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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 project in the past few years. The dipole 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 fundamental mode passband (a.k.a. the same passband) of all the cavities. In this paper, we will present the HOM survey methodology and results from CMTF and CEBAF survey, as well as the same passband mode results. We will also discuss the causes and mitigation measures of the high Q modes.

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Keywords: Cryomodule; HOM, BBU, SRF cavities;

1. 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, and 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

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external couplers, it can be easily excited to significant amplitude 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 as low as 40 µA [2].

If only one HOM in one cavity is considered, the threshold current for 2-pass BBU is [3, 4]:

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

here pc is the particle energy on the second pass, q is the particle charge, R_d is the transverse shunt impedance of the cavity dipole HOM (the ratio R_d/Q_0 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; $k=\omega/c$ is the HOM wave number, T_r is the beam recirculation time; and m^* is:

$$m^* = m_{12}\cos^2\alpha + (m_{14}+m_{32})\sin\alpha\cos\alpha + m_{34}\sin^2\alpha \tag{2}$$

where α is the mode polarization angle and m_{ij} are components of the recirculation transport matrix from first to second cavity crossings. Eq. 1 is only valid with $m^*\sin(\omega T_r) < 0$, which results in a positive threshold current; otherwise numeric method is needed to determine the threshold [3, 4].

To ensure CEBAF operating at certain current and energy without BBU, the impedance $(R_d/Q_0)Q_d k$ 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 6 GeV and ~875 µA total current (~175 µA injection current), with more stringent impedance budget of 1.0×10^{10} Ω/m [5].

The dipole HOMs in a C100 cavity have three passbands, namely TE111, TM110 and TM111, as listed in Table 1. In a 7-cell cavity, there are seven modes with different phase advance in each passband, ranging from π/7 to π. The axial symmetry in the cavity was broken due to the coupler layout, as well as fabrication errors and gravity, so the vertical and horizontal polarized modes (V modes and H modes) become non-degenerate with small separation in frequency, doubling the number of modes to 14 in each passband and 42 in all [6]. Additionally, there are two more modes in the TE111 passband coming from the HOM coupler can, and one fundamental power coupler (FPC) waveguide mode in the TM110 passband. All the 45 modes need to be damped and surveyed, with extra attention on the modes with higher R/Q.

In addition to the HOMs, the TM010 passband also has seven different phase advance (also known as same passband modes SPM), among which the π mode is the fundamental accelerating mode. The non-π modes are close to the accelerating π mode in frequency, with very high Q and R/Q. The frequencies of SPM need to be closely monitored, so the beam optics design can avoid resonances at these frequencies.

A C100 cavity uses two coaxial DESY-type couplers (115° apart) on one side of the cavity to damp differently polarized transverse HOMs [2], as shown in Fig. 1. This design is similar to the revised "*Renascence*" prototype, which removed the pair of HOM couplers on the FPC side due to heating in the HOM probes. For multi-cell cavities, this design might be insufficient if the field of certain HOM is tilted toward the FPC side. The BBU observed in 2007 at CEBAF was caused by the TM110 4π/7 V mode of one "high-gradient" type cavity in the "*Renascence*" cryomodule, which had a severely tilted field. To damp those tilted modes, waveguide HOM filters can be installed at FPC side of selected cavities. The angles between the two HOM couplers in C100 are also adjusted in favor of damping TM110 modes, nonetheless at the cost of TM111 damping. Fig. 2 shows the line-up of 8 cavities in a cryomodule, as well as the locations of HOM couplers and FPCs. The HOM couplers are connected to type-N ports outside the CM. When a C100 CM is installed in the CEBAF tunnel, waveguide filters are installed at cavity #1 and #8 between FPC and the klystron, as shown in Fig. 3. Additional waveguide filters will be installed at those cavities with high impedance HOMs found in the CMTF HOM survey.

Table 1. C100 SPM and Dipole HOM Passbands

Passband	Frequency range	Other modes in the frequency range
TM010	1474-1497 MHz	
TE111	1850-2050 MHz	two more modes in HOM coupler can
TM110	2050-2250 MHz	one additional FPC waveguide mode
TM111	2850-3000 MHz	Overlap with TE210 passband

Figure 1. C100 cavity

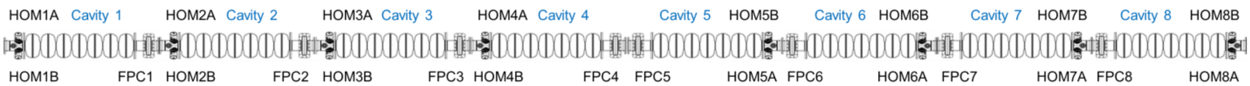

Figure 2. Cavity line up in a C100 cryomodule

Figure 3. Waveguide filters (red) installed at the FPC of C100-2, cavity #1 and #8, in CEBAF section SL25

