75 mA OPERATION OF THE CORNELL ERL SUPERCONDUCTING RF INJECTOR CRYOMODULE*

M. Liepe†, R. Eichhorn, B. Dunham, G.H. Hoffstaetter, R. Kaplan,
S. Posen, P. Quigley, E. Smith, V. Veshcherevich
CLASSE, Cornell University, Ithaca, NY 14853, USA

Abstract

Cornell University has developed a SCRF injector cryomodule for the acceleration of high current, low emittance beams in continuous wave operation. This cryomodule is based on 1.3 GHz superconducting RF technology, and has been tested extensively in the Cornell ERL injector prototype with world record CW beam currents exceeding 70 mA. High CW RF power input couplers and strong Higher-Order-Mode damping in the cavities are essential for high beam current operation. This paper summarizes the performance of the cryomodule during the high beam current operation.

INTRODUCTION

Cornell University's Laboratory for Accelerator based Sciences and Education is currently conducting an extensive R&D program to fully develop the SRF technology for a 5 GeV, 100 mA Energy-Recovery Linac (ERL) [1]. This work includes a short SRF section in the ERL injector as well as a multi-GeV main linac operated in CW mode in the ERL loop. The main challenges for these SRF sections arise from the CW operation of the cavities and from supporting very high beam currents. An overview of these ERL related SRF activities at Cornell University is given in [2, 3]

The Cornell ERL SRF injector section will host 12 SRF 2-cell 1.3 GHz cavities [4] providing a total energy gain of up to 15 MeV. A 5 cavity prototype version of this cryomodule has been developed [5] and fabricated at Cornell, and is now under operation in the Cornell high current ERL prototype [6]. The injector cryomodule is shown in Fig. 1, and key parameters are listed in Table 1.

Extensive tests of the injector module have shown that it meets and exceeds specifications for cavity performance, coupler performance, cavity alignment, and field stability [7]. In this paper we discuss the high beam current operation of the injector cryomodule at record CW beam currents of up to 75 mA, especially the performance of the Higher-Order-Mode (HOM) beam line absorbers and RF power input couplers during the high current operation.

INJECTOR SRF CRYOMODULE

For details on the module design refer to [5]. The injector cryomodule hosts 5 superconducting 1.3 GHz 2-cell cavities [4]. Each cavity is powered by an individual high power (120 kW) CW klystron, with the RF power being coupled into each cavity via a symmetric twin high power input coupler [8]. High beam current operation requires strong damping of Higher-Order-Modes (HOM) in the SRF cavities, which is achieved by beamline HOM absorbers located between the cavities [9]. The loads must operate cold, with an 80 K heat intercept provided by high pressure Helium gas. Three types of RF absorbers are used to provide broadband RF absorption (two ferrite materials, TT2-111R and Co2Z, and a lossy ceramics, 137ZR10).

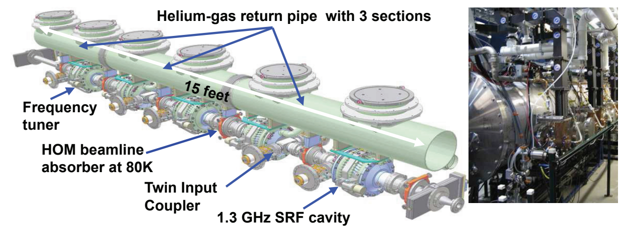

Figure 1: Left: CAD model of the cold mass of the ERL injector module with 5 SRF cavities and HOM beamline absorbers in between. Right: Injector module installed in the Cornell ERL injector prototype.

Table 1: Injector Specifications

	injector
Number of cavities	5
Number of cells per cavity	2
Accelerating gradient	5-15MV/m
Fundamental mode frequency	1.3GHz
R/Q (circuit definition)	111Ω
Loaded quality factor	4.6×10^4
RF power per cavity	120kW
Required amplitude stab. (rms)	1×10^{-4}
Required phase stab. (rms)	0.1°
Design CW beam current	100mA
Total 2K / 5K / 80K loads	26/60/700W
Overall length	5.0m

HIGH CURRENT OPERATION

During high current operation of the Cornell ERL injector, CW beam currents of up to 75 mA were accelerated to an energy of 4 MeV by the five SRF cavities in the injector cryomodule, setting a new record for this type of SRF linac operation. Figure 2 shows the ramp up of the current to

