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HIGH ORDER MODES SURVEY AND MITIGATION OF THE CEBAF C100 CRYOMODULES*

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Abstract

Ten new C100 cryomodules have been fabricated and installed for the CEBAF 12 GeV upgrade in the past few years. The high order modes (HOM) of these modules need to be controlled to avoid beam breakup (BBU) instability. Over the last few years, we surveyed the HOM for all the 80 cavities of the C100 modules in the Vertical Test Area (VTA), as well as in the JLAB Cryomodule Test Facility (CMTF) and the CEBAF tunnel. Additional measures such as waveguide filters were applied to reduce the quality factor of the out of spec modes. In addition, we also measured the same passband modes of all the cavities. In this paper, we will present the HOM survey methodology and results from CMTF and CEBAF survey (not including the VTA survey), as well as the same passband modes. The mitigation measures and their effects will also be discussed.

INTRODUCTION

The CEBAF 12 GeV upgrade added 10 new cryomodules (CM) in its 5.5 passes linac. Each CM is designed to provide ~100 MV acceleration voltage (which gives the name C100), or 108 MV including a ~10% overhead. Each C100 CM contains 8 low-loss shape 7-cell 1497 MHz superconducting RF (SRF) cavities [1]. Due to the low loss in the SRF cavities, HOMs usually have high unloaded quality factors. If one HOM is not well damped through external couplers, it can be easily excited to significant level by the beam, resulting beam instabilities. The main concern for the CEBAF linac is the beam breakup (BBU) instability caused by the dipole HOMs in the cavities. In 2007, with the installation of the prototype cryomodule "*Renascence*" in CEBAF, recirculating BBU was observed at about 40 μA [2].

If only one HOM in one cavity is considered, the threshold current for 2-pass BBU is [3]:

$$I_{th} = -\frac{2pc}{q}\frac{1}{(R_d/Q_0)Q_d k m^* \sin(\omega T_r)}, \quad (1)$$

where pc is the particle energy on the second pass, q is the particle charge, (R_d/Q_0) is the transverse shunt impedance of the cavity dipole HOM (which can be obtained from cavity 3-D simulation); ω is the HOM angular frequency; Q_d is the loaded quality factor of the dipole HOM, usually obtained from network analyzer (NWA) measurement; k=ωc is the HOM wave number, T_r is the recirculation time; and m^* is a parameter determined by the beam recirculation transport matrix. To ensure CEBAF operating at certain current and energy without BBU, the impedance $(R_d/Q_0)Q_dk$ of each HOM needs to be controlled under certain threshold. For the CEBAF baseline of 12 GeV and ~438 μA total circulating current operation (~87.5 μA injection current), the impedance threshold is specified at 2.4×10^{10} Ω/m. The stretched goal will allow CEBAF to operate at 6GeV and ~875 μA total current (~175μA injection current), with more stringent impedance budget of 1.0×10^{10} Ω/m [4].

The dipole HOMs in a C100 cavity have 3 passbands, namely TE111, TM110 and TM111. In each passband, there are 7 different phase advance modes, ranging from π/7 to π. The axial symmetry in the cavity was broken due to the couplers, gravity, and fabrication errors, so the vertical and horizontal modes are non-degenerate, double the number of modes to 14 in each passband and 42 in all. All the 42 modes need to be damped and surveyed, with extra attention on the modes with higher R/Q. In addition to the HOMs, the fundamental accelerating TM010 π mode also brings 6 extra modes with different phase advance, also known as same passband modes (SPM). These modes are close to the accelerating π mode and are hard to damp. The frequencies of SPM need to be closely monitored, so the beam optics design can avoid resonances at these frequencies.

