A MAGNETOSTRICTIVE TUNING SYSTEM FOR PARTICLE ACCELERATORS[1]

Chiu-Ying Tai[2], Jordan Cormier, William Espinola, Zhixiu Han, Chad Joshi, Anil Mavanur, Livia Racz, Energen, Inc. Lowell, MA 01854, U.S.A.
Kenneth Shepard, Argonne National Laboratory, Argonne, IL 60439, U.S.A.
Edward Daly, Kirk Davis, Jefferson Lab, Newport News, VA 23606, U.S.A

Abstract

Energen, Inc. has designed, built, and demonstrated several fast and slow tuners based on its magnetostrictive actuators and stepper motor. These tuners are designed for Superconducting Radio Frequency (SRF) cavities, which are important structures in particle accelerators that support a wide spectrum of disciplines, including nuclear and high-energy physics and free electron lasers (FEL). In the past two years, Energen's work has focused on magnetostrictive fast tuners for microphonics and Lorentz detuning compensation on elliptical-cell and spoke-loaded cavities. These tuners were custom designed to meet specific requirements, which included a few to 100 micron stroke range, hundreds to kilohertz operation frequency, and cryogenic temperature operation in vacuum or liquid helium. These tuners have been tested in house and at different laboratories, such as DESY, Argonne National Lab, and Jefferson Lab. Some recent results are presented in this paper.

INTRODUCTION

Background

Superconducting radio frequency (SRF) cavities, which include both elliptical and spoke types, are devices inside particle accelerators that are used to bring the charged particles to the required energy and speed. The performance of these cavities can be affected by many different sources, such as manufacturing defects, asymmetries in the cooling process, and noise from the surrounding environment. *Cavity tuners* - devices used to physically change the shape of the cavities - are used to correct for these non-idealities and tune the resonant frequency of the structure to match the frequency of the input energy. There are two kinds of tuners – "slow" or "coarse", and "fast" or "fine". Slow tuners provide large forces and hundreds of kHz tuning range to compensate for static defects, while fast tuners respond quickly but only over a few hundreds to a few thousand Hz. They are used to compensate the frequency shift caused by microphonics (from mechanical sources) and Lorentz detuning (from electromagnetic sources).

Since 1997, Energen has been working with engineers and scientists at Jefferson Laboratory, the National Superconducting Cyclotron Laboratory, the Spallation Neutron Source, Deutsches Elektronen–Synchrotron (DESY), and Argonne National Laboratory (ANL) to develop and demonstrate tuning mechanisms based on magnetic "smart" materials (MSM) for a variety of SRF cavities. Details of the tuner designs and a subset of the test results have been reported previously [1][2][3]. In the past two years, Energen has focused on fast tuners for active microphonics control and Lorentz detuning compensation. The present paper reports on the detailed design and testing of these tuners.

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[2]ctai@energeninc.com

Magnetic "Smart" Materials (KelvinAll®)

Magnetic "smart" materials (MSM) change their shape in a predictable and reversible manner when exposed to a magnetic field. Energen has developed the MSM KelvinAll® to have considerable advantages over other smart materials for SRF cavity tuners. Other candidate materials include TbDyZn, developed by the U.S. Navy for cryogenic applications to approximate the properties of the common room-temperature material Terfenol-D ($Tb_{0.3}Dy_{0.7}Fe_2$). This material has a Curie temperature around 170 K – the maximum temperature at which it will respond to a magnetic field – forcing even preliminary tests to be done at cryogenic temperatures. Further, this alloy is only available in small quantities through custom fabrication, making it very expensive. The most commonly-used smart material for SRF cavity tuners is the piezoelectric lead zirconate titanate (PZT). Its main disadvantage is that its elongation drops drastically with decreasing temperature. Figure 1 compares the temperature-dependent elongation of the materials discussed [4].

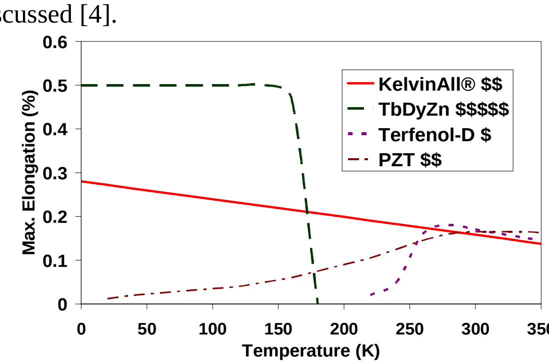

Figure 1: Temperature-dependent elongation for several smart materials and their relative costs.

FAST TUNER DESIGN

Specifications

Energen has custom designed and built several different fast tuner prototypes for different facilities based on the requested specifications listed in Table 1.

