Commissioning and Operational Experience With an Intermediate Upgrade Cryomodule for the CEBAF 12 GeV Upgrade*

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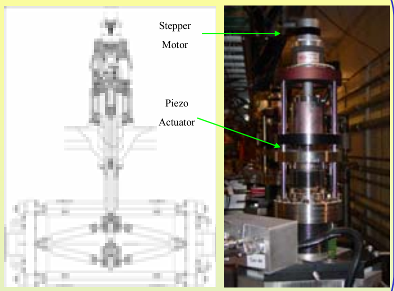
Cryomodule installed in FEL



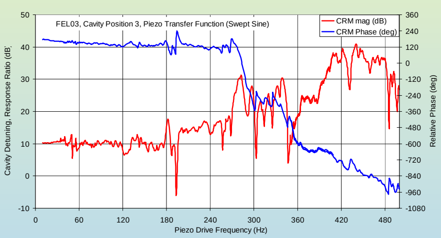
Tuner Layout and Photo of the Actuator Stack

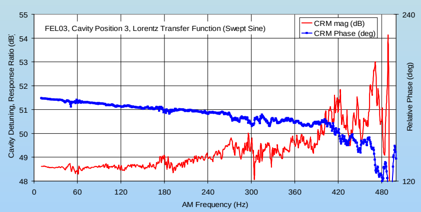
ABSTRACT

Three cryomodules have been designed and built as intermediate prototypes for the CEBAF 12 GeV upgrade. This paper will discuss the commissioning and operational experience with the second of these cryomodules, which was installed and commissioned in the Jefferson Lab 10 kW Free Electron Laser Facility. Within the cryomodule are eight 7-cell, 1497 MHz cavities. It was designed to accelerate 1 mA of beam in excess of 70 MV and to have the same footprint as a standard CEBAF cryomodule. The cryomodule was installed in parallel with the FEL beam line in the spring of 2004 and characterized simultaneous with beam delivery. It was installed in the beam line in the early summer of 2004 and has since been operated as part of an energy recovered linac with 5 mA of beam current and 75 MV accelerating gradient for extended periods of time. Additionally, it was operated at 1 mA of beam current and 80 MV of accelerating gradient for several hours without a trip. In the latter operating mode the beam current was limited by the injector setup.

	Cavity 1	Cavity 2	Cavity 3	Cavity 4	Cavity 5	Cavity 6	Cavity 7	Cavity 8
Emax in vertical test area	19.0	16.5	15.5	12.5	20.5	17.5	22.0	18.5
Emax limit in vertical test area	RF PWR			F.E.	RF PWR	F.E.	F.E.	Quench
Emax in FEL (MV/m)	18.0	16.0	18.1	17.7	12.6	16.1	15.8	16.3
Emax Limit in FEL	Quench	Quench	Quench	Quench	Quench	Quench	Quench	Quench
Emax Stable Operation in FEL (MV/m)	14.5	14.0	16.0	16.0	12.0	15.1	15.0	15.3
F.E. onset in FEL (MV/m)	None	7.2	None	13.2	8.5	11	13.4	9.7
Qo at 12 MV/m in FEL	8.2e9	6.4e9	8.2e9	8.1e9	7.0e9	6.4e9	7.9e9	7.4e9
Qext of Fundamental Power Coupler	2.21e7	2.19e7	2.04e7	2.41e7	2.32e7	2.10e7	1.65e7	2.33e7
FPC Bandwidth (Hz)	68	68	73	62	65	71	91	64
Field Probe Q in FEL	1.37e12	2.03e12	1.53e12	1.36e12	0.96e12	1.56e12	2.08e12	1.35e12
HOM1 Q at 1497 MHz in FEL	1.42e11	6.66e12	3.5e12		8.32e12	3.4e12	6.17e11	6.98e12
HOM2 Q at 1497 MHz in FEL	4.04e11	3.29e12	9.36e12	6.10e12	2.92e12	2.56e12	3.78e12	3.00e11
Lorentz Force Coefficient (Hz//(MV/m)^2)		0.91	1.13		1.09	0.91	1.04	.99
Piezo range (Hz)	790	870	550	547	511	615	1190	655
Piezo Hysteresis, full range after cycle (Hz)	151	146	83	81	57	104	177	92

Summary of cryomodule testing and commissioning testing.





