HOM DAMPING PERFORMANCE OF JLAB SL21 CRYOMODULE#

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Abstract

The SL21 cryomodule is a first 1.5GHz, 12.5MV/m, 7-cell cavity, 8-cavity string superconducting accelerator module produced at JLab. The first two passbands of TE111 and TM110 high order modes (HOM) have to be damped to avoid beam breakup problems at 460μA current. External Q's of the HOM couplers and waveguide were measured on a copper model, on cold niobium cavities in vertical tests and finally in the cryomodule without beam. This paper presents all HOM data and general measurement techniques. A threshold current predicted by MATBBU code based on these data and the 6GeV machine beam optics is 10mA.

INTRODUCTION

The new SL21 cryomodule is the first example of a 7 cells/cavity, 8-cavities/string superconducting accelerator module developed for the JLab 12GeV Upgrade project. The specified accelerating gradient is 12.5MV/m to achieve total voltage of 70MV. It replaced a 5MV/m, 5 cells/cavity, 8-cavities/string old CEBAF cryomodule in the South Linac tunnel No.21 slot. Adding two more cells in each cavity to gain more beam voltage was the original design goal. The cavity cell shape remained the "Original Cornell" (OC) design. The cavity irises and beam pipe radii are 35.3mm. The HOM couplers resemble the DESY welded type. Two are attached at one end of the cavity outside the tuner hub, separated azimuthally by 115°. The couplers' center is 80mm from the first end cell edge. A λ/4-stub fundamental power coupler (FPC) waveguide is located at the other end of cavity (see Figures 1&2). Without changing the tuner design, the HOM couplers could not be brought closer to the end cell or moved to the other side of cavity.

MAFIA SIMULATION

A MAFIA 2D(R, Z) simulation was preformed for this "OC" shape with ~1mm mesh steps and double precision. Up to 50 monopoles and 50 dipoles were calculated in the frequency domain. The TE111 and TM110 dipole modes are the first two HOM passbands above the TM010 fundamental passband. Those with high R/Q values were identified as potentially dangerous modes for the beam breakup (BBU) problem in the CEBAF accelerator. The R/Q was calculated for each mode at 1cm off-axis distance and normalized in Table 1. It agrees with an early URMEL calculation [1]. One mode in the TE112 passband was also found to have a high R/Q. It is included in the last row of Table 1. We did not calculate the Q externals of HOM couplers with MAFIA. They were determined by measurements on a copper model.

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Figure 1: JLab "OC" shape, 1.5GHz, 7-cell niobium cavity with helium vessel removed.

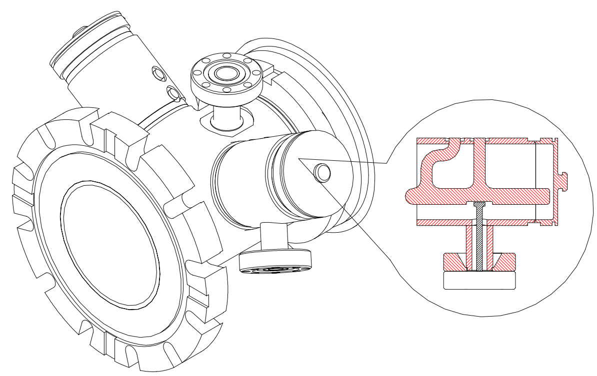

Figure 2: HOM coupler design adopted from DESY.

Table 1: MAFIA R/Q calculation for "OC" shape with a 9cm-long beam pipes and the electric boundary on each end. Here k=2π/λ, a=off-axis distance. Shaded rows are high R/Q modes dangerous for BBU problem.

Frequency [MHz]	R/Q [Ω/cm^2]	(R/Q)/(ka)^2 [Ω]
1725.3	0.03	0.3
1746.4	0.005	0.04
1780.2	0.56	4.0
1824.0	0.37	2.5
1874.3	13.3	85.9
1926.0	10.1	61.9
1991.5	0.47	2.7
2000.6	2.93	16.7
2068.6	0.35	1.9
2089.2	5.73	29.9
2102.5	5.59	28.8
2109.7	0.03	1.4
2113.5	0.005	5.2
2113.9	0.56	0.7
2953.1	11.38	29.7

COPPER MODEL MEASUREMENT

The HOM coupling was measured on the bench by using a calibrated network analyzer to get two-port S parameters. Port 1 is the launching electric antenna, Port 2 is the HOM coupler pickup in which the Q external to be determined. To get more accurate data when $Q_{ext}>>Q_0$ for room temperature copper, a good launching position to get nearly critical coupling $\beta_1=1$, and less perturbation to the intrinsic cavity field is preferred. An array of small holes along the cavity wall from irises to equators at different azimuths was drilled, so an optimum hole with a minimum antenna insertion can be chosen. Q external can be calculated from the S parameters as follows.