2. HOM Survey Methodology

During the C100 cryomodule HOM survey, the RF transmission between the HOM ports of two neighboring cavities is measured to determine the HOM frequencies and Qs. Typically, a 4-port NWA like Agilent ENA 5071C is used, connected to the four HOM ports of the two neighboring cavities (i.e., when surveying cavity 1, connect port 1 to HOM1A, port 2 to HOM1B, port 3 to HOM2A, port 4 to HOM2B). Data of the 4 traces (S31, S32, S41 and S42) over the HOM passbands will be taken. With the Polfit [7] Mathematica package, the NWA S-matrix traces are analyzed during the survey to get the HOM frequencies and Qs. Modes from Polfit with Q higher than 1×10^6 or other suspicious behavior will be confirmed with NWA manual measurement.

In general cases, a measurement contains the modes from two cavities in the pair, and the source cavity can be identified by comparing neighboring measurements. However, when the modes are too close or have low Qs, it becomes hard to identify. TM111 modes may travel through more cavities and show up in more measurements, because it's above the TE11 mode cut-off frequency of the beam-pipe. The TM111 passband also overlaps with the quadrupole TM210 passband, complicating the mode identification, therefore we need to focus on the π/7 and 2π/7 modes with high R_d/Q only, ignoring the other TM111 modes. 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 [4] and found that the BBU threshold is well above the specification.

3. C100 HOM and SPM Survey Results

3.1. Same Passband Mode Results

We summarized the TM010 passband mode frequency and Q distribution measured on all the 80 C100 cavities, shown in Fig. 4 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. For cavities with no tuned data available in either CEBAF or CMTF, we scale the untuned cavity data to 1497 MHz.

With π mode tuned or scaled to 1497MHz, all the measured non-π mode frequencies are slightly below the design frequencies, as shown in Table 2. The design frequencies are obtained by Superfish 2D simulation. Data show that the non-π mode frequency centroid f_{mean} and standard deviation σ are linear to the difference between the simulated non-π mode frequency f_{sim} and π mode frequency f_π, as shown in Fig. 5. For all the non-π modes, the maximum frequency is slightly lower than the simulated frequency.

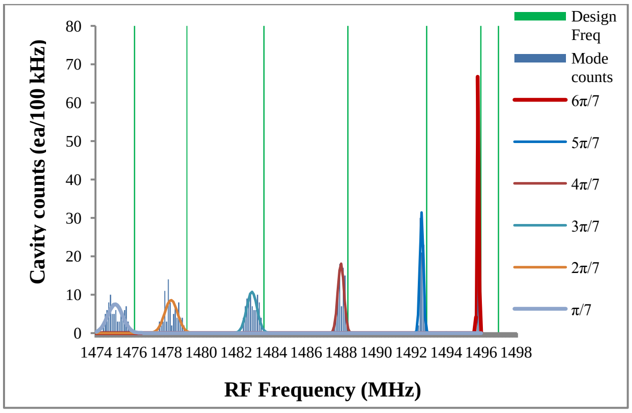

Figure 4. Frequency distribution of SPM (80 cavities), with π mode tuned or scaled to 1497.000±0.008MHz.

By fitting the scaled frequencies data available from 35 untuned cavities, the measured frequency centroid f_{mean} and standard deviation σ of the non-π modes can be written as:

$$\begin{aligned} f_{sim} - f_{mean} &= 0.0375(f_\pi - f_{sim}) + 0.0514 \text{ MHz} \\ \sigma &= 0.0182(f_\pi - f_{sim}) + 0.0133 \text{ MHz} \end{aligned} \tag{3}$$

From the available data of 66 tuned cavities, the measured centroid is 30% to 50% larger than the untuned cavities, and the standard deviation also increases slightly:

$$\begin{aligned} f_{sim} - f_{mean} &= 0.0484(f_\pi - f_{sim}) + 0.0846 \quad \mathrm{MHz} \\ \sigma &= 0.0196(f_\pi - f_{sim}) + 0.0173 \quad \mathrm{MHz} \end{aligned} \tag{4}$$

The deviation of non-π mode frequency centroid from the simulated frequency may be mainly attributed to the systematic error in the size of cell iris. Larger iris enhances the cell-to-cell coupling and decreases the non-π mode frequencies. The chemical process usually etches more at the iris and less in the equator. The C100 cavity tuner stretches the cavity, which will also decrease the size of equators and probably increase the size of iris, further increases the frequency deviation. For cavities designed with squeezing tuners, the frequency deviation may behave differently.

