EXPERIENCE WITH THE CORNELL ERL INJECTOR SRF CRYOMODULE DURING HIGH BEAM CURRENT OPERATION *

M. Liepe[†], D. Hartill, G. Hoffstaetter, S. Posen, V. Veshcherevich
CLASSE, Cornell University, Ithaca, NY 14853, USA

Abstract

Cornell University has developed and fabricated a SCRF injector cryomodule for the acceleration of high current, low emittance CW beams. This cryomodule is based on superconducting RF technology with five 2-cell SRF cavities operated in CW mode. Strong Higher-Order-Mode damping and high power RF input couplers support accelerating beam currents of tens of mA. The cryomodule is currently under extensive testing in the Cornell ERL injector prototype with CW beam currents exceeding 25 mA. This paper gives an overview of the experience gained during the high beam current operation of the cryomodule, with a focus on the intrinsic cavity quality factors, input coupler performance, and HOM damping.

INTRODUCTION

Continuos progress in Superconducting Radio-Frequency (SRF) technology during the last three decades had transformational impact on particle accelerators for many different applications. Multi-GeV SRF linacs running in CW mode and supporting beam currents of tens of mA are now coming into reach, which will enable novel high current accelerators like an x-ray light source based on the Energy-Recovery-Linac (ERL) principle as under development at Cornell University's Laboratory for Accelerator based Sciences and Education [1]. One of the most critical and demanding components of such an accelerator is its CW high current injector. The Cornell ERL injector section will host 12 SRF 2-cell 1.3 GHz cavities [2] providing a total energy gain of 15 MeV for beam currents up to 100 mA. A 5 cavity prototype version of this cryomodule has been developed [3] and fabricated at Cornell, and is currently under operation in the Cornell high current ERL prototype [4] ; see Fig. 1 and Table 1.

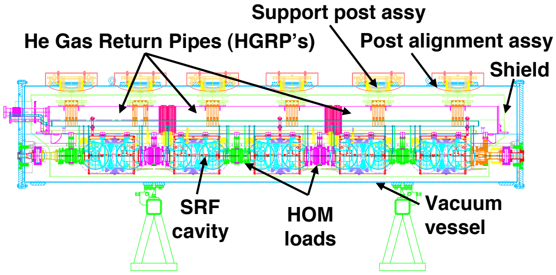

Figure 1: Cross-section of the ERL injector module with 5 SRF cavities and HOM beamline absorbers in between.

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
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 beam current	100mA
Total 2K / 5K / 80K loads	26/60/700W
Overall length	5.0m

SRF INJECTOR MODULE

Key challenges that had to be addressed in the injector cryomodule design include: (1) Limiting emittance growth of the very low emittance beam, (2) supporting high beam current operation up to 100 mA with short (2 ps) bunches, and (3) transferring up to 100 kW of CW RF power per cavity to the beam. The Cornell ERL SRF injector cryomodule was specifically designed and optimized to meet these specifications. The module 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. For details on the module design refer to [3]. The injector cryomodule hosts 5 superconducting 1.3 GHz 2-cell cavities [2]. 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 [6]. 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 [7].

OPERATIONAL HIGHLIGHTS

In this section we give a high level overview of the performance of the SRF injector module. As shown, it meets or exceeds all specifications listed above.

---

[*] Work supported by NSF award DMR-0807731.

[†] MUL2@cornell.edu

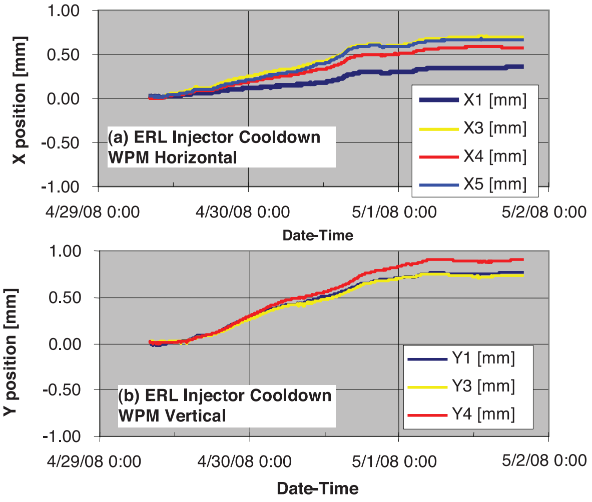

Figure 2: WPM data during cool-down of the injector module. Top: Horizontal position of WPM blocks on cavities 1, 3, 4, and 5. Bottom: Vertical position of WPM blocks on cavities 1, 3, and 4. WPM #2 is not functional.

