PERFORMANCE OF THE CORNELL MAIN LINAC PROTOTYPE CRYOMODULE FOR THE CBETA PROJECT*

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Abstract

The Cornell Main Linac Cryomodule (MLC) is a key component in the Cornell-BNL ERL Test Accelerator (CBETA) project, which is a 4-turn FFAG ERL under construction at Cornell University. The MLC houses six 7-cell SRF cavities with individual higher order-modes (HOMs) absorbers, cavity frequency tuners, and one magnet/BPM section. Here we present final results from the MLC cavity performance and report on the studies on the MLC HOMs, slow tuner, and microphonics.

INTRODUCTION

The Cornell-BNL ERL Test Accelerator (CBETA) is a collabolation project between BNL and Cornell to investigate eRHIC's non-scaling Fixed Field Alternating Gradient (NS-FFAG) optics and its multi-turn Energy Recovery Linac (ERL) by building a 4-turn, one-cryomodule ERL at Cornell (Fig. 1 top) [1, 2, 3]. CBETA will be built with many components that have been developed at Cornell under previous R&D programs for a hard x-ray ERL [4]. The main accelerator module, one of the key components for CBETA, will be the Cornell Main Linac Cryomodule (MLC) which will provide 36MeV energy gain for a single-turn beam of the CBETA. The MLC was built as a prototype for the Cornell hard x-ray ERL project and designed to operate in CW at 1.3GHz, 2ps bunch length, 100mA average current in each of the accelerating and decelerating beams, normalized emittance of 0.3mm- mrad, and energy ranging from 5GeV down to 10MeV, at which point the spent beam is directed to a beam stop [5]. In this paper, we report the performance test results of the MLC, such as cavity RF test, measurements and analysis of HOMs in the MLC cavities, slow tuner test, and micropohonics studies on the MLC.

MAIN LINAC CRYOMODULE PROTOTYPE

Figure 1 (bottom) shows an image of the Cornell ERL Main Linac Cryomodule (MLC) prototype. The design of the MLC for the Cornell ERL has been completed in 2012. It is 9.8 m long and houses six 1.3 GHz 7-cell superconducting cavities, three of them are stiffened cavities, another three are un-stiffened, with individual HOM beamline absorbers located between the cavities. Each cavity has a single 5kW coaxial RF input coupler, which transfers power from a solid-state RF power source
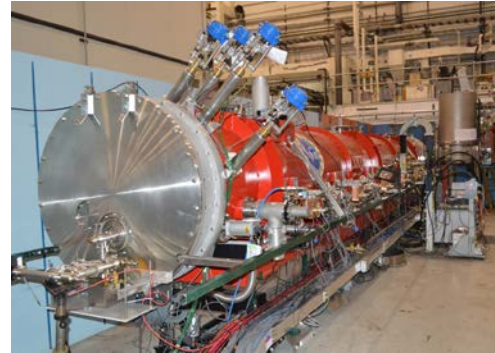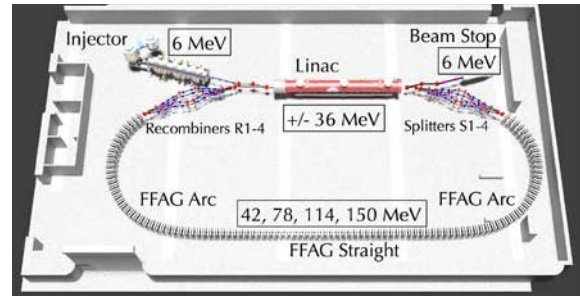
Figure1: The layout of CBETA project (top) and the MLC prototype (bottom).

to the cavity (the design Q_{ext} is 6.0×10^7). The MLC cavity surface preparation consists of bulk Buffered Chemical Polishing (BCP, 140μm), degassing (650degC, 4days), cavity frequency tuning, light BCP (10μm), low temperature baking (120degC, 48hrs), and HF rinse. The fabrication and testing of MLC components (cavity, high power input coupler, HOM dampers, tuners, etc.,) and assembly of the MLC cold mass have been completed in 2014 [6, 7, 8]. RF tests with different cool down conditions, including the first cool down, have been performed in 2015 [9].

