

## STATUS OF THE CORNELL ERL INJECTOR SCRF CRYOMODULE\*

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### Abstract

The Cornell Energy Recovery Linac (ERL) injector cryomodule is part of a prototype electron beam source to demonstrate production of CW 1.3 GHz, 100 mA average current, 2 ps, 77 pC bunches with emittance of 1 mm-mrad. After a successful initial run of the cryomodule with beam, an improvement program was initiated in the Fall 2009. The goals of the reconfiguration were to replace the RF absorbers in the beamline HOM loads that were subject to static charging, re-process the SRF cavities that exhibited a low Q that further decreased by 50% during the run, and improve diagnostic sensor accuracy within the cryomodule. The upgraded cryomodule was re-commissioned in early 2010 with excellent performance. Details of the investigation and remedies for HOM load charging and cavity Q recovery will be presented along with the ERL injector module performance.

### INTRODUCTION

Cornell University's Laboratory for Accelerator based Sciences and Education is currently exploring the potential of a x-ray light source based on the Energy-Recovery-Linac (ERL) principle [1], which promises superior X-ray performance as compared to conventional third generation light sources [2]. As a first step, to study and demonstrate the production and preservation of a high current, ultra-low emittance beam, a prototype of the ERL injector has been developed and constructed [3].

One of the most challenging and critical components in the injector is its superconducting radio-frequency (SRF) cryomodule, hosting five SRF 2-cell 1.3 GHz cavities [4]. The cavities in the module are powered by individual high power (120 kW) CW klystrons. The ERL injector cryomodule design is based on the TTF cryomodule [5], with beam line components supported from a large diameter helium gas return pipe (HGRP) and all cryogenic piping located inside the module. This concept has been significantly redesigned to fulfill ERL specific requirements. Key features and innovations of the injector prototype cryomodule include among others (see also Fig. 1 and Table 1): (1) A symmetric beamline avoids transverse on-axis fields, which would cause emittance growth. (2) The 2K, 4.5K, and 80K cryogenic systems in the module have been upgraded to intercept the high dynamic heat loads. (3) Three

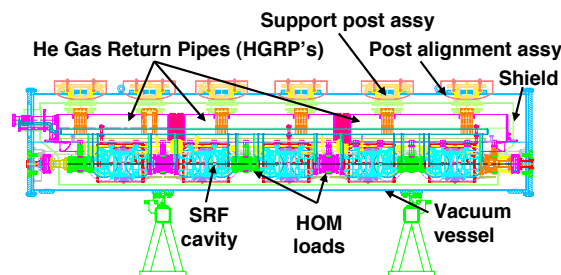


Figure 1: Longitudinal cross-section of the ERL injector module with 5 SRF cavities and HOM beam line absorbers in between. The module is longitudinally separated in three sections, each supported and aligned independently.

magnetic shield layers effectively shield external magnetic fields. (4) Only one layer of thermal shield (at 80K) is used. (5) Short module end sections minimize the distance between the photo-emission DC gun and the first cavity. (6) Gate-valves on each module end, located inside of the module with their drive units outside of the module, make external gate valves obsolete. (7) A new cavity string alignment concept simplifies module assembly and provides improved alignment tolerances. In this concept, the cavities and HOM loads are supported via precisely machined, fixed supports to the HGRP sections. The alignment of the cavities can be improved even further by adjusting the cavity positions via alignment bolts at the HGRP support posts once the cryomodule is cold. Refer to [6] for details.

A first commissioning phase ended in fall of 2009, followed by a few months of component rework to implement improvements in the DC gun, diagnostics, and the superconducting RF cryomodule. A second commissioning phase started in April 2010. In the following we discuss initial cryomodule challenges found during the first run period, the implementation of solutions to these issues during the cryomodule rework at the end of 2009, and highlights from the cryomodule performance after the rework.