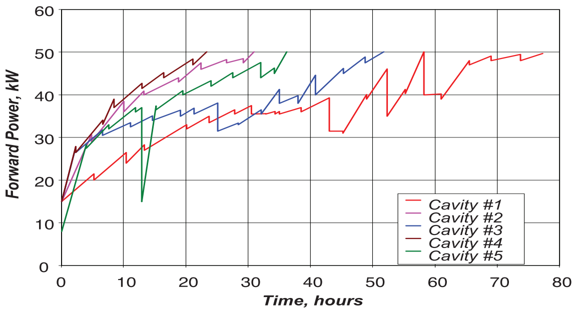

Figure 3: Input coupler processing under full refection (cavity detuned) up to 50 kW. Shown is the maximum forward power per twin-coupler vs. processing time (pulsed operation with 2 ms pulse length and 50 Hz repetition rate).

Cavity Alignment

Emittance preservation in the SRF injector section requires a symmetric beam line, thereby avoiding transverse on-axis kick fields, and excellent cavity alignment within ± 0.5 mm. This is achieved by using rotational symmetric HOM beamline loads and a symmetric twin high power input coupler design. A new cavity string alignment concept was developed to simplify module assembly and to provide improved cavity alignment. In this concept, the cavities and HOM loads are mounted via precisely machined, fixed supports to the helium-gas return pipe. Excellent cavity string alignment within ± 0.2 mm was confirmed by a wire-position-monitor (WPM) system after module cool-down, see Fig. 2, exceeding specifications.

Input Coupler and Cavity Performance

The twin high power input couplers [6] are currently conditioned to 50 kW per pair. All couplers conditioned well, reaching these power levels in pulsed operation within 25 to 75 hours of processing (RF on time), see Fig. 3. During 25 mA beam operation, 25 kW of RF power per cavity (125 kW total) were transferred to the beam.

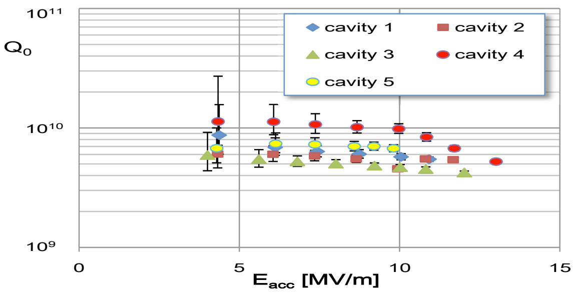

Figure 4: Intrinsic quality factor Q_0 vs. accelerating field E_{acc} of the injector SRF cavities at 1.8K.

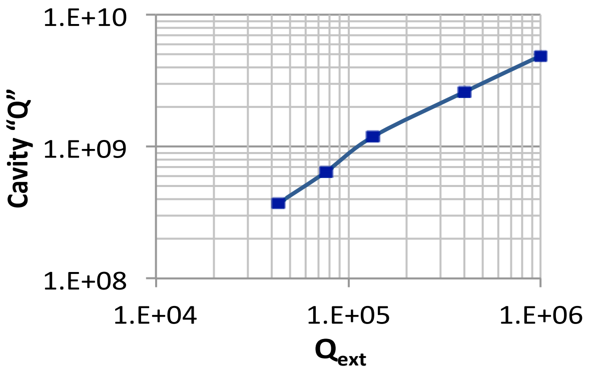

Figure 5: Intrinsic quality factor Q_0 vs. external quality factor Q_{ext} of the twin input coupler for one of the SRF injector module cavities.

The SRF performance of the five SRF cavities was studied in detail, see Figure 4. While the cavities are meeting gradient specifications, their intrinsic quality factors Q_0 are a factor of 1.5 to 3 lower than expected at the operating temperature. Measurements of the dynamic cavity heat load as function of the coupling strength of the input couplers reviled that the losses strongly increase with increased fields in the couplers (see Fig. 5), thus pointing to the 1.8K coupler sections as the source of the lowered intrinsic quality factors of the cavities. Detailed simulations of this section of the RF input coupler were therefore done, showing that the small exposed stainless steel sections at the Conflat flanges between the cavities and input couplers cause RF losses in agreement with what was found experimentally, see Fig. 6.

The fields in the SRF injector cavities are stabilized by a fast digital low-level RF system designed in-house. At optimal gains, exceptional field stabilities of $\sigma_A/A < 2 \times 10^{-5}$ in relative amplitude and $\sigma_p < 0.01°$ in phase (in-loop measurements) have been achieved, significantly exceeding requirements.

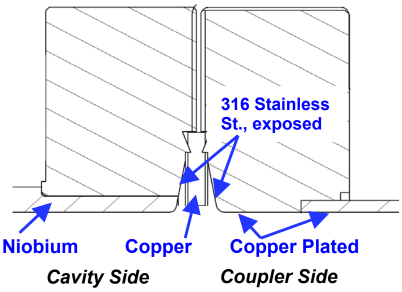

Figure 6: Cross section of the Conflat type flange on the SRF injector cavities for in input coupler.