Table 1: Specifications of Energen's fast tuners

	ANL–1st generation	**DESY**	**JLab**
Operation environment	4.2 K in LHe	2.1 K to 18 K in vacuum	2 K in LHe
Max compressive load	445 N	1500 N	15000 N
Stroke	50 to 100 µm	20 µm	8 µm
Bandwidth	< 160 Hz	> 60 Hz	> 1 k Hz
Waveform	Continuous sine wave	Square wave: 250 µs rise time, 1.6 ms pulse length	Continuous sine wave

Actuator Designs

The core technology underlying all of these devices is KelvinAll® material in rod form. However, in order to achieve the different requirements, the material may be used in monolithic (bulk) or composite (laminated) form, together with different rod and electromagnetic coil geometries and device designs. The geometry of the KelvinAll rod is determined by the specified stroke and load. A bulk rod with certain diameter has an upper operating frequency limit due to eddy current effects. To exceed this limit, alternating sheets of KelvinAll® and epoxy can be used. In Table 1, such laminated rods were used in both the DESY and JLab actuators.

Different superconducting coils were used in these actuators. The superconductor NbTi has its critical temperature at 9 K, and is able to drive the MSM rod at 4.2 K or below in liquid helium (ANL and JLab designs) without special cooling concerns. In the DESY actuator design, a Nb_3Sn coil with higher critical temperature (18 K) was used. In order to ensure normal operation, extra thermal strips were used to connect the coil and the heat sink for enhanced cooling in vacuum.

Another way to increase the coil efficiency without quenching it is to use field concentrators such as laminated silicon steel housing, as was done in both the DESY and JLab actuators. The purpose of the lamination in the field concentrators is to reduce eddy currents and heat generation.

Each actuator system underwent a mechanical design process for the mass-spring system to ensure the specified bandwidth, which was dependent on the natural frequency of the structures. Figure 2 shows some actuators and

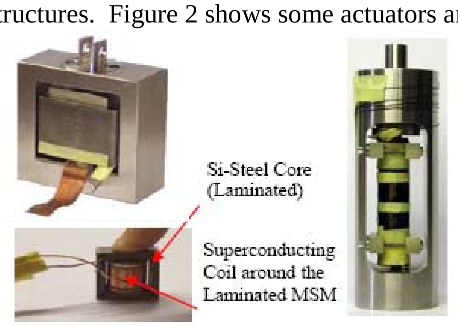

Figure 2: Energen's fast tuners – DESY actuator (upper left); central portion of DESY actuator (lower left); and ANL actuator (right).

components; more details can be found in previous publications [3][5].

TUNER TESTS

Laboratory Tests at Energen

All the fast tuners mentioned above have been tested at Energen under actual operating conditions. Figure 3 shows stroke vs. input current for the 1st generation ANL tuner. Data were measured at 4.2 K in liquid helium. More than 70 µm of full stroke under different loading forces was obtained in DC operation, and 80 to 90% of full stroke is available in AC operation up to 160 Hz.

A 2nd generation tuner for ANL is being developed, discussed elsewhere in this paper.

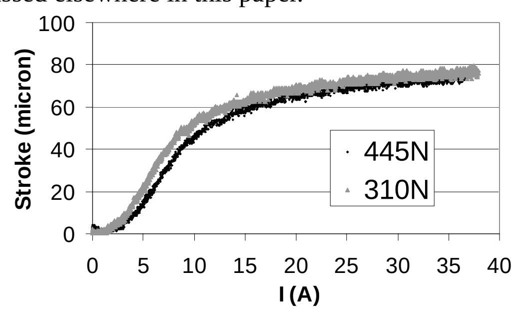

Figure 3: Stroke vs. input current for ANL tuner under two loads, 310 and 445 N.

Test Preparation at ANL

The 1st generation ANL tuner is currently ready for final test. It is attached to an adjustable holder (see Figure 4), and will be installed in the beta 0.5 triple-spoke cavity. The tuner assembly is inside the helium vessel. The turner will be slightly pulled back from the cavity during the cooling process, and adjusted to contact when ready for tuning. Figure 5 shows the location of the tuner in the system.

Figure 4: ANL tuner and adjustable holder.

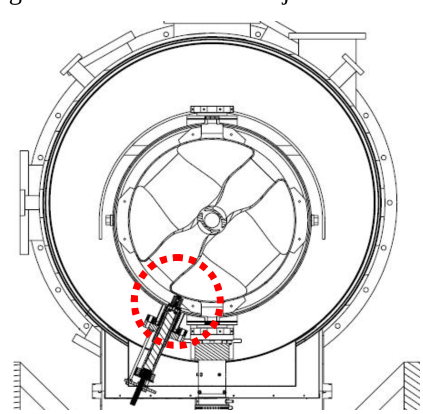

Figure 5: Location (inside dashed line) of the fast tuner in the beta 0.5 triple spoke cavity (drawing from ANL).

