First results from the Cornell high Q cw full linac cryo-module

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Abstract. Cornell University has finished building a 10 m long superconducting accelerator module as a prototype of the main linac of a proposed ERL facility. This module houses 6 superconducting cavities - operated at 1.8 K in continuous wave (CW) mode - with individual HOM absorbers and one magnet/ BPM section. In pushing the limits, a high quality factor of the cavities (2•10^10) and high beam currents (100 mA accelerated plus 100 mA decelerated) were targeted. The design of the cryomodule and the results of components tested before assembly will be presented in this paper.

1. Introduction
Energy-Recovery Linacs (ERLs) can provide beams with high currents, small emittances, and low energy spread. The current can be as large as typically in rings, 100mA in the case of Cornell’s x-ray ERL, while the emittances and the energy spread can stay as small as only possible in linacs. While the current limit for conventional linacs is determined by the available acceleration power, ERLs recapture the energy of the spent beam and the current then becomes limited by other effects like higher order mode (HOM) heating and beam-break up (BBU). Cornell University has started an extensive R&D program to address these questions and proposed an ERL as a driver for hard x-ray sources [1].

Figure 1. Rendered 3-D CAD model of Cornell’s Main linac cryo-module. The 11 m long module houses six 7-cell cavities (1.3 GHz, optimized for high BBU thresholds).

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One part of that R&D program was building a linac cryo-module, based on 1.3 GHz cavities, optimized for a high BBU-limit and good HOM damping, with extraordinary high quality factors to reduce operating cost. This module, shown in fig.1, has been completed recently which allows us to highlight our findings within this paper.

2. Concept of the module
The Main Linac Cryomodule (MLC) prototype houses six superconducting 7-cell cavities and has an overall length of 10 m. The cavities were optimized in shape to have a high beam-break-up (BBU) limit for the beam current. Due to the high beam current combined with the short bunch operation, a careful control and efficient damping of the HOMs is essential. As we expect an average of 200 W of higher order mode (HOM) power per cavity, HOM beam line absorbers are placed between the cavities, damping the RF by absorption.

Our design has been guided by the ILC Cryomodule while necessary modifications have been made to allow CW operation. In addition, we decided to align all components inside the module by reference surfaces on the helium gas return pipe (HGRP). As a consequence, the cold-mass as a whole will shrink during cool-down, requiring the power couplers to flex, too.

The cryogenic scheme of the module is shown in figure 2, which also indicates the choices we had made: we have decided to omit the 5 K thermal shield, but have active intercept cooling of the beam pipes and the couplers. The 80 K circuit actively cools the thermal shield, the intercepts on the couplers and cools the HOM absorbers. The concept allows an individual cool-down of the module, with two cool-down lines per cavity located symmetrically near the cavity end to avoid thermocurrent excitation[2].

There are more comprehensive details on the design in [3-6].

Figure 2. Cryogenic scheme of the MLC. Cool-down is achieved individually per module, every cavity is fed by two cool-down lines connecting symmetrically to avoid excitation of thermocurrents. The intercept cooling at 5 K and 80 K is provided by parallel flows.

3. Parallel Flows
As indicated in figure 2 the module relies on active cooling provided by parallel cryogenic flows. We have investigated the challenges associated with that in the past [7,8]. For the MLC a more careful analysis was required for the 80 K circuit, where the coolant first cools the intercept of the power coupler.
Figure 3. Parameter studies performed to calculate the behaviour of the parallel flow channels under different conditions. On the left we depicted the model used, the diagram in the middle shows the mass-flow ratio with increased heat load on one branch (the other is kept at 200 W) with and without an inlet impedance. On the right the impact of the heat load and the inner diameter of the inlet impedance tube influence the mass flow ratio.

and then HOM absorber. Six streams exist in parallel, with a seventh stream only feeding one HOM absorber. While the heat load on the coupler, predicted by a simulation, is 10-15 W, the heat load of on the HOM absorber is- by the nature of the higher order mode power- a statistical quantity, and the expectation range is from 0 to 400 W. As a consequence, a flow with no HOM power parallel to a flow with 400 W heat load would be highly imbalanced.

The analytical model (based on a configuration as depicted in figure 3 on the left) we set up investigated the stability of the parallel under the variation of the heat load on one branch while the heat-load on the other branch remained constant at 200 W. As can be seen by the middle plot of figure 3, adding an inlet impedance on every branch can significantly reduce the change in the mass flow ratio between the channels under variation of the heat load. This non linear behaviour is also described by figure 3, right plot, where a parameter study was made investigating the influence of the pipe diameter on the stability of the system.

4. Cavity Production
For the cavities, a 7-cell, 1.3 GHz design was made while an envisaged Q of $2 \times 10^{10}$ was targeted at a gradient of 16 MV/m. All 6 cavities for the MLC module have been produced in-house starting from

Figure 4. Quality factors of the 6 cavities built for the MLC, measured at 1.8 K. All cavities performed above specification with no retreatment being necessary.  

