Status of the Cornell ERL Injector Cryomodule*

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Abstract

Cornell University is developing and fabricating a SRF injector cryomodule for the acceleration of the high current (100 mA) beam in the Cornell ERL prototype and ERL light source. Major challenges include emittance preservation of the low energy, ultra low emittance beam, cw cavity operation, and strong HOM damping with efficient HOM power extraction. Axial symmetry of HOM absorbers, together with two symmetrically placed input couplers per cavity, avoid transverse on-axis fields, which would cause emittance growth. Fabrication of five 2-cell niobium cavities and coaxial blade tuners, ten twin high power input couplers, and six beam line HOM absorbers has finished. The injector cryomodule is presently under assembly at Cornell University with beam test planned for early 2008. In this paper we report on the cryomodule fabrication and assembly status.

INTRODUCTION

Cornell University's Laboratory for Accelerator based Sciences and Education (CLASSE) is exploring the potential of a x-ray light source based on the Energy-Recovery-Linac (ERL) principle [1]. This type of light source promises superior X-ray performance as compared to conventional third generation light sources [2], but several accelerator physics and technology challenges need to be addressed before a full energy ERL light source can be built. These challenges result primarily from the high current, ultra low emittance beam required at the undulator locations beyond the main linac. As a first and crucial step, Cornell has launched an extensive R&D program to study and demonstrate the production and preservation of the ultra-low emittance beam in the ERL injector. A prototype of the injector is presently under construction at Cornell, and first beam in the full injector is expected for 2008 [3].

One of the most challenging components in the injector is its cryomodule hosting five superconducting (SC) 2-cell cavities. In CW operation, the cavities not only have to transfer a total power of 500 kW to the beam, but also have to do so without destroying its ultra-low emittance. These requirements together with a high beam current of up to 100 mA and short bunch lengths of less then 600 μm put high demands on the superconducting cavities, the Higher-Order-Mode (HOM) damping scheme, the RF input couplers, and the cryovessel itself. Table 1 summarizes critical ERL injector beam parameter goals. Solutions to all these challenges have been found [4], and prototypes of all beam line components (SRF cavities, HOM loads, input couplers, and frequency tuners) have been fabricated and tested individually. Recently, a one cavity horizontal test cryostat (HTC) has been assembled and tested successfully at Cornell. The HTC follows the same design as the full injector cryostat, but hosts one cavity with two HOM loads only instead of five cavities with six HOM loads.

In the following we report on the performance of the individual beam line components, summarize results from the HTC assembly and its test, as well as discuss the status of the full injector module assembly.

Table 1: ERL injector beam parameters.

Parameter	
Energy	5 - 15 MeV
Beam current	100 mA at 5 MeV
Beam current	33 mA at 15 MeV
Norm. emittance	0.1 - 1 mm mrad
Beam power	500 kW, cw
Bunch length	0.6 mm (2 ps)

BEAM LINE COMPONENTS

All components of the SRF injector module have been fabricated, and tested individually. The injector beam line string consists out of the following main components:

SRF Cavities: Five superconducting RF cavities will provide 5 to 15 MV/m of field gradient (1 to 3 MeV energy gain per 2-cell cavity) to the beam. Twin input couplers per cavity result in zero transverse fields on the beam axis, which is essential to preserve the ultra-low beam emittance. A prototype 1.3 GHz 2-cell ERL injector cavity [5] has been fabricated in house, tested vertically and equipped with a He-vessel. After the successful vertical test of the first prototype, five more 2-cell cavities have been built and tested successfully at Cornell. Refer to [6] for details about the cavity fabrication and test. All cavities performed satisfactory in vertical acceptance tests, reaching intrinsic quality factors above $Q_0 = 10^{10}$ and accelerating fields above 15 MV/m. A multipacting barrier was found in the large beam pipe at lower fields (3 to 7 MV/m), in correspondence with multipacting simulations [6], which could be processed easily within a few minutes.

