HOM SURVEY OF THE FIRST CEBAF UPGRADE STYLE CAVITY PAIR*

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Abstract

The planned upgrade of the Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Laboratory (JLab) requires ten new superconducting rf (SRF) cavity cryomodules to double the beam energy to the envisaged 12 GeV. Adequate cavity Higher Order Mode (HOM) suppression is essential to avoid multipass, multibunch beam break-up (BBU) instabilities of the recirculating beam. We report on detailed HOM surveys performed for the first two upgrade style cavities tested in a dedicated cavity pair cryomodule at 2K. The safety margin to the BBU threshold budget at 12 GeV has been assessed.

INTRODUCTION

In April 2009 groundbreaking of the 12 GeV CEBAF upgrade project has been celebrated. With the project completion planned in 2015 CEBAF will have doubled the beam energy from 6 GeV to 12 GeV (1.1 GeV per linac), upgraded and expanded the beam transport systems, doubled the capacity of the central helium liquefier and added a new experimental hall (D) and beamline at 12 GeV (figure 1).

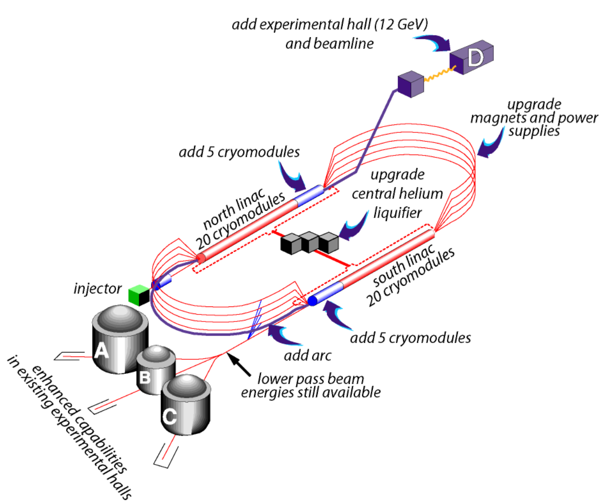

Figure 1: Layout of CEBAF indicating the planned upgrades to provide up to 12 GeV beam energy with 5½ recirculating passes using CW SRF linac technology.

The specified accelerating field (E_{acc}) of the original CEBAF five-cell cavities (figure 2 top) was 5 MV/m at the time of installation. Today, with the advance in chemical processing and improved understanding of limiting factors much higher fields can be attained. This facilitates the 12 GeV upgrade by reasonable measures, i.e. the removal, refurbishment and reinstallation of old style cavities to improve E_{acc} to an average usable 12.5 MV/m [1] and the production and installation of seven-cell upgrade style cavities (figure 2 bottom) with the aim to reach 19.2 MV/m in average.

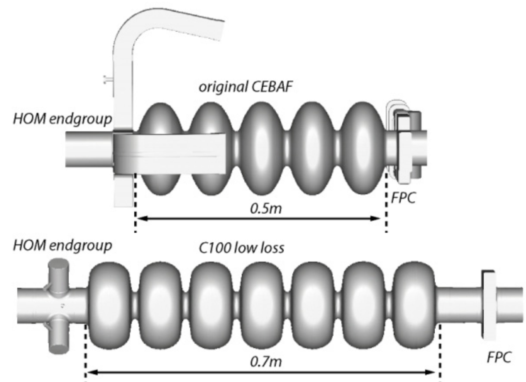

Figure 2: 1497 MHz original CEBAF 5-cell cavity in comparison to the low loss 7-cell upgrade style cavity.

