

CRITICAL DIPOLE MODES IN JLAB UPGRADE CAVITIES*

F. Marhauser, J. Henry, H. Wang, JLab, Newport News, Virginia, U.S.A.

Abstract

The upgrade project of the Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Laboratory (JLab) is in progress. Eighty cavities will be installed in ten new superconducting RF (SRF) cavity cryomodules to double the maximum achievable beam energy from 6 GeV to 12 GeV. One major concern in CEBAFs recirculating machine is the potential of multipass, multibunch beam break-up (BBU) instabilities due to Higher Order Modes (HOMs) interacting with the beam in the first accelerator pass and subsequent passes. Such an instability has been encountered in 2007 due to an upgrade prototype cavity in a then newly installed cryomodule. Insights into the underlying problems and their mitigation are presented in this paper including most recent results for in-house built upgrade type cavities.

INTRODUCTION

CEBAF is a recirculating electron facility for nuclear physics research, operating SRF cavities CW at 1497 MHz. The facility will be upgraded by 2015 to achieve 12 GeV beam energy in up to 5½ passes. This includes the installation of ten new cryomodules (CMs) in empty slots available at the end of each linac. Each CM must provide ~100 MV (“C100”), *de facto* 108 MV leaving 10% contingency overhead. This gain is achieved with eight seven-cell Low Loss (LL) cavities of 0.7 m active length operated at an average usable accelerating field of 19.2 MV/m. A C100 cavity is depicted in figure 1. It makes use of two coaxial DESY-type couplers (115° apart) to capture differently polarized transverse HOMs.

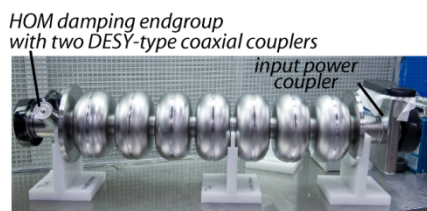


Figure 1: CEBAF upgrade type cavity (C100).

Both HOM-couplers are sitting on one end of the cavity. This is rather unfavorable for a multi-cell cavity since potential mode tilting effects can deteriorate the damping efficiency. In fact, tilted fields in a previous upgrade prototype cavity installed in CEBAF in 2007 have caused the first, serious transverse BBU phenomena since delivery of the first beam to users in 1994 [1]. The incident has led to more cautious considerations regarding

cavity fabrication, handling, post-processing and improved documentation to include quality control especially for dipole HOMs. Below a description of the rationale why this HOM damping scheme was chosen and an understanding of the impact for this decision will be outlined.

HISTORY OF CAVITY DEVELOPMENT

In previous years JLAB has performed enormous in-house R&D efforts to design, manufacture, qualify and commission cavity and CM prototypes in order to demonstrate voltages beyond 100 MV. This included two intermediate “70 MV” CMs making use of seven-cell cavities with the “Original Cornell” (OC) shape [2]. The HOM damping concept had been chosen adopting DESY’s coaxial coupler design [3] instead of using the OC five-cell cavity in-helium-vessel cold waveguide dampers. This facilitated to improve the CM design, assembly and overall efficiency. Subsequently a “final” third CM prototype dubbed *Renascence* has been fabricated at JLab [4]. It had been equipped both with High Gradient (HG) type cavities (to reduce $E_{\text{peak}}/E_{\text{acc}}$) and LL cavities and was intended to extend the usable voltage to 110 MV, but was ultimately constrained to only ~59 MV [5]. *Renascence* cavity design added a second set of HOM couplers on the fundamental power coupler (FPC) side to improve the broadband damping efficiency beyond CEBAF requirements. Although all cavities passed acceptance testing in JLab’s vertical test area (VTA), thermal instabilities were later encountered in the cryomodule (2005) arising from elevated heating of HOM coupler RF feedthroughs. This eventually caused premature cavity quenches with RF power when the interior niobium HOM pickup probes went normal conducting [5]. The problem was diagnosed and remedied by improving the conductive cooling and *Renascence* could be commissioned for beam operation in CEBAF in 2007. However, HOM pickup probes on the FPC side were removed as a precaution still having confidence of adequate damping, i.e. leaving two active HOM couplers on one side. This single-sided damping concept was finally accepted for the C100 cavities with additional changes made on HOM can locations as well as orientation of coupler inner hooks and pickup probes [6]. In 2006 two C100 cavities have been produced to demonstrate the integrity of the final design choice. The cavities were successfully high power tested in 2007 in a dedicated cavity-pair cryomodule meeting all 12 GeV performance specifications. While the production of 80 required C100 cavities (plus six spares) was already awarded to Research Instruments GmbH, Germany [7] in 2009, JLAB could yet not demonstrate or qualify a true C100 CM. Therefore in parallel to the upgrade activities, an in-house cavity fabrication for a CM named R100

