LATEST RESULTS AND TEST PLANS FROM THE 100 mA CORNELL ERL INJECTOR SCRF CRYOMODULE*

M. Liepe†, S. Belomestnykh, E. Chojnacki, Z. Conway, G. Hoffstaetter, R. Kaplan, S. Posen, P. Quigley, J. Sears, V. Shemelin, V. Veshcherevich,
CLASSE, Cornell University, Ithaca, NY 14853, USA

Abstract

Cornell University has developed and fabricated a SCRF injector cryomodule for the acceleration of a high current, low emittance beam in the Cornell ERL injector prototype. This cryomodule is based on superconducting rf technology with five 2-cell RF cavities operated in the cw mode, supporting beam currents of up to 100 mA. After a rework of this cryomodule in 2009 to implement several improvements, it is now in beam operation again. In this paper we summarize the rework of the module and report on latest test results and test plans

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]. 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.

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 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 vales 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.

In the following we discuss the rework of the cryomodule together with the improvements implemented as well as first test results of the injector module from the second ERL injector run period in 2010. For test results of the injector cryomodule from the first run period refer to [7, 10].

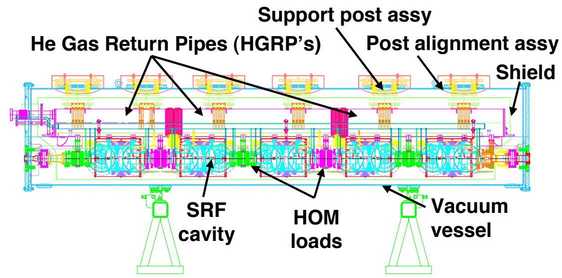

Figure 1: Longitudinal cross-section of the ERL injector module with 5 SRF cavities and HOM beam line absorbers in between. The module is longitudinally separated in three sections, each supported and aligned independently.

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	4.6×10^4 to 10^6
RF power installed per cavity	120 kW
Required amplit. / phase stab. (rms)	1×10^{-3} / $0.1°$
Maximum beam current (design)	100 mA
Total 2K / 5K / 80K loads	$\approx$ 26 / 60 / 700 W
Overall length	5.0 m

* Work supported by the NSF Grant No. PHY-0131508 and NSF/NIH-NIGMS Grant No. DMR-0937466.
† MUL2@cornell.edu

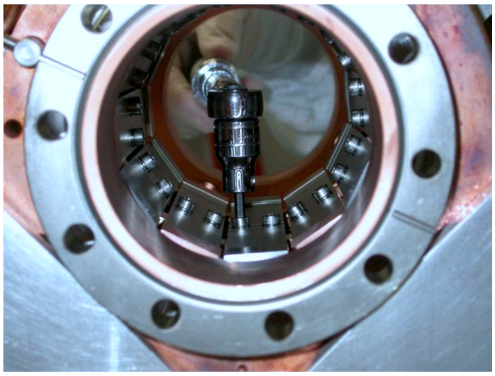

Figure 2: Reassembly of an ERL injector beamline HOM load in a clean room after panel EDM cuts and thorough cleaning. The remaining RF absorber tiles face outwards, and the fields by potential charging of the tiles are shielded from the beam by the by the metallic substrate.

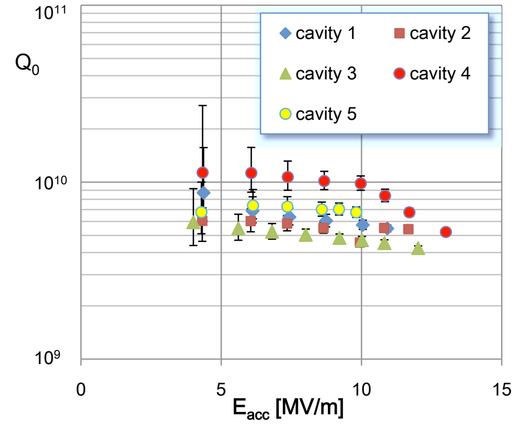

Figure 3: Intrinsic quality factor Q vs. accelerating field E_{acc} of the injector SRF cavities at 1.8K after rework of the cryomodule.