RF tests of the MLC cavities

We performed one-by-one RF test of all six cavities at 1.8K after 1) the initial cooldown from room temperature [10], 2) a thermal cycle with "fast cool down" with cool down rates of ~36K/min., with large vertical spatial temperature gradient ($dT_{vertical}$) of 36K when the cavities passed the critical temperature T_c of niobium (9.2K), and 3) after a thermal cycle with "slow cool down" maintaining cool down rate of 0.23mK/min. on average, and a small horizontal spatial temperature gradient ($dT_{vertical}$) of 0.6K from 15K to 4K. The 7-cell cavities in the MLC on average have successfully achieved the specification values of 16.2MV/m with Q_0 of 2.0×10^{10} at 1.8K. Figure 2 summarizes the maximum field gradient performance and the cavity quality factor Q_0 (1.8K) of the MLC cavities.
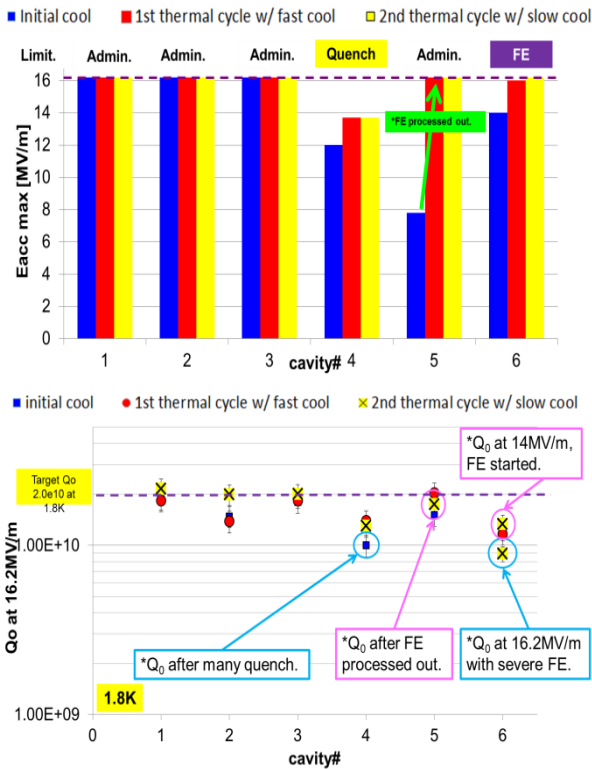
Figure 2: Summary of the performance of the MLC cavities.

Our results show that a slow cool down with small $dT_{vertical}$ gave the highest Q_0 for the 7-cell cavities in the MLC prototype. The benefit of slow cool down with smaller dT on the MLC is likely due to a reduction of thermal-currents and their induced magnetic fields. A fast cool with large $dT_{vertical}$ showed no clear impact on the MLC cavity performances. This might be caused by two competing effects. The first one is that the larger $dT_{vertical}$ during fast cool down were beneficial for efficient magnetic field expulsion, which by itself would result in a reduction of R_{res} of the cavities. The second effect however is the increased $dT_{horizontal}$ during fast cool, which by itself would give increased thermo-currents and thus larger R_{res} of the cavities. These two aspects partly compensate each other; and for the MLC cavities, no net impact on cavity Q_0 was seen. It should be noted that a different surface preparation (e.g. nitrogen doping) than what was used for the MLC cavities, can shift the relative balance between the two competing effects, and therefore some cavities can instead show optimal performance after fast cool down.

MLC HOM SCANS AND ANALYSIS

Figure 3 (left) shows a cross section view of the production version of the Cornell HOM absorber, the absorbing material is Silicon Carbide, SC-35® from Coorstek [11].
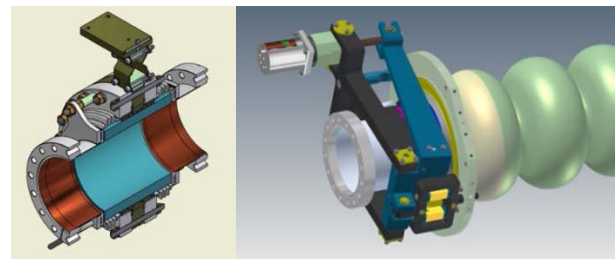

Figure 3: Cornell's HOM beamline absorber used in the MLC (left), 3D image of the MLC cavity tuner (right).