$$\beta_1 = \frac{|1\mp S_{11}|}{|1\pm S_{11}|} \qquad \beta_2 = \frac{|1\mp S_{22}|}{|1\pm S_{22}|} \tag{1}$$

$$Q_{ext,trans} = \frac{4\beta_1}{1+\beta_1+\beta_2} Q_{load} \times 10^{\frac{|S_{21}|(dB)}{10}} \quad \text{(Transmission)} \tag{2}$$

$$Q_{ext,refl} = Q_{load} \frac{1+\beta_1+\beta_2}{\beta_2} \quad \text{(Reflection)} \tag{3}$$

Here, Q_{load} is measured at –3dB bandwidth of S_{21}. In Equations (1), upper signs are for under coupling $\beta<1$, lower signs are for over coupling, $\beta>1$. In the case of $\beta_2<<1$, Equation (1) gives a large error. Equation (4) can be used instead.

$$\beta_2 = |1 - S_{22}/S'_{22}| / |1 + S_{22}/S'_{22}| \tag{4}$$

Here S_{22} is at resonance and S'_{22} is at off-resonance where there is nearly full voltage reflection. In this case, transmission method Equation (2) will give a more accurate result with a careful cable calibration. In Figure 3, the port-dependent Q externals were plotted.

For the positive mode identification and the electric field profile, a bead-pull system with a dielectric bead passing through the cavity off-axis was integrated with this bench setup.

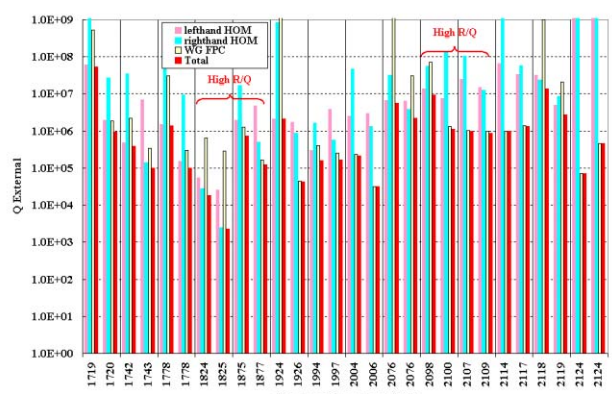

Figure 3: Q external measurement on a copper model.

VERTICAL COLD TEST

Five of eight niobium cavities in the SL21 cryomodule were tested at our Vertical Test Area (VTA) with the both HOM couplers and the Field Probe (F.P.) installed and with their cable connections up to the warm interface. The waveguide (WG) is at bottom and shorted with a niobium blank. The whole assembly including HOM couplers at the top can be cooled to a temperature of 2K. The power coupling port is at the bottom beam pipe flange with a Q external of the TM010 π mode ~10^9. The S_{21} measurement was done from this port 1(PC) to the F.P. port 2. A phase shifter was used with its input connected on each HOM coupler warm connector. So the –3dB frequency bandwidth of Q load can be minimized ($\Delta f'_L$) to get the highest Q'_L by adjusting the phases with the shifters' outputs shorted (or open), see Equation (5). When a 50Ω load is put on one of the shifters' outputs, for example, on HOM coupler 1. The loaded Q is changed as Q_L in Equation (6). So the Q external of HOM coupler 1 $Q_{ext,HOM1}$ can be determined by the new bandwidth (Δf_L) from Equation (7). Here the f is the resonance frequency when the 50Ω load is put on. The condition of approximation is when $Q'_{ext,HOM1}>>Q_{ext,HOM1}$. That means the loss in the standing wave at lossy cable and joints has to be much less than the loss to the 50Ω load. We found that when the Q external of the HOM coupler is very high (>10^8), this method doesn't apply. The power transmission method, Equation (2), could be used instead.

$$\frac{1}{Q'_L} = \frac{1}{Q'_{ext,HOM1}} + \frac{1}{Q'_{ext,HOM2}} + \frac{1}{Q_0} + \frac{1}{Q_{ext,PC}} + \frac{1}{Q_{ext,F.P.}} \tag{5}$$

$$\frac{1}{Q_L} = \frac{1}{Q_{ext,HOM1}} + \frac{1}{Q'_{ext,HOM2}} + \frac{1}{Q_0} + \frac{1}{Q_{ext,PC}} + \frac{1}{Q_{ext,F.P.}} \tag{6}$$

$$Q_{ext,HOM1} \approx \frac{1}{1/Q_L - 1/Q'_L} = \frac{f}{\Delta f_L - \Delta f'_L} \tag{7}$$

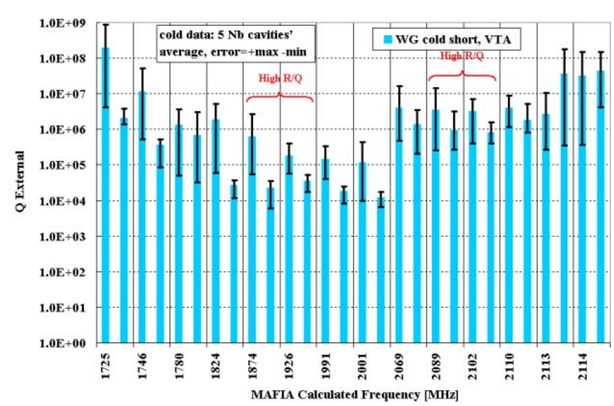

Figure 4: Q external measurement in vertical tests.