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incorporating all design changes has been initiated [8]. Eight *R100* cavities have been built this year with the majority of cavities successfully qualified in the VTA promising voltages well beyond 100MV. First results are shown in figure 2. Note that only *R100-4* was quench limited at 37.5 MV/m, while others have not been tested to the “hard” limit. Detailed information on cavity post-processing can be found in reference [8].

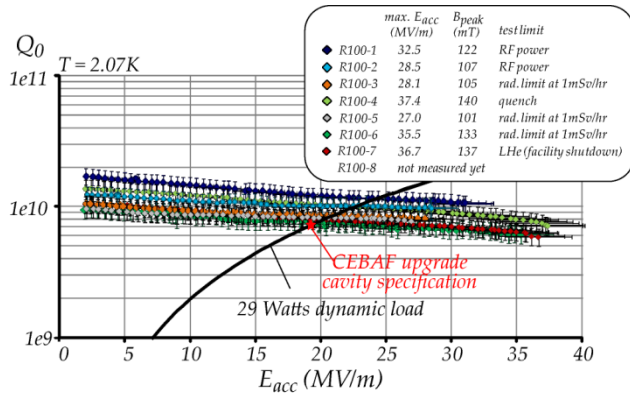


Figure 2: VTA RF performance of *R100* cavities.

CEBAF BBU POST-ANALYSIS

Shortly after installation of *Renascence* in CEBAF, a BBU was encountered limiting the injected beam current to as low as 40 μ A remediable only by adjusting the optics in the recirculating arcs [1]. Experimental studies could attribute the cause to vertically polarized TM_{110} $4\pi/7$ - or $5\pi/7$ -modes in one of the *Renascence* HG cavities (*HG002*) at frequencies around 2.15 GHz. The corresponding loaded Q_s were as high as $\sim 10^8$ exceeding anticipated BBU impedance thresholds at the $1e10 \Omega/m$ level. With *Renascence* still in CEBAF, extensive numerical investigations have been carried out to predict the cavity shape of *HG002* from frequency and external Q measurements at HOM couplers [9]. This effort has forecast that both BBU-causing modes are tilted unfavorably away from the HOM couplers. The findings could not be proven until *HG002* became available for field profile measurements after removing *Renascence* from CEBAF and disassembly in 2009. In fact, the tilted modes could be verified, though profiles deviated somewhat from the numerical results. More recently, the helium vessel of *HG002* has been removed to map external cell contours with a coordinate-measuring machine (CMM). This enabled to reconstruct the cavity interior with a parametric CAD model assuming uniform wall thickness [8]. Utilizing this model, HOMs have been found by numerical Eigenmode analysis that differed significantly from expected fields in an undeformed cavity. When compared with field profile measurements however, the BBU-generating HOMs could be identified unambiguously (Figure 4). Remaining amplitude deviations can be explained by the fact that the wall thickness is not uniform as assumed and that cells are not fully concentric confirmed by CMM measurements (not taken into account numerically). The analysis also

revealed that the culprit of the BBU scenario was a single deformed cell that required extensive tuning to flatten the accelerating field. This eventually caused modes to tilt severely leaving practically no field at the HOM coupler positions.

