PROGRESS ON SUPERCONDUCTING RF FOR THE CORNELL ENERGY-RECOVERY-LINAC *

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Abstract

Cornell University is developing the superconducting RF technology required for the construction of a 5 GeV, 100 mA light source driven by an energy-recovery linac. Currently, a high current injector cryomodule is under extensive testing and has been operated successfully with beam currents up to 25 mA, thereby transferring 125 kW of RF power to the beam. Excellent field stability with $\sigma_A/A < 2 \times 10^{-5}$ and successful compensation of cavity microphonics were demonstrated. Prototypes of the components of the SRF main linac cryomodule are also under development, including a novel 7-cell main linac SRF cavity. The cavity design is optimized for efficient ERL operation with high beam currents by achieving a high R/Q of the fundamental mode of 387 Ω, by achieving strong HOM damping resulting in a BBU current above 400 mA, and by achieving a low sensitivity of the fundamental mode frequency to changes in the LHe bath pressure, which is a main source of cavity microphonics. In this paper we give an overview of these recent activities at Cornell.

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].
An extensive R&D program is currently ongoing at Cornell University to fully develop the SRF technology for an 5 GeV, 100 mA ERL. This includes the short SRF linac in the ERL injector section as well as the multi-Gev main linac in the ERL loop. The following two sections of this paper discuss these two SRF linacs separately, giving an overview of key challenges and solutions found.

ERL INJECTOR SRF

The Cornell ERL SRF injector section will host 12 SRF 2-cell 1.3 GHz cavities [2] providing a total energy gain of 15 MeV. 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 also Fig. 1 and Table 1. 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. Emittance preservation is achieved by a symmetric beamline (including symmetric twin high power input couplers), which avoids transverse on-axis kick fields, and by providing excellent cavity alignment. A new cavity string alignment concept was implemented 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 re-

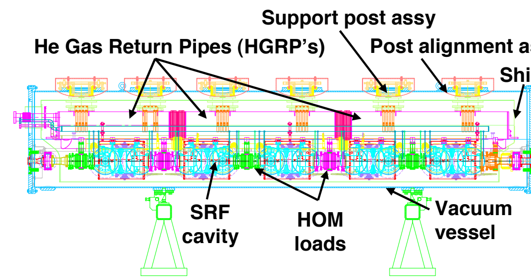

Figure 1: Cross-section of the ERL injector module with 5 SRF cavities and HOM beamline absorbers in between.

Table 1: Injector and Main Linac Cryomodule Specifications

	injector	main linac
Number of cavities	5	6
Number of cells per cavity	2	7
Accelerating gradient	5-15MV/m	16.2MV/m
Fundamental mode frequ.	1.3GHz	1.3GHz
R/Q (circuit definition)	111Ω	387Ω
Loaded quality factor	4.6×10^4	6.5×10^7
RF power per cavity	120kW	5kW
Required amp.. stab. (rms)	1×10^{-4}	2×10^{-4}
Required phase stab. (rms)	0.1°	0.1°
Design beam current	100mA	2x100mA
Total 2K / 5K / 80K loads	26/60/700W	76/70/1500W
Overall length	5.0m	10m

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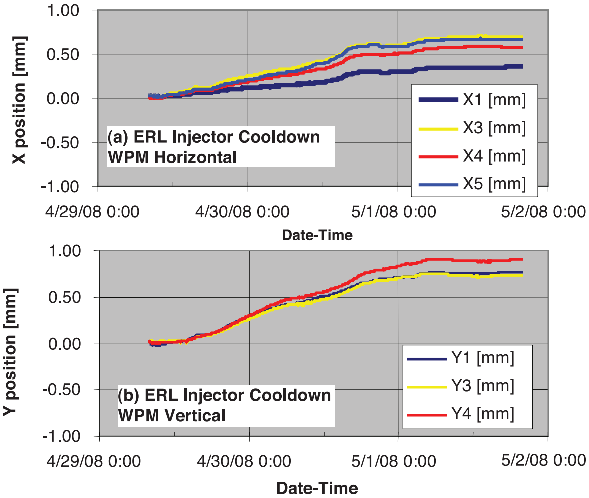

Figure 2: WPM data during cool-down of the injector module. Top: Horizontal position of WPM blocks on cavities 1, 3, 4, and 5. Bottom: Vertical position of WPM blocks on cavities 1, 3, and 4. WPM #2 is not functional.

