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Fermilab Engineering Specification

Specification for SSR1 Tuner

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Rev.	Date	Description	Originated By	Checked By	Approved By
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Introduction

This document defines the requirements for a frequency-tuning system operating on SSR1 cavities. The tuning system allows regulating the resonant frequency of the cavity by applying a controlled force on the cavity, producing an elastic change in shape. The system operates in a closed loop to maintain the resonant frequency of the cavity locked to the nominal value of 325 MHz.

Fundamental Tuner Requirements

Fundamental requirements guarantee the RF performance of the cavity. These have been defined within the Functional Requirement Specification (FRS) for SSR1 cavities (Project X doc n.1079) and are listed below. Together with a few known characteristics of SSR1 cavities, these comprise the starting point for this specification.

The passive spring constant of the tuner is the spring constant seen by the cavity when the actuators are locked. This spring constant influences the sensitivity of the cavity to helium pressure variations. To satisfy the requirements set in the FRS, the goal for this spring constant was set to 30 kN/mm.

Table 1 Fundamental requirements for the tuning system. The parameters defined in the FRS are highlighted.

Parameter	*Value*	*Notes*
Total Frequency Range	> 135 kHz	From FRS
Frequency Resolution of stepper motor	< 20 Hz	From FRS
Piezo Frequency Range	> 1 kHz	From FRS
Tuner Passive spring constant	30 kN/mm	Derives from df/dP requirement
Sensitivity of end-wall	540 kHz/mm	Simulation/Experimental
Cavity wall spring constant (K_{cav})	20-30 kN/mm	Simulation/Experimental

Main assumptions on the tuning system

With the intent of maintaining this document reasonably short, the main aspects such as the general layout, the principle of functioning and the types of actuators, will be considered as known. The discussions that lead to these decisions are not considered part of this document.

The tuning system (see Figure 1) operates on the beam-pipe region of the cavity and only generates forces directed towards the cavity (push only). The mechanism is actuated by one stepper motor (motor) placed in series with two piezo-electric actuators (piezos) which are in parallel to each other. The performance of the motor and piezos is known and included in the table below.

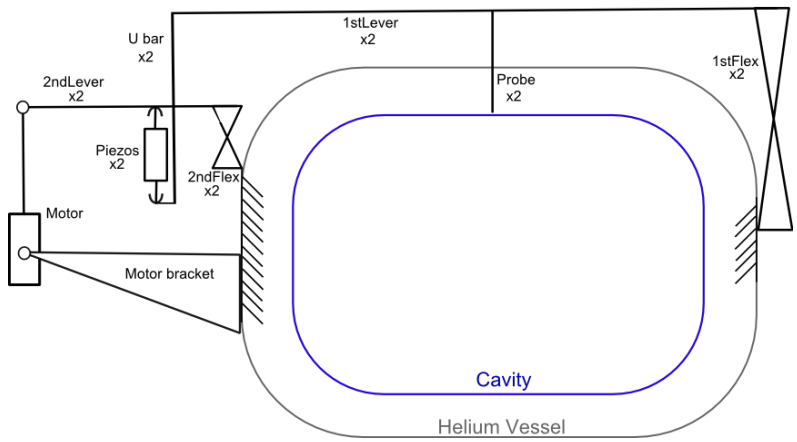

Figure 1 Schematic for the tuning system showing the cavity inside the helium vessel. The beam pipe region is engaged with the probes. The first lever and second lever comprise the main moving parts of the mechanism. The motor and the piezos are visible in the left side. Flexure joints are considered in two locations.

Table 2 Performance of stepper motor and piezo-electric actuators to be used.

Parameter	*Value*	*Notes*
Stepper motor max force	± 1300 N	Symmetrical
Stepper motor resolution*	0.1 µm (100 nm)	At interface with 2nd lever
Piezo stroke @ RT	64 µm ± 2%	Measured
Piezo stroke @ operating T=20K	15µm (25% of RT)	Estimated
Piezo max rated force	3360-5040 N	4200 N ± 20% (blocking force)
Piezo max operating force	2688 N	3360 · 80%
Piezo min operating force	840 N	4200 · 20%

* This is the motion caused by a single step of the motor. The motor has 200 steps/revolution, the reduction box has a ratio of 50:1, the lead screw has a pitch of 1 mm. Res = 1/200 * 1/50 * 1mm.

Mechanical Requirements

In addition to the fundamental requirements, it is possible to derive a series of mechanical requirements based on the aforementioned characteristics of SSR1 cavities.
With reference to Figure 2, we can define the following figures of merit for a tuning system.

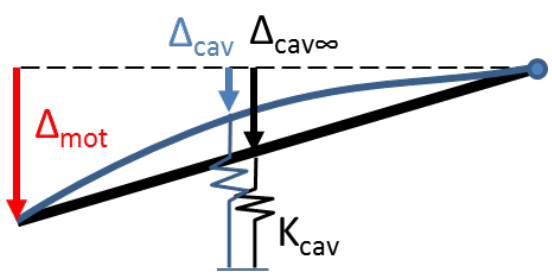

Figure 2 Schematic of a simple tuner arm actuated by a motor. The cavity to be deformed is idealized as a spring (K_{cav}). The ideal behavior of the tuner (infinite rigidity) is shown in black; the real behavior with actual rigidity is shown in blue.

