ERL CRYOMODULE TESTING AND BEAM CAPABILITIES*

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Abstract

The main linac cryomodule (MLC) prototype is a key component for the Cornell-BNL ERL Test Accelerator (CBETA) project, which is a 4-turn FFAG ERL under construction at Cornell University. This novel cryomodule is the first SRF module ever to be fully optimized simultaneously for high efficient SRF cavity operation and for supporting very high CW beam currents. Initial MLC testing has demonstrated that cavity performance and HOMs damping meet specification values. Recent, additional tests have focused on RF field stability, and cavity microphonics. In this paper, we summarize the performance of this novel ERL cryomodule and evaluate its beam capabilities based on the measured performance.

INTRODUCTION

The Cornell-BNL ERL Test Accelerator (CBETA) is a collaboration 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) [1-3]. CBETA will be built in the L0E area of Wilson lab at Cornell 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 beam energy gain per pass through the MLC. The MLC was built as a prototype for the Cornell hard x-ray ERL project and designed to operate in CW at 1.3GHz with 2ps bunch length, normalized emittance of 0.3mm-mrad, and 100mA average current in each of the accelerating and decelerating beams [5]. In this paper, we report on the performance test results of the MLC, such as cavity RF test, slow tuner test, microphonics studies on the MLC cavities, and initial beam test through the MLC.

MAIN LINAC CRYOMODULE PROTOTYPE

Figure 1 (bottom) shows an image of the Main Linac Cryomodule prototype in its final location for the CBETA ring. The design of the MLC for the Cornell ERL had been completed in 2012. It is 9.8m long and houses six 1.3GHz 7-cell superconducting cavities. Three of them are stiffened cavities, and another three are un-stiffened, with individual HOM beamline absorbers located between the cavities. Each cavity has a single 10kW coaxial RF input coupler, which transfers power from a solid-state RF power source to the cavity (the designed Q_{ext} is $6.5x10^7$). The fabrication and testing of MLC components (cavity, high power input coupler, HOM dampers, tuners, etc.,) and assembly of the MLC cold mass had been completed from 2013 to 2014 [6-8]. The MLC was moved into the South-West area of L0E in early 2015 for an initial RF test. Initial cooldown, RF tests, and LLRF test have been performed in 2015 and 2016 [9-11].

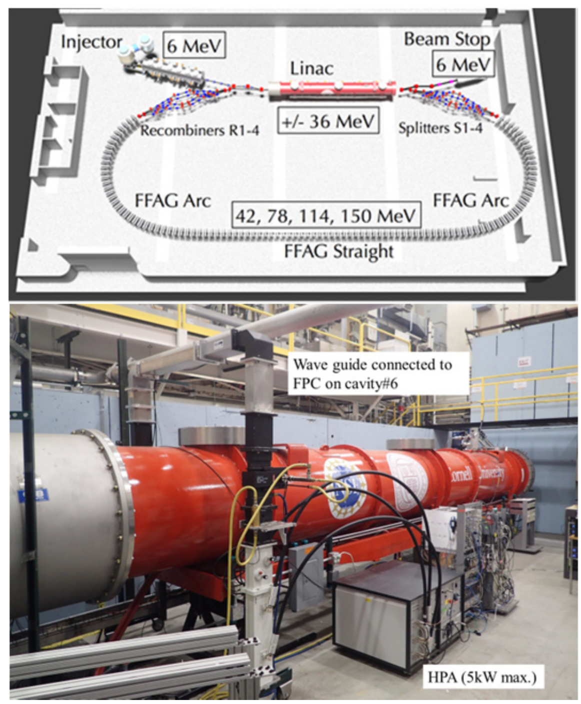

Figure 1: The layout of CBETA project at Cornell (top); the MLC prototype in its final location (bottom).