Table 1: C100 SPM and Dipole HOM Passbands

TM010	1474-1497 MHz
TE111	1850-2050 MHz
TM110	2050-2250 MHz
TM111	2850-3050 MHz

A C100 cavity uses two coaxial DESY-type couplers (115° apart) on one side of the cavity to damp differently polarized transverse HOMs [2]. For multi-cell cavities, this design might be insufficient if the field of certain HOM is tilted. To damp those tilted modes, waveguide HOM filters can be installed at the fundamental power couplers (FPC) of selected cavities. When the C100 CMs are installed in the CEBAF tunnel, waveguide filters are installed at cavity 1, 8, and additional cavities with high impedance HOM found in the CMTF HOM survey. Fig. 1 shows the line-up of cavities in a cryomodule, as well as the locations of HOM couplers and FPC. The HOM couplers are connected to type-N ports outside the CM.

HOM SURVEY METHODOLOGY

The C100 cryomodule HOM survey uses NWA to measure the RF cross-talk between one cavity's HOM ports and its neighbouring cavity's. Each cavity pair measurement contains the modes from both cavities in the pair. TM111 modes may travel through more cavities and show up in more measurements, because it's above the

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Figure 1: Cavity line up in a C100 cryomodule.

cut-off frequency of the beam-pipe. The source cavity of each mode also needs to be identified.

Typically, a 4-port NWA like Agilent ENA 5071C is used, connected to the 4 HOM ports of the two neighboring cavities (i.e., port 1 to HOM1A, port 2 to HOM1B, port 3 to HOM2A, port 4 to HOM2B). 4 traces (S31, S32, S41 and S42) over the HOM passbands will be taken. With the polfit [5] Mathematica package, the NWA S-matrix traces are analysed during the survey to get the HOM frequencies and Qs. Modes from polfit with Q higher than 1×10^6 or other suspicious behaviour will be confirmed with NWA manual measurement. Once a high impedance mode is identified, we will request for a waveguide filter on that cavity.

We have surveyed all the 10 cryomodules in both the CMTF and the CEBAF. For the first two modules (C100-1 and C100-2), beam experiment was made after they were installed in CEBAF in 2011 [6] and found that the BBU threshold is well above the specification.

C100 HOM AND SPM RESULTS

SPM Results

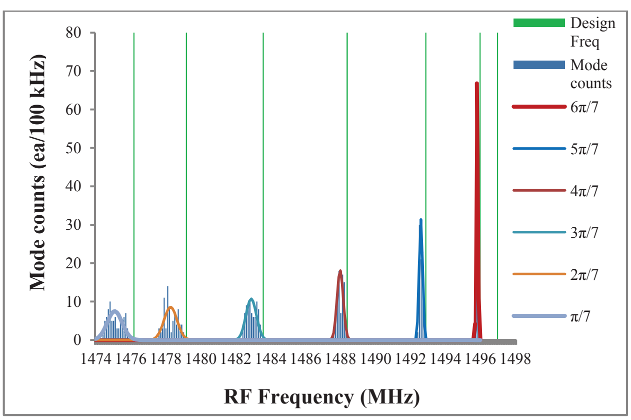

Figure 2: Frequency Distribution of SPM (80 cavities), with π mode tuned or scaled to 1497.000±0.008MHz.

We summarized the frequency and Q distribution measured on all the 80 C100 cavities, shown in Fig. 2 and Table 2. Most of the data were measured at CEBAF when the cavities' TM010 π modes were tuned close to 1497 MHz. In the case the CEBAF tuned cavity data were missing, we may use CMTF tuned cavity data, or scale the untuned cavity data to 1497 MHz.