* Work supported by NSF Grant NSF DMR-0807731.
† MUL2@cornell.edu

ISBN 978-3-95450-143-4

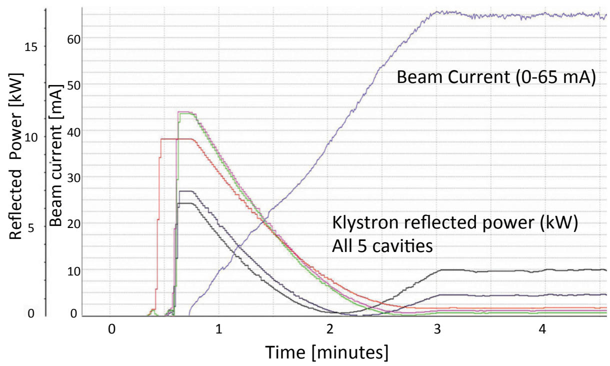

Figure 2: Ramp up of beam current to 65 mA: beam current (blue curve) and the reflected RF power from each of the five SRF cavities.

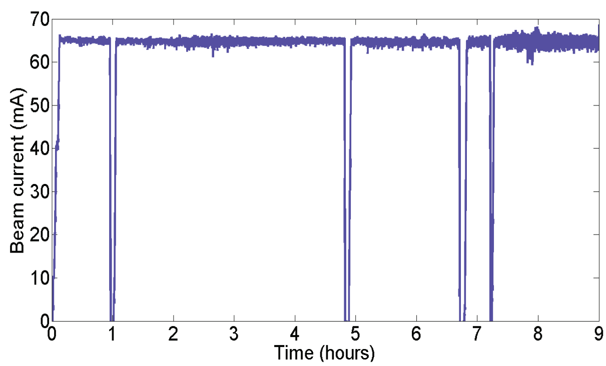

Figure 3: Beam current vs. time during high current operation of the injector cryomodule (cw operation , 1.3 GHz bunch repetition rate): 9 hour operation at 65 mA.

65 mA together with the RF power reflected from the cavities. As can be seen, the coupling of the RF power input couplers was adjusted to minimize reflection at high beam currents, i.e. to achieve matched coupling for $\approx$ 60 mA operation.

Figure 3 shows beam current vs. time during a recent 65 mA beam current operation of the injector cryomodule with 1.3 GHz bunch repetition rate and $\approx$ 2 ps bunch length. As shown, the module was operated continuously for nine hours at 65 mA with four short interruptions only. Beam operation at 65 mA was very stable, and good energy stability was demonstrated ($\sigma_E/E < 10^{-3}$). Temperature sensors mounted on the shielded bellow sections of the HOM beamline absorbers and elsewhere along the beamline showed no significant temperature increases during the high beam current runs. The performance of the RF input couplers and of the HOM beamline loads is discussed in detail in the next two sections.

INPUT COUPLERS

RF power is coupled into each cavity via two high power input couplers, see Fig. 4. This coupler is designed for CW

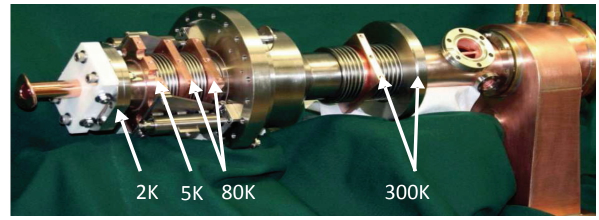

Figure 4: Cornell ERL injector 50 kW CW RF input coupler. Positions of thermal anchors at 5 K, 80 K, and 300 K are shown.

