HIGH FORCE, PRECISION POSITIONING USING MAGNETIC SMART MATERIALS [1]

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ABSTRACT

Magnetostrictive and magnetic shape memory alloys respond to externally imposed magnetic fields in a reversible and repeatable manner. These new materials will enable more compact actuators for a wide range of applications such as linear motors, translation stages, robotics, and active vibration control.

Energen, Inc. has designed, built and demonstrated a fine tuning mechanism for superconducting radio frequency (SRF) cavities used in particle accelerators. This tuner is based on giant magnetostrictive materials being developed by Energen, Inc. Magnetostrictors elongate when exposed to a small magnetic field. This extension is reversible and repeatable enabling a wide range of applications. The magnetostrictive tuner was specifically designed to meet the requirements of the Thomas Jefferson National Accelerator Facility in Newport News, VA. The tuner consists of a high force linear actuator that elongates the cavity along its axis thereby changing its resonant frequency. It is installed in the dead leg of the existing mechanical tuner. This mechanism has a force capability of over 5000 lbs. and provides a tuning range of 2000 Hz. Preliminary tests at Jefferson Laboratory demonstrated its cavity tuning capability.

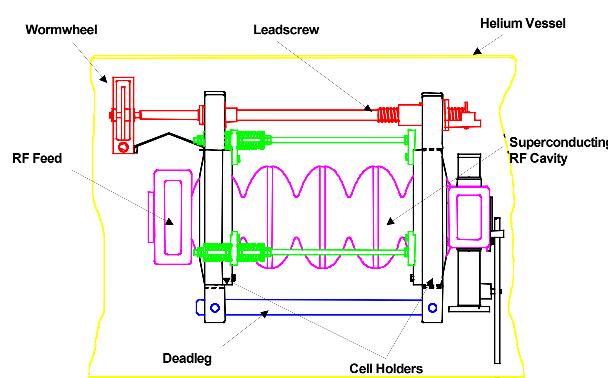
Energen, Inc. is presently developing a new generation of SRF cavity tuners that can eliminate the mechanical tuners that are presently employed. The basis of this new tuning mechanism is a linear stepper motor that provides several millimeters of motion with nanometer positioning resolution. The features of this stepper motor include high force motion and the ability to hold position when powered off. These capabilities enable multiple cavities to be tuned with a single set of electronics. Furthermore, with only electrical wires connecting the electronics and the stepper motor, the complexity of rotating vacuum and cryogenic feedthroughs associated with mechanical tuners can be eliminated.

INTRODUCTION

The Jefferson Laboratory of Newport News, VA operates the largest continuous beam electron accelerator in the world. Approximately 344 superconducting RF cavities operate at a resonant frequency of 1497 MHz to accelerate the electrons as they pass through each cavity. To obtain a homogeneous and continuous electron beam, these cavities are designed to exacting geometric tolerances. However, small imperfections in their manufacture and the large dimensional change that occurs as a result of cooling from room temperature to 2.0 K necessitates active compensation for the cavity length during the actual operation of the accelerator in order to match the resonance frequencies of multiple SRF cavities used in any accelerator.

SRF cavity tuning is accomplished by physically elongating or compressing the cavity along its axis. Jefferson Laboratory uses a mechanical system as shown in Figure 1. The system uses a stepper motor at room temperature to drive a wormwheel gear reduction connected to a ball screw shaft. As the shaft turns, the two cell holders are squeezed together compressing the cavity and changing its resonant frequency. This mechanical system is relatively simple in concept, however, it is difficult to use for accurate cavity tuning. In operation, this system, like any other mechanical assembly, has backlash. In addition to the elastic behavior of the components, split shaft couplers are used for the rotating feedthrough to allow for thermal contraction during cooldown. This split assembly adds to the inherent backlash of the system.

Figure 1 - The CEBAF superconducting RF cavity showing its mechanical tuner.



Jefferson Laboratory is currently in the process of upgrading its cryomodule to achieve a higher average gradient, and increase the electron beam energy. As part of this upgrade project, a new cavity design is being

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developed that will result in a higher packing density. Energen is developing tuners based on magnetostrictive actuators that will provide a total tuning range of ±200 kHz with a tuning resolution of ±1 Hz. The goal of the present development effort is to design and demonstrate a cost-effective tuning solution on a timeline consistent with the upgrade schedule.