### INITIAL CHALLENGES

Test results of the injector cryomodule from the first run period are discussed in detail elsewhere [7, 8]. Overall, the cryomodule performed well, meeting most specifications. However, two performance issues were found (refer to [7, 8] for details): (1) All five SRF cavities showed lower than expected intrinsic quality factors in the range of

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Table 1: ERL Injector Cryomodule Specifications

|                                      |                                  |
|--------------------------------------|----------------------------------|
| Numb. of cavities / HOM loads        | 5 / 6                            |
| Accelerating voltage per cavity      | 1 - 3 MV                         |
| Fundamental mode frequency           | 1.3 GHz                          |
| R/Q (circuit definition) per cavity  | 111 Ohm                          |
| Loaded quality factor                | $4.6 \times 10^4$ to $10^6$      |
| RF power installed per cavity        | 120 kW                           |
| Required amplif. / phase stab. (rms) | $1 \times 10^{-3}$ / $0.1^\circ$ |
| Maximum beam current (design)        | 100 mA                           |
| Total 2K / 5K / 80K loads            | $\approx 26$ / $60$ / $700$ W    |
| Overall length                       | 5.0 m                            |

$3 \times 10^9$  to  $6 \times 10^9$ , that further decreased by 50% during the run. (2) Operation with low beam energy (250 keV) showed significant transverse kick fields present on the beam axis in the cryomodule. It was found that these fields were caused by electrostatic charging of the RF absorber tiles in the Higher-Order Mode loads by small amounts of beam loss and field emission electrons from the SRF cavities during cavity conditioning [8, 9]. After a successful initial run of the prototype Cornell ERL injector cryomodule, the cryomodule was disassembled in the fall of 2009 to address these performance issues.

## MODULE REWORK

The goals of the cryomodule rework were to implement a solution to the HOM absorber tile charging, to re-process the SRF cavities, and to improve some of the diagnostic sensors within the cryomodule. Since there were no alternative RF absorbers available at the time that met the stringent requirements of the beamline loads, the remedy was to remove the RF absorber tiles facing the beam while retaining the absorbers shielded by the metallic substrate. This was accomplished by performing EDM wire cuts of the HOM absorber panels to remove the beamside tiles, as well as EDM cuts to provide some mechanical stress relief to the remaining tiles. The beamline HOM load components then received numerous cycles of cold shock between 77K and 293K, a new thorough cleaning procedure, and then were re-assembled in a clean room as shown in Fig. 2.

In parallel to the HOM load re-work, the injector SRF cavities received vertical tests after disassembly from the module to first confirm their degraded Q. A simple High Pressure Rinse (HPR) and 120C vacuum bake of the cavities restored the cavities to their best vertical test Q values of  $1.6 \times 10^{10}$  at 1.8K and 15 MV/m gradient. The remaining ERL Injector beamline components received individual thorough cleaning, and the beamline string was reassembled in a clean room on a fixture. The string was then removed from the clean room and the rest of the cryomodule assembled in a high bay area. There were also upgrades to the wiring of some of the temperature sensors on the cold

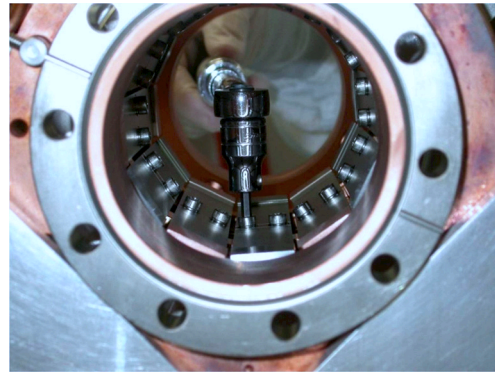


Figure 2: Reassembly of an ERL injector beamline HOM load in a clean room after panel EDM cuts and thorough cleaning. The remaining RF absorber tiles face outwards, and the fields by potential charging of the tiles are shielded from the beam by the metallic substrate.

mass and to the piezos in the cavity tuners. Reassembly of the cryomodule was completed in the first week of February 2010 and subsequently the module was installed in the Cornell ERL injector and module testing resumed.