When the damping by the HOM couplers was found to be limited, a separate cavity vertical test was carried out with the WG connected to a warm load through a warm window. The result [2] indicates that the waveguide has a limited damping which is different from an early measurement [1] done on a horizontal test bed (HTB). This result was confirmed by the later cryomodule tests.

CRYOMODULE COLD TEST

After the SL21 cryomodule was cooled down to 2K and before the waveguides were connected to the high power source in our Cryomodule Test Facility (CMTF), we were able to measure the loaded Q of the HOMs by the transmission from HOM1 to HOM2 with the "WG short" and the "WG load" conditions. The "WG load" is a low power waveguide load with a tapered RF absorber inside. We found out from a separate measurement that the VSWRs of this load within the HOM spectrum are between 1.07:1 and 1.34:1. When the cryomodule was finally installed in the CEBAF tunnel, 8 HOM waveguide filters were installed in a "T" joint with the high power waveguides. Gamma Microwave made these filters in 1990. The specification range of the VSWRs in the HOM spectrum is 2.0~3.0:1. In Figure 5, we summarize all data in the cryomodule measurements. The error bars in this plot represent the range's values among the 8 cavities in the module. The difference of data between the "WG short" and the "WG load" in CMTF should indicate the additional waveguide damping to the HOM couplers. "WG HOM filter" data is the end performance of HOM damping at the SL21 cryomodule in CEBAF tunnel. We have also searched for the 2953MHz mode. It mixes up within monopole and quadruple modes. So we measured all Q loads in the frequencies around 2953 MHz. No modes with more than 1.0×10^6 Q external were found in any cavity even with the waveguide shorted.

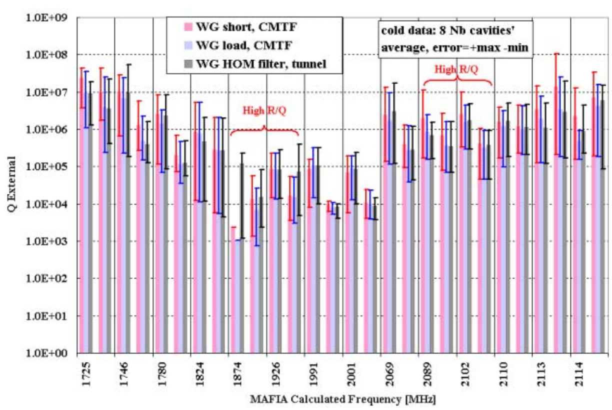

Figure 5: Q external measurement in cryomodule.

MATBBU SIMULATION

The MATBBU is a code for calculating beam breakup threshold current in a re-circulating linac [3]. The Q external data of "WG short, CMTF" were input into the MATBBU with the current beam optics of 6GeV machine. The predicted lowest threshold current is 10mA, which is limited by two high R/Q modes in the TE111 passband. All other modes have higher threshold currents. Figure 6 shows the final results, where the beam impedance is normalized by $(R/Q)Q_{ext}/(ka)^2$. The data points are averaged beam impedance pre cavity. The error bars indicate the frequency spread range over the 8 cavities within the module.

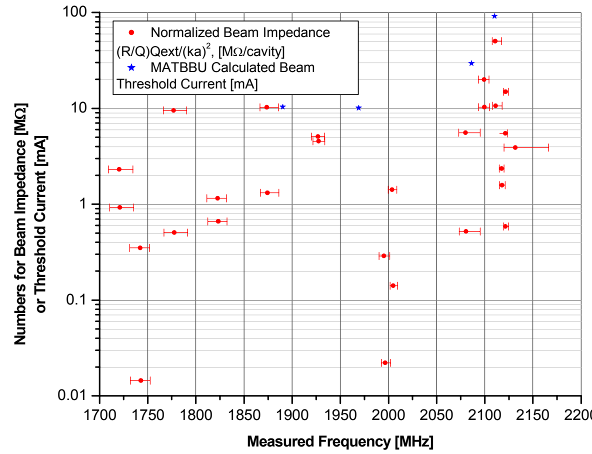

Figure 6: SL21 beam impedance and threshold current for 6GeV CEBAF machine.

SUMMARY

All HOM data measured for SL21 cryomodule without beam indicate that the TE111 and TM110 mode damping is sufficient for the 12GeV Upgrade machine (460 μA). To improve other performance, two types of 7-cell cavities for the Upgrade [4] have been developed.

It was found out by MATBBU that the SL21 damping was not sufficient for a high current (>10mA) FEL's etc. In order to improve the HOM damping to the $Q_{ext}=10^3\sim10^4$ level, some trials were done on this copper model by extending the HOM coupler antenna tip or putting an extra elliptic coupler at the FPC side. No significant improvement was possible without a major redesign of the end groups and tuner. No further attempt was done on this structure. Instead a 2×5-cell Superstructure type cavity was proposed [5].

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