RF Tests of the MLC Cavities

We performed one-by-one RF tests of all six cavities at 1.8K after different cool down conditions. The 7-cell cavities in the MLC on average have achieved successfully the specification values of 16.2MV/m with Q_0 of $2.0x10^{10}$ at 1.8K. Figure 2 summarizes the maximum field gradient performance and the cavity quality factor Q_0 (1.8K) of the MLC cavities after the thermal cycles and RF processing. The MLC can provide 76MeV energy gain per ERL turn, which significantly exceeds the CBETA requirement of 36MeV per ERL turn.

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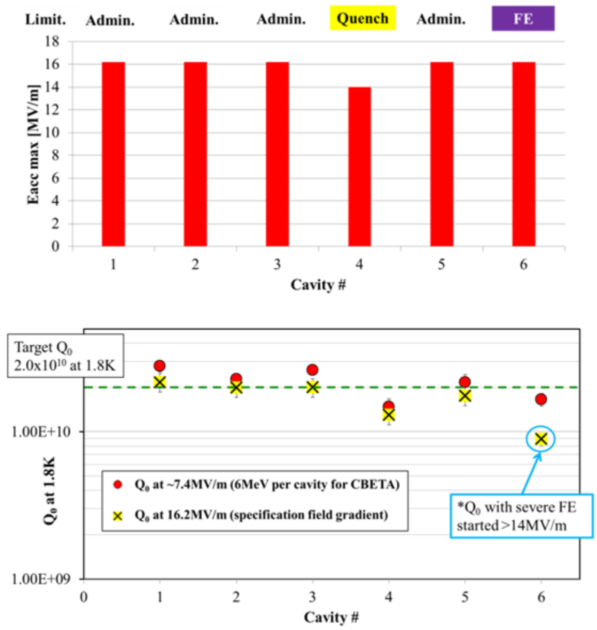

Figure 2: Summary of the performance of the MLC cavities at 1.8K. Top: Maximum fields (primarily administratively limited to 16.2 MV/m). Bottom: Intrinsic quality factors at 1.8K.

MLC SLOW TUNER TEST

The design of the MLC cavity tuner assembly is based on the Sacray I tuner [12-14]. The slow tuner with a coarse tuning range of ~600kHz worked as designed and was used to tune the cavities on resonance at 1.8K (Fig. 3). Two of the six MLC cavities reached the mechanical limit of the slow tuner screw revolution below the target frequency of 1.3GHz (cavity#4; -4kHz off, cavity#6; -60kHz off). Therefore, CBETA operation will be at 1.299940 GHz. Testing of the piezoelectric fast tuner with a fine tuning range of ~1kHz has also started, and Lorentz-force detuning as well as slow cavity frequency changes were compensated successfully.

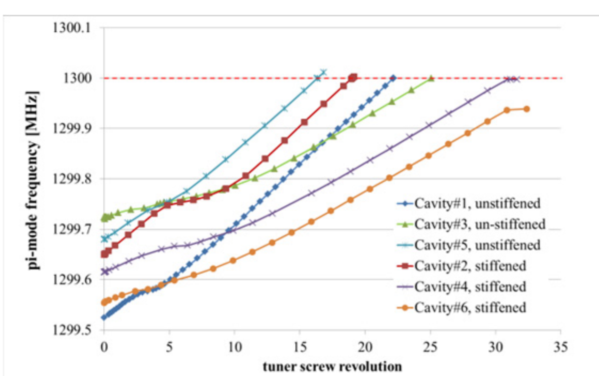

Figure 3: MLC cavity resonance frequency at 1.8K vs. tuner screw revolution

INITIAL MICROPHONICS MEASUREMENTS AND ANALYSIS

The initial microphonics measurements were carried out at an accelerating field gradient of ~1.3MV/m, 1.8K after tuning the MLC cavities to resonance at 1.3GHz [11]. Figure 4 shows a histogram of the sampled detuning events of the MLC cavities to compare the microphonics level in the individual cavities. Average peak detuning of the three stiffened cavities was about 40Hz, and that of un-stiffened cavities was about 100Hz during the initial test. Investigation of the microphonics sources found that dominant vibration contributions were due to the 2K pumping skid and the insulation vacuum pump. It has to be pointed out that these initial microphonics measurements were done in a "mechanically noisy" environment without any optimizations against sources or without applying fast tuner compensation. Further optimization of the MLC cooling scheme and compensation of microphonics with piezoelectric fast tuner are in progress [15].

