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RESULTS OF ACCELERATED LIFE TESTING OF LCLS-II CAVITY TUNER MOTOR

N. Huque, E. F. Daly, Jefferson Lab, Newport News, VA 23606, USA
Y. Pischalnikov, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

Abstract

An Accelerated Life Test (ALT) of the Phytron stepper motor used in the Linear Coherent Light Source – II (LCLS-II) cryomodule cavity tuner has been carried out at Jefferson Lab (JLab). Since the motor will reside inside the cryomodule, any failure would lead to a very costly and arduous repair. As such, the motor was tested for the equivalent of 9 lifetimes before being approved for use in the production cryomodules. The 9-cell LCLS-II cavity is simulated by disc springs with an equivalent spring constant. Degradation in performance is measured with hysteresis plots of the motor position vs. tuner position – measured via an installed linear variable differential transformer (LVDT). The titanium spindle and traveling nut have been inspected for damage and loss of lubrication. The Phytron motor passed the ALT and is currently being installed in LCLS-II cryomodules.

INTRODUCTION

The LCLS-II Cavity Tuner is a lever-style tuner, consisting of the frame, two piezo actuators, and a Phytron stepper motor - the LVA 52-LCLS II-UHVC-X1 (Fig. 1). In the current testing setup, the piezo actuators are not present and replaced by solid cylinders. Table 1 describes the working parameters of the tuner and motor [1].

The motor itself consists of four main components: the stepper motor, gearbox, titanium spindle and traveling nut. A copper heat sink is located at the edge of the motor section to attach to a thermal strap. The planetary gearbox has a ratio of 1:50. The spindle is a titanium M12x1 thread with a diamond-like carbon (DLC) coating, which attaches to a similarly sized stainless steel traveling nut. The traveling nut has a TECASINT 1041 insert which mates to the M12x1 thread [2].

The motor manufacturer Phytron has the capability to test motors in vacuum at 77K. A test in vacuum at 4K as done here is a more realistic simulation of the motor's operating environment.

TESTING SETUP

The cavity is simulated via two sets of disc springs, designed to imitate the cavity's stiffness of 3kN/mm [3]. The tuner frame and springs are attached to an Aluminium base plate (Fig. 2), which is positioned inside the Tuner Test Can [1].

The can is evacuated and lowered into a vertical test area (VTA) dewar for cold testing at ~4K. Unlike the cryomodule, there is no active pumping on the test can.

An LVDT is positioned between the main lever arm of the tuner and the Aluminium base plate. The LVDT is the primary means of recording and measuring the tuner arm's movement, and the motor's operation. The feedback voltage of the LVDT is used to define the tuner arm displacement. In the provided graphs, the zero-position of the LVDT is at a value of 0.016V [1].

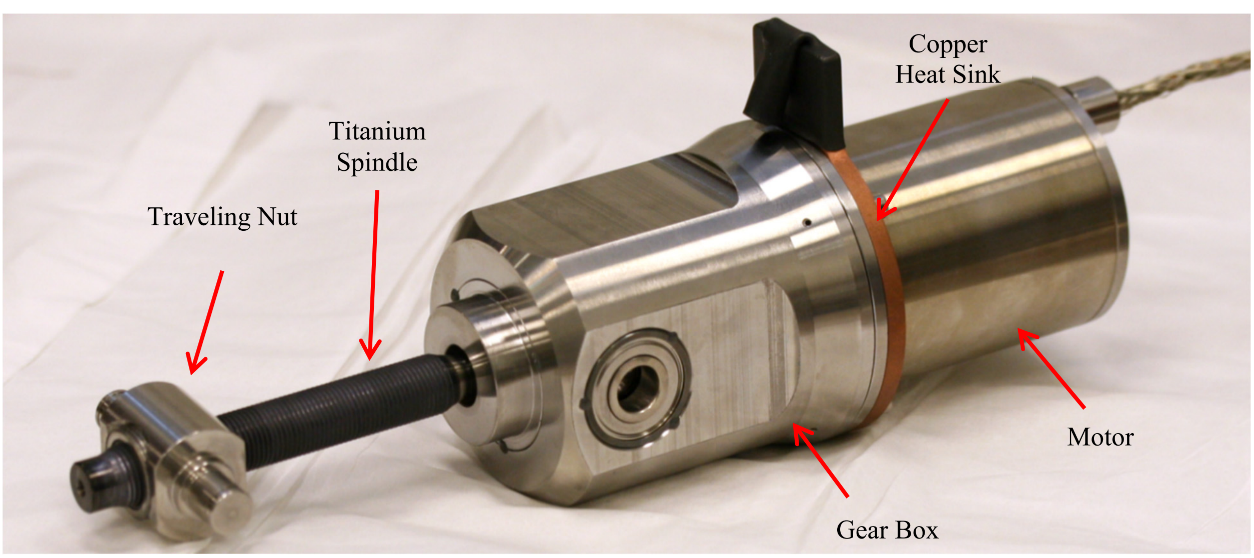

Figure 1: Phytron motor assembly, showing the main components.