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	3.12×10^{7}	2.77×10^{7}	7.00×10^{6}
6π/7	1495.9081	1495.7604	0.0466	1495.6762	1495.8511	1.68×10^{7}	1.40×10^{7}	3.27×10^{6}
5π/7	1492.8245	1492.5484	0.1017	1492.3332	1492.7317	2.06×10^{7}	1.50×10^{7}	3.11×10^{6}
4π/7	1488.3920	1487.9314	0.1756	1487.5663	1488.2565	2.88×10^{7}	2.06×10^{7}	5.08×10^{6}
3π/7	1483.5045	1482.8434	0.2980	1482.3150	1483.3737	4.77×10^{7}	3.47×10^{7}	1.02×10^{7}
2π/7	1479.1317	1478.2272	0.3729	1477.5521	1478.9709	1.03×10^{8}	6.99×10^{7}	3.20×10^{7}
π/7	1476.1070	1475.0307	0.4262	1474.3147	1475.8021	4.05×10^{8}	1.58×10^{8}	1.09×10^{8}

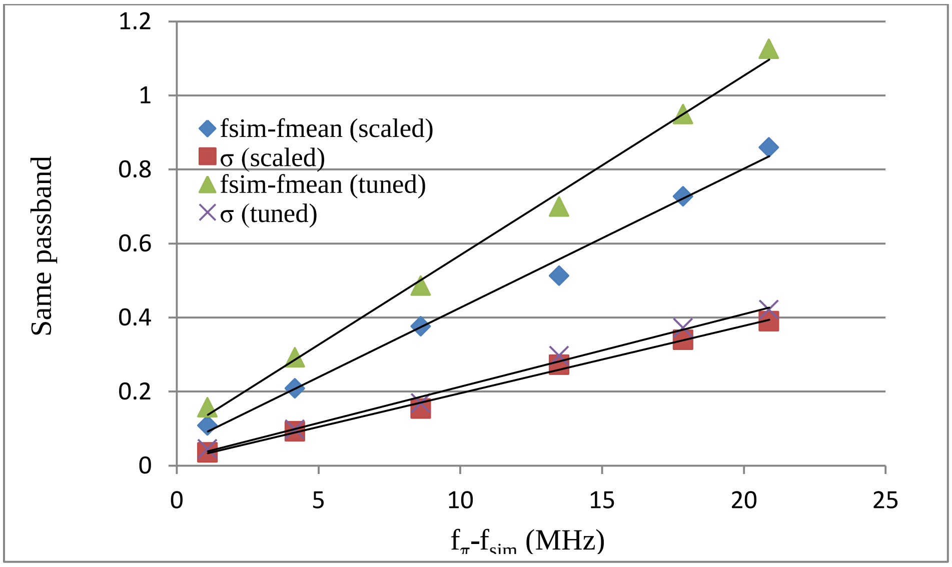

Figure 5. Same passband frequency deviation and fitting

3.2. HOM Results

During the CMTF HOM survey, we found seven modes in four cryomodules (five cavities) that exceeded the stretched Q threshold. All these modes are the TM111 π/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 were below the baseline specification during the CMTF test, and were brought down below or close to the stretched threshold with additional waveguide filters installed after the cryomodules were moved to the CEBAF tunnel. The only exception is the pair of TM111 π/7 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. Experiments showed that stub tuners at the HOM port could bring the V mode Q to 3.2×10^6 (below the baseline spec) and the H mode Q to 1.5×10^6. However, currently this pair of modes are left at high Q without stub tuners applied, so further beam experiments can be carried out to confirm the BBU threshold calculation. The out-of-spec modes are summarized in Table 3.

Table 3: Summary of out-of-spec HOM in C100 cryomodules

Cavity ID	Mode	Frequency (MHz)	Q		CEBAF Impedance R·k (Ω/m)
			CMTF	CEBAF	
C100-4-3	TM111 π/7 V	2887.5	2.68×10^6	9.21×10^5	5.95×10^9
C100-4-3	TM111 π/7 H	2887.8	2.93×10^6	1.62×10^6	1.06×10^{10}
C100-6-2	TM111 π/7 V	2890.8	2.34×10^6	1.15×10^6	7.49×10^9
C100-9-3	TM111 π/7 H	2881.9	1.88×10^6	7.03×10^5	4.58×10^9
C100-9-6	TM111 π/7 V	2884.0	2.55×10^6	5.83×10^6	3.76×10^{10}
C100-9-6	TM111 π/7 H	2884.2	6.02×10^6	2.05×10^6	1.34×10^{10}
C100-10-2	TM111 π/7 V	2881.4	1.81×10^6	9.08×10^5	5.86×10^9

Modes exceeding the baseline specification $R_d\cdot k<2.4\times10^{10}$ Ω/m will have the Qs and impedance colored in red; those modes exceeding the stretched goal $R_d\cdot k<1.0\times10^{10}$ Ω/m will be colored in purple.