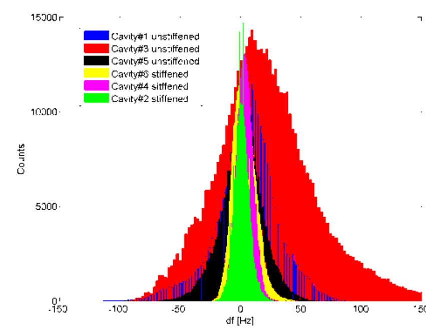

Figure 4: Histogram of the sampled detuning events of each cavity at initial MLC test location.

RF POWER REQUIREMENT

The maximum energy gain of the MLC with the measured initial microphonics levels has been calculated (Fig. 5) [11]. The designed loaded-Q of ~$6x10^7$ of the MLC cavities requires ~3kW peak RF power per cavity to provide the nominal 36MeV energy gain per ERL turn. Q_L could be reduced to ~$2x10^7$ using a 3 stub waveguide tuner to increase the maximum possible energy gain or reduce the required peak power to ~2kW . Based on these calculations and making allowance for the higher microphonics levels of the un-stiffened cavities, three 5kW solid state RF amplifiers (SSAs) for stiffened cavities and three 10kW SSAs for the un-stiffened cavities were selected to be ordered.

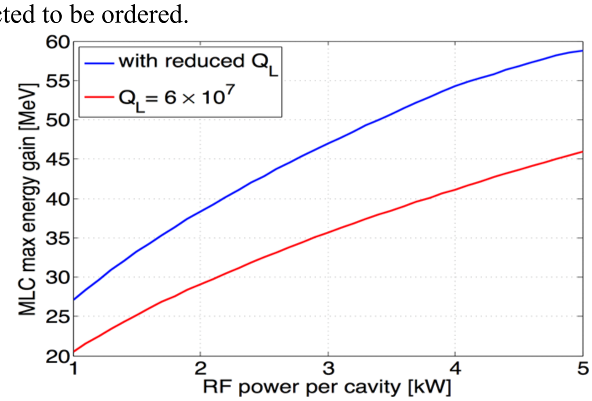

Figure 5: Maximum total energy gain of the MLC versus RF power available per cavity, assuming initial peak microphonics levels.

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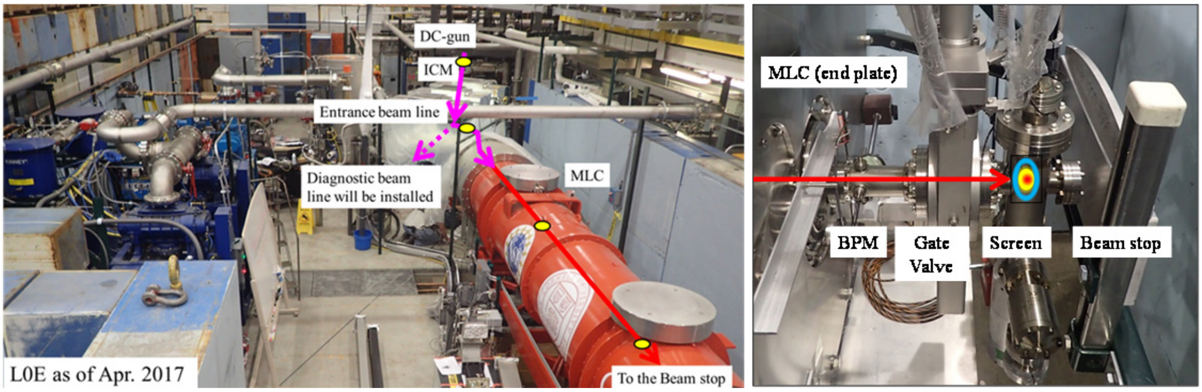

Figure 6: MLC at its final location (left); beam stop assembly (right).