MODULE REWORK

After a successful initial run of the prototype Cornell Energy Recovery Linac (ERL) Injector cryomodule, an improvement was initiated in the Fall 2009. The goals of the cryomodule reconfiguration were to remove the RF absorbers in the beamline HOM loads [8] that were subject to electrostatic charging [9, 10], re-process the SRF cavities that exhibited a low Q that further decreased by 50% during the run [10], and 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 where 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 x 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 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.

TEST RESULTS

After reassembly and cool-down of the cryomodule, the performance of the five SRF cavities was measured, see Figure 3. The average intrinsic quality factor at low field has increased from 4×10^9 in April 2009 before the rework of the module to about 7×10^9 after the rework, with one cavity exceeding 1×10^{10}. While the average intrinsic quality factor is still lower than desirable, it is sufficient for the 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.

The amplitude and phase stability of the accelerating fields in the SRF cavities was improved further by adding large bandwidth (> 1 MHz) feedforward to the LLRF controller. The main source of field perturbation in the injector cavities is a strong ripple on the high voltage of the klystrons, with relative amplitudes of several percent and frequencies ranging from 360 Hz to may kHz at 60 Hz harmonics. In the feedforward controller, the measured fast fluctuation of the high voltage is used together with a model of the klystron for calculating a feedforward signal added to the klystron drive signal, which then stabilizes the klystron output signal. As Figure 4 shows, the feedforward control reduces the 60 Hz harmonics caused by the high voltage ripple by more than one order of magnitude. In addition to feedforward, a feedback loop is 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 $\sigma_A/A < 4\times10^{-5}$ in relative amplitude and $\sigma_p < 0.01°$ in phase (in-loop measurements) have been achieved, far exceeding the ERL injector and ERL main linac requirements.

Microphonics cavity detuning was studied in more detail after the module rework, and the source of the repetitive detuning impulse responses (sudden detuning by several

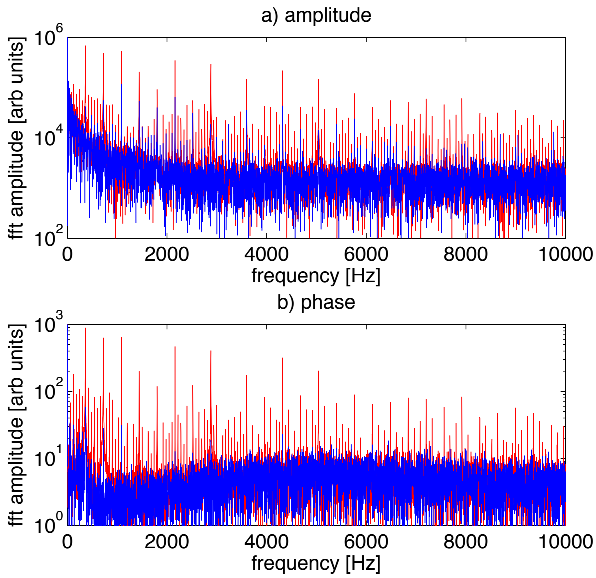

Figure 4: Field stability without (red) and with (blue) feed-forward klystron high-voltage ripple compensation. Top: FFT of the cavity field amplitude. Bottom: FFT of the cavity phase. The ripples in the HV are harmonics of 60 Hz.