HOM Loads: HOM loads are placed at an elevated cryogenic temperature (80K) between all SRF cavities for aggressive HOM damping of HOMs excited by the high beam current with short bunches. An axial symmetric

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layout minimizes transverse emittance growth. Two Cornell ERL prototype HOM loads have been fabricated in house and have be used in the HTC test [7]. A combination of three different RF absorbing materials (two ferrite types and one ceramic) is used to guarantee efficient RF absorption starting from low frequency to 100 GHz, as required by the high beam current and short bunch length [8]. Reliable parameters have been developed for the soldering and brazing of the absorber materials to thermally matched metals. Additional HOM loads for the full injector cryomodule have been fabricated by industry. All of these production HOM loads have been cooled down to 80 K at a cool-down rate of about 30 K per hour without showing any potential problems from thermal stresses.

Input Couplers: Each input coupler needs to couple up to 50 kW of RF power to the beam. Two prototype Cornell ERL CW 1.3 GHz input couplers have been fabricated by industry and have been high power tested at Cornell. The specified maximum RF power of 50 kW was reached in CW operation, but insufficient cooling of some coupler sections was found [9]. The coupler design was modified to increase cooling of these sections, and 10 couplers of the improved design have been fabricated by industry. Two of these couplers have been tested at high power and did exceed specifications without showing excessive heating.

Frequency Tuner: The frequency tuner for the 2-cell ERL injector cavities has been adopted from the DESY/INFN blade tuner design [10]. Short piezo-electric actuators have been integrated in the frequency tuner mechanism to allow for fast microphonics compensation. In addition, the tuner mount has been redesigned for easy exchange of the motor/harmonic drive assembly while the cavity string is installed in the vacuum vessel. In the Cornell ERL cryomodule, the tuner motor can be accessed through ports in the vacuum vessel and shields to allow for replacement in case of a motor failure. Six blade tuners have been fabricated by industry.

CRYOMODULE DESIGN

The ERL injector module and the horizontal test module design is based on the well established TTF cryomodule [11], with beam line components supported from a large diameter helium gas return pipe and all cryogenic piping located inside the module. Although this cryomodule concept has primarily been optimized for longer superconducting linacs, it has been chosen here for the short injector SRF section so that it also can serve as a prototype for the cryomodules in the long ERL main linac. The TTF type module design was significantly redesigned to fulfill ERL specific requirements and to include several innovations (see also Figure 1, Figure 2 and Table 2):

- CW cavity operation results in high 2K cryogenic loads of up to 5 W per 2-cell cavity. The 2K-2-phase line diameter has been increased to 10 cm to support high loads.
- A high cavity quality factor Q_0 is important for efficient CW cavity operation. Three layers of magnetic shield (two around the individual cavities and a third on top of the 80K thermal shield) give effective shielding of external magnetic fields to support high Q_0 cavity operation.
- The power dissipation at the cold HOM loads and the cold part of the high power input couplers can not be intercepted by thermal conduction through copper braids. Direct gas cooling of chosen 5K and 80 K intercept points with He-gas flow through small heat exchangers is used in the Cornell ERL cryomodule. The 5K and 80K He-gas is supplied via large pipes and distributed to the individual heat exchangers at the HOM loads and input couplers through 1/4” tubing.
- The cryomodule design has been simplified by using only one layer of thermal shield (at 80K). A 5K shield is of less importance in CW SRF cryomodules, since the high dynamic loads dominate over static loads.
- The cavities and HOM loads are supported via fixed (i.e. non-sliding) supports to Helium-Gas-Return-Pipe (HGRP) sections made out of Titanium. The HGRP sections are connected by bellows. The fixed support uses precise machined surfaces and alignment fiducials. This does not only simplify attaching the beam line to the HGRP, but also makes any final cavity alignment at this stage obsolete, resulting in a stiff and well aligned cavity string.
- The alignment bolts at the HGRP support posts are accessible even while the module is cold. This allows for beam based fine alignment of the cavities, which are mounted to the short HGRP sections, while the cryomodule is cold.
- New short module end sections without He reservoir give short cold-warm transitions at the module ends. This is essential especially in the ERL injector, where the distance between the photo-emission DC gun and the first SRF cavity needs to be minimized. The beam line has one gate-valve on each module end, which is located inside of the module with its drive unit outside of the module. This way no external gate vales are required at the module ends.
- Access ports in the vacuum vessel allow for easy replacement of the tuner stepper motor units after the cryomodule has been warmed up in case of a motor failure, without the need to move the cold mass out of the vacuum vessel.
- A rail system inside the vacuum vessel is used to insert the cold mass into the vessel.
- An in-situ bake of warm coupler parts can be done after the warm coupler sections have been installed. This minimizes the required coupler conditioning time.

