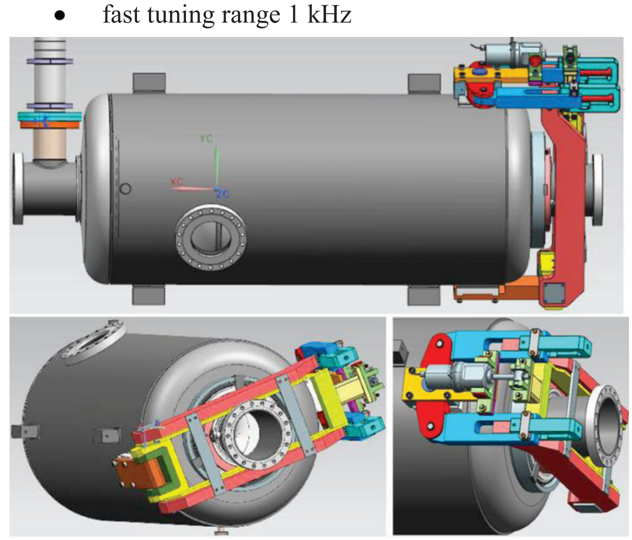

Figure 9: Design of the Lever Tuner for 650 MHz beta 0.92 and 0.90 cavities.

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SUMMARY

A variety of tuners for 1.3 GHz elliptical cavities have been built and tested. Four distinctly different candidate cavity/tuner designs were compared during ILC/S1G tests at KEK in 2010. Each demonstrated excellent performance following compensation. A variety of control algorithms have been implemented and tested. Feed-forward LFD compensation and resonance stabilization against He pressure variations are now well understood. At narrower bandwidths microphonics becomes more important and feedback will be needed. There is no fundamental reason why detuning from all sources cannot be controlled to 1 Hz or better.

While the tuner represents only a few percent of overall cryomodule cost, tuner failure can render cavities or the entire cryomodule useless. Selection of tuner for collider cavities should focus on lifetime and reliability. The required reliability can be achieved but it needs careful engineering of each element in the electro-mechanical chain, and extensive cold testing of each component and of entire tuner assembly. A Tuner reliability evaluation and improvement program for any new accelerator should be initiated and completed well before commencement of procurement and production.

For 650 MHz 5-cell cavity the compact fast/slow Lever Tuner was chosen as a baseline design. Electro-mechanical analysis of the cavity, helium vessel and lever tuner design was done to minimize LFD coefficient, df/dP and sensitivity to microphonics.

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