MAGNETOSTRICTIVE MATERIALS

Magnetostrictive materials belong to a class of materials known as “smart materials”. Magnetostriction arises from a reorientation of the atomic magnetic moments. In ferromagnetic materials, an applied magnetic field causes rotation of the magnetization towards the field direction within domains and/or motion of the domain walls to increase the size of the domains with magnetization vectors close in direction to the applied field. When the magnetization is completely aligned, saturation occurs and no further magnetostriction can be produced by increasing the applied magnetic field. Magnetostriction only occurs in a material at temperatures below the Curie temperature. The amount of magnetostriction at saturation is the most fundamental measure of a magnetostrictive material. Table 1 shows a compilation of some materials and the maximum strain they exhibit at saturation. Note that the materials exhibiting the highest magnetostrictive strain have Curie temperatures below room temperature. These materials show great promise for cryogenic actuator applications such as the SRF cavity tuners.

Table 1 -- Saturation strain and Curie temperatures of selected materials. [1]

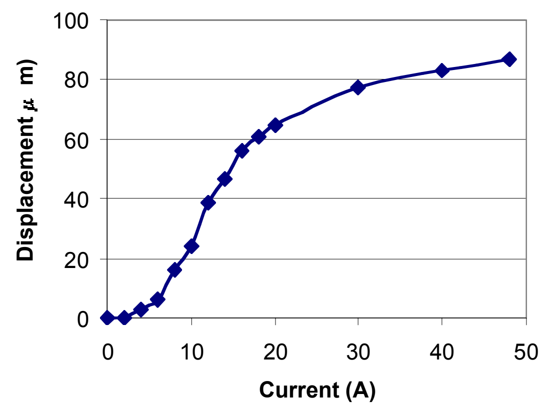
Material	Saturation Strain ($x 10^{-6}$)	Curie Temperature (K)
Ni	-50	630
Fe	-14	1040
$SmFe_2$	-2340	690
Fe_3O_4	60	860
$DyFe_2$	650	630
$TbFe_2$	2630	700
$Tb_{0.3}Dy_{0.7}Fe_{1.9}$ (Terfenol-D)	1600-2400	650
$Tb_{0.6}Dy_{0.4}$ @ 77 K	6300	210
$Tb_{0.5}Zn_{0.5}$	5500	180
$Tb_{1-x}Dy_xZn$	5000	200

Magnetostrictive materials for cryogenic applications are not currently commercially available but are being produced at research laboratories. Energen, Inc. has worked with the Ames Laboratory’s Materials Preparation Center to obtain samples of the materials for testing and building prototype devices. Energen has identified and is in the process of procuring the equipment necessary to fabricate these materials on a production basis. The company intends to have these facilities in place in time to deliver the tuner for the Jefferson Laboratory upgrade.

Several alloys from the $Tb_{1-x}Dy_xZn$ family of materials were fabricated as follows. Appropriate quantities of the elemental constituents were alloyed together in a sealed tantalum crucible. The crucible was then held just below the melting temperatures to promote crystal growth. Once cooled, the crucible was removed and the resulting ingot was machined into rods for testing purposes. For testing the magnetostriction, samples of each alloy were cut into 2-mm diameter rods of lengths varying from 20 to 30 mm.

Measurements of magnetostriction were made at 77 K and at 4.2 K. The data for 77 K are very reproducible and agree with available data from the literature.[2] Figure 2 shows the measurements on one sample of the TbDyZn alloy at 4.2 K. These data are believed to be the first direct measurement of magnetostriction in this material system at 4.2 K and indicate that the high saturation strain remains at these low temperatures.

Figure 2 - Magnetostriction of a TbDyZn alloy at 4.2 K shows high saturation strain.



FINE TUNER PERFORMANCE

Energen, Inc. designed a magnetostrictive tuner based on these materials that replaces the deadleg of the existing mechanical tuner. This tuner was designed to provide fine tuning capability in parallel with the existing tuner. The mechanical tuner would be used for coarse tuning of the resonant frequency and then the magnetostrictive tuner would be used for fine tuning.

Figure 3 shows the magnetostrictive dead leg. Because of limitations in the size of magnetostrictor rods currently available, the magnetostrictor consists of six 0.5 inch disks of equal thickness on a 1.108" bolt circle. They are surrounded by a NbTi coil and compressed between two ferromagnetic end pieces that connect to the dead leg. The coil has 20 turns of superconductor with a critical current of 325 A at 4.2 K, 5.0 T. The ferromagnetic end pieces serve to focus the magnetic flux from the coil onto the magnetostrictor. The peak field in the end pieces and in the magnetostrictor is less than 1.6 tesla.