HOM Results

During the CMTF HOM survey, we found 7 modes in 4 modules (5 cavities) that exceeded the stretched Q threshold. All the modes are the TM111 $\pi/7$ modes, which have the highest R/Q value and lowest Q threshold among all the dipole modes. The baseline Q threshold for this pair of modes is 3.7×10^6 and the stretched Q threshold is 1.55×10^6. Most of those modes are below the baseline specification during the CMTF test, and are brought down below or close to the stretched threshold with waveguide filters after being moved to the CEBAF tunnel. The only exception is the pair of modes in cavity C100-9-6. The H mode was above baseline in CMTF and damped to a level between baseline and stretched threshold in CEBAF; the V mode was between the baseline and stretched goal at CMTF, but Q increased to 5.83×10^6 in CEBAF. We tried to use stub tuners at the HOM port and was able to bring the V mode Q to 3.2×10^6 (below the baseline spec) and the H mode Q to 1.5×10^6. Nonetheless, this cavity is currently running without the stub tuners at the request of beam physicists, providing an opportunity for future BBU beam experiments. Additional measures are still available to bring down the Q further, such as an additional waveguide filter at cavity 7.

Fig. 3 shows the frequency distribution of the TM110 $4\pi/7$ mode from CMTF survey, with impedance value well below the specification. That's one mode with high *R/Q* and one of the modes observed to cause the "*Renascence*" BBU (although the cavity causing BBU in the "*Renascence*" is the High-Gradient shape). Fig. 4 compares the impedance of all the HOM modes observed in cryomodule C100-9 at CMTF and in the CEBAF tunnel. Due to the length limitation of this paper, we can only present a small selection of our results. The full results will be published in [7].

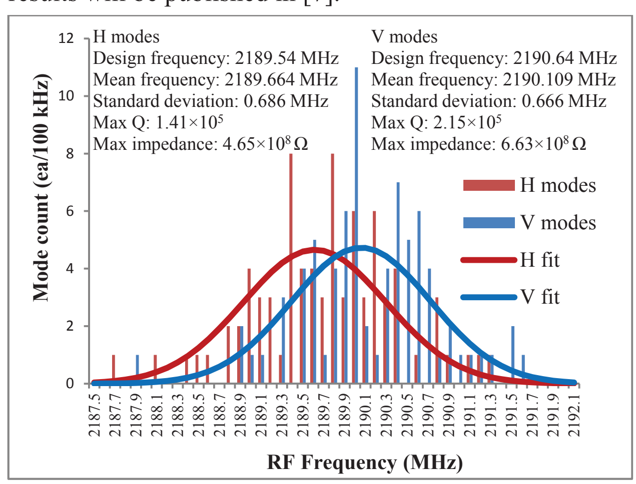

Figure 3: Frequency distribution of TM110 $4\pi/7$ modes, all 80 cavities from CMTF survey.

CONCLUSION

We have summarized the HOM and SPM survey results of the C100 cryomodules, including the frequency and Q distribution. After the cryomodules were installed in the CEBAF, most of the high impedance HOMs satisfied the BBU current threshold requirement. Only one mode needs additional coax stub tuners to meet the baseline specification in CEBAF, but is left as is for BBU beam experiment.

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Table 2: C100 Same Passband Modes Frequency and Q Statistics (all 80 cavities)

	Frequency(MHz)					Q		
Mode	Design	Mean	Standard Deviation	Min	Max	Design	Mean	Standard Deviation
π	1497.0000	1496.9998	Tuned	1496.9927	1497.0078	3.12E7	2.77E7	7.00E6
6π/7	1495.9081	1495.7604	0.0466	1495.6762	1495.8511	1.68E7	1.40E7	3.27E6
5π/7	1492.8245	1492.5484	0.1017	1492.3332	1492.7317	2.06E7	1.50E7	3.11E6
4π/7	1488.3920	1487.9314	0.1756	1487.5663	1488.2565	2.88E7	2.06E7	5.08E6
3π/7	1483.5045	1482.8434	0.2980	1482.3150	1483.3737	4.77E7	3.47E7	1.02E7
2π/7	1479.1317	1478.2272	0.3729	1477.5521	1478.9709	1.03E8	6.99E7	3.20E7
π/7	1476.1070	1475.0307	0.4262	1474.3147	1475.8021	4.05E8	1.58E8	1.09E8