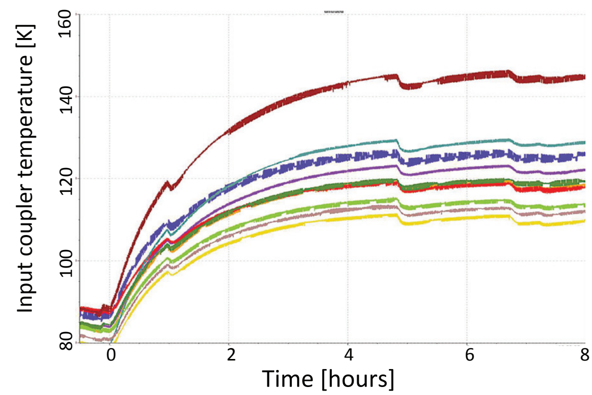

Figure 5: Temperature of the 80 K intercepts on the RF input couplers vs. time during the 65 mA beam current operation shown in Fig. 3. Steady state temperatures are reached after $\approx$4 hours of high power operation.

operation with up to 50 kW, and has been operated at CW power levels of up to 60 kW in a coupler test stand. During 75 mA operation, 60 kW of RF power per SRF cavity (30 kW per input coupler) were coupled into each cavity and transferred to the beam.

While the input couplers themselves performed well, operation at high power levels over hours resulted in significant temperatures increases of the 80 K intercepts as can be seen in Fig. 5. It was determined that this temperature increase is due to insufficient cooling gas flow in the small diameter 80 K distribution tubing to the 80 K thermal intercepts on the couplers. In the cryomodule, 80 K helium cooling gas is supplied in parallel to the HOM beamline loads and the RF input couplers. Incorrect sizing of the impedance of the parallel cooling circuits let to significant larger gas flow to the HOM loads than to the input couplers, thus resulting in marginal cooling of the 80 K coupler intercepts.

HOM DAMPING

Temperature measurements at the HOM beamline loads showed only small temperature increases during the high current runs (see Fig. 6), as expected from absorbing the HOM power excited by the beam. Measuring the increase in cooling gas temperature in the HOM loads allows for estimating the RF power absorbed by the absorbers. Pre-

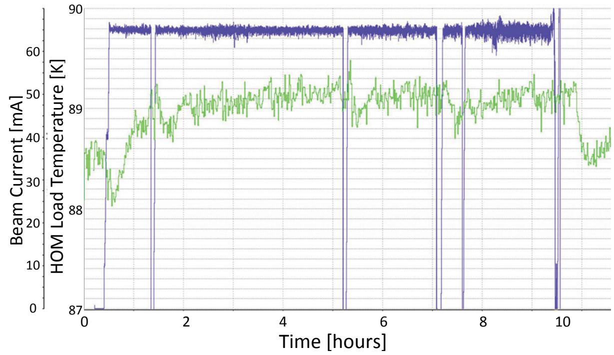

Figure 6: Beam current (blue curve) and 80 K HOM load temperature (green curve) vs. time during high current operation of the injector cryomodule (cw operation , 1.3 GHz bunch repetition rate) .

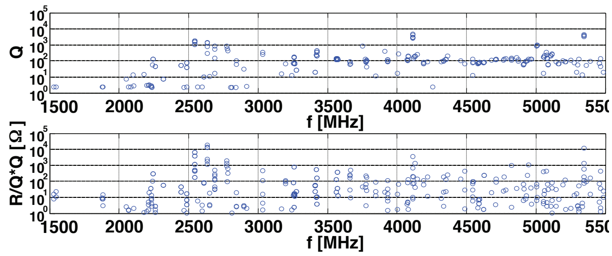

Figure 7: CLANS simulation results for monopole higher-order modes in the 5 cavity beamline of the injector cryomodule. Top: Quality factor. Bottom: $(R/Q)Q$.

liminary measurements show good agreement of the total power absorbed with results from wakefield and longitudinal loss factor simulations [10].

These high beam current results are consistent with HOM simulations predicting very efficient damping of HOMs in the 5-cavity beamline of the injector cryomodule by the beamline absorbers, see Fig. 7, with typical quality factors of a few 100 to few 1000. This was further confirmed experimentally in the injector cryomodule by exciting the HOMs via pick-up antennas located at the cavity beam tubes and at the HOM loads; see Fig. 8. These measurements show very strong suppression of monopole and dipole modes with typical quality factors of only a few 1000.

The spectrum of the HOMs excited by the beam current was measured for 50 MHz and 1300 MHz bunch repetition rate; see Fig. 9 The total HOM power and the spectra showed the expected behavior with varying beam current and bunch repetition rate ($P \propto I^2/T_{rep}$), and showed no weakly damped HOMs.