INITIAL BEAM TEST THROUGH MLC

The MLC was warmed up to room temperature and moved to its final location for the CBETA ring in February 2017 (Fig. 1; bottom). 2nd cool down to 4K was successfully performed. The Cornell ERL high voltage DC gun and Injector Cryomodule (ICM, operation temperature is 2K) were connected to the MLC via the entry beam line; the beam stop assembly was also installed as the exit line (Fig. 6). MLC was cooled down to 1.8K prior to initial beam test. Initial beam test has launched in May 2017. The first beam with an energy of 6MeV was passed through the MLC on May 4th, 2017, without active acceleration in the MLC at that moment. The preliminary result is shown in Fig. 7 (left), comparing the beam image on a beam monitor screen at the beam stop with simulation (Fig. 7, right). After stabilization of the RF field of cavity #2 via the LLRF system with active detuning compensation using the piezoelectric tuner, a beam with an energy gain of 12MeV (6MeV from the ICM plus 6MeV from cavity #2 in the MLC) was transported through the MCL on May 15, 2017. Future progress and more details will be reported during coming conferences.

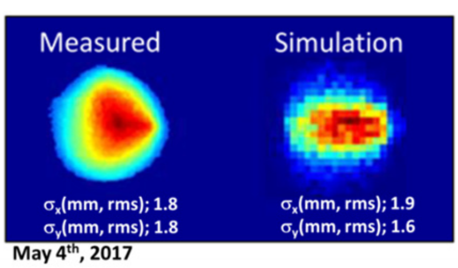

Figure 7: Image of the initial beam through the MLC with 6MeV. Beam operation and images by Adam Bartnik.

MICROPHONICS MEASUREMENT IN FINAL LOCATION

Measurements of the microphonics levels in final location have started. The preliminary result from cavity#5 is shown in Fig. 8. More microphonics measurements and studies on an active compensation with the piezoelectric fast tuner are in progress [15].

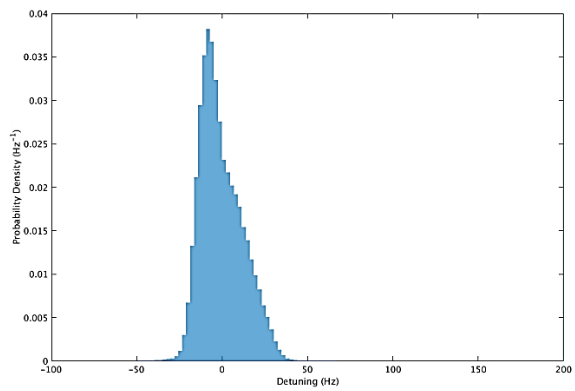

Figure 8: Histogram of the sampled detuning events of MLC cavity#5 at the final MLC location.

SUMMARY

The 7-cell cavities in the MLC can provide an energy gain of up to 76MeV per ERL turn. The nominal energy gain of 36 MeV per pass for the CBETA project may be reached with the available RF power at the measured initial microphonics levels. The MLC was moved to its final location and cooled down to 1.8K again. Preliminary detuning measurement on cavity#5 (un-stiffened) was performed. After stabilizing the RF field of cavity #2, including active detuning compensation using the piezoelectric tuner, a beam with a total energy gain of 12MeV was transported through the MCL, reaching the defined goal for the initial CBETA beam test. The authors thank the entire Cornell ERL team for their tremendous work allowing to achieve this important milestone.

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