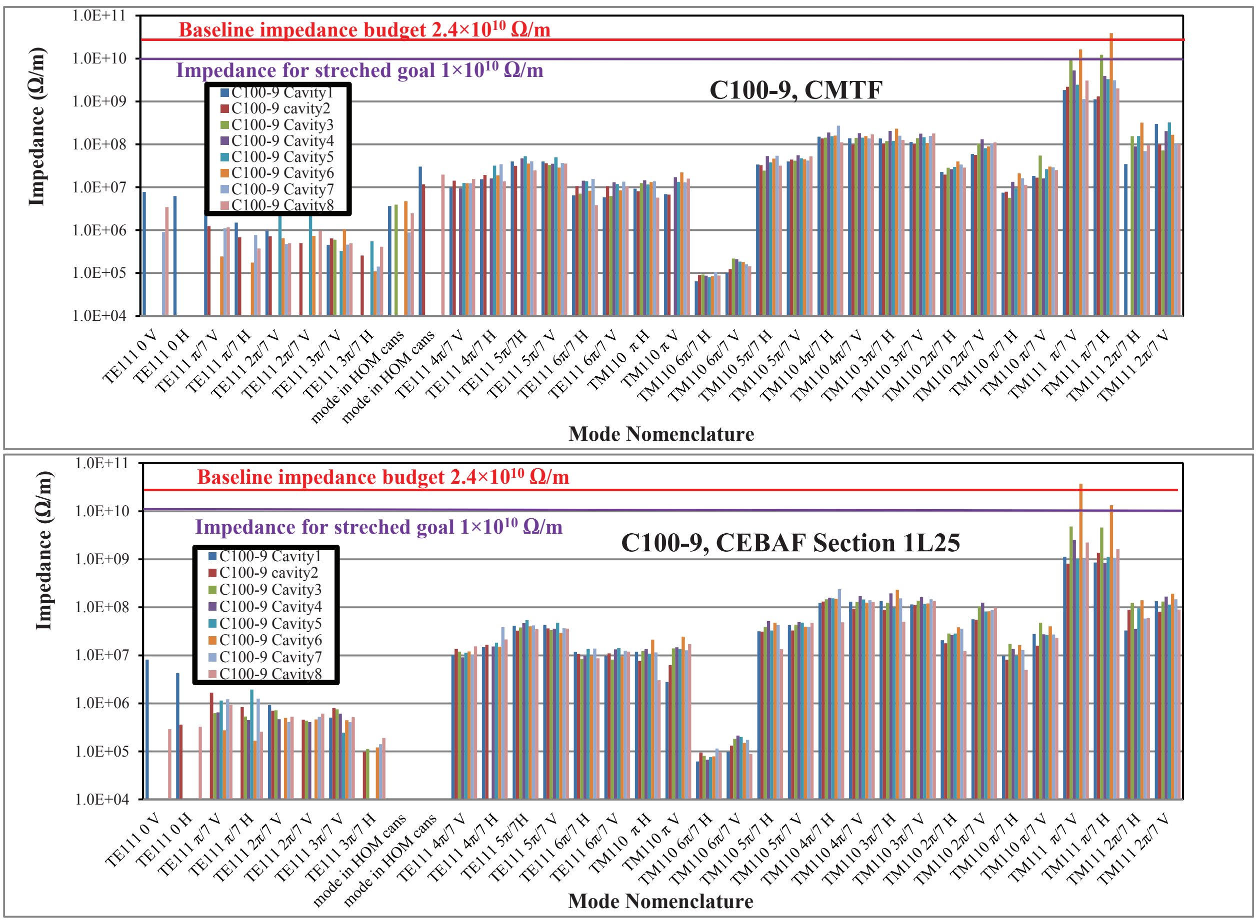

Figure 4: Dipole HOM impedance for Cryomodule C100-9, measured at CMTF and in CEBAF north linac section 1L25. The TM111 π/7 modes have the highest impedance overall. Cavity 6 TM111 π/7 V mode is the only mode that exceeds the baseline impedance budget in CEBAF for now, but it can be brought down below baseline by stub tuners.

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