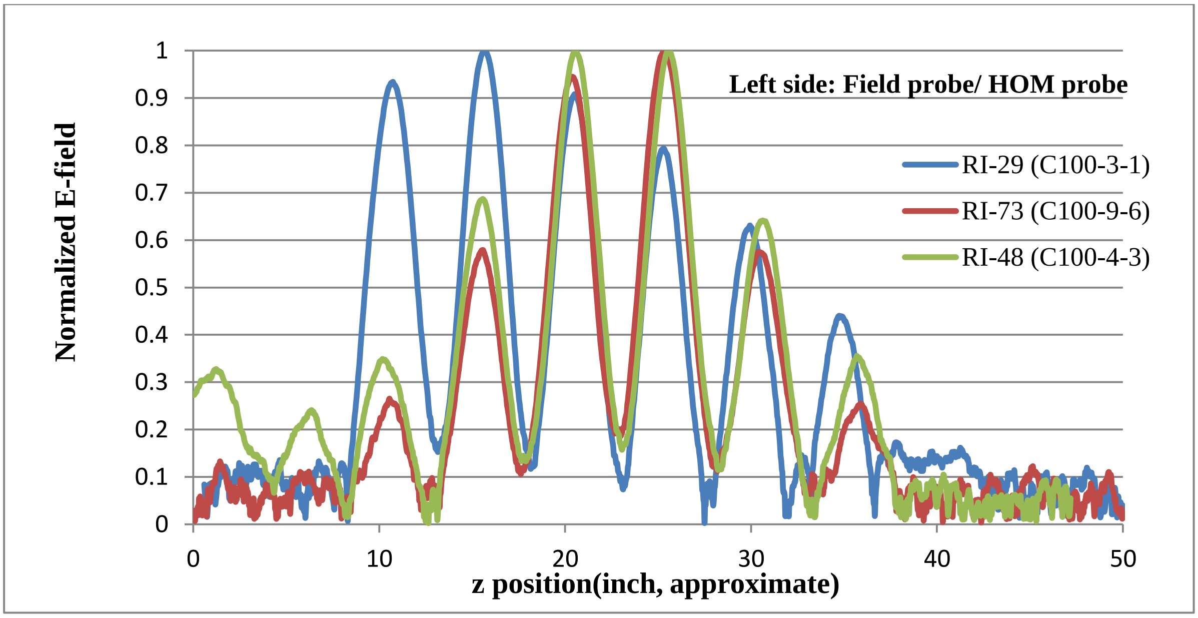

Figure 6. Room temperature bead-pull data comparison, TM111 π/7 V modes

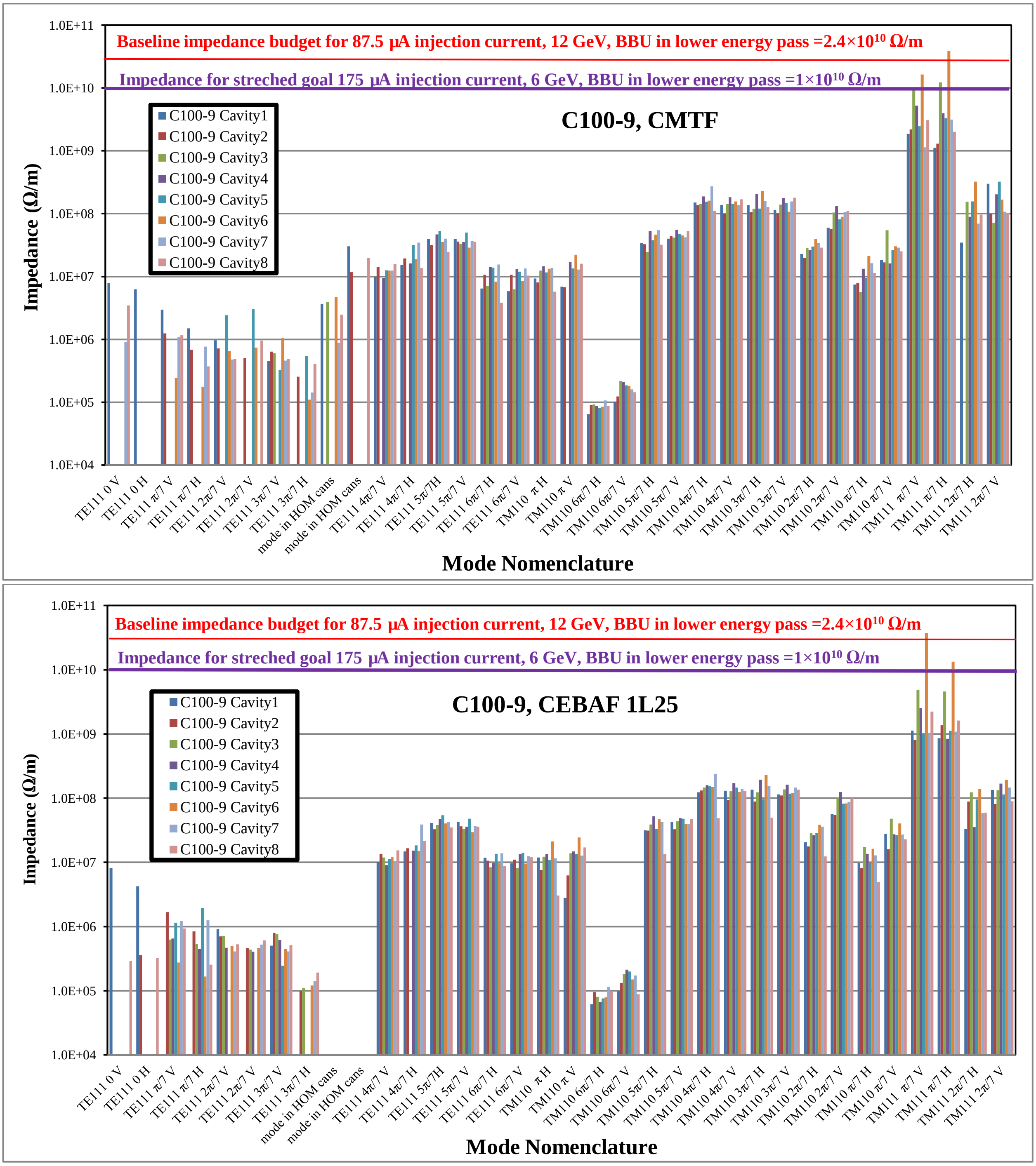

Figure 7. Dipole HOM impedance for Cryomodule C100-9, measured at CMTF and in CEBAF north linac section 1L25. The TM111 π/7 modes have the highest impedance overall. Cavity 6 TM111 π/7 V mode is the only mode that exceeds the baseline impedance budget in CEBAF for now, but it can be brought down below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

Similar to the high Q TM110 modes in the "Renascence", the high Q TM111 π/7 modes in the C100 cavities are mainly due to the insufficient coupling resulted from low field in the end-cells. Non-flat field distribution is very common for this mode, generating a lot of high Q modes in different cavities. Combined with the fact that this pair of modes have the highest $(R_d/Q_0)k$ among all the dipole modes, TM111 π/7 modes have the highest impedance in most of the C100 cavities. Fig. 6 compares the TM111 π/7 V mode room temperature bead-pull measurement results of cavity C100-3-1 (with normal Q and typical field profile) with the out-of-spec cavities C100-4-3 and C100-9-6. Out-of-spec cavities such as C100-9-6 have field concentrated in the center cells and low field in both end-cells, making it hard to be damped even with an additional waveguide filter on the FPC side. The boundary condition at the beam pipe ends changed after the modules have been moved from CMTF to CEBAF, resulting different cavity field pattern and different coupling at both the HOM couplers and FPC [6]. This may explain why the Q of a small number of HOMs increased from CMTF to CEBAF. High resolution time-domain reflectometry (TDR) measurement also showed some correlation between the high Qs and the loose Inconel® center conductor pin of some cavities' HOM feedthrough. Fig. 7 compares the impedance of all the HOM modes observed in cryomodule C100-9 at CMTF and in the CEBAF tunnel.

4. 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 threshold requirement. Only one cavity has one out of spec TM111 π/7 V mode after being installed in CEBAF. Additional coaxial stub tuners can damp this mode to the baseline specification, but we left this mode with high Q for further BBU beam experiment. The bead-pull data shows that the TM111 π/7 V mode in that cavity has very low field in the end-cells and is very hard to damp by either HOM couplers or the FPC HOM filter.

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