Cavity #	1	2	3	4	5	6	7	8
RMS amplitude (Hz)	1.5	1.1	1.0	1.1	0.6	0.8	1.5	1.3
6σ (Hz)	7.6	4.9	4.5	4.4	3.7	4.3	6.8	6.2

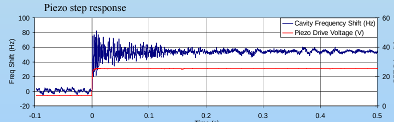
MICROPHONICS AND VIBRATIONAL MODES OF THE CAVITIES

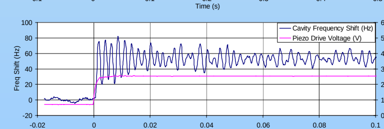
The vibration response of each cavity in the cryomodule was measured using the cavity resonance monitor instrument to characterize the detuning. The background microphonics level while operating at gradient is summarized in the table. The mechanical modes of each cavity was measured by applying a swept-frequency sinusoid drive to the tuner piezo-actuator. A similar swept-sine test was performed using amplitude modulation of the gradient, the resultant Lorentz pressure excites the mechanical modes. Although the general shapes of the curves are similar, it is not understood why the dynamic range of the amplitude response to Lorentz forces is compressed, as compared to the piezo response.

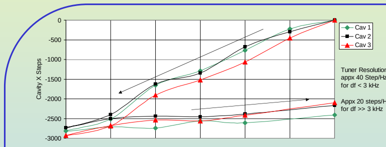
The piezo step response was measured, and correlates well with the swept sine response. Note the decaying exponential envelope in the time domain is dominated by 400 Hz component. This mode also dominated the swept sine measurement.

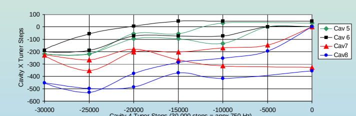
Research into the vibration response of CEBAF cryomodules is continuing. The latest upgrade cryomodule in production (Renascence) has four cryogenic accelerometers installed on one of the cavities. Using the piezo actuator as a driving source, these sensors are being used to measure the mode shapes and frequencies warm. We will measure the modes again at 2K for comparison. We also plan to compare the accelerometer measurements to RF modulation measurements in order to better understand the relationship between specific vibrational mode shapes and perturbations in the RF frequency of the cavity.

Piezo step response



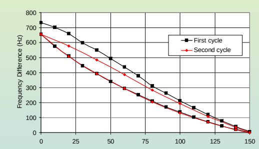






TUNER CROSS TALK BETWEEN CAVITIES

In order to reduce cost and increase the packing factor within the cryomodules, four cavities on each end of this cryomodule are hard coupled at the beam pipe with center position between cavities 4 and 5 fixed in relative to the space frame. The entrance and exit beam pipes for the cryomodule are coupled to the cavities with bellows. Deformation of one cavity by the tuner will cause the other cavities in that end of the cryomodule to become slightly detuned. The coupling was measured by operating 7 of the 8 cavities the cryomodule in CW with standard LLRF controls and running the cavity 4 with a VCO-PLL. The tuner on cavity 4 was operated manually and the shift in tuner positions on the other cavities was recorded. The coupling is about 10% for cavities within same end of the cryomodule and possibly as high as 1% in the cavities in the other end of the cryomodule. Thus in a worst case a cavity suddenly turning off will cause the adjacent cavities to detune approximately 10% of the bandwidth. The LLRF system and klystron power head room are sufficient to compensate for this while the mechanical tuners adjust the changed cavity's lengths.

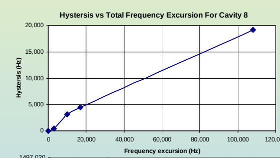


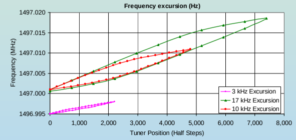
Piezo tuner voltage vs frequency difference from maximum for cavity 2. Note. Measurements were made in the order base measurement, then -500 steps, then +1000 steps.

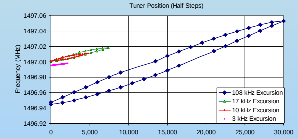
TUNER HYSTERESIS

In general this cryomodule has the lowest hysteresis and most stable tuners yet to be produced at Jefferson Lab. The hysteresis was measured for both the motor drive portion of the tuner and the piezo drive portion. The motor drive portion operates as expected with a moderate amount of hysteresis for long excursions and very small hysteresis for lesser excursions. When operated in the ranges of a few hundred hertz, which corresponds to the Lorentz force detuning, the tuner is almost free of hysteresis.

The Piezo tuner exhibited a behavior that was not expected. Frequently there was moderate offsets when the tuner was initially cycled. After the first cycle the hysteresis loop behaved as expected with a hysteresis on the order of a 10% of full range. The existence of an offset was correlated to whether or not the stepper motor had been moved substantially between piezo operations. This offset should not negatively impact the operability of the tuner and the behavior has not been investigated further since its initial discovery.







SUMMARY

The cryomodule was commissioned and successfully operated with an accelerating voltage of 80 MV which is the highest level for a CW cryomdule to date. The tuner has proven to be a robust, low hysteresis design that operates well with the pre-existing control hardware and software. Microphonics measured during operation were low in amplitude, with no large mechanical resonances at low frequencies where most the background excitation energy lies. Further characterization of the mechanical modes of the cavity/cryomodule structures and their interactions with the RF fields is presently in progress.

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