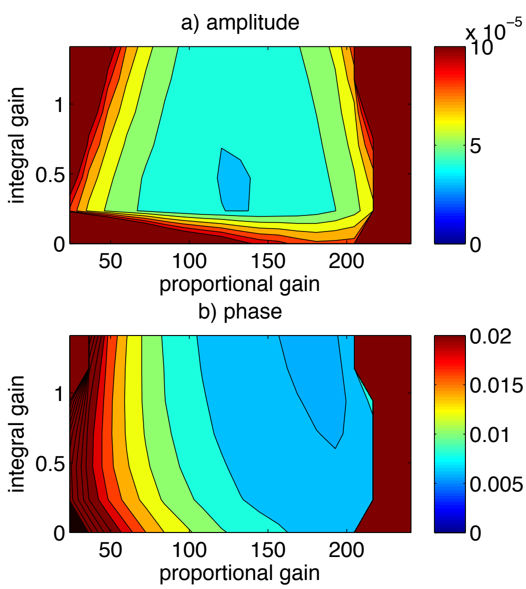

Figure 5: Integral and proportional gain scan to optimize the gains used in the field control loop. Top: Relative amplitude stability (blue: $\sigma_A/A < 4 \times 10^{-5}$). Bottom: Phase stability (blue: $\sigma_p < 0.01°$).

100 Hz with repetition rates of less then 1 Hz) was found. They were caused by cryogenic instabilities in the warm-up cool-down pipe, which was used only during the initial cool-down of the cavities, and was valved off afterwards in the cryogenic feed box. Setting up a slow LHe flow though this pipe eliminated the detuning events, see Fig. 6.

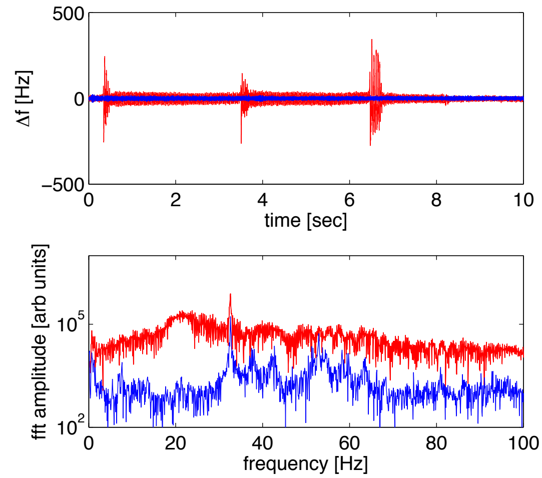

Figure 6: Cavity detuning before (red) and after (blue) setting up LHe flow though the warm-up cool-down pipe. Top: Detuning vs. time. Bottom: Microphonics spectrum.

FUTURE PLANS

Future work will focus on two areas: (1) The compensation of cavity microphonics by fast piezoelectric frequency tuners, and (2) studies of higher-oder-mode excitation by the high current (up to 100 mA) beam. Microphonics and its compensation is not a main concern in the low loaded Q injector cavities, but will be of highest importance in the main linac, where the loaded Q will be several 10^7.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude for the hard work of all those involved in the cryomodule rework.

REFERENCES

[1] J. A. Crittenden et al.,"Developments for Cornell's...", PAC'09, Vancover, May 2009, paper MO4PBC03 (2009).

[2] D. H. Bilderback, Proceeding of Future Light Sources 2006 meeting in Hamburg, PLT03, p1-6 (2006).

[3] I. Bazarov et al.,"Initial beam results from the Cornell high-current ERL..." PAC'09, Vancover, May 2009 (2009).

[4] V. Shemelin, et al., Proc. of PAC'03, pp. 2059-2061 (2003).

[5] C. Pagani et al., Advances in Cryogenic Engineering, Vol. 45A, Edited by Q-S. Shu, Plenum Press, New York (1999).

[6] M. Liepe et al., "Design of the CW Cornell ERL Injector Cryomodule," PAC'05, Knoxville, TN, USA (2005).

[7] M. Liepe et al., "SRF Experience with the Cornell ...", PAC'09, Vancouver, Canada (2009).

[8] V. Shemelin et al., EPAC 2006, Edinburgh, Scotland (2006). V. Shemelin et al., NIM A 557 (2006) 268-271.

[9] E. Chojnacki et al., "DC Conductivity of RF Absorbing Materials", SRF 2009, Berlin, Germany (2009).

[10] M. Liepe et al., "High-current ERL Injector ", SRF 2009, Berlin, Germany (2009).