## CRYOMODULE PERFORMANCE HIGHLIGHTS

In the following we discuss recent highlights from the commissioning and operation of the ERL injector SRF cryomodule. Additional results can be found in [7, 8, 10].

### Cavity Alignment

The cryomodule was cooled down from room temperature to 4.2 K over a period of several (3 - 5) days. During cool-down, the shift in cavity positions was monitored by a wire-position-monitor (WPM) system, see Figure 3. To each cavity, a WPM block is directly mounted for measuring the horizontal and vertical positions of the cavities independently. The observed position shifts during cool-down are in very good agreement (within 0.2 mm) with values expected from thermal shrinkage of the cavity support structure and of the WPM block support. After cool down, the maximum transverse alignment errors of the SRF cavities in the injector module are  $\pm 0.2$  mm. Such excellent cavity string alignment is important for emittance preservation of the low energy beam in the ERL injector.

### Cavity Performance

After reassembly and cool-down of the cryomodule, the performance of the five SRF cavities was measured, see Figure 4. The average intrinsic quality factor at low field has increased from  $4 \times 10^9$  in April 2009 before the rework of the module to about  $7 \times 10^9$  after the rework, with one cavity exceeding  $1 \times 10^{10}$ . While the average intrinsic quality factor is still lower than desirable, it is sufficient for the

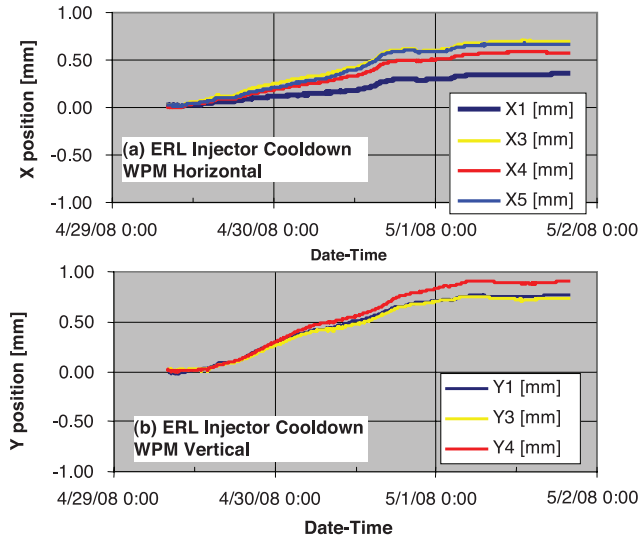


Figure 3: WPM data during cool-down of the injector module. Top: Horizontal position of WPM blocks on cavities 1, 3, 4, and 5. Bottom: Vertical position of WPM blocks on cavities 1, 3, and 4. WPM #2 is not functional.

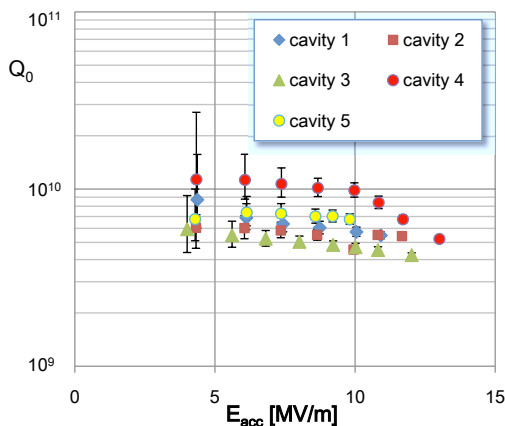


Figure 4: Intrinsic quality factor  $Q$  vs. accelerating field  $E_{acc}$  of the injector SRF cavities at 1.8K after rework of the cryomodule.

operation of the module in the ERL injector. In addition, the spread in the individual quality factors points to cleanliness issues during the cavity assembly as the source of the reduced quality factors instead of a more fundamental module design issue.

### Input Couplers

All high power RF input couplers have so far been processed up to 25 kW per coupler under full reflection. All couplers conditioned well, reaching these power levels in pulsed operation within 25 to 75 hours of processing (RF on time).