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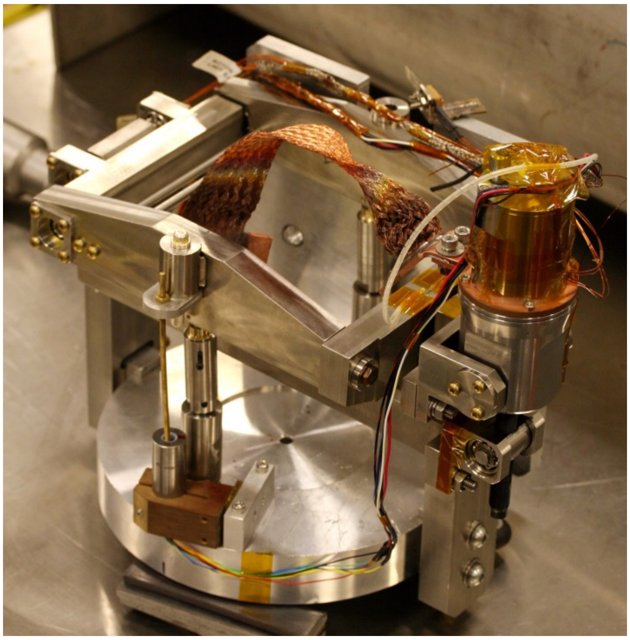

Figure 2: Tuner assembly attached to Aluminium base plate and spring stack for testing.

The motor is fitted with a thermocouple for recording the running temperature. However, its readings were found to be too noisy due to the close proximity of other wires. Instead, a resistance temperature diode (RTD) is attached to the side of the motor portion of the assembly [1].

A set of limit switches is attached adjacent to the spindle to act as a safety mechanism. The limits are set just inside the maximum mechanical travel of the traveling nut. The motor is stopped once either of the switches are tripped [1].

Table 1: Tuner and Motor Operating Specifications

Description	Value
Slow Tuner Frequency Range	Nominal 250 kHz Max 600 kHz
Slow Tuner Dimensional Range	Nominal 6.25 mm Max 15 mm
Motor Operating Condition	Insulating Vacuum
Motor Operating Temperature	20K – 60K
Motor Design Lifetime	1000 revs (20 years)
Nominal Motor Current	1.2A
Maximum Motor Force	+ 1300N, -200N

TESTING PLAN

It is estimated that the tuner motor will run once a day during regular operation. The motor's effect on the tuner and cavity frequency can be seen in Table 2. This part of the testing will involve travel along a small portion of the motor's spindle. For each year of life, this motion is estimated at ~330 cycles (once a day, minus down time). Twice a year, the motor will detune the cavity along its entire range.

Table 2: Tuner Operation Characteristics

Description	Value
Steps per Rotation	200
Gear Box Ratio	1:50
Motor Stroke per Revolution	1
Tuner Ratio	1:20
Cavity Stroke per Step	0.005 µm
Cavity Sensitivity	300 Hz/µm
Cavity Frequency Change per Step	1.5

Each of the tested cycles consisted of 2.14 revolutions of the motor spindle, or 429 steps. A cycle during operation consists of 600 Hz of cavity shift (Table 3). The 42,800 revolutions of the motor spindle during the test is over 40 times the vendor's design lifetime.

Table 3: Motor Testing Specifications

Description	Value	
	Short Range	Long Range
Frequency Shift (kHz)	0.6	600
Steps for Frequency Shift (kSteps)	0.4	400
Number of Cycles Per Year	330	2
Number of Steps Per Year (kSteps)	132	800
Steps Per 20 year Life (kSteps)	18,640	
Cycles Tested	20,000	
Steps Per Cycle	429	
Steps Tested	8.5×10^6	
Lifetimes Simulated	9	

PRELIMINARY TESTS

A set of parameter studies were conducted to determine the most efficient operating setting for the test. The goal was to enable to fastest testing speed while keeping the temperature of the motor within the allowable limits. The following variables were examined:

- Motor velocity
- Dwell time between cycles
- Motor current

The short testing runs during the parameter studies revealed that the LVDT signals were drifting lower as the test progressed (Fig. 3). The decrease in voltage of the LVDT implies a compressing motion of the disc springs. Periodic tightening of the screws holding the piezo blanks reduced this drift but did not eradiate it. The drifting was deemed acceptable for the remainder of the test.