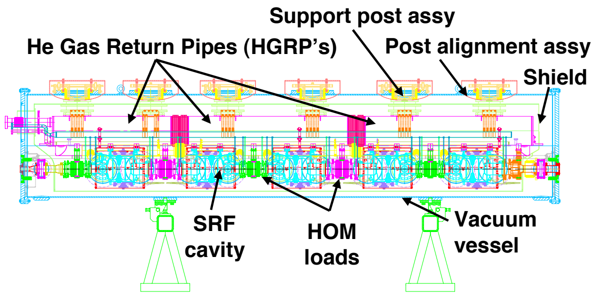

Figure 1: Longitudinal 2D cross section of the ERL injector module.

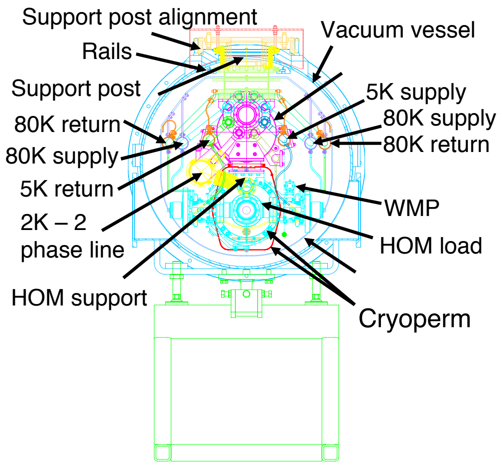

Figure 2: Transverse 2D cross section of the ERL injector module.

TEST CRYOMODULE ASSEMBLY AND TEST RESULTS

A horizontal test cryomodule (HTC) has been assembled and tested at Cornell in 2007 for a fully integrated system test of the prototype beam line components as well as for a first test of the new cryomodule design realized in the ERL injector. The HTC is a short version of the full injector module, following the same design concepts as the full injector module, but has one RF cavity with one HOM load per end only.

Table 2: HTC and full injector module parameters.

Parameter	HTC	Injector
Number of 2-cell cavities	1	5
Number of HOM loads	2	6
Total 2K load	$\approx$ 6 W	$\approx$ 26 W
Total 5K load	$\approx$ 12 W	$\approx$ 60 W
Total 80K load	$\approx$ 50 W	$\approx$ 700 W
Overall length	2.6 m	5.0 m

The beam line string for the horizontal test cryomodule has been assembled in Cornell's class 100 clean room, using a special support fixture to align the beam line components for easy flange connection. The finished cavity string on its clean room support fixture is shown in Figure 3. Figure 4 shows different stages during the subsequent cryomodule assembly. Extensive diagnostics has been installed for the first test [12]. The first module assembly revealed no significant design problems. The fixed support system proved to allow for a fast and easy assembly. Alignment measurements confirmed good alignment of the beam line components within specifications. The rail system for sliding the cold mass into the vacuum vessel worked well. The beam line vacuum was maintained after a bake of the cold input coupler sections and the RF cavities throughout the entire assembly process. A final warm-coupler in-situ bake was done after the module was assembled, to help with coupler processing. Insight gained from the HTC assembly has been applied to the full injector module design to reduce cost and simplify the module assembly further.