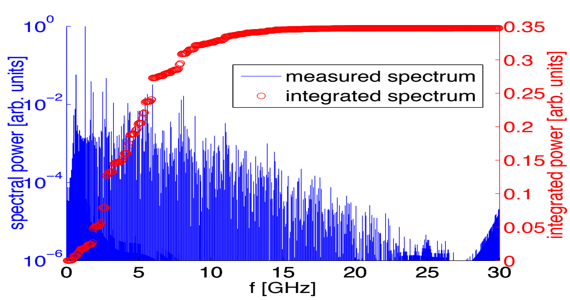

Figure 3: HOM spectrum excited by the beam as measured at one of the HOM loads. The integrated spectrum is plotted on the secondary axis.

turn 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. 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 [5]. Detailed studies of the HOMs excited by the beam have confirmed excellent HOM damping [6]. HOM spectra measurements up to 50 GHz show the expected behavior with varying beam current and bunch repetition rate, and show no weakly damped HOMs, see Fig. 3. As of spring 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. 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. During 25 mA operation, 25 kW of RF power per cavity (125 kW total) were transferred to the beam. The twin high power input couplers [7] are currently conditioned to 50 kW per pair, and have individually exceeded 50 kW during coupler tests. 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, far exceeding the ERL injector and main linac requirements. For more details about the Cornell ERL injector SRF module performance refer to [8].

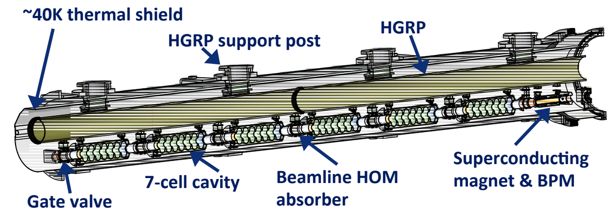

Figure 4: Cross-section of the ERL main linac module with six SRF cavities and HOM beamline absorbers in between.

ERL MAIN LINAC SRF

The 5 GeVCornell ERL main linac will have 384 7-cell SRF cavities, running CW at 16.2 MV/m accelerating gradient. Each main linac cryomodule will host 6 SRF cavities; see Fig. 4 and Table 1. Key challenges that need to be addressed in the main linac cryomodule include: (1) Support of CW cavity operation with high dynamic cryogenic loads, (2) supporting high beam current ERL operation up to 2x100 mA with short (2 ps) bunches, and (3) operating the SRF cavities at a high loaded quality factor $Q_L \geq 6.5 \times 10^7$ while still achieving excellent RF field stability. The module design is based on the successful injector module, employing the same fixed, high precision cavity support and alignment [9] . The cryogenic manifolds inside the cryomodule are sized to handle the substantial cryogenic loads. Three layers of magnetic shields achieve very low residual magnetic fields at the cavity locations to support intrinsic quality factors of the SRF cavities of $Q_0 \geq 2 \times 10^{10}$. The 7-cell main linac cavities are optimized for a high R/Q of the fundamental mode of 387 Ω (circuit definition) and for strong HOM damping by optimizing the shape of the end cells [10], see Fig. 5. HOMs up to 10 GHz in frequency were calculated taking into account realistic material properties of the RF absorbing rings in the HOM beamline dampers. Robustness of the obtained cavity design to small shape imperfec-

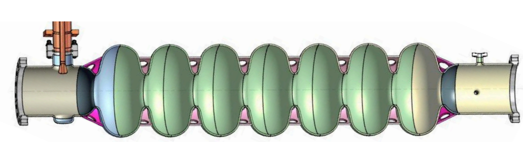

Figure 5: CAD model of the ERL main linac cavity with stiffening ring between the cells, input coupler, and opposite coupler kick compensating stub.

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tions was verified by calculating HOMs in deformed cavity shapes, resulting in a tolerance specification for the cavity cell shape of ± 0.25 mm. Beam-break-up (BBU) simulations were done taking into account the strongest dipole modes found in HOM calculations for the 7-cell cavity shape with realistic RF absorber materials, see Fig. 6. As

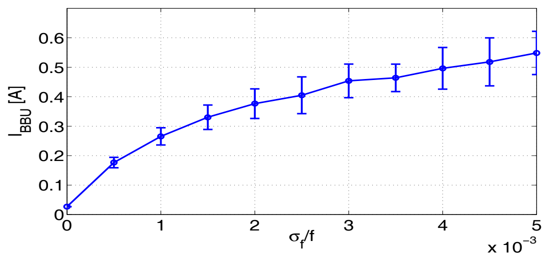

Figure 6: Simulated BBU current in the Cornell ERL main linac vs. relative HOM cavity to cavity frequency spread.