Figure 3 – Magnetostrictive fine tuning mechanism.

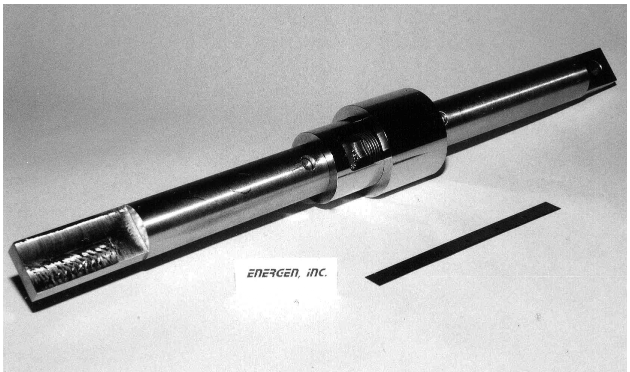
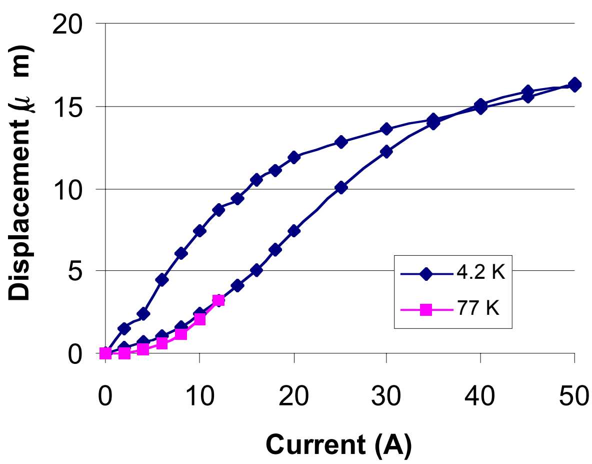


Figure 4 - Measurement of the tuner motion.



The tuner was tested at Energen's facility at 77 K and at 4.2 K. At 77 K, the current in the coil was limited to 15 A to prevent potential damage to the coil and actuator from overheating. Figure 4 shows the results of tests at 77 K and 4.2 K

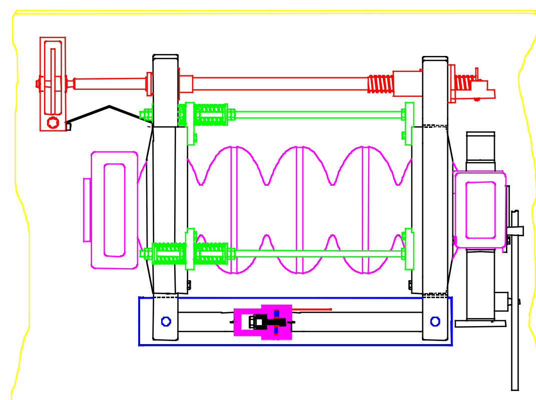
Figure 4 indicates that a total stroke of 16 microns is available for tuning the SRF cavity . Based on the known characteristics of the Jefferson Laboratory SRF cavities, this corresponds to a tuning bandwidth of 6400Hz. This is greater than the design goal by a factor of three.

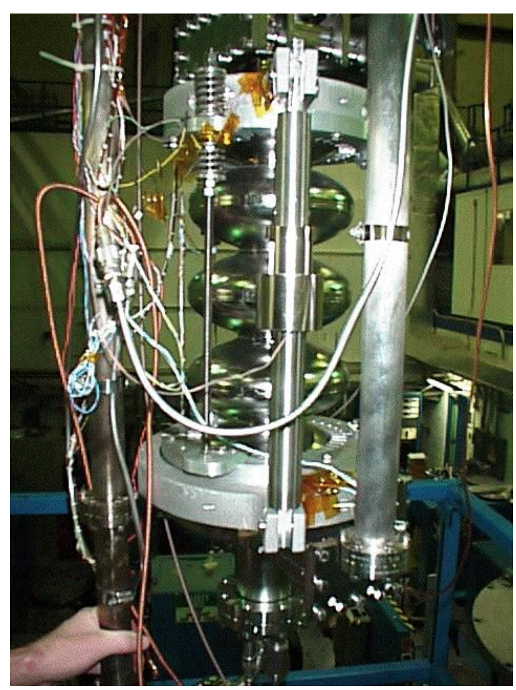
It is clear that there is some hysteresis in these measurements. The source of this hysteresis is the anisotropic magnetic properties of the material and can be reduced by properly adjusting the chemistry of the material.

