MAGNETOSTRICTIVE TUNERS FOR SRF CAVITIES[1]

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Abstract

Energen, Inc. has demonstrated two new tuners to address slow and fast SRF cavity tuning requirements. The slow tuner uses a linear stepper motor to deliver high-force, sub-micron linear motion of tens of millimeters at cryogenic temperatures resulting in hundreds of kilohertz tuning range. A separate actuator delivers fast tuning capability for microphonics and Lorenz detuning compensation. These tuning systems are based on magnetostrictive actuators that can deliver high force precision motion at cryogenic temperatures. Performance and capabilities of this prototype SRF cavity tuner will be reported.

1 BACKGROUND

Since 1997, Energen has been working with engineers and scientists at Jefferson Laboratory, The National Superconducting Cyclotron Laboratory and the Spallation Neutron Source to develop and demonstrate several tuning mechanisms for elliptical, superconducting RF cavities.

Energen has built a fine-tuning mechanism for a Jefferson Lab SRF cavity, which provided 2 kHz of tuning range on a 1497 MHz resonant frequency. Details about the tuner and it performance were reported previously[1].

Subsequently, Energen began developing a new tuning system that would replace the entire mechanical tuner system and eliminate the rotating mechanical feed through the vacuum system of the cryomodules. The details of the tuner design are reported in a paper presented at PAC01[2].

The present paper reports on the detailed testing of that tuner and its capabilities along with a new fast tuning actuator that is used for active microphonics control and Lorentz detuning compensation. The technology underlying all of these devices is cryogenic magnetic "smart" materials.

1.1 Magnetic "Smart" Materials (KelvinAll)

Magnetic "smart" materials (MSM) change their shape (elongate) in a predictable and reversible manner when exposed to a magnetic field. The amount of elongation at saturation is the most fundamental measure of a magnetostrictive material.

The most widely available MSM, $Tb_{0.3}Dy_{0.7}Fe_2$ (Terfenol-D) does not work at cryogenic temperatures because of temperature-dependent changes in its magnetic characteristics. For cryogenic applications, the U. S. Navy has developed a TbDyZn alloy which exhibits much higher elongation than $Tb_{0.3}Dy_{0.7}Fe_2$ but has a Curie temperature around 150 K. TbDyZn is only available in small quantities through custom fabrication and is therefore, very expensive.

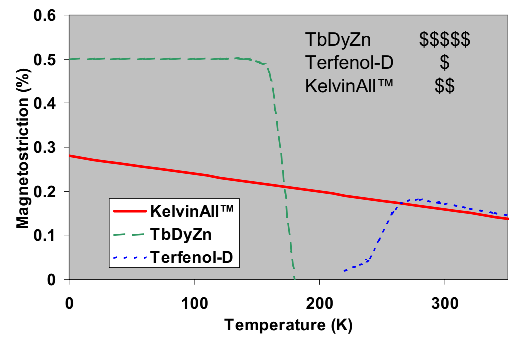

Figure 1 - Temperature dependent magnetostriction for several materials and their relative costs.

Through extensive materials research and development, Energen has developed KelvinAll, a new MSM that has excellent performance over a broad range of temperature from above room temperature to near absolute zero. Figure 1 shows a comparison of the saturation magnetostriction of the three MSM materials[3].

1.2 Actuators & Linear Motors

In its simplest configuration, an MSM-based actuator consists of a rod of MSM surrounded by a coil. When current passes through the coil, the rod elongates and the motion can be used to do useful work. These devices are ideal for applications where short stroke, high force and rapid response are needed.

Linear motors are capable of delivering long range high force motion. Detailed information about the stepper motor operation has been presented previously [4]. The control electronics provide manual and computerized control capability for the linear motors.

2 SLOW TUNER SYSTEM

2.1 Cavity Interface

Under a Cooperative R&D Agreement (CRADA) between Energen and Jefferson Laboratory, Energen

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obtained a 5-cell SRF cavity from Jefferson Laboratory for the testing of the tuner. The Energen tuner is designed to be a replacement for the mechanical tuner that is currently used providing the added benefit of better tuning resolution.