Ten upgrade style 100 MeV cryomodules (dubbed “C100”) equally distributed in empty slots at the end of the north and south linac in addition to ten refurbished 50 MeV cryomodules (dubbed “C50”) will be necessary to double CEBAF’s energy. Presently eight out of ten refurbished cryomodules have been reinstalled. Commissioning of the last two C50 cryomodules is planned within this year. As for C50 each new C100 cryomodule will consist of eight cavities but with an increased active length from 4 to 5.6 meters. This actually provides an energy gain of 108 MeV. So far two C100 cavities have been produced. These cavities were manufactured during 2006 and successfully high power tested in 2007 in a horizontal test bed (HTB), a dedicated upgrade style cavity-pair cryomodule. At this time the cavities met all performance specifications for the 12 GeV project with a thermally stable CW operation up to E_{acc} = 25 MV/m [2]. HOM suppression is facilitated by a single HOM endgroup located on the opposite side from the waveguide fundamental power coupler (FPC). The original CEBAF cavities utilize two cutoff waveguides with lossy absorbers placed at 2K providing adequate HOM damping. Upgrade style cavities on the other hand rely on two DESY-type coaxial couplers to capture the HOMs and dissipate their energy in standard room temperature loads. A thorough HOM survey for both C100 cavities has been performed to verify that the dipole impedance requirements for the 12 GeV upgrade can be met.

* Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.

IMPORTANCE OF HOM SUPPRESSION AND QUALITY ASSURANCE

Suppression of unwanted beam generated HOMs is of utmost importance particularly for recirculating accelerators like CEBAF to avoid BBU instabilities at the desired operating currents. The objective required by the 12 GeV baseline physics is to provide full machine stability for all operating conditions up to 100µA injected beam. Considerations also take into account physics outside the original baseline design to support lower energy, lower pass beam operation with up to 400µA injected beam. With these constraints, the impedances for all deflecting dipole modes have to be restricted to [3]:

$$R_{\perp,\text{threshold}} = \frac{R_\perp}{Q} Q_l k = \frac{R}{Q}\frac{1}{kr^2} Q_l < 1.0 \cdot 10^{10} \frac{\Omega}{m} \quad (1)$$

Herein $R/Q_\perp = R/Q/(kr)^2$ denotes the transversely normalized characteristic shunt impedance derived from the longitudinal R/Q at a radial offset r. By multiplication with the HOM wave number $k = 2\pi f/c$ this formulation takes into account the dependence of the threshold impedance with frequency f.

The importance to survey critical HOMs before the assembly in a cryomodule has become apparent in November 2007 when the first multipass BBU at CEBAF was observed [4]. The consequence was beam loss at surprisingly low currents which for some optics configurations limited the maximum injection current to 40 µA compared to the nominal 85 µA. The source of the BBU was quickly confined as originating from a cryomodule in the north linac - installed shortly before the incident and only recently removed - that has served as a test bed for demonstrating key technological components towards C100 [5]. It houses intermediate designs of upgrade High Gradient (HG) and LL seven-cell cavities Although successful measures were applied to mitigate the BBU by adjusting the CEBAF optics in the recirculating arcs, large efforts have been invested to characterize the BBU phenomena to prevent a recurrence in future C100 cavities. Dedicated beam experiments could pinpoint the cause to one out of five HG cavities. Inspection records revealed that this cavity has been deformed inadvertently during fabrication exceeding tolerable measures at a single cell. We assume that the subsequent mechanical tuning must have been done in a very non-uniform manner to correct both for the fundamental frequency and field flatness. Thus very asymmetric cell distortions along the cavity cells have likely been introduced. Extensive numerical analysis taking into account experimental data have predicted the expected cell deformations, large enough to generate tilted dipole fields not sufficiently captured by the HOM-endgroup [6]. Consequently two BBU-causing HOMs have been produced with dipole impedances more than an order of magnitude higher than expected [7].

With the understanding that BBU at CEBAF can be generated by a single inadvertently deformed cavity, adequate quality assurance (QA) and handling during and after cavity fabrication is obligatory. Consequently, QA measures have been implemented to verify the integrity of the cavities for HOM impedance variations arising from fabrication tolerances. Particularly HOM surveys are foreseen in a vertical Dewar for each single cavity before assembly in a cryomodule.

C100 CAVITY PAIR HOM SURVEY

A systematic HOM survey has been performed at the 2K operational temperature for both existing cavities (C100-1, C100-2) assembled in the HTB (figure 3). All ancillary components (e.g. mechanical tuners, thermal intercepts at HOM ports) were in place as needed for a subsequent high power characterization.