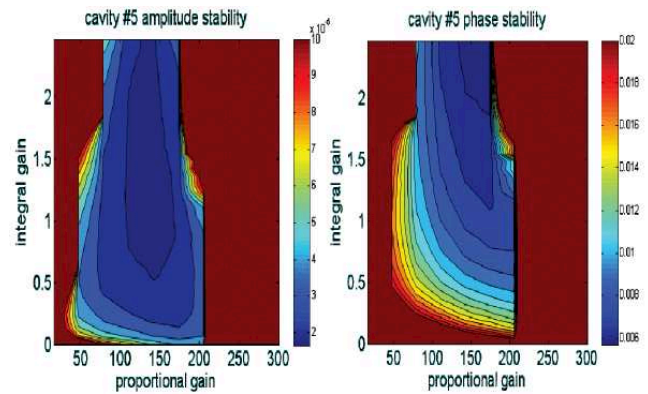


Figure 5: Integral and proportional gain scan to optimize the gains used in the field control loop. Left: Amplitude stability (blue:  $\sigma_A/A < 2 \times 10^{-5}$ ). Right: Phase stability (blue:  $\sigma_p < 0.01^\circ$ ).

### Field Stability

The amplitude and phase of the accelerating fields in the SRF cavities (loaded  $Q_L \approx 1 \times 10^6$ ) is stabilized by an advanced digital control system. A combination of fast feedback loops ( $< 1 \mu s$  latency) and broadband feedforward loops are used for stabilizing the cavity fields. The integral and proportional gains of the proportional-integral loop have been optimized as shown in Figure 5. At optimal gains, exceptional field stabilities of  $\sigma_A/A < 2 \times 10^{-5}$  in relative amplitude and  $\sigma_p < 0.01^\circ$  in phase (in-loop measurements) have been achieved, far exceeding the ERL injector and ERL main linac requirements.

### Microphonics and Compensation

Cavity microphonics is not a mayor concern in the injector cryomodule where the loaded  $Q_L$  of the cavities is in the  $10^5$  to  $10^6$  range, but will be of great importance in the ERL main linac with  $Q_L > 5 \times 10^7$ . Initial studies of microphonics, its coupling to the SRF cavities, and its potential reduction by fast frequency tuning have therefor been done on the injector cryomodule. Figure 6 shows the distribution of the cavity detuning over a long time period for several cavities. The largest measured peak magnitude of the detuning is less then six times the rms detuning, with typical rms values of a few Hz. The peak detuning will determine the peak RF power required in the ERL main linac, and needs to be estimated well to avoid underestimating the RF power to be installed in the main linac, which would results in frequent cavity trips.

The coupling strength of vibration sources outside of the cryomodule to the SRF cavities inside the cryomodule was studied by placing a modal shaker on several components connecting to the cryomodule, see Fig. 7. Sinusoidal forces applied by the modal shaker where in the 100 N range, with frequencies scanned from 1 Hz to several 100 Hz. No coupling to the cavity microphonics (at a sensitivity of 0.1 Hz)

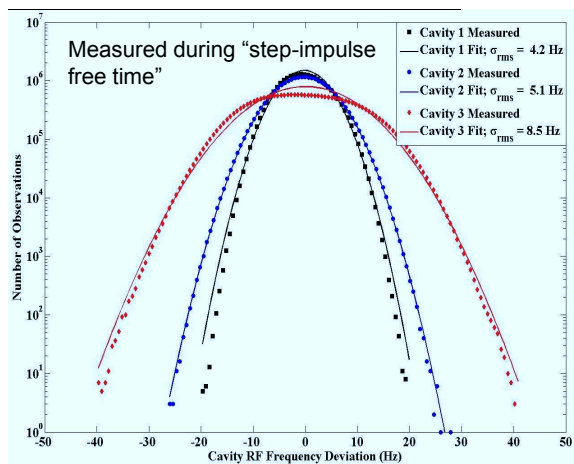


Figure 6: Distribution of cavity detuning measured for three cavities over a period of one hour. The distributions are well described by Gaussian functions.