Initial testing runs also found that the motor temperature was rising above what was considered the standard operating temperature for the motor. Tests run with between 1.0A and 1.4A or current resulted in stabilized temperatures of 80K to 115K. Decreasing the motor speed and adding a dwell time between cycles decreased the temperatures, but not to within acceptable levels. A detailed account of the parameter testing can be found in [1].

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A thermal strap was attached to the motor's copper heat sink for the final test runs. This brought the equilibrium temperature to ~25K.

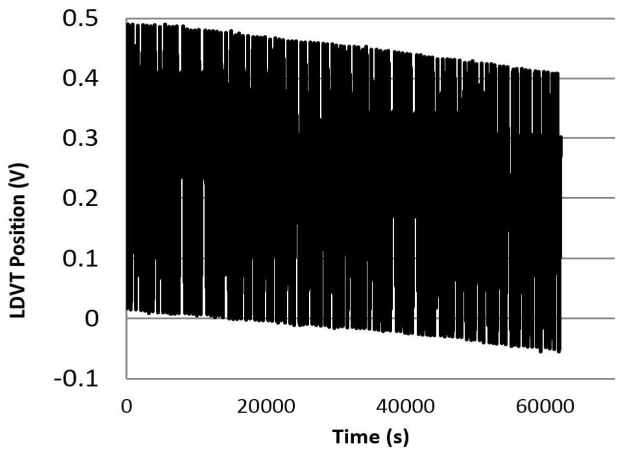

Figure 3: LVDT readings showing drift in tuner testing.

FINAL TEST

The experiment was stopped after the tuner assembly had completed ~20,000 cycles. The test was run between the dates of January 16th and February 1st, 2016. The parameters used for the final test run are shown in Table 4. The current was increased to 1.8A from the nominal 1.2A, to ensure overcompensation for any static friction; this would cause the temperature to be higher than that regularly expected. The running speed was increased after ~5,000 cycles due to time constraints. Figure 4 shows the temperature profile of the test run. At 150 rev/s, each cycle took ~80s, while at 200 rev/s, each cycle took ~60s.

Table 4: Parameters of Test Run

Parameter	Value
Motor Velocity (5,000 cycles)	150 rev/s
Motor Velocity (5,000 – 20,000 cycles)	200 rev/s
Motor Acceleration	10 rev/s^2
Motor Deceleration	10 rev/s^2
Dwell Time	0 s
Motor Current	1.8A

The initial 5,000 cycles at the slower motor speed had the temperature stabilizing at ~68K. The increase in speed raised it to ~78K. Though both values are considered too high for actual operation of the tuner, it is considered acceptable for this test. The temperature of the tuner frame was found to stabilize at ~17.5K.

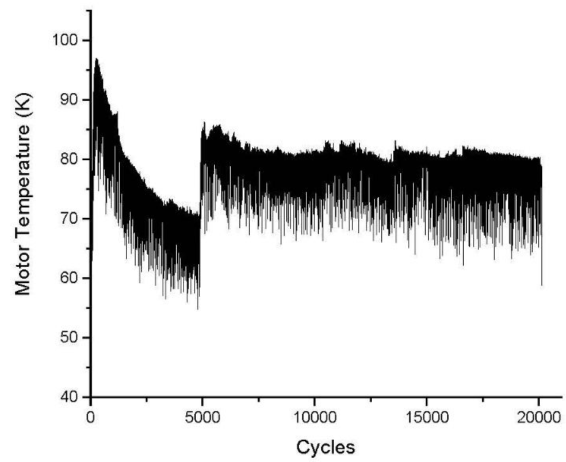

Figure 4: Motor temperature during test run.

The preliminary testing had found relatively constant rates of LVDT drift during the motor operation. As mentioned above, the drift was minimized by adjusting the connections in the testing plate. However, this was not possible during the long, final test run. In this instance, the drift was found to be erratic and non-uniform. At several times, the LVDT reading was seen to jump to different positions. This can be seen in Fig. 5, which shows the full test.