At Jefferson Laboratory, the tuner was installed on a SRF cavity as shown in Figure 5. In operation, a combination superconducting and mu-metal shield would be used to prevent the magnetic field generated by the magnetostrictive tuner from affecting the performance of the cavity.

The cavity was inserted vertically in a dewar and cooled in liquid Helium to approximately 2 Kelvin. A network analyzer (Hewlett Packard 8753) was used to drive the cavity and measure the cavity's resonant frequency (f_o). An RF frequency preamp was use to boost the signal from the cavity field probe before returning to the analyzer. A Sorenson programmable power supply capable of 45 A was used as the current source for the tuner. A 50 Amp shunt was installed in the return leg of the circuit between tuner and power supply. The shunt was calibrated for 1 mV/A. A digital multimeter was used to measure the shunt voltage. The apparatus was controlled with a laptop computer running Labview using a GPIB card to talk to the network analyzer and the multimeter. A National Instruments analog box was attached to the parallel port. This provided an analog output with which we could control the current source. The resolution of the current drive under this setup was about 0.5 A. The resolution of the network analyzer was about 10 Hz.

Figure 5 - The magnetostrictive tuner was installed in place of the dead leg of the mechanical tuner.





Four different current sweep tests were done. In the first two tests, the maximum current for the tuner was 30 A. While the pressure in the helium vessel was constant during each test, there is a slight variation over a longer period of time. This pressure variation affects the tuning of the cavities. During the third test, when the current was increased to 50 A, a large change in pressure from 21 torr to 12 torr occurred during the test. There was likely a shift in frequency because of the pressure change exacerbating the hysteresis that is evident in the data. In the final test, the cryostat pressure was maintained at 12 torr and the resultant tuning capability measured shows a frequency range of 2 kHz.

Figure 6 – Measurement of the cavity tuning capability of the fine tuning mechanism

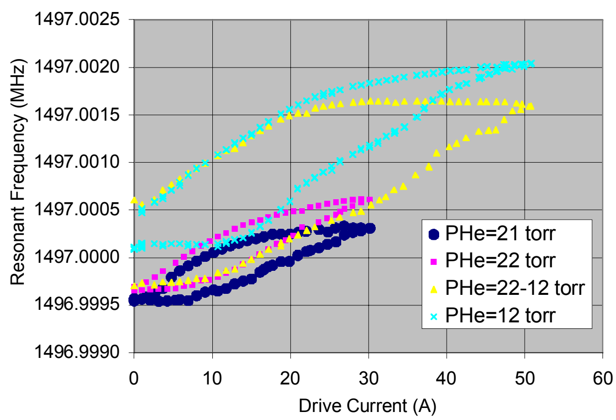


Figure 7 - A compact linear stepper motor built by Energen, Inc.

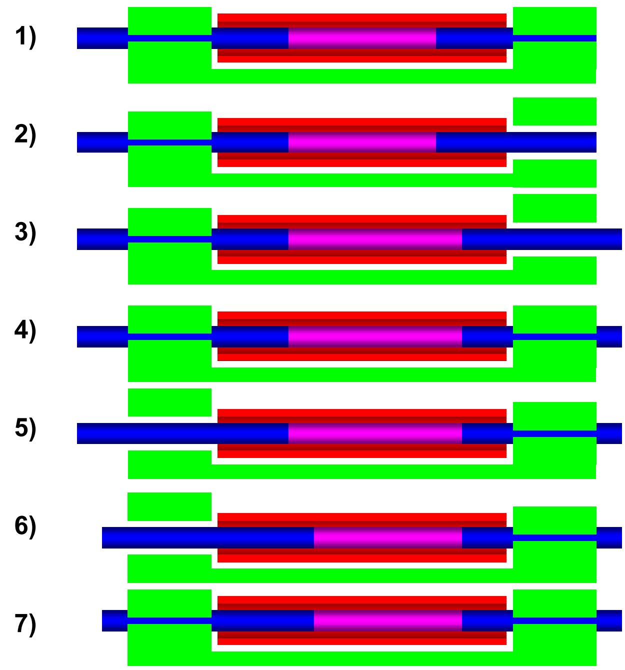
Figure 6 - Stepper motor operating sequence.

