RECIRCULATING BEAM BREAKUP STUDY FOR THE 12 GEV UPGRADE AT JEFFERSON LAB *

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Abstract

Two new high gradient C100 cryomodules with a total of 16 new cavities were installed at the end of the CEBAF south linac during the 2011 summer shutdown as part of the 12 GeV upgrade project at Jefferson Lab. We surveyed the higher order modes (HOMs) of these cavities in the Jefferson Lab cryomodule test facility and CEBAF tunnel. We then studied recirculating beam breakup (BBU) in November 2011 to evaluate CEBAF low energy performance, measure transport optics, and evaluate BBU thresholds due to these HOMs. This paper discusses the experiment setup, cavity measurements, machine setup, optics measurements, and lower bounds on BBU thresholds by new cryomodules.

BACKGROUND

The CEBAF 12 GeV upgrade requires reliable 5-pass operation of upgraded 7-cell 1497 MHz cavities, named C100. Each cryomodule will contain 8 cavities, designed to provide CW 108 MV per cryomodule (including overhead) at 5-pass total beam currents up to approximately 400 μA, limited by electron gun current to two 1 MW hall dumps. In 2007, CEBAF with an earlier high-gradient cryomodule prototype experienced recirculating BBU at about 40 μA, so great effort was made to improve C100 HOM damping and performance with DESY-type coaxial HOM couplers and careful control of fabrication methods [1, 2].

The first two C100 cryomodules, named C100-1 and C100-2, were surveyed in the Jefferson Lab cryomodule test facility (CMTF) and installed in the west (high energy) side of the CEBAF south linac (SL) during the 2011 summer shutdown. The availability of these cryomodules with beam enabled an experimental evaluation of C100 dipole HOM damping and BBU thresholds in November 2011 during CEBAF startup for the 2011-2 run.

THEORY AND EXPERIMENTAL SETUP

Assumming one cavity, one HOM, and one recirculation, the threshold current for two-pass BBU is given by [3]

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

where pc is the particle energy on the second pass, $q = e$ is the particle charge, (R_d/Q_0) is the dipole HOM shunt impedance, ω is the HOM frequency, Q_d is the quality factor of the dipole HOM, $k = \omega/c$ is the HOM wave number, T_r is the recirculation time, and

$$m^\star \equiv m_{12}\cos^2\alpha + (m_{14}+m_{32})\sin\alpha\cos\alpha + m_{34}\sin^2\alpha, \qquad (2)$$

where α is the mode polarization angle and m_{ij} are components of the recirculation transport matrix from first to second cavity crossings. This equation is valid when $m^\star\sin(\omega T_r) < 0$ to make the threshold current positive; if $m^\star\sin(\omega T_r) > 0$, numerical methods are required to determine threshold current [3, 4, 5] .

The only variables available in the CEBAF BBU experiment were particle energy pc and optics $m^\star$ contributions. Attempts to lower pc and thus $I_{\rm th}$ by tuning CEBAF to 150 MeV/linac failed after several attempts. A low-energy setup of 282 MeV/linac (compared to nominal 551 MeV/linac) succeeded, providing pc =1160 MeV after two passes. Unfortunately the Hall C high-current dump was not available, so operational beam current was limited to 80 μA. We also acquired C100-1 data at 180 μA parasitically during the CEBAF experimental program. These currents are much lower than the lowest BBU threshold currents of about 26 mA predicted from simulation (see next section). We were therefore unable to observe BBU directly as was done in previous BBU studies at the Jefferson Lab FEL [5, 6].

Instead, we surveyed C100 HOMs for both cryomodules with three beam currents and three optics configurations as shown in Table 1 to compare to offline simulations and to extrapolate lower bounds on measured BBU thresholds. Recirculation optics to calculate $m^\star$ were measured using RayTrace, which transports a synthetic beam ellipse through CEBAF [7].

Table 1: BBU Experiment Parameters

Second-pass beam energy pc	1160 MeV
Beam current I	0, 40, 80, 180 μA
Phase advance/cell in linacs	90, 105, 120°

BBU SIMULATIONS

TDBBU is a multi-pass beam breakup simulation program developed at Jefferson Lab [8]. The beamline information for TDBBU was obtained from snap shot data

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files from the CEBAF control system for comparison with the experimental data. The RF focusing effect was implemented into TDBBU to improve optics calculation [9].

The threshold current predicted by simulation is about 26 mA due to TM111 $\pi/7$ modes in C100-1, which are sharp and narrow peaks near 2893 MHz in Fig. 2. Simulations were performed to predict threshold currents in the primary TM110 and TM111 modes of concern.

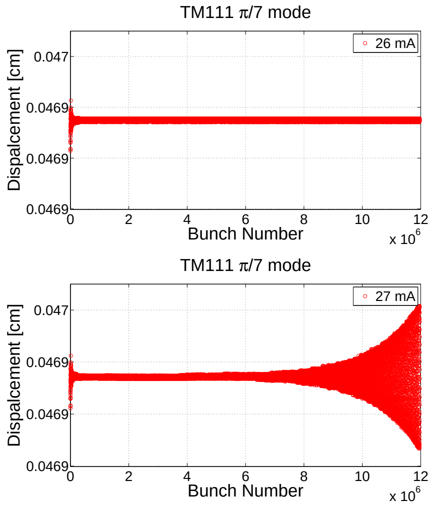

Figure 1: TDBBU simulation results. The x axis represents bunch numbers, and the y axis is transverse positions. Beam is stable at 26 mA, but the transverse position increases exponentially at 27 mA, which means beam instability.

Table 2: CEBAF C100 HOM Survey Parameters

C100 fundamental mode	1497 MHz
TE111 survey range	1850-2050 MHz
TM110 survey range	2050-2250 MHz
TM111 survey range	2850-3050 MHz

DATA ACQUISITION AND ANALYSIS

HOM surveys for frequency ranges listed in Table 2 were conducted for all cavities in both C100-1 and C100-2 cryomodules in the CMTF and the CEBAF tunnel through external HOM coupler ports using a 4-port vector network analyzer (VNA). C100 cavities are installed in the cryomodule with their HOM ports oriented away from the cryomodule centerline. VNA channels 1 and 2 were connected to horizontal and vertical HOM ports of the surveyed cavity while channels 3 and 4 were connected to corresponding HOM ports of the next cavity towards the center of the module. 2×10^4 points were sampled on each survey range with 1 kHz IF bandwidth. Previous HOM survey procedures have required time-consuming, manual Q measurements using the VNA at each HOM of interest. We took advantage of recent advances in efficient extraction of pole