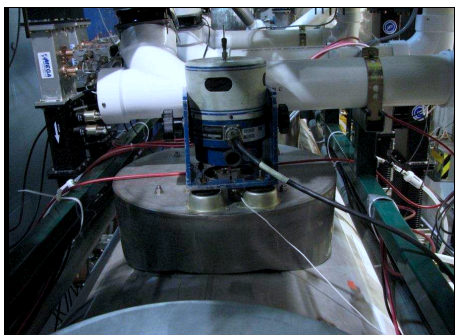


Figure 7: Modal shaker mounted on top of the helium-gas return pipe support post at the top of the cryomodule.

was found when connecting the modal shaker to the module support stands, the RF waveguides, the input couplers, the beam pipe at the module ends, and the cryogenic supply line. A small level of microphonics could only be excited when the modal shaker was placed directly on top of the helium-gas return pipe support post at the top of the cryomodule as shown in Fig. 7. The conclusion from these tests is that ground and other external vibrations do not strongly couple to the SRF cavities in the injector module, and are not the dominating source of microphonics. The main source of cavity microphonics is likely fast pressure fluctuation of the 2K LHe system, which couples directly to the SRF cavities.

The frequency tuners of the injector cavities are equipped with fast piezo-electric actuators for fast frequency tuning. First steps have been done to explore the potential and robustness of microphonics compensation using these fast tuners in a feedback loop. For robustness, a PID frequency feedback loop was implemented with a simple digital filter in the LLRF system. Optimizing the gains and the digital filter allowed to achieve a 70% reduction in the rms microphonics level, see Fig. 8.

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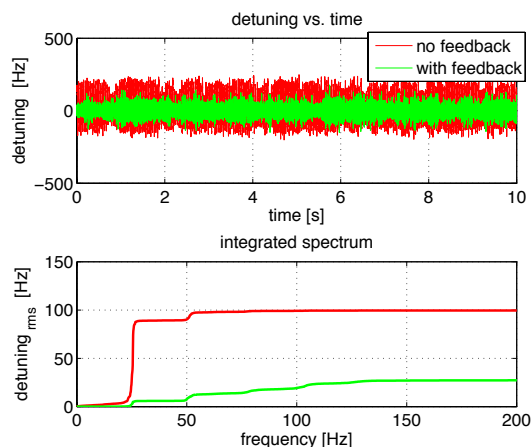


Figure 8: Microphonics compensation by a fast piezo-electric tuner in feedback mode. Top: Detuning vs. time with and without compensation. Bottom: Integrated microphonics spectrum for the two detuning cases shown above.

### HOM and Beam Performance

Beam operation with energy gains of up to 14 MeV and currents of up to 9 mA were achieved so far, limited by instabilities in the high voltage of the DC electron gun and in the power of the gun laser. The High-Order Mode (HOM) power excited by such a beam is only a few 100 mW per cavity, which is too low to be detected. However, at the design bunch charge (77 pC) and beam current (100 mA), about 40 W of HOM power will be excited per cavity [11]. HOM absorbers are located at 80K between the SRF cavities to strongly damp HOMs and to extract the HOM power left behind by the beam. The damping of HOMs in the injector cavities by the beamline absorbers was investigated using a vector network analyzer to excite modes via pick-up antennas located at the cavity beam tubes and at the HOM loads, see Figure 9. Preliminary results confirm very strong suppression of monopole and dipole modes with typical quality factors of only a few 1000.

Beam operation with a low energy beam (250 keV) showed that removing the RF absorber tiles facing the beam during the cryomodule rework did indeed solve the beam steering issue observed before the rework, which was caused by charging up of the absorber tiles.

The HOM absorbers allow for measuring the total HOM power excited by the beam. Heaters mounted on the HOM load bodies are used to calibrate the increase in temperature of the He cooling gas of the loads as a function of power absorbed in each HOM load, see Figure 10. In addition, small pick-up antennas located at the HOM loads allow measuring the spectrum of the HOMs excited by the beam up to high frequencies; see Fig. 11 for an example. The corresponding integrated HOM power is shown in Fig. 12 for two different beam currents. As expected, the total HOM power scales quadratically with the beam current (at fixed bunch repetition rate). These type of measurements

contain information about the  $(R/Q)Q$  of the modes, the bunch length, and the impedance of the cavities, and will be continued in the near future at higher beam currents.