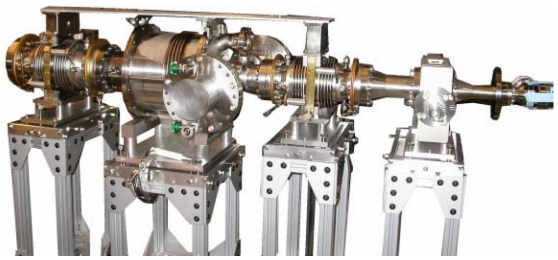

Figure 3: HTC beam line string.

The cryogenic system performed well allowing for quick cryostat cool down and warm up and stable operation at low temperatures (1.6K to 2K). The cold mass shifted during cool-down as predicted. Only minor coupler processing was required at RF power levels above 10 kW. The performance of the SRF cavity was studied in detail. Measurements of the intrinsic quality factor Q_0 showed a low intrinsic quality factor of $Q = 1.5 \times 10^9$ at 1.8 K, see Figure 5. In cw operation, the accelerating gradient was limited to 9.5 MV/m by the high power dissipation at the low intrinsic quality factor. In pulsed operation, fields above 13 MV/m where achieved. Detailed HOM measurements showed no high quality modes with quality factors above a few 1000, thereby demonstrating the effectiveness of the beam line absorber based HOM damping concept. First studies on microphonics and microphonics feedback show promising results and will be continued on the full injector module. After disassembly of the test module, the cause of the low intrinsic quality factor was investigated. Ferrite chips from two broken tiles in the large diameter HOM load where found in the cavity beam tube; see Figure 6. To verify that

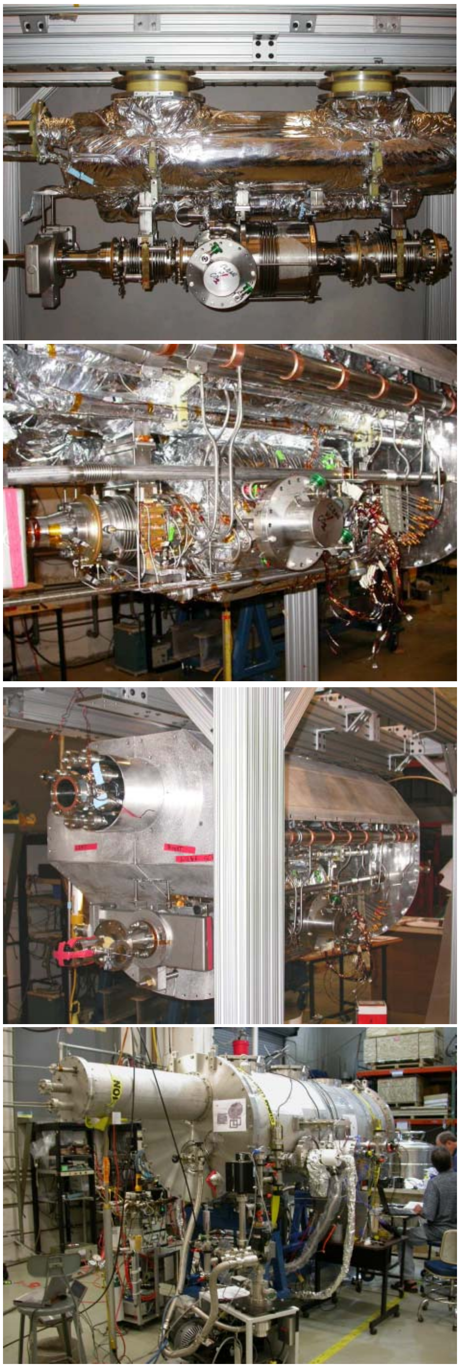

Figure 4: HTC module assembly. Top: Beam line string supported by HGRP. Second from top: After adding of 5K and 80K tubing. Third from top: Nearly closed 80K shield. Bottom: Finished cryomodule.

small ferrite particles where the cause of the low quality factor, the SRF cavity was removed from the HTC, high-pressure rinsed and tested vertically in cw mode. As expected, the rinsing did remove the ferrite particles, and did restore a high intrinsic quality factor of above 10^{10}. We believe that the cause of the failure of the two tiles lies in the too fast cool-down rate during this first HTC test of more than 50K per hour, thereby generating thermal stresses in the tiles. Subsequently, all production HOM loads have been cooled down to 80K at a rate of 25K per hour, and no tile failures have been found. The injector module will be cooled down to 80 K at a rate of well below 20K per hour to minimize thermal stress in the module parts.