can be seen, larger variation in the cavity to cavity HOM frequencies leads to a larger BBU current, since it reduces the likelihood of coherent excitation of a given HOM in multiple cavities by the beam. While relaxed cavity shape tolerances would increase the HOM frequency spread, they also increase the risk of trapped HOMs which would result in a drastic reduction in the BBU current. Cornell's solution is using several classes of cavities in the main linac, which are small, controlled variations of the baseline 7-cell cavity design [10]. This approach allows increasing the HOM frequency spread significantly to $\sigma_f/f > 4 \times 10^{-3}$, thereby increasing the BBU current to $>$ 400 mA, while still preserving the optimized properties of the accelerating mode. The mechanical design of the cavity was optimized for low microphonics by placing stiffening rings between the cells. Selecting an ideal radial position of these rings reduces the sensitivity of the fundamental mode frequency to changes in the LHe bath pressure (see Fig. 7), which is a main source of cavity microphonics. Prototype cavities are under fabrication, and will be tested without and with beam in test/prototype cryomodules. Tests of Cornell's LLRF control system at HZB have shown that excellent RF field stability can be achieved even at record high loaded quality factors of $Q_L = 2 \times 10^8$ and in presence of very strong field perturbations by cavity microphonics exceeding several cavity bandwidths; see Fig. 8. The potential of actively reducing microphonics was successfully demonstrated at one of the ERL injector cavities, reducing the rms microphonics by as much as 70% as shown in Fig. 9. Other components currently under development at Cornell include a 5 CW kW fixed input coupler [11], a cold frequency tuner with piezoelectric actuators, and a second generation beampipe HOM absorber. Two reliable RF absorbing materials meeting all specifications have been identified: graphite loaded SiC, and carbon-nanotube loaded ceramics [12]. Prototypes of these components will be fabricated and tested in 2011.

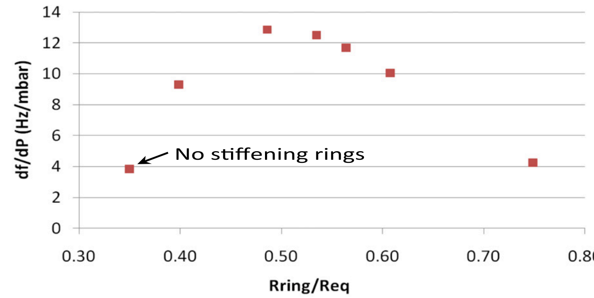

Figure 7: Sensitivity of the fundamental mode frequency to small changes in the LHe bath pressure vs. radius of the stiffening rings between the cells (ANSYS simulations).

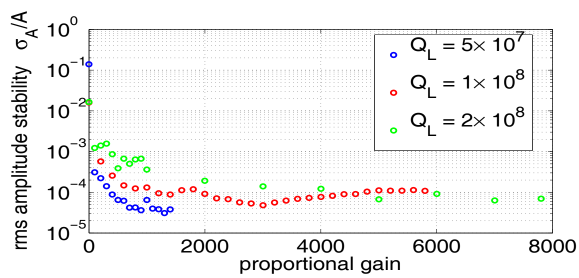

Figure 8: Measured RF field amplitude stability vs. proportional gain for a 9-cell cavity operated at different loaded quality factors in presence of $\approx$ 30 Hz peak microphonics.

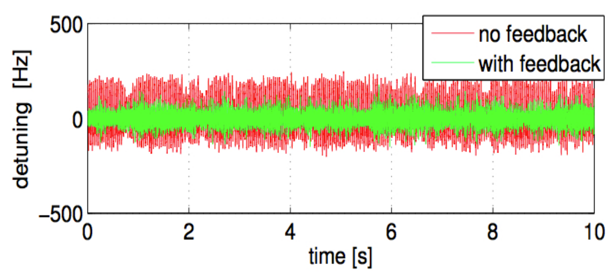

Figure 9: Microphonics compensation by a fast piezoelectric tuner in feedback mode.

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

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

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

[8] M. Liepe et al., SRF 2009, Berlin, Germany (2009). M. Liepe et al., LINAC 2010, Tsukuba, Japan (2010).

[9] E. Chojnacki et al., PAC09, Vancouver, Canada, (2009).

[10] N. Valles, M. Liepe, PAC 2011, New York, USA (2011).

[11] V. Veshcherevich et al., SRF 2009, Berlin, Germany (2009).

[12] E. Chojnacki et al., SRF 2009, Berlin, Germany (2009).

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