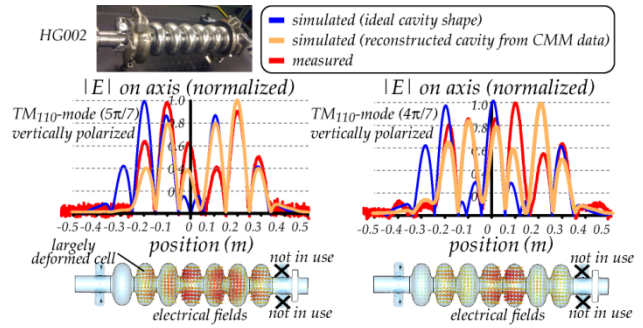


Figure 3: Tilted TM_{110} BBU-generating HOMs in *HG002*.

HOM DAMPING QUALITY ASSURANCE

The existence of tilted modes in a cavity deformed during fabrication and the subsequent cavity tuning was able to generate a serious BBU event in CEBAF and has raised the awareness of HOMs being sensitive to fabrication tolerances. The importance of HOM quality assurance (QA) has been pointed out in ref. [10] and has led to the implementation of field profile measurements on the bench as well as VTA loaded Q -measurements prior to CM assembly as part of routine QA. The QA not only includes trapped dipole modes (TE_{111} and TM_{110} passband) but also propagating TM_{111} modes above the first beam tube cutoff ($TE_{11} = 2.51$ GHz). Of particular interest are TM_{111} $\pi/7$ -mode pairs around 2.9 GHz with the highest R/Q-values among dipole modes. These are rather confined in the cavity and react very sensitively on boundary conditions. Figure 4 plots the loaded Q_s for various cavities measured at 2 K. The black dots (connected for better visibility) represent the mode-dependent Q -thresholds for BBU for LL cavities, when operating CEBAF at lower passes and lower beam energy up to 400 μ A of beam current (the Q thresholds and HOM frequencies for HG cavities are different).

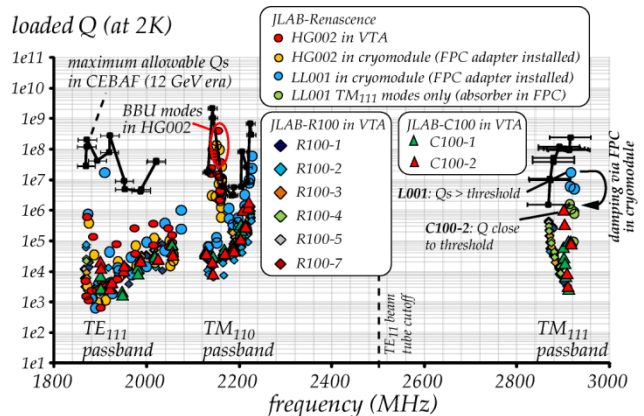


Figure 4: Q_1 measured at 2K for upgrade type cavities.

The horizontal error bars in figure 4 reflect the frequency uncertainty of similar modes experienced in different LL cavities. The QA can prevent cavities from being installed in a CM when not conform to HOM requirements, e.g. would have eliminated HG002. No HOM damping issues have been encountered with the latest *R100* cavities with all Q_s below acceptable levels and - of high importance - consistent results among cavities. These cavities have been built with emphasis to symmetrize not only the fundamental mode field profile but also the HOM fields, i.e. avoiding cell asymmetries during fabrication and bench tuning as far as possible [8]. Data for other cavities in figure 4 show large variations and elevated Q_s for critical modes. A measurement for a LL cavity positioned at one cryomodule end in *Renascence* (LL001) in fact has shown Q_s for TM_{111} modes at 2.9 GHz exceeding BBU thresholds. It has been proven that these HOMs can be damped more efficiently by the FPC rather than the HOM couplers, i.e. when inserting absorber material in the FPC [10]. Under normal operating conditions this is accomplished with waveguide filters. It has to be guaranteed though, that the FPC's double RF window waveguide configuration (see figure 4 right) is able to transmit the HOM energy effectively.