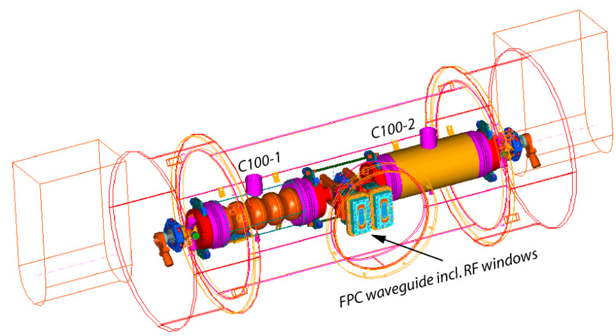

Figure 3: 3D view inside the cavity-pair HTB.

Each cavity was equipped with a coaxial line to waveguide transformer attached to the FPC waveguide. Using a Vector Network Analyzer the power was launched in to the FPC and extracted from either of the two HOM coupler ports, whichever yielded the most accurate Q_l measurement. The unused port was terminated at the same time with a 50 Ω load. The generally weakly-coupled cavity field probe located between the HOM ports was terminated as well. At 2K the signal-to-noise ratio for all HOMs was sufficiently good to omit any further signal amplification. Figure 4 shows the results of the Q_l-measurements.

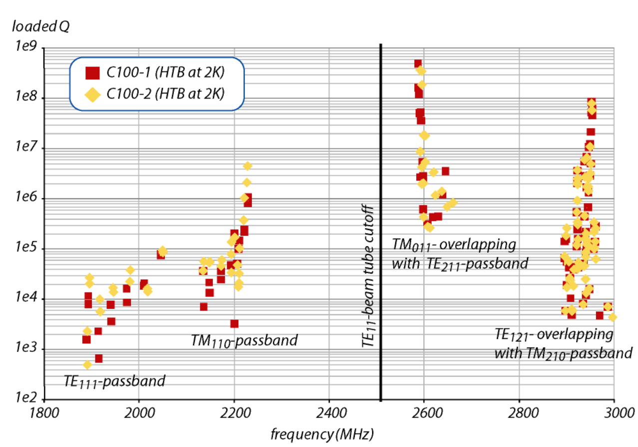

Figure 4: Loaded HOM Qs measured in the HTB at 2K.

We have measured all detectable HOMs up to 3 GHz comprising the TE_{111}- and TM_{110}-passband modes below, as well as the TE_{121}-passband modes above the first beam tube cutoff frequency. It should be mentioned that one of the HOM-coupler cables on C100-2 has been found defective after assembly close to the outer load connection. At this port only the cable's reflection loss provided residual damping. Modes with $Q_l >> 10^6$ are quadrupole modes confined in the inner cells, which are not of concern at the operating currents [8]. Also monopole modes, even if entirely left undamped, have been estimated to not cause longitudinal BBU instabilities [9]. We therefore have concentrated on the dipole modes. Each HOM impedance is evaluated by the product of the measured Q_l and the R/Q-value according to eq.(1). The latter has been determined numerically. Figure 5 eventually shows the corresponding results.

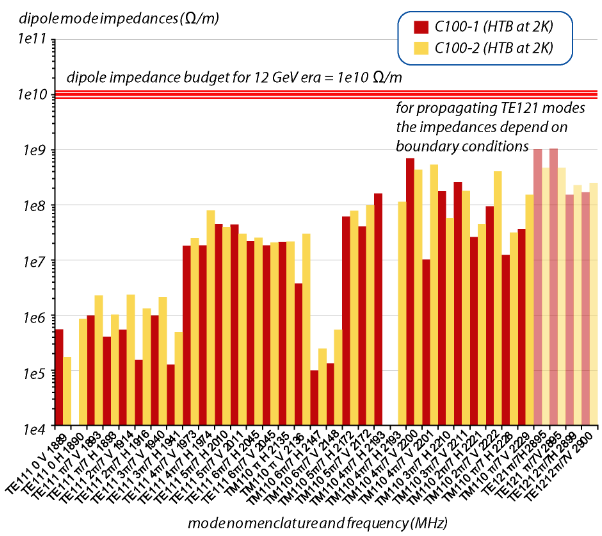

Figure 5: Dipole mode impedances in C100-1 and C100-2 respectively as measured in the HTB at 2K.