LINEAR STEPPER MOTOR

Energen has taken the basic concept of the magnetostrictive actuator and develop a linear motor capable of longer range motion than the linear actuator.

The stepper motor actuator consists of a shaft held by a pair of magnetostrictive clamps. The shaft consists of a linear actuator with a connecting rod extending from each end. Clamps that hold each of the connecting rods, are opened by energizing the magnetostrictive actuator contained therein thereby enabling the connecting rod to move along its axis. A photograph of a stepper motor is shown in Figure 7.

Figure 8 – Stepper motor operating sequence.



OPERATION

The stepper motor can be operated in one of two modes – in stepper mode or fine tune mode. In stepper mode, the translating rod is moved in discrete steps along its axis by operating the clamp and translating actuators in a predefined sequence. The sequence is as follows and is illustrated in Figure 8.

1) Starting from the power off position,
2) The forward clamp is energized causing it to release its hold on the connecting rod.
3) The translating actuator is energized causing the magnetostrictor rod to elongate pushing the front connecting rod forward.
4) The forward clamp is then closed to grab onto rod.
5) The rear clamp is energized to release.
6) The translating actuator is de-energized causing the rear half of the rod to be pulled forward.
7) The rear clamp is then closed to provide maximum holding.

The rod has moved a step forward. Reversing the sequence of operations above causes the rod to move in the opposite direction.

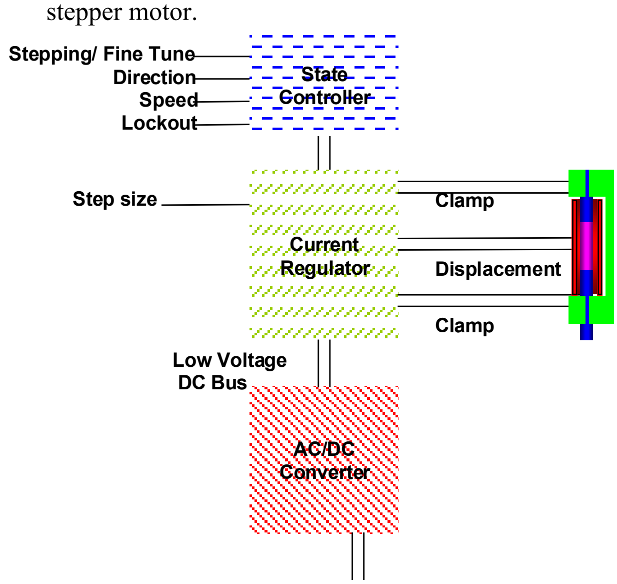
To achieve high positioning resolution Energen provides a fine tuning mode of operation. In this mode, the forward actuator is energized to release and the current in the translating actuator is modulated thereby moving the forward connecting rod proportionally.

Thus this linear motor is capable of providing a long stroke with high positioning resolution. It is capable of holding position with zero power dissipation since the clamps hold at zero current.

DRIVE ELECTRONICS

The drive electronics for the position control actuator enables a wide range of actuator operational flexibility through a digital state control circuit. In addition to setting the operating mode (stepper or fine tune), the direction of motion, the step size and stepping frequency can be adjusted. Figure 9 shows a block diagram of the drive electronics.

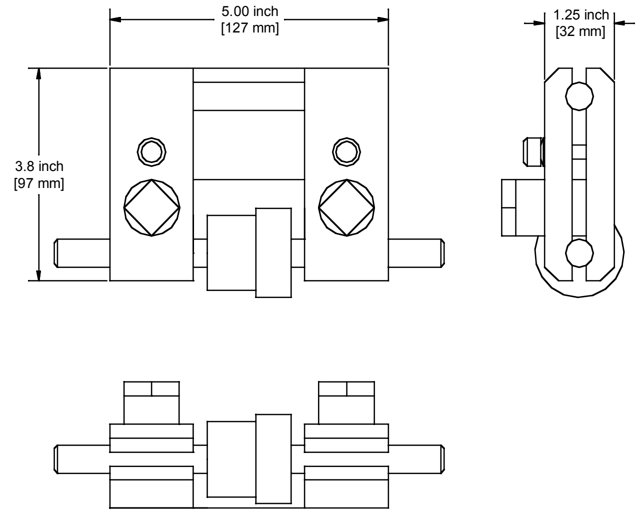
Figure 9 -A digital state control circuit allows complete flexibility in positioning control with the stepper motor.