The jumps in LVDT feedback happens at seemingly random times, and have differing magnitudes. The upward drift seen during the first ~1000 cycles can be attributed to the frame not having fully cooled. Due to nature of the connections between the traveling nut and the tuner, it is unlikely that the jumps are due to the motor assembly itself. Upon inspection of the testing plate, it was found that the spring stacks had significantly loosened during the course of the experiment and that there was no slack in the tuner apparatus.

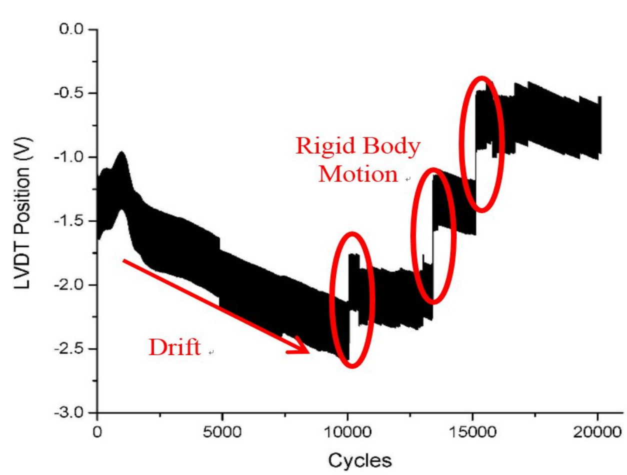

Figure 5: Rigid body botion in LVDT.

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RESULTS

Nut and Spindle Inspection

The titanium spindle was examined under a magnification of X35 to look for any signs of wear. Figure 6 shows an area of the spindle, near the hub, which did not have contact with the traveling nut, compared with the region over which the nut travelled during the test.

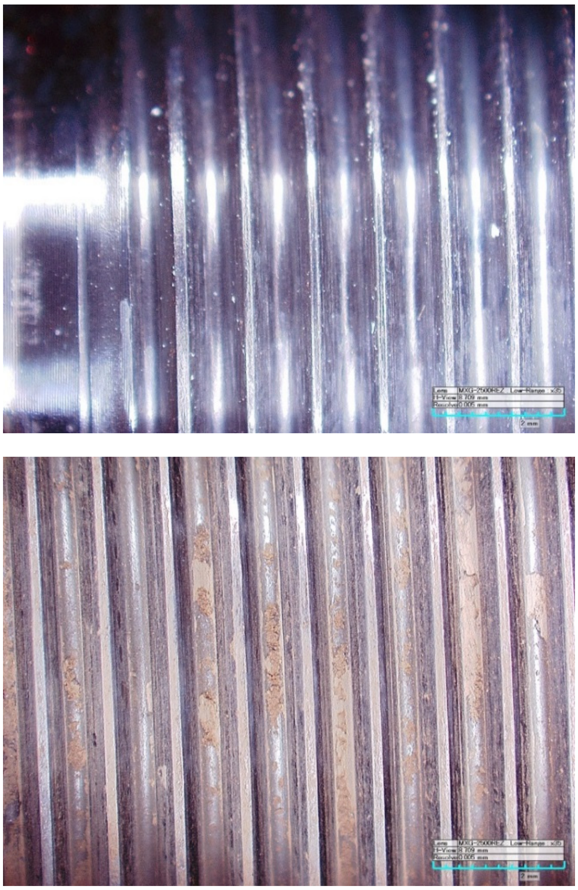

Figure 6: Unused section of the spindle (top) compared with used section of spindle (bottom) under X35 magnification.

The TECASINT insert in the traveling nut was also examined for wear. Due to its geometry, a full examination was not possible. The nut will be disassembled and inspected again at a later time. Figure 7 shows a section of the nut thread under magnification. Though there are signs of wear, there is no significant damage seen on the threads.

Figure 7: Threads on the TECASINT insert inside the traveling nut (X35 magnification). Top image is an unused nut, and bottom image is nut used for ALT.

Figure 8 shows the material found in between the spindle threads, taken with a Hirox 3D microscope. It can be seen that the substance is above the undamaged substrate.

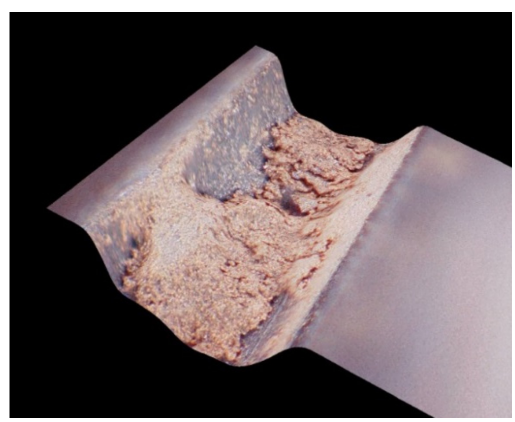

Figure 8: Material found between spindle threads (X400 magnification).