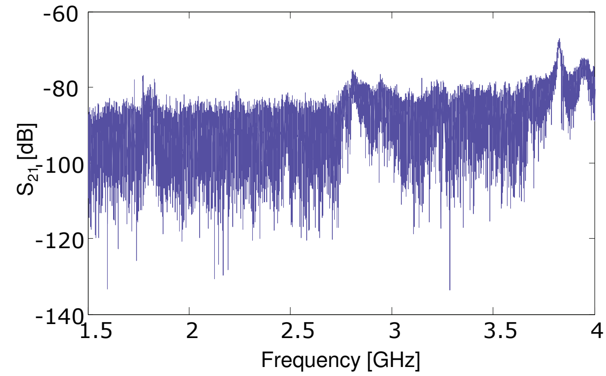

Figure 8: Vector network analyzer scan for HOMs between 1.5 GHz to 4 GHz. Shown is the transmission amplitude vs. scan frequency. Pick-up antennas on the cavities and HOM loads were used to couple to the HOMs.

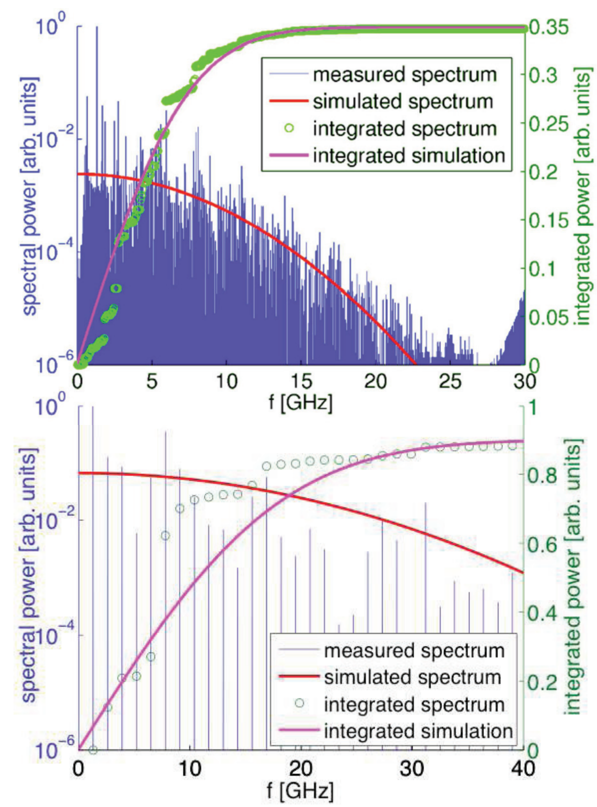

Figure 9: HOM spectrum excited by the beam as measured at one of the HOM loads. The integrated spectrum is plotted on the secondary axis. Also shown are results obtained by ABCI simulations for the entire beamline in the injector module [10]. Top: 50 MHz bunch repetition rate. Bottom: 1.3 GHz bunch repetition rate.

SUMMARY

The Cornell superconducting RF ERL injector cryomodule has been operated successfully with world record CW beam currents exceeding 70 mA. Based on HOM damping measurements and high beam current operation results, we expect that the HOM damping scheme of the injector cryomodule will easily support operation at the full 100 mA specification.

ISBN 978-3-95450-143-4

ACKNOWLEDGMENTS

The authors would like to express their thanks to the ERL injector operations team for their tireless effort in pushing the beam current.

REFERENCES

[1] C. Mayes et al., PAC 2011, New York, NY, USA (2011).

[2] M. Liepe et al., IPAC 2012, New Orleans, USA (2012).

[3] R. Eichhorn et al., SRF 2013, Paris, France (2013).

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

[5] M. Liepe et al., PAC 2005, Knoxville, TN, USA (2005).

[6] B. Dunham et al., IPAC 2012, New Orleans, USA (2012).

[7] M. Liepe et al., PAC 2011, New York, NY, USA (2011). M. Liepe et al., SRF 2011, Chicago, IL, USA (2011).

[8] V. Veshcherevich, et al., SRF'2005 Workshop (2005).

[9] V. Shemelin et al., EPAC 2006, Edinburgh, Scotland (2006).

[10] S. Posen, M. Liepe, PAC 2011, New York, USA (2011)