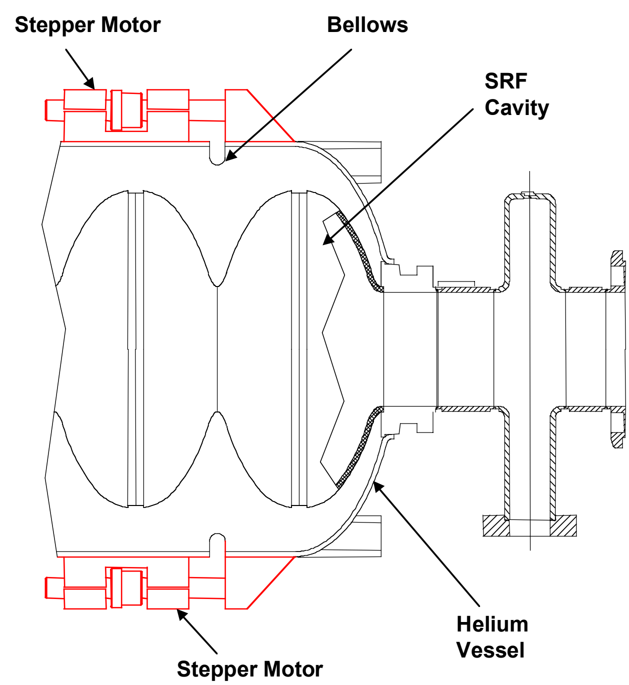


STEPPER TUNER DESIGN

Energen has developed a SRF cavity tuner based on its stepper motor. The basic principal of operation for the tuner is to use a pair of stepper motors to expand or compress the cavity along its axis relative to the cryostat. For this application, a large force capacity is required of the stepper motor. The force capability is directly related to the cross section of the magnetostrictive element. The geometry of the stepper motor and its interface to the cavity is shown in Figure 10. The stepper motor can move forward or backward with a total stroke of 12.5 mm with a force capability of 3100 N. As it moves forward, it pulls on the cavity with respect to the helium vessel. Reversing the direction of motion causes the cavity to be compressed. When the desired resonant frequency is reached, power to the stepper motor can be turned off and the stepper motor will remain locked in position.

Figure 10 - Conceptual design of stepper motor and its interface to the SRF cavity.





ADVANTAGES

This tuning technique has several advantages over existing systems.

- Accurate tuning – positioning resolution of 0.01 micron gives accurate frequency tuning
- Compact design – since only wires re needed to connect to this tuner from outside the cryostat, the tuner is more compact that a more conventional tuner system

- Low hysteresis – since the actuators are turned on and off, the stepping motion is digital in nature and minimizes the effect of the hysteresis of the magnetostrictor material.
- Elimination of mechanical penetrations through cryostat reduces the complexity of the cryostat system and increases reliability since mechanical penetrations through the vacuum space are eliminated.
- "Set and forget" tuning – the tuner will hold position when the power is turned off
- Multiplexing of cavity tuners – one set of electronics can be used to tune multiple cavities
- Low cost – it is anticipated that as the production quantities increase, the cost of the magnetostrictive material will be reduced by a factor of 5 to 20 from the present costs.

CONCLUSION

Energen, Inc. has designed, built and demonstrated a fine tuning mechanism for superconducting radio frequency (SRF) cavities used in particle accelerators. The tuner is designed specifically for the Jefferson Laboratory and operates in parallel with an existing mechanical tuning system that uses a wormwheel and ball screw assembly. The magnetostrictive fine tuner has demonstrated the desired 2000 Hz of tuning bandwidth and can be actively controlled during the operation of the SRF cavity.

A new SRF cavity tuner design based on Energen's linear stepper motor promises to provide reliable, accurate tuning capability and will eliminate the complexity and expense of mechanical tuning systems. This new tuning system is being considered for use with the upgrade of the electron beam accelerator at Jefferson Laboratory.

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[1] *Magnetostrictive Materials*, K. B. Hathaway and A. E. Clark, MRS Bulletin, Vol. XVIII, No. 4, April 1993.
[2] A. E. Clark, *High Power Magnetostrictive Materials from Cryogenic Temperatures to 250 C*, Materials Research Society Fall Meeting, Boston, MA, November 28-30, 1994.