The material was analysed using an energy dispersive system (EDS). Figure 9 shows the material composition. The presence of Molybdenum and Sulfur – approximately in the ratio 1:2 – likely represents Molybdenum Disulphide. The compound is used in the TECASINT 1041 material of the traveling nut to lower the coefficient of friction. The TECASINT or the DLC coating could be the source of the carbon. In addition, there are traces of titanium from the spindle itself, but the low quantity seems to imply that it was scraped off at the time the sample was taken; the iron and chromium are most likely from the tool used to take

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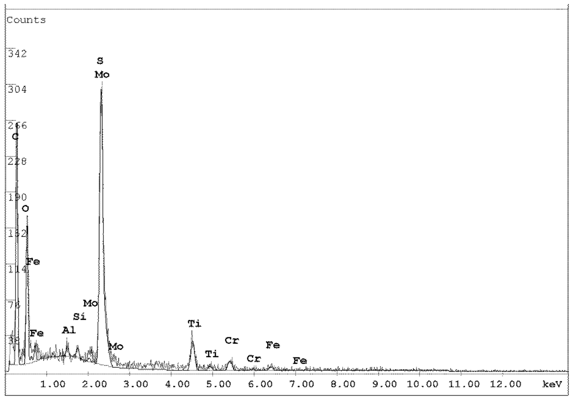
the sample. This analysis agrees with the theory that there was little to no damage to the spindle substrate, indicating that the degraded lubricating layer of the nut and spindle were still functional. As expected, there is far more wear on the TECASINT insert than the titanium spindle, though magnified images show that the former was still intact, even after such a high number of cycles.



EDAX ZAF Quantification (Standardless)
Element Normalized
SEC Table : User c:\edax32\eds\genuser.sec

Element	Wt %	At %	K-Ratio	Z	A	F
C K	45.58	68.91	0.1226	1.0733	0.2507	1.0001
O K	14.93	16.94	0.0362	1.0508	0.2308	1.0002
AlK	0.44	0.30	0.0035	0.9706	0.8195	1.0047
SiK	0.46	0.30	0.0041	0.9956	0.8899	1.0090
MoL	14.75	2.79	0.1222	0.7810	1.0592	1.0012
S K	10.63	6.02	0.1011	0.9829	0.9665	1.0013
TiK	6.53	2.47	0.0564	0.8719	0.9840	1.0067
CrK	3.81	1.33	0.0328	0.8652	0.9893	1.0045
FeK	2.87	0.93	0.0245	0.8598	0.9942	1.0000
Total	100.00	100.00				

Figure 9: EDS analysis of material found on the spindle.

Hysteresis

Figure 10 shows a comparison of the LVDT reading at cycle 1,500 and cycle 20,000. The values have been adjusted to remove the rigid body motion. Despite the apparent degradation of the TECASINT insert, there is no change in the profile of each cycle.

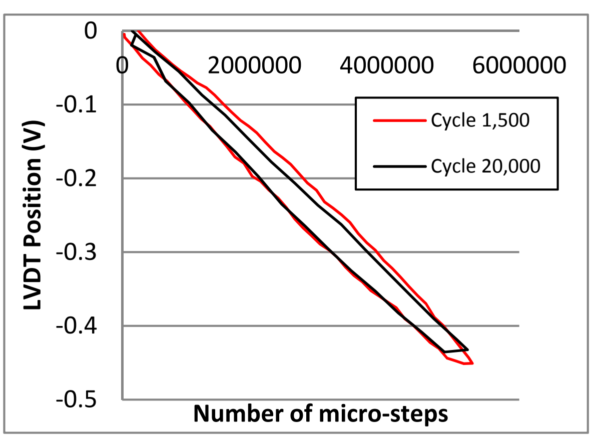


Figure 10: Profile of cycle near the start of and at the end of the experiment.

CONCLUSION

The tuner and motor went through accelerated life testing in the JLab VTA in vacuum at an ambient temperature of 4K. The motor was successfully run for 20,000 cycles, representative of 9 lifetimes of regular operation. Inspections of the spindle and the traveling nut under a microscope found degradation of the TECASINT 1041 nut material but no damage to the titanium spindle. Despite the degradation, there was little change in the motor's performance at the end of the test. The motor has been cleared for use in the production LCLS-II cryomodules.

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