A drawing of the tuner connected to the cavity is shown in Figure 2 below. The end cells of the cavity are attached to cell holders. The inactive cell holder (shown on the right side) is rigidly connected to the end plate by four connecting rods. The active cell holder (shown on the left side) is free to move axially. The end plate and the active cell holder are connected to a lever arm by stainless steel wire ropes. The linear stepper motor is mounted on a

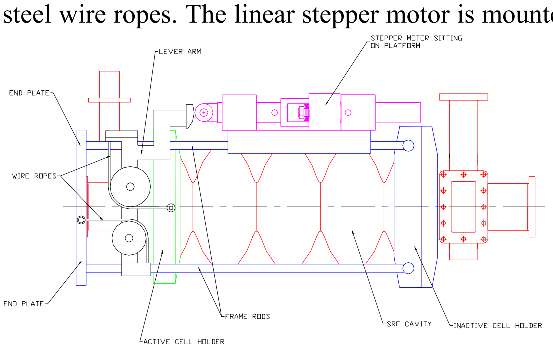

Figure 2 – Geometry of the Energen SRF cavity tuner.

platform beside the SRF cavity. When activated it pulls a cable connected to the lever arm. The rotation of the lever arm pulls the active cell towards the endplate stretching the cavity along its axis thereby changing its resonant frequency.

2.2 Advantages

This type of tuning system has several distinct advantages, it:

- Eliminates sliding or rotating penetrations through the vacuum cryostat
- Simplifies cryostat design and assembly
- Delivers both coarse and fine tuning in a single device
- Can be used for fast tuning (microphonics)
- Locks in position when powered off

2.3 Measurements

The tuning range of the cavity was tested at 77 K in a liquid nitrogen bath at Energen facilities. For these tests, the SRF cavity was evacuated to 10 mTorr. The resonance was measured using a network analyzer, which indicated a resonance at 1,497 MHz. The linear motor was then operated and the frequency shift was measured as a function of lever displacement. As the motor advances, the force required to elongate the cavity increases. This result of the increased load on the stepper motor was a decrease in the step size. At the end of its travel, the step size is reduced to zero. The force generated by the stepper motor is estimated to be approximately 2600 N.

Figure 3 shows the resonance peak shift near 1497 MHz at the beginning of the test and after the motor was advanced to the farthest distance. The frequency shift of 160 kHz is equal to the capabilities of the existing Jefferson Laboratory mechanical tuner.

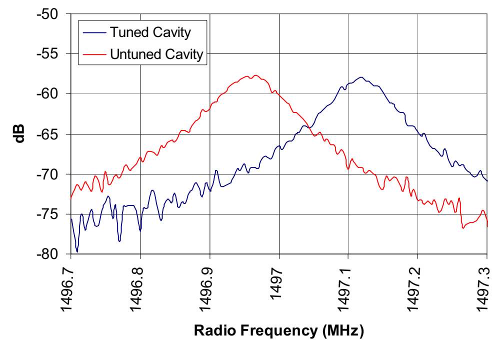

Figure 3 - Resonant frequency range of the slow tuner mechanism.

The slow tuner system was tested at 4 K at the National Superconducting Cyclotron Laboratory located at Michigan State University in a 35 in (0.89 m) diameter Dewar. There were some difficulties encountered during the tests such as vacuum leaks and a limited time available for conducting the tests. During the testing, were able to successfully demonstrate that the tuner system is capable of changing the resonant frequency of the cavity by 60 kHz. When the tuner is adjusted, there is a slight relaxation that occurs in the tuner system causing a frequency shift of approximately 25 Hz. Thereafter, the tuner demonstrated a stability of better than 5 Hz on a resonant frequency of 1497 MHz. – 3.3 ppb.

3 FAST TUNER

3.1 Actuator Design

A short stroke fast responding high force actuator is needed to damp out vibrations due to microphonics and Lorenz detuning. Figure 4 shows the actuator designed for this purpose. The MSM and the superconducting coil are enclosed in a laminated Silicon-steel housing. The coil

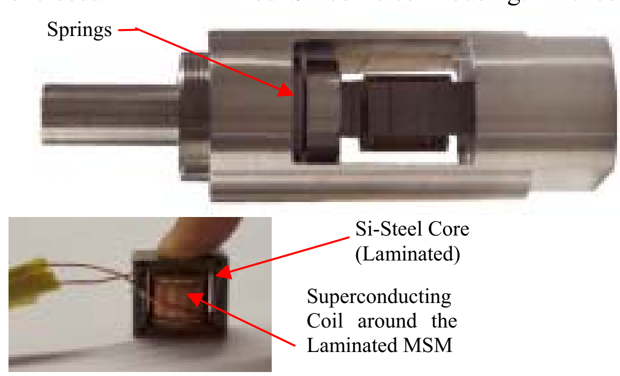

Figure 4 – The Fast tuner

is made of Nb_3Sn as it has a comparatively high critical temperature (18 K), low filament coupling and hysteresis losses. The core concentrates the magnetic flux in the MSM and provides partial magnetic shielding as well. A superconducting niobium shell, not shown in Figure 4, shields the entire actuator. The MSM and the silicon steel housing are laminated to reduce eddy current heat generation and to achieve fast response. Belleville springs are used to preload the MSM.