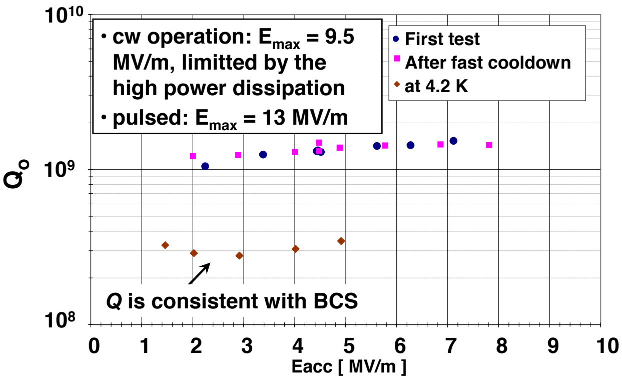

Figure 5: Cavity performance during the HTC test.

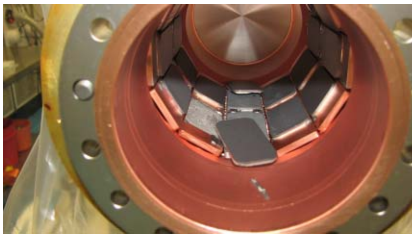

Figure 6: Broken ferrite tile in the large HOM load.

In order to exclude high residual magnetic fields at the cavity location as the cause of the low intrinsic quality factor, the magnetic field in the beam line has been measured after the module has been warmed up. As expected, the field near the cavity was very low - see Figure 7 - thereby excluding residual magnetic fields as the cause of the low intrinsic quality factor.

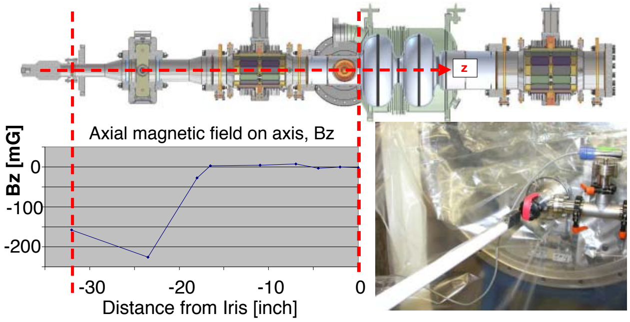

Figure 7: Measured magnetic field along the beam axis with warm cryomodule.

INJECTOR MODULE ASSEMBLY AND FUTURE WORK

The cavity string for the full ERL injector module is presently under assembly at Cornell. The design and modeling of this module have been finished and all components of the cryovessel have been ordered and are presently under fabrication. We expect to finish the assembly of the injector module by early 2008. Subsequently, the module will be cooled down, RF tested and then operated with beam.

SUMMARY

All beam line components for the Cornell ERL injector cryomodule have been designed, fabricated, and tested successfully. A horizontal test cryomodule has been assembled and tested for a first full system test of prototype module components. The module design has profen to allow for a fast and easy assembly and alignment. During the cryogenic test, the cryomodule performed well. The SRF cavity reached field specifications, while its intrinsic quality factor was reduced due to ferrite dust from two broken ferrite tiles in the HOM loads. The cause of the failure of the the two tiles is well understood and subsequent tests on all production HOM loads showed no failures. The experience gained during the HTC assembly and test has been applied to the design of the full injector cryomodule to further reduce cost and ease module assembly. The injector module assembly is ongoing, with a first cool down and test scheduled for early 2008.

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