Development and Testing of a 3.9 GHz Third Harmonic Superconducting RF System at Fermilab

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Abstract

A 3.9 GHz third harmonic Superconducting RF (SRF) system was proposed to increase the peak bunch current of the particle beam and to linearize the accelerating voltage acting on the electrons within a bunch in the longitudinal phase space for the Free Electron Laser in Hamburg (FLASH) user facility in Germany. Fermilab, as part of the FLASH collaboration, participates in developing and testing the 3.9 GHz third harmonic SRF system. Theoretical consideration, design and simulation, and high-power testing of the 3.9 GHz SRF components including superconducting cavities and main couplers will be presented in this paper.

1. Introduction

The FLASH which stands for Free Electron Laser in Hamburg is an electron linear accelerator providing laser-like radiation in the vacuum ultraviolet and soft X-ray range to various user experiments in many scientific fields. It is also a test bed for further research and development for linear collider related superconducting accelerator technologies. In FLASH system the electron beam bunches are produced in a laser-driven photo-injector and accelerated by a 1.3 GHz superconducting linear accelerator. Producing electron bunches is based on using a long laser pulse to pull a long electron bunch from the photocathode. It is presently impossible to generate ultra-short and highly charged bunches out of an RF gun because of the strong space charge coupling especially at low energy levels [1]. Therefore, in the 1.3 GHz accelerating module, the sinusoidal accelerating voltage profile distorts the long bunches. Such distortion, if not corrected, sets a lower limit on the compression process and can thus significantly decrease the available peak bunch current [1].

A 3.9 GHz third harmonic Superconducting RF (SRF) system shown in Fig. 1 was proposed to increase the peak bunch current and to linearize the accelerating voltage (energy distribution) acting on the electrons within a bunch in the longitudinal phase space for the FLASH user facility [2]. A 3.9 GHz SRF module with four superconducting cavities will be installed downstream of the 1.3 GHz SRF module, containing eight superconducting cavities. The 3.9 GHz superconducting cavities can provide a required accelerating gradient of 14.5 MV/m. The whole accelerating voltage with the consideration of 1.3 GHz and 3.9 GHz SRF modules is actually the cumulative effect of two sine-like accelerating voltages in the cavities the electron beam bunch has gone through. Comparison of the energy distributions in the bunch with or without the 3.9 GHz SRF module is shown in Fig. 2. Installation of the third harmonic SRF module will allow us to generate ultra-short and highly charged electron bunches with an extremely small transverse emittance. This innovative technology is essential to support a new generation of linear accelerators, colliders, and free electron lasers [3].

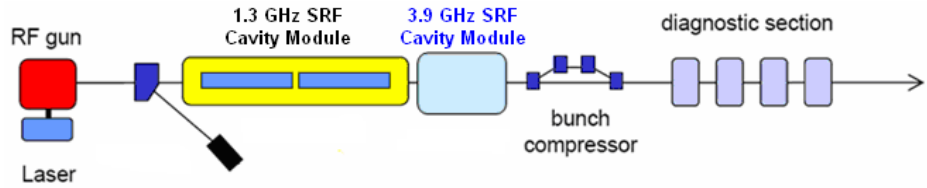

Figure 1: Schematic layout of the FLASH photo-injector

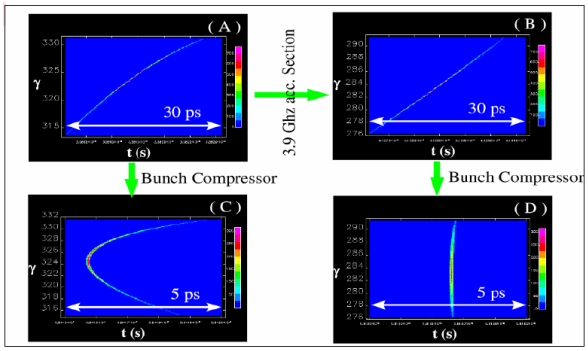

Figure 2: Energy distributions in the bunch before and after bunch compressor without (left) and with (right) the 3.9 GHz SRF module, calculated by P. Piot and W. Decking, Fermilab

2. Design and Simulation

The third harmonic cavity shown in Fig. 3 is made of nine cells with elliptical shape in iris and equator areas. The cavity design has been revised to increase the coupling between couplers and the cavity cells. Regular cells have 30 mm iris diameter, while the end cell iris was increased up to 40 mm in diameter for better coupling with the main coupler and better damping of the higher order modes (HOM) which can lead to bunch instabilities and beam breakup [3]. The cavity design parameters are shown in Table 1.

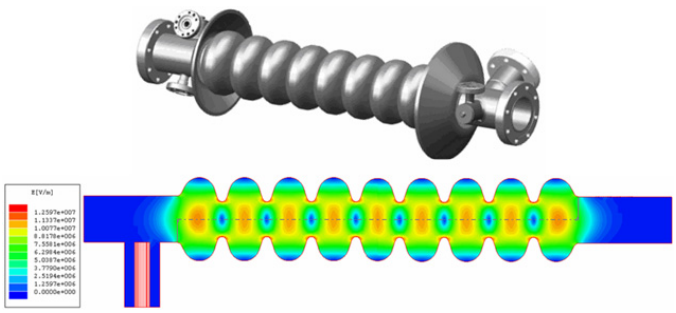

Figure 3: 3.9 GHz third harmonic SRF niobium cavity and electric field map inside the cavity

Table 1: Design parameters of the 3.9 GHz SRF cavity

3.9 GHz SRF cavity design parameters	
Type of Accelerating Structure	Standing Wave
Frequency	3.9 GHz
Active Length	0.3459 m
Number of Cells	9
R/Q	750 Ohm
G Factor	273 Ohm
Accelerating Gradient	14.5 MV/m
Stored Energy	2.5 J
Peak E Field/Accelerating Gradient	2.26
Peak H Field	97 mT (<critical 200 mT)

The final chosen layout of the 3.9 GHz main coupler is shown in Fig. 4. This is a 50 Ohm coaxial line with a 30 mm diameter of outer conductor. For the cold window, we adopted the cylindrical ceramic window with TiN coated to reduce the second yield coefficient. For the warm window, we are using a waveguide circular window with good RF performance at 3.9 GHz frequency. We also applied a two-bellows design for obtaining better RF performance and more mechanical flexibility. Hollow coupler tip can help to reduce the mechanical stress on cold window area. All components of the main coupler including cold window, warm window, bellows section, waveguide-to-coax transition, and diagnostic ports were optimized by high frequency simulation software HFSS for

low reflection at the operating frequency. Finally full geometry was simulated to check the resulting return loss, insertion loss, and field distributions. After careful selection of the geometry and the materials, the return loss was reduced to -23 dB and the insertion loss was only -0.2 dB, respectively.

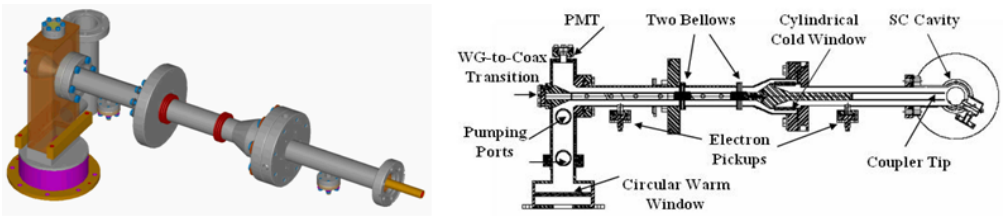

Figure 4: 3.9 GHz main coupler structure

3. Testing Procedures of the 3.9 GHz SRF System

It is important for the main couplers to be tested with high power prior to the assembly on a cavity cryostat since any flaws or contamination of the main couplers can degrade the cavity performance. Two main couplers were assembled in back-to-back arrangement with their probes (tips) connected by a waveguide transition on a test stand. The test was usually done at traveling wave condition with pulsed power at the repetition rate of 1 Hz and under room temperature environment. The maximum peak power measured at the input port of the test stand was 61 kW which is much higher than the FLASH operating level. 54 kW of output power of the test stand was reached at all pulse lengths. The return loss and insertion loss of the test stand were around -18 dB and -0.6 dB, respectively, as shown in Fig. 5. While running the test, no sparks and only minimal temperature and vacuum activities were observed.

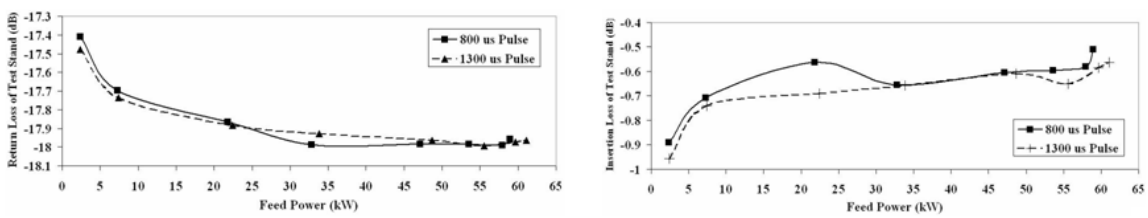

Figure 5: Return loss and insertion loss of the main coupler test stand

During cavity performance test, a low continuous-wave power (RF voltage) was applied to a superconducting cavity and the cavity intrinsic quality factor (Q_0), a measure of the rate of energy loss, was also measured. A high Q_0 means that the cavity will better retain the energy transferred into it. The cavity performance test thus becomes part of the qualification process for determining that the cavities meet all of the extraordinary needs of the FLASH user facility [4]. The goal for the cavity performance test is to obtain an accelerating gradient (E_{acc}) of 14.5 MV/m with a Q_0 in the order of 10^9. The measurements were done during the cool-down from 4 K to 1.8 K. Typical measurements including the accelerating gradient and Q_0 of the cavity No. 5 are shown in Fig. 6. The cavity was running at the gradient of 25 MV/m limited by the power source restriction. Neither X-ray not quench was observed during the test [5].

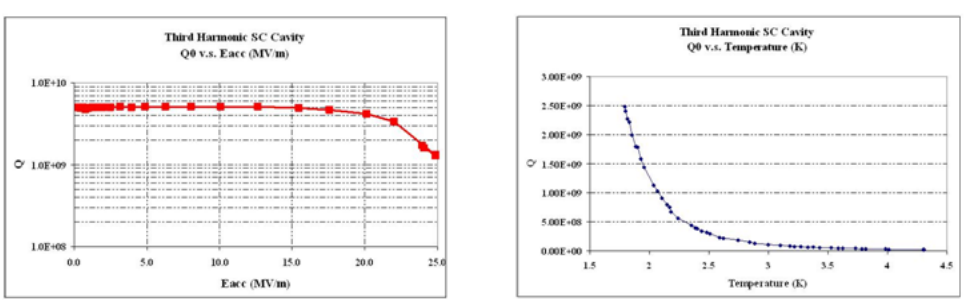

Figure 6: Typical SRF cavity performance testing results

After a cavity passes the performance test, it gets welded inside a helium vessel and dressed with a main coupler, two HOM couplers, a pick-up coupler, and a frequency tuner, as shown in Fig. 7. The cavity gets tested horizontally with high pulsed power inside a cooled cryostat, in order to mimic the conditions inside the accelerator, only without the beam [4]. It is the first time that the cavity will experience the pulsed RF power that will be similar to the conditions inside the FLASH user facility. The maximum accelerating gradient we obtained was around 23 MV/m limited by the cavity quench. The loaded quality factor (Q_L) on the SRF system was measured both before and after the system cool-down. At room temperature and with low level powers, the SRF system operated in the under-coupling regime with a Q_L of 5600. As shown in Fig. 7, the Q_L measured at superconducting state and with high RF powers was about 8.87e5. At this extraordinarily low temperature the SRF system worked in the over-coupling regime due to the almost vanished cavity surface resistance. The Q_0 was also calculated from the measurement of the cryogenic loss of the helium liquid. It was equal to 3.06e9 which is higher than the cavity design specification.

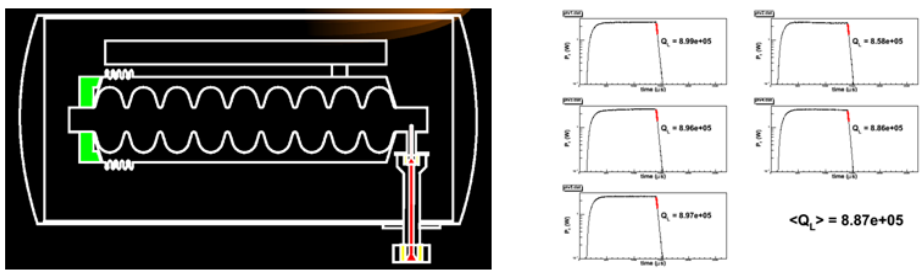

Figure 7: The Q_L curves measured in a coupler-cavity horizontal test stand

4. Conclusion

A novel 3.9 GHz third harmonic SRF system for the FLASH user facility has been proposed and investigated. After design, simulation, and optimization the SRF components have been tested in the test stands for high-power processing and cryogenic measurements. The testing results agree well with the simulation and expectation. The SRF system has shown an excellent performance during the tests. The 3.9 GHz SRF module designed in this way can meet the FLASH system's strict requirements and is suitable for numerous superconducting accelerator applications.

5. Acknowledgments

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