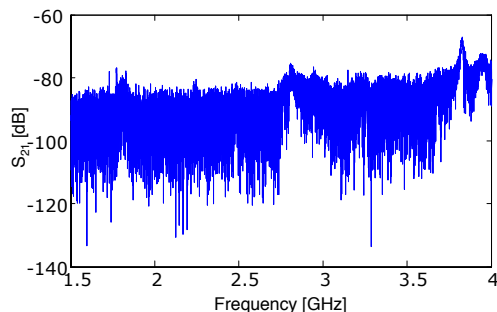


Figure 9: Vector network analyzer scan for HOMs between 1.5 GHz to 4 GHz. Shown is the transmission amplitude vs. scan frequency. Pick-up antennas on the cavities and HOM loads were used to couple to the HOMs.

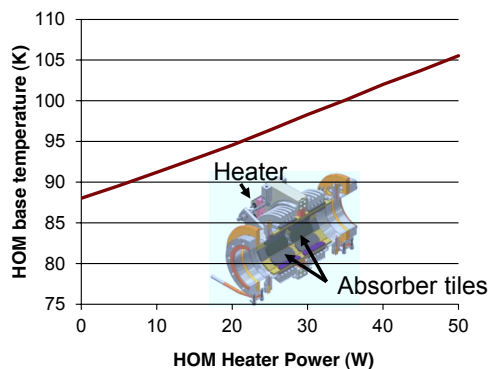


Figure 10: Measured temperature increase of the 80K He outlet gas vs. HOM heater power during calibration.

## SUMMARY AND OUTLOOK

The Cornell ERL injector cryomodule has been commissioned and is meeting or exceeding most performance specifications. Excellent cavity alignment and RF field stability were demonstrated. Beam operation with energy gains of up to 14 MeV and currents of up to 9 mA were achieved, limited by the DC electron gun system. The RF input couplers were conditioned within a few 10 hours to above 25 kW RF power under full reflection. Active compensation of cavity microphonics was demonstrated. HOM measurements confirm very strong damping of all relevant HOMs. Future work will focus on high beam current operation (up to 100 mA) and studies of higher-order-mode excitation by the high current beam.

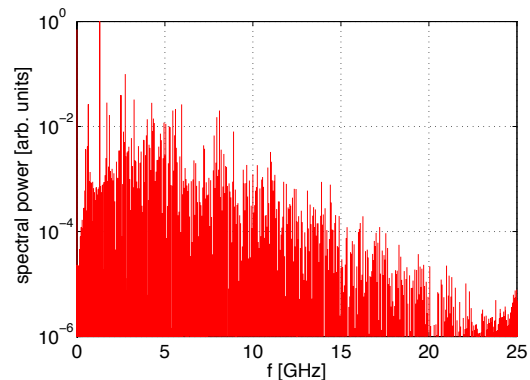


Figure 11: Spectrum of HOMs excited in the cryomodule cavities by a 2 mA, 50 MHz bunch repetition rate beam.

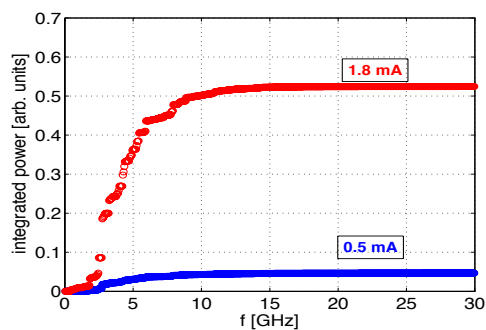


Figure 12: Integrated HOM power for two different beam currents (50 MHz bunch repetition rate) as function of the frequency up to which the HOM power was integrated.

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