The **Mechanical Advantage** is the ratio between the motor displacement and the cavity displacement in the theoretical case of an infinitely rigid tuning mechanism.

$$Mechanical\ Advantage\ (M) = \frac{\Delta_{mot}}{\Delta_{cav\infty}}$$

The **Tuning Efficiency** is the ratio between the displacements at the cavity in the real case and in the theoretical case.

$$Tuning\ Efficiency\ (E) = \frac{\Delta_{cav}}{\Delta_{cav\infty}}$$

The **Tuning Transmission** is the ratio between the displacement at the cavity and the displacement at the motor, this includes both rigid and elastic contributions.

$$Tuning\ Transmission\ (T) = \frac{\Delta_{cav}}{\Delta_{mot}} = \frac{E}{M}$$

The entities M, E and T are defined both for the motor and for the piezos.

The requirement on tuning efficiency (function of E and M) is determined by the contrasting requirements on resolution and travel. For the motor, the travel is not an issue. For the piezos, the resolution is not an issue.

Table 3 Mechanical requirements derived from fundamental requirements

Parameter	*Value*	*Notes*
Motor Travel at beam pipe	> 0.25 mm	135 kHz / 540 kHz/mm
Piezo Travel at beam pipe	> 1.85 µm	1 kHz / 540 kHz/mm
Maximum Force at beam pipe	7500 N	0.25 mm · 30000 N/mm
Maximum Hysteresis (motor)	200 Hz	1/5 of Piezo range
Motor Resolution at beam pipe	< 37 nm	20 Hz / $5.4 \cdot 10^8$ Hz/m
Motor Tuning Transmission (T)	< 37 %	37 nm / 100 nm
Motor Mechanical Advantage (M)	> 5.8	7500 N / 1300 N → **T < 17 %**
Piezo Tuning Transmission (T)	> 12 %	1.85 µm /15 µm
Piezo Mechanical Advantage (M)	> 1.4	0.5* · 7500 N / 2688 N, → **T < 71 %**
Piezo Tuning Efficiency (E)	> 17 %	1.4 · 12 % (T · M)

* The two piezos share the load in normal operating conditions

Known Risks

A list of known risks is given with the intent of guiding the design of the system. These items of risk shall be considered and mitigated in the ways deemed more appropriate.

Table 4 Known risks for the tuning system

Risk	*Description*
Reliability	The reliability of a frequency-tuning system is always of great concern. The actuators are prone to failures if not integrated and operated carefully. Failure of the tuning system has an immediate impact on the accelerator complex.
Hysteresis	The resolution requested from the tuning system is extremely fine. The details of each joint in the mechanism shall be carefully evaluated and measures taken to mitigate phenomena such as stick-slip, play, backlash that would increase the hysteresis.
Maintainability	Due to the concerns on reliability, the system shall be designed to allow the replacement of the actuating devices in case of failure or deterioration. Maintenance operations shall be simplified where possible considering the system will be serviced manually through access ports in the vacuum vessel of the cryomodule.
Precision fitting	Cavities have manufacturing variances; also they may be shortened or lengthened (inelastic tuning) at different stages of development. The changes in dimensions (especially flange-to-flange length) may cause interface and assembly issues. A fine-adjustment system, fixed or free, should be integrated to compensate for these variances.
Magnetism	Magnetic permeability of components may affect cavity performance. “Low” magnetic permeability materials shall be utilized such as Stainless Steel of the 300 series (e.g. 316). Residual magnetic field should be below specifications.
Cleanliness	Cavities are often handled in clean-room environment. Tuner parts must be easy to clean and keep clean. If not possible, groups should be easy to remove and re-install.
Installation	The system and its components will be installed and uninstalled frequently, especially on the first prototype. Design must be robust in this aspect. Weak links such as wires, small fasteners and all other delicate parts shall be resistant to normal handling at a minimum.
Bench tests	The system will be tested prior to installation on the cavity. Aspects to be considered are: self-consistent sub-assemblies, ease of transport, locking features, protection features.
Spring constant	The actual spring constant of the device could be different from the estimations due to the uncertainties in stiffness of contact regions, complex joints and bearings. FE Analyses should be performed and small prototypes tested to verify the accuracy of predictions.
Transmission	The actual displacement the cavity will see may result being smaller than anticipated due to excessive flexibility of components, excessive stiffness of cavity, erroneous mechanical advantage. A safety margin shall be considered.
Pressure tests	Pressure test analyses shall be performed on the complete assembly comprised by the cavity, helium vessel and tuning system.

Lifetime	Components, groups and possibly the entire assembly, Tests on critical components of the tuning system shall be performed to identify possible issues with reliability and life expectancy.