HOM Damping and High Current Operation

Strong damping of the HOMs in the SRF cavities by the beamline HOM loads is essential to support high beam current operations. Vector network analyzer measurements were done, confirming very strong suppression of monopole and dipole modes with typical quality factors of only a few 1000 as predicted by HOM simulations; see Fig. 7. As of summer 2011, short bunch ($\approx$ 2 ps) beam currents of up to 25 mA were accelerated in the prototype cryomodule to 5 MeV in CW operation as shown in Fig. 8. Temperature measurements at the HOM absorbers showed only small increases at this beam current of $\Delta T < 0.5$K, and thereby confirm that the HOM damping scheme in the ERL injector module can easily handle beam currents of more that 100 mA. These HOM power measurements also allow estimating the total longitudinal loss factor of the cryomodule beamline. Again, good agreement with simulations is found [8]. Detailed studies of the HOMs excited by the beam have confirmed excellent HOM damping. HOM spectra measurements up to 50 GHz show the expected behavior with varying beam current and bunch repetition rate ($P \propto I^2/T_{rep}$), and show no weakly damped HOMs, see Fig. 9.

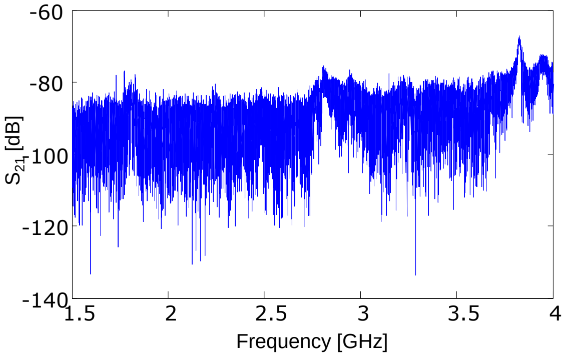

Figure 7: Vector network analyzer scan for HOMs between 1.5 GHz to 4 GHz. Shown is the transmission amplitude vs. scan frequency. Pick-up antennas on the cavities and HOM loads were used to couple to the HOMs.

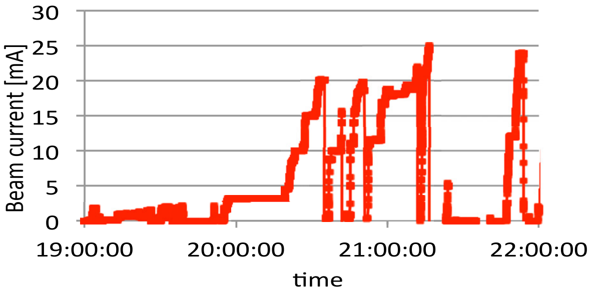

Figure 8: Beam current vs. time during a high current injector run (cw operation , 1.3 GHz bunch repetition rate).

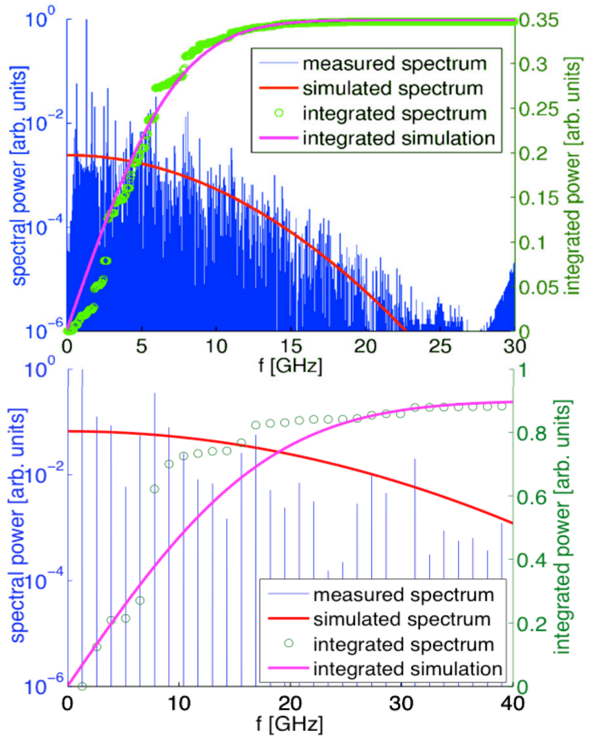

Figure 9: HOM spectrum excited by the beam as measured at one of the HOM loads. The integrated spectrum is plotted on the secondary axis. Also shown are results obtained by ABCI simulations for the entire beamline in the injector module [8]. Top: 50 MHz bunch repetition rate. Bottom: 1.3 GHz bunch repetition rate.

REFERENCES

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

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

[3] M. Liepe et al., PAC'05, Knoxville, TN, USA (2005).

[4] I. Bazarov et al., PAC'09, Vancover, May 2009 (2009).

[5] C. Pagani et al., Adv. in Cryo. Eng., Vol. 45A (1999).

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

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

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