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Finite element analysis of the cavity (provided by Advanced Energy Systems) indicates that a 20 µm actuation at this location can generate a 120 Hz frequency shift. Based on this analysis, Energen's MSM tuner with up to 70 µm stroke could provide a tuning range of more than 400 Hz.

Blocking Force Test at DESY

A blocking force test of the tuner was recently conducted at DESY using the apparatus shown in Figure 6. In this setup, the MSM tuner pushes against a very stiff piezostack, which measures displacement and pushing force of the MSM tuner by monitoring change in output voltage as the piezostack is compressed. A pre-load force of ~1 kN was applied using the top screw. The test was performed at 4.2 K in vacuum. Some results are shown in Figure 7. It is very promising that the MSM actuator can still move and provide significant pushing force under 1000 N pre-load against a very stiff structure (the piezostack).

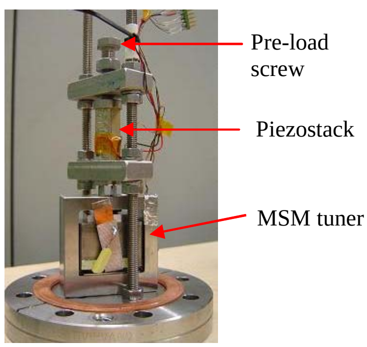

Figure 6: Test apparatus at DESY.

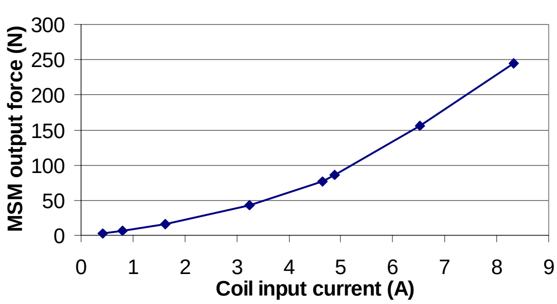

Figure 7: Output force vs. input current for DESY tuner.

Tuner Tested at Jefferson Laboratory (JLab)

The fast tuner developed for JLab was tested on a prototype 12 GeV 7-cell cavity system (see Figure 8). The JLab tuning system has a stepper motor for slow tuning of the cavity, and the load on the MSM actuator depends upon the distance moved by the stepper motor. The total frequency shift due to the MSM tuner was measured using an RF network analyzer at different compressive loads. Test results show that the tuning range of Energen's tuner was more than twice the required 1200 Hz shift under all loading conditions. The smallest controllable frequency shift was found to be 1.2 Hz, implying an actuator resolution of 4 nm. More details have been presented [5].

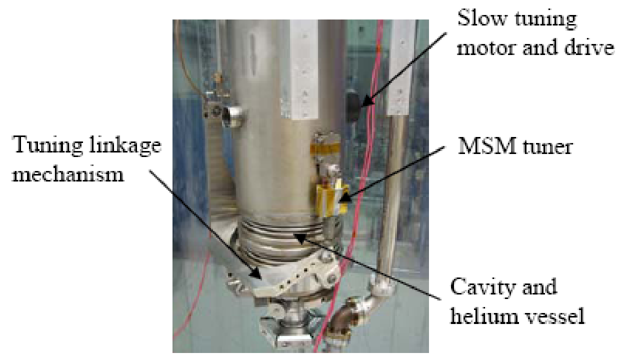

Figure 8: Magnetostrictive actuator/tuner JLab cavity

CONCLUSIONS AND FUTURE WORK

Several different SRF cavity tuners built to varying specifications based on KelvinAll® magnetic smart material have been tested under different conditions, successfully demonstrating Energen's fast tuner design and development capabilities. Future work includes on-site testing of the 1st generation ANL tuner, development of a 2nd generation ANL tuner with improved bandwidth, on-site tests at DESY, and development of a low-cost combined slow-fast tuning system.

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REFERENCES

[1] C.H. Joshi, B. Bent, M. Drury, J. Preble, V. Nguyen, "A Magnetostrictive Tuning Mechanism For SRF Cavities," Proceedings of the Particle Accelerator Conference, New York, New York, March 29-April 2, 1999.

[2] C.H. Joshi, A. Pappo, D. Upham, J. Preble, "Progress In The Development of SRF Cavity Tuners Based On Magnetic Smart Materials," Proceedings of the Particle Accelerator Conference, Chicago, Illinois, June 18-22, 2001.

[3] A. Mavanur, C.Y. Tai, C.H. Joshi, T. Grimm, "Magnetostrictive Tuners for SRF Cavities," Proceedings of the Particle Accelerator Conference, Portland, Oregon, May 12-16, 2003.

[4] Energen, Inc. website, http://www.EnergenInc.com, 2005.

[5] A. Mavanur, C.Y. Tai, C.H. Joshi, E. Daly, and K. Davis, "Magnetostrictive Fast Tuners for SRF Cavities," Proceeding of the Applied Superconducting Conference, Jacksonville, Florida, Oct. 4-8, 2004.