Among all HOMs a safety margin of an order of magnitude or higher is achieved with respect to the specified threshold of 1e10 Ω/m. Three gaps with missing data indicate that one polarization of a mode pair could not be detected in either C100-1 or C100-2. In these cases we can assume similar impedances as for the measured mode. We have refined the accuracy of mode identification using the 3D modeling capability of CST Microwave Studio [10]. We have tried to identify HOMs by the corresponding pillbox mode nomenclature as far as applicable denoting the phase advance per cell and the horizontal or vertical polarization (H/V) respectively. In fact, modes in excess of the usual dipole mode pairs are possible arising from coupling effects due to the symmetry breaking FPC and HOM ports [7]. E.g. for the TM_{110}-like $4\pi/7$ modes, different candidates were measured resonating either at 2193 MHz and 2200 MHz (three modes in C100-1 and four modes in C100-2). The problematic modes found in the deformed HG cavity to generate BBU instabilities (TM_{110}-like $4\pi/7$ and $5\pi/7$ modes) principally do not pose a threat for the 12 GeV operation.

TE_{121}-like modes generally tend to propagate out of the beam tubes, which helps lowering the Q. However, mode identification turned out to be more complicated than for the trapped modes due to the overlap with TM_{210}-quadrupole modes. Artificial modes ringing in the FPC also led to residual ambiguity. We have therefore included only the first two TE_{121}-like mode pairs of largest impedance in figure 4 indicated by transparent bars. These are of special interest since they comprise the highest R/Q-values among dipole modes. Hereby we used the maximum loaded Q measured of several possible candidates of adjacent modes to evaluate worst case impedances. Yet the numbers can strongly depend on the boundary conditions once cavities are installed in a C100 cryomodule. E.g. the first TE_{121}-like dipole pair exhibited Qs in the 10^5 range in the HTB. After disassembly measurements have been repeated individually for each cavity in a vertical Dewar [7]. Whereas the impedances for the trapped modes did not alter significantly, the first TE_{121}-like dipole pair showed Qs elevated to the 10^6 range due to the closed beam tubes. Further experimental and numerical studies are under way for such propagating modes paying attention on the effects of beam tube boundary conditions on mode damping.

SUMMARY

We have performed a detailed HOM survey of the first two existing C100 upgrade style cavities for the 12 GeV project. Dipole impedances have been evaluated by measuring the loaded Qs at 2K in a cavity pair cryomodule correlated to simulated R/Q-values for each HOM. The results indicate that the requirements for operating CEBAF at 12 GeV are met for all operating conditions up to the required 100μA accelerated through five passes and supporting also lower energy, lower pass beam operation with up to 4x higher (400μA) beam. Among all HOMs a safety margin of at least an order of magnitude to the corresponding impedance budget has been achieved.

REFERENCES

[1] M. Drury et al., Proc. PAC07, Albuquerque, NM, WEPMS059.
[2] C. Reece at al., Workshop on SRF Superconductivity, Peking University, Beijing, China, 2007, WEP31.
[3] G. Krafft et al., JLAB-TN-09-015, 2009.
[4] R. Kazimi et. al., Proc. EPAC08, Genoa, Italy, WEPP087.
[5] C.E. Reece at. al., Proc. PAC 2005, Knoxville, TN, TPPT081.
[6] Z. Li et al., JLAB-TN-08-026 (2008), SLAC-PUB-13266 (2008).
[7] F. Marhauser et. al., JLAB-TN-08-37, 2008.
[8] B. Yunn, JLAB-TN-01-023, 2001.
[9] G. Krafft et al. , personal note, JLAB, 2009.
[10] www.cst.com.