Figure 4 shows a comparison of the measured and simulated HOM loaded quality factors (Q_L). The measurements were done with a S21 Network analyser at cavity temperature of 1.8K. The scanned frequency range was 1.5GHz to 6GHz with a frequency step (df) of 125Hz. For the simulation, we used a full cavity model without the coupler and field probe ports. Without ports, it is axially symmetric and we used the 2D electromagnetic solver CLANS [12] for simulation of monopole modes and CLANS2 [13] for simulation of multipole modes.
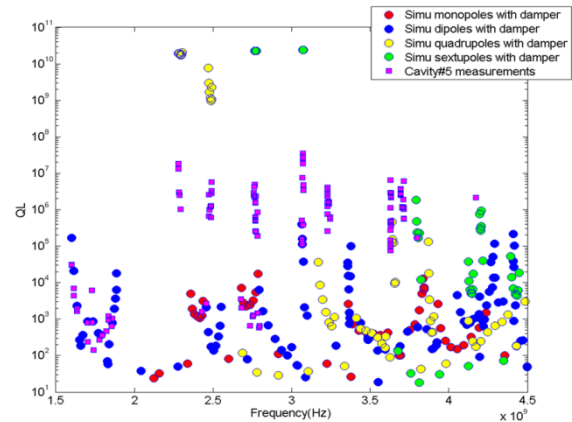

Figure 4: Comparison of MLC HOMs measurement results (cavity#5) and HOM damping simulation results.

The comparison indicates 1) scanned HOM frequencies agreed well with simulation results, 2) Q_L of dipole HOMs of the MLC cavities are strongly damped below the target value of $\sim 10^4$, and 3) the higher Q modes measured in the MLC are very likely from quadrupole and sextuple modes, as their frequencies line up very well with the simulated frequency bands for these modes, and high Q is expected for these. These mode types are not a concern for causing BBU. The results shown in Figure 4 also agree well with those from a previous HOM study on a prototype 7-cell cavity, which was an un-stiffened cavity in the Horizontal Test Cryomodule (HTC) [14]. The results of HOM absorbers test with high current (40mA) beam in the HTC can be found in reference [15, 16].

MLC SLOW TUNER TEST

Figure 3 (right) shows a 3D model of the MLC cavity tuner assembly attached to the helium tank flange. The design is based on a Sacray I tuner [17, 18, 19]. The slow tuner for a coarse tuning with a range of ~600kHz worked

as designed and tuned cavities to resonance at 1.8K (Fig. 5). Piezoelectric fast tuner for a fine tuning with range of ~1kHz will be tested for the future.
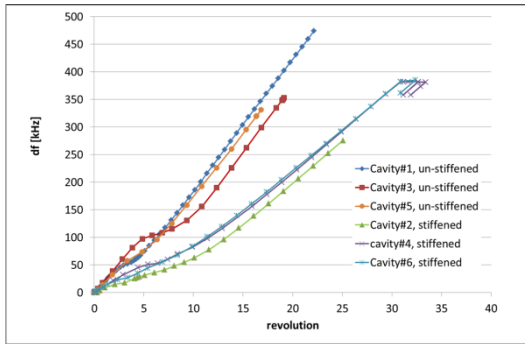

Figure 5: Tuning range vs. tuner screw revolution

MICROPHONICS MEASUREMENTS AND ANALYSIS

The initial microphonics measurements were carried out at the accelerating field gradient of ~1.3MV/m, 1.8K after tuning the MLC cavities to the resonance of 1.3GHz [20]. Figure 6 shows a histogram of the sampled detuning events of MLC cavities to compare the microphonics level in the individual cavities. The average peak detuning of the three unstiffened cavities is about 100Hz, which is 2.5 times larger than for the three stiffened cavities (~40Hz).
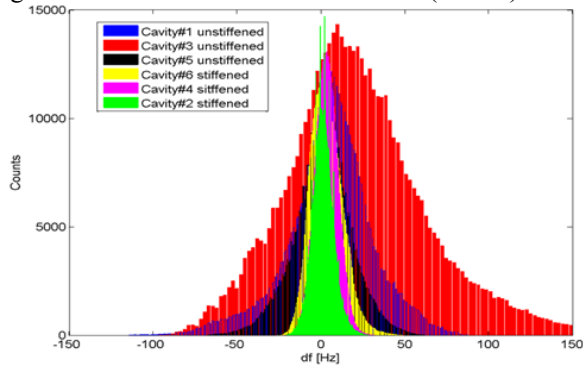

Figure 6: Histogram of the sampled detuning events of each cavity.