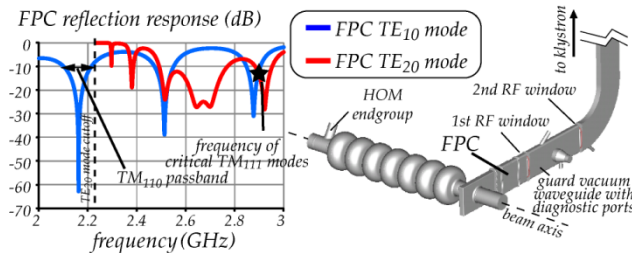


Figure 5: Reflection response (left) of the FPC double window configuration (right).

Hence, numerical efforts were made to minimize the HOM power reflection from the FPC back to the cavity around 2.9 GHz by changing the distance between the RF vacuum windows such to allow both the FPC's TE_{10} -mode (1.1 GHz cutoff) and TE_{20} -mode (2.2 GHz cutoff) to propagate with much better efficiency than originally designed [11]. This enables capturing both horizontally and vertically polarized modes. At the same time the throughput for TM_{111} passband modes has been improved. Mode damping via the FPC waveguide in fact may become crucial especially when modes are tilted away from the HOM coupler side. For the propagating modes in a cryomodule, fields can leak through multiple cavities. It beneficially reduces the loaded Q in a cavity-combined effort. This effect however is reduced at the ends of a CM cavity string as observed for LL001. At these locations (see figure 6) improvements have been made to particularly capture high impedance TM_{111} modes [12]. The cold-to-warm transitions - exhibiting a step down in the tube diameter similar on each side - have been optimized (changing the tube length) to alter the resulting standing wave pattern thereby maximizing damping by the HOM couplers. In this way the Q_s can be lowered by

three orders of magnitude from the worst ($Q_{ext} = 10^7$) to the best case ($Q_{ext} = 10^4$). An appropriately optimized beam tube length is also in use for VTA testing since a blind-flanged HOM-coupler side beam tube tends to tilt the TM_{111} $\pi/7$ -modes and will underestimate Q_s [13].

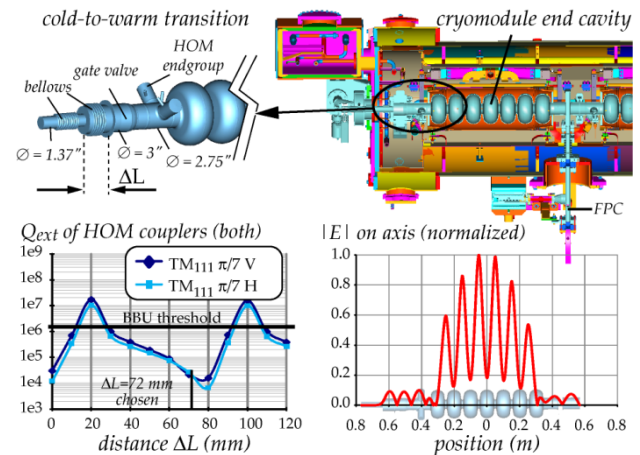


Figure 6: Optimized cold-to-warm transition to improve HOM damping of crucial TM_{111} modes (see text).

SUMMARY

CEBAF upgrade type cavities make use of DESY-type coaxial HOM couplers positioned on one end of the cavity. Critical dipole modes close or above the expected BBU impedance threshold can be generated when fields are tilted away from the HOM couplers as experienced in CEBAF with a cavity prototype in an upgrade type cryomodule removed since 2009. Several other previously built cavity prototypes have exhibited tilted mode effects as well, which compromise HOM damping. These effects can be best explained by cavity cell fabrication errors. For the most recent in-house built cavity series it has been demonstrated that such effects can be controlled with more thorough fabrication measures. HOM QA controls are in place to exclude the assembly of any cavity in a cryomodule not meeting HOM specifications, the reason for past BBU events in CEBAF. Furthermore, several improvements for cavity external components (FPCs, cold-to-warm transitions) have been made to enhance damping of critical HOMs.

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