Analyses of the magnetic design were performed on the active element to optimize the geometry of the coil, the Si-Steel core and the flux distribution in the MSM. The geometric configuration was then refined using 3-D magnetic analysis, to get more accurate field distribution plots, stray magnetic field numbers and the coil inductance.

A superconducting shield is used to minimize stray magnetic fields. The field leakage values obtained from the 3-D analysis are used as inputs in the Bean's model to determine the thickness of superconductor required to shield the field.

Since the fast tuner will be installed in the vacuum space surrounding the helium vessel, providing a conduction path for the small amount of heat generated in the actuator is critical to stable operation. Heat generated in the actuator is due to 1) eddy currents 2) AC operation of the coil 3) hysteresis losses in magnetic materials manifested as heat. The heating due to eddy currents was estimated using a 3-D dynamic analysis and is calculated to be 0.04 Watts. The heating in the coil and due to hysteresis losses is estimated to be 0.05 W and 0.01 W respectively. So the total heat generated is of the order of 0.1 W

3.2 Laboratory Testing

.The fast tuner was tested under the operation conditions for stroke, ramp rate and stray magnetic fields. Figure 5 is a plot of the fast tuner stroke verses the input current and shows the linearity of the actuator.

Figure 6 shows the current ramp rate in the coil. It is seen that the current can be ramped in the coil from 0 to maximum in the required 130 Microseconds.

An open ended Niobium cup is used to shield the stray magnetic field. The magnetic field at a distance of 30 mm from the surface of the actuator is found to be 50 mG. Efforts are on to fabricate a more complete Niobium enclosure to bring down this number. Tests are also being performed to determine the heat generated.

3.3 Advantages

The advantages of the fast tuner include:

1) Very fast response and can be operated at frequencies as high as 2 kHz
2) Sub-micron precision motion.
3) High Force generation
4) Can be operated under extreme conditions
5) Long life.
6) Compact reliable and robust

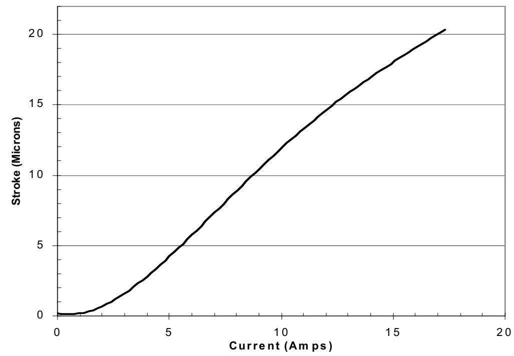

Figure 5: The linearity of the fast tuner

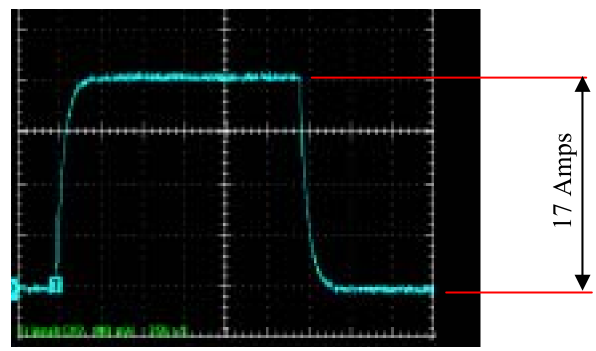

Figure 6: Response of the coil to a step input.

4 FUTURE DESIGNS

Future tuner designs where in both the fast and slow tuners are integrated into a complete tuning system are being considered. More compact fast tuners are being designed and fabricated for custom applications. The smallest one is 62mm x 50mm and 22mm deep. Smaller configurations are possible as the active element is only 25 mm wide, 26 mm high and 17 mm deep.

5 CONCLUSIONS

Energen Inc. has demonstrated a comprehensive tuning system performing both slow and fast tuning for SRF cavities. High-force, compact, magnetostrictive actuators are capable of precisely positioning stiff objects. Reliable and robust operation under extreme conditions of temperature and pressure has been demonstrated.

REFERENCES

[1] Joshi, et al, "A Magnetostrictive Tuning Mechanism For SRF Cavities," PAC 1999.

[2] Joshi, et al, "Progress In The Development Of SRF Cavity Tuners Based On Magnetic Smart Materials," PAC 2001.

[3] http://www.EnergenInc.com

[4] Joshi et al, "High Force, Precision Positioning Using Magnetic Smart Materials," RF Superconductivity Workshop, Santa Fe, NM, Nov. 1-5, 1999.