During an investigation of the microphonics sources, some important contributors we noticed are the 2K pumping skid and the insulation vacuum pump as summarized in Fig.7. Fig. 7(a) shows the microphonics spectra with strong excitations near 30Hz, 60Hz, 90Hz, etc. without optimization and compensation. Fig. 7(b) shows that the microphonics at 30Hz and 90Hz have been reduced when the 2K pump skids were turned off and the flow rate in 80K line was reduced. Fig 7(c) shows that when the insulation vacuum pump was closed, the microphonics at 60Hz was decreased. It has to be pointed out that the measurements were done in a "mechanically noisy" environment and without applying fast tuner compensation. Further optimization on the MLC cooling scheme and compensation of microphonics with piezoelectric fast tuner are planned for the future.
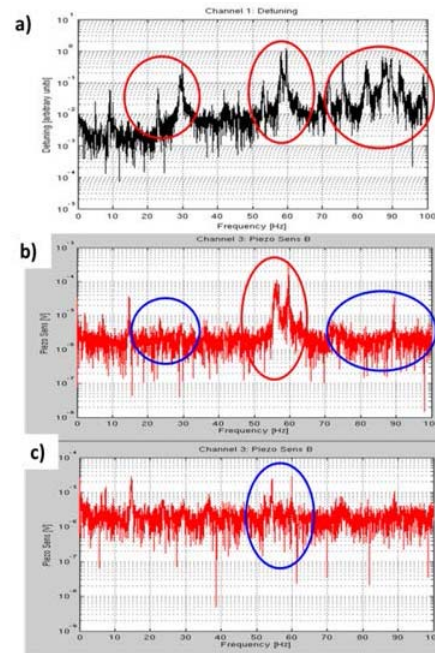

Figure 7: Results of microphonics sources analysis.

The maximum energy gain of the MLC with the current microphonics levels has been calculated (Fig. 8) [20]. The loaded-Q of the cavities could be further reduced to Q_L ~2×10^7 using a 3 stub waveguide tuner to increase the maximum possible energy gain. Here R/Q=774Ω, $Q_0=2\times10^{10}$. It requires ~3kW RF power per cavity to provide the nominal 36MeV energy gain with Q_L ~6×10^7; while ~2kW would be sufficient with reduced Q_L. current Solid state
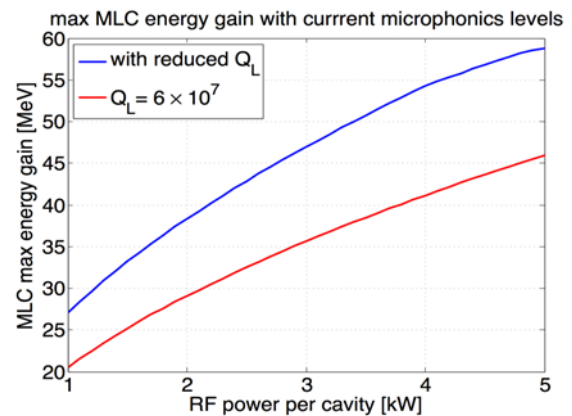

Figure 8: Maximum total energy gain of the MLC versus RF power available per cavity, assuming current microphonics levels.

SUMMARY

The 7-cell cavities in the MLC can provide enough voltage and cooling for 76MeV per ERL turn. HOM dampers and slow tuners work as designed. Piezoelectric fast tuner test is planned for the future. The nominal energy gain of 36 MeV per pass for the CBETA project may be reached with the available RF power at the current level of microphonics. The MLC is now qualified for the CBETA project.

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