Figure 5. Q versus E curve of cavity ERL 7-3 at different temperatures. Results for the other cavities were similar.
flat metal niobium sheets. To investigate microphonics, we decided to build 3 unstiffened cavities as well as 3 cavities with stiffening rings. All cavities were tested vertically, the summary of these test are given in figure 4 and 5. All six cavities exceeded the design quality factor, averaging to 2.9*10¹⁰ at 1.8K. At 2 K, the average Q was 1.8*10¹⁰, at 1.6 K we found 4.3*10¹⁰[9]. It should be noted that the Q we measured on the prototype cavity at 1.8 K was 2.5 *10¹⁰ in the vertical test, but 6*10¹⁰ in the horizontal test where magnetic shielding is more efficient [10]. The reproducibility of the Q versus E curves for all cavities is remarkable, also the fact that none of the cavities needed additional processing- giving a 100 % yield.

5. Higher Order Mode Absorber
For the MLC, the design of the HOM absorber has been finalized and 7 full assemblies were built [11]. Figure 6 shows an isometric view of the Cornell HOM Absorber and a picture taken during string assembly inside the clean room. The centre assembly consists of the absorbing cylinder, which is shrink fit into titanium cooling jacket and flange. The cooling jacket and flange locate, support, and provide cooling at 80 K to the absorbing cylinder using a cooling channel inside the titanium. The absorbing material is Silicon Carbide, SC-35® from Coorstek.

Initial reservations against the material could be cleared up: After a careful cleaning we did not see particle generation during the mounting procedure. In addition, no Q degradation of the cavity mounted next to the absorber in a horizontal test cryo-module was observed. We ran a 25 mA beam through the absorbers, in particular defocussed and off axis, and saw no charge-up of the material[9].

6. RF Power couplers
The ERL main linac input couplers deliver up to 5 kW CW RF power to the cavities. At this CW power level, active cooling (by air) of the inner conductor is required. The design of the ERL main linac coupler is based on the TTF-III and Cornell ERL injector couplers. For simplicity reasons the input coupler has a fixed coupling with a nominal external Q of 6.5*10⁷. Two sets of bellows are placed on the warm portion of the coupler, on both the inner and outer conductor, to allow for significant lateral motion of the cavities during cool down (being 10 mm for the outmost cavity) while keeping the cold antenna fixed relative to the cavity coupler port.

All couplers have been procured at CPI and were tested upon receiving on a test stand, applying 5 kW CW RF power under full reflection without seeing any vacuum action. Essentially, no conditioning was required to reach this power level. Figure 7 shows the layout of the coupler, testing data is given in figure 8.
7. Alignment

The alignment concept of the cryomodule relies on the helium gas return pipe, a 30 cm ID titanium pipe, acting as a strong-back of the module. Suspended by 3 composite post assemblies from the outer vessel, it provides precision surfaces for all cavity mounts and beam line components, as can be seen in figure 9. The position of these surfaces where surveyed upon receiving the pipe, displaying larger than the specified +/- 1 mm accuracy. However, when preloaded with the approximate weight of the cold-mass alignment was within specs. This data is given in figure 10. The sagging on the right end of the module will be hindered in a module string by the support of the adjacent module.

![Figure 9. Assembly frame, supporting the HGRP which acts as a strongback for all beam line components, hung under the precision machined mounting feet.](image)

![Figure 10. Vertical position of the reference surfaces on the helium gas return pipe defining the positions of all beam line components. In a module string, the right end will receive more support resulting in a better vertical positioning.](image)

**Figure 8.** Typical testing results of the couplers, measured on a test-stand before the coupler was mounted to the string. Top curve shows the RF power as being ramped up, the curve below is the coupler vacuum, rising to \(2 \times 10^{-8}\) torr while the cavity vacuum (bottom curve) is only slightly affected.
8. Assembly Process
While production of components started earlier, the virtual assembly began in March 2014, when the first cavities were connected to a string inside the cleanroom. For space reasons, two half strings, consisting of three cavities with attached cold section of the coupler and 4 HOM absorbers as well as a gate valve were assembled. Each substring was leak checked and connected to the other later on. In May, cold mass assembly continued outside the cleanroom. Mating the pre-aligned cavity string with the precision surfaces on the HGRP strong-back turned out to be not an issue at all. All bellows located at the HOM absorber package were able to compensate for deviations and only the longitudinal position of one HOM absorber had to be adjusted.

Installation of the cavity magnetic shield, the tuner, the thermal and magnetic shield, all cryogenic piping and jumpers, instrumentation and cabling as well as a wire position monitor to track alignment during cool-down took 3 months. After a minor modification of the wheel, supporting the cold-mass on our rail system we were able to slide it into the vacuum vessel in September.

As final assembly steps we installed the warm portion of the couplers, feed-throughs and cryogenic valves. All circuits were leak checked and pressure tested. In November, the team could celebrate the completion of the module, which was achieved within time and budget.

9. Preparation for Testing
In preparation for the testing of the MLC, the module was transported across the Cornell campus. No special damping frame was used. However, all movements were done with extreme care and

![Figure 11. Accelerometer data taken during the transportation of the cryo-module across the campus.](image)
transportation speed was set to 5 km/h max. In addition, we measured mechanical shocks using accelerometers. The data, given in figure 11, revealed a maximum g force of 2.3 (lasting less than 10 ms), which occurred while pulling the module (sitting on its own wheels) in place after lifting it from the truck. During the road trip, max g-factors were below 1.5.

As of May 2015, preparations continue for the first cool-down being scheduled for July.

10. Acknowledgments
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