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DESIGN AND MEASUREMENT OF THE 1.4 GHz CAVITY FOR LEReC LINAC*

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Abstract

The Low Energy RHIC electron Cooler (LEReC) is the first electron cooler based on rf acceleration of electron bunches. To further improve RHIC luminosity for heavy ion beam energies below 10 GeV/nucleon, a normal conducting RF cavity at 1.4 GHz was designed and fabricated for the LINAC that will provide longer electron bunches for the LEReC. It is a single cell cavity with effective cavity length shorter than half of the 1.4 GHz wavelength. This cavity was fabricated and tested on site at BNL to verify RF properties, i.e. the resonance frequency, fundamental power coupler (FPC) coupling strength, tuner system performance, and high-power tests. In this paper, we report the RF test results for this cavity.

INTRODUCTION

During RHIC run 2019 and 2020, using LEReC to cool gold ion beams to improve the luminosity was experimentally demonstrated in the Relativistic Heavy Ion Collider at Brookhaven National Laboratory [1]. The linear accelerator (Linac) of the LEReC consists of a DC electron gun, a 704 MHz superconducting radiofrequency (SRF) booster cavity [2], three warm cavities: 2.1 GHz, 704 MHz [3] and 9 MHz. With an additional 704 MHz warm deflecting cavity in the diagnostic beamline [4]. To further improve the cooling capability, a 1.4 GHz warm cavity is designed, fabricated, and tested to stretch the electron bunches in LEReC longer. The cavity design was started from Jan 2020, and the cavity was installed and conditioned in the RHIC tunnel in Nov. 2020.

DESIGN OF THE 1.4 GHz CAVITY

The 1.4 GHz cavity, shown in Fig. 1, is designed to provide 50 kV cavity voltage, it is required to give relatively small beam loading while comparing with the other cavities, and the higher order modes (HOMs) in this cavity should not drive the beam voltage fluctuation to a number higher than the specification at 1 kV.

Key RF parameters are listed in Table 1. The R/Q of this cavity is 104.5 Ω in accelerator definition. Such a low R/Q ensures a low wake potential at 0.23 V/pC. For comparison, for the 2.1 GHz warm cavity it is 1.16 V/pC, and for 704 MHz warm cavity, it is 0.21 V/pC, and for 704 MHz SRF booster cavity it is even lower since it is a 0.4cell cavity. Beam loading from this cavity is not a concern in this case. To get this low R/Q, we use a single-cell pillbox cavity shape, with length shorter than half of the 1.4 GHz wavelength λ, 3” ID beampipe, and without nose cone structure. For comparison, the 704 MHz warm cavity right on the downstream of this cavity has an 82mm ID, and the beampipes connected to this cavity has a 2.375” ID. For convenience, this cavity uses the same tuner and FPC RF window as the 2.1 GHz cavity. Cavity length longer than half λ may also be used to achieve lower R/Q, the HOM induced voltage fluctuation determines the cavity length, which will be discussed later.

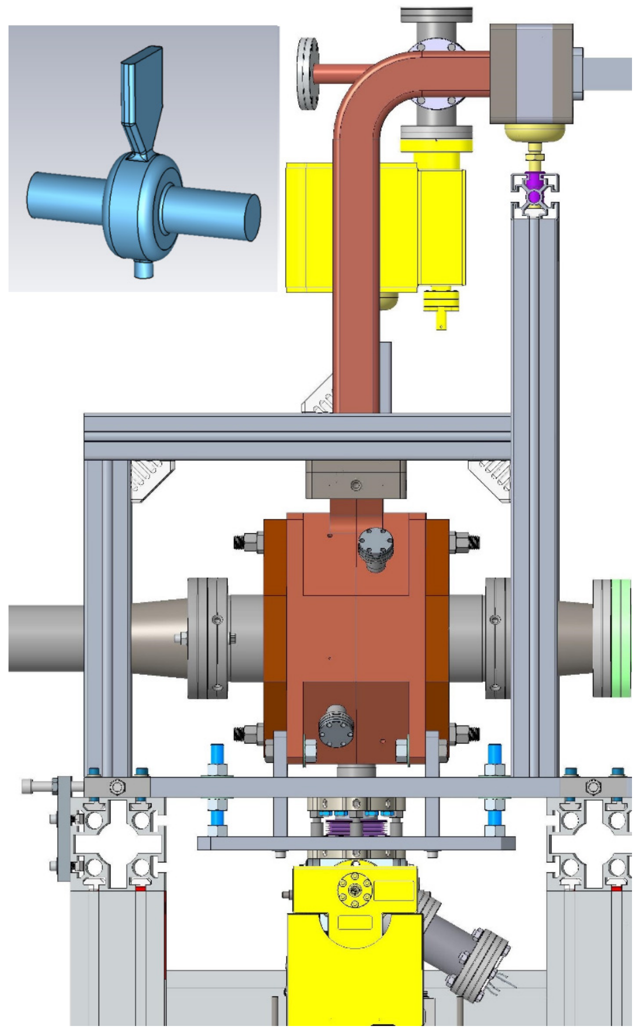

Figure 1: Vacuum model of the 1.4 GHz warm cavity. The L shape rectangular waveguide on the top is the FPC, with RF window on the top right, and an arc detector port with line of sight on the left of the window. The tuner is on the bottom. There are four ports on the cavity wall, with two shown in the plot and the other two on the back side, that serve as ports for fixed tuners and pickup couplers. The figure on the top left is the vacuum model of this cavity.

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Table 1: Key RF Parameters of 1.4 GHz Warm Cavity

Parameter	Value
Voltage [kV]	50
Freq [GHz]	1.408
R/Q [Ω] acc. def.	104.5
Q_0 (Cu with roughness)	20,600
Stored energy [Joule]	0.0027
Q_{FPC}	20,600
Power dissipation on cavity [kW]	1.2
Loss on waveguide & circulator [dB]	2
Power amplifier [kW]	3

The FPC design is similar to the 2.1 GHz warm cavity design. To comply with the tight schedule, we use the same L shape waveguide with JLab530 RF window as used in the 2.1 GHz. Instead of JLab530 to WR430 waveguide transition for 2.1 GHz, in this cavity, JLab530 to WR650 aluminium (Al) adaptor on the air side is used. The FPC external quality factor Qext is set at 20,600. Due to the uncertainty in the surface roughness of the Cu, the cavity unloaded quality factor Q0 may vary from 20,000 to 27,000, with which the FPC coupling strength β may vary from 0.97 to 1.31, a maximum dissipated power on cavity wall at 1.2 kW, and a maximum reflected power at 16 W. Decision is made that no FPC tuner is needed for this cavity.

For the main frequency tuner, a straight coaxial design similar to the 2.1 GHz cavity tuner is used [5]. To determine the tuner length, we use an Al tuner with a variety of spacers so that different tuner lengths can be realized. With the tuner aligned to the center of the tuner housing, which is realized by adjusting the port aligner to minimize the RF leakage (the amplitude of the S21 from the FPC to the antenna on the tuner), three resonant modes adjacent to 1.4 GHz are monitored, see Fig. 2. By extrapolating the data to shorter and longer tuner lengths, conclusion is made that tuner with 195.4 mm or 300.3 mm vacuum length is preferred so that in the tuner section, adjacent resonances can be away from 1.4 GHz. It is difficult to make the tuner with 195.4 mm length since certain length is needed to accommodate the port aligner, the cube, and the bellow for the tuner. We have two backup tuners for LEReC 2.1 GHz, one with 270.3 mm length and the other one with 291 mm length. The tuner with 270.3 mm has a resonance that is only 27 MHz away from 1.4 GHz, 291 mm tuner is chosen for 1.4 GHz cavity. The tuner is designed to be tuned -10 mm to +6 mm from nominal position (flush to the cavity inner wall), corresponding to -1.0 MHz to +1.1 MHz.

Two fixed tuner knobs that are the same as the ones in the 2.1 GHz cavity [3] are designed to compensate possible frequency shift due to fabrication and brazing, with each one provides 0.32 MHz frequency shift with the knob +8 mm inserted into the cavity comparing with the knob flush to the cavity inner wall. Two knobs provide a total ±0.32 MHz frequency shift, with nominal position +4 mm insertion. The RF power dissipation on each knob is < 7.4 W, which is not a major concern.

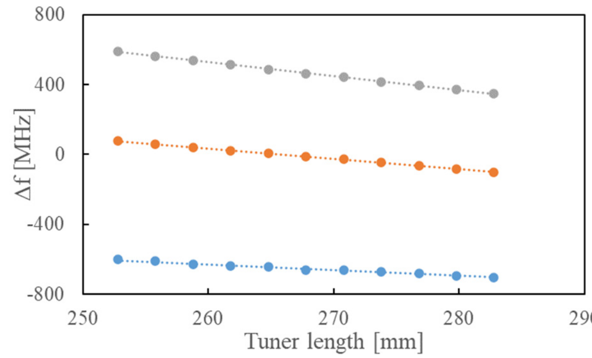

Figure 2: Three resonances (showed as three lines in the plot) in the tuner that are adjacent to 1.4 GHz, with x axis the tuner length and y axis the frequency away from 1.4 GHz.

Multiphysics simulation is also done to this model. With 35 °C cooling water, the maximum cavity mass temperature will be 2.6 °C higher at 50 kV cavity voltage, resulting maximum Von-Mises stress of 5.2 MPa, much less than the yield at 33.3 MPa, and maximum displacement of 7.3×10^{-5} meters. During operation, the water temperature is 26.5 °C, with ±3 °C fluctuation, corresponding to ±0.08 MHz frequency fluctuation. The cavity resonance frequency, measured at 22 °C with cavity under vacuum, is set at 1.4078 GHz with fixed tuners flush to the cavity. Cavity inner diameter is set at 6.8360 inch ±0.0005 inch.

As shown in Fig. 1, two 3" to 2.375" ID, 4" long tapers are used to connect the cavity with adjacent beampipes. Within this design, there are two modes, TM_{020} and TM_{011}, that need to be taken care of to suppress the voltage fluctuation. For the TM_{020} mode, a λ/2 cavity with 58 Ω R/Q in accelerator definition could produce a voltage fluctuation beyond the specification, while in this design, with cavity length shorter than λ/2 to suppress the R/Q of fundamental mode, the R/Q of TM_{020} mode is also suppressed to 0.15 Ω. The length of this cavity is also tailored so that the frequency of TM_{011} mode is always from the multiple of 704 MHz, thus the voltage fluctuation is suppressed. Based on simulation, the HOM induced voltage fluctuation is ±0.15 kV considering the worst case scenario [3]. For comparison, in case there is no tapers, with 3" beampipes, this number is lowered to ±0.12 kV. A combination of the insertion of fixed tuners and main frequency tuner can also be used to fine adjust the frequency of TM_{011} mode while maintaining working frequency at 1.408 GHz. The total HOM power generated in this cavity is estimated to be less than 15 Watts, with 20% on the stainless-steel section of the tuner.

TEST OF THE 1.4 GHz CAVITY

An aluminium (Al) cavity was first fabricated, with two halves bolted on instead of brazing. With main tuner flush to the cavity inner wall, and both fixed tuners 4 mm

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insertion, the cavity frequency at room temperature in air is 1.40738 GHz, with Q_0 at 13,400, close to our expectation at 1.40744 GHz and Q_0 15,700. The degradation of Q_0 came from: 1, Al's conductivity is not as good as ideal; 2, The joint between two half cells cannot provide ideal contact, tighten the bolts/nuts makes Q_0 increasing from 5,100 to 13,400. We had similar degradation on 2.1 GHz Al cavity, so it is not a concern. Frequency is off by 0.06 MHz, corresponding to 0.2 mm measurement error of main tuner insertion. The FPC external Q Q_{FPC} is measured at 22,000, close enough to the simulated result at 20,600 while considering the following facts: 1, cavity and waveguide are connected using clamps, they are not perfectly aligned; 2, homemade JLab530 to type N waveguide adaptor, the match is not perfect. Frequency ranges -0.8 ~ +1.0 MHz, with -10 ~ +6 mm tuning range, close to simulation result at -1.0 ~ +1.1 MHz. Each fixed tuner gives 0.32 MHz tuning range, as expected. The resonances in the main tuner section are at least 150 MHz away from 1.408 GHz, as expected.

For the Cu cavity, two fixed tuners give 0.4 MHz/each frequency tuning range, they are both set at the center of tuning range (nominal), 0.2 MHz/each. Port aligner of the main frequency tuner was carefully adjusted to minimize the amplitude of S_{21} from FPC to antenna on the tuner. The tuner tip was not located in the center of the tuner port after adjusting the port aligner, possibly due to some misalignment of the tuner housing. With main tuner location from 15 mm to 40 mm, and fixed tuners in nominal position, the cavity resonance frequency is 1.4077 GHz +/-1.05 MHz with air, corresponding to vacuum frequency at 1.4081 GHz, with estimated RF/water induced thermal expansion caused frequency shift (lower) of 0.1 MHz. Without RF window and the airside Al adaptor with tuning knobs, the FPC coupling coefficient is 1.1, slightly over coupled. Cavity's Q_0 is 24,800, Q_{FPC} is 22,800. With the full setup including RF window and Al adaptor, the tuning knobs were adjusted so that the FPC coupling coefficient is 1.015, almost critical coupled. There are two PU couplers on the cavity, one with Q_{ext} at 8.5e6, and the other with 3.1e7. Both provide Watts range output power at 50 kV cavity voltage. The resonances in the main tuner are 0.66933 GHz, 1.27312 GHz, 1.83699 GHz, far away from 1.408 GHz. The port aligner is fine-tuned so that the tuner PU can only detect noise level signal from fundamental mode. The cavity was conditioned to 56 kV cavity voltage, with some degassing during the voltage increasing, with vacuum level up to 1e-7 torr. During operation, the cavity voltage will be < 50 kV.

CONCLUSION

A normal conducting cavity at 1.4 GHz was designed and tested for LEReC project to stretch the electron bunch length longer. Some components designed for LEReC 2.1 GHz cavity were used in this design. This cavity provides low beam loading and low HOM induced voltage fluctuation while comparing with 2.1 GHz cavity. The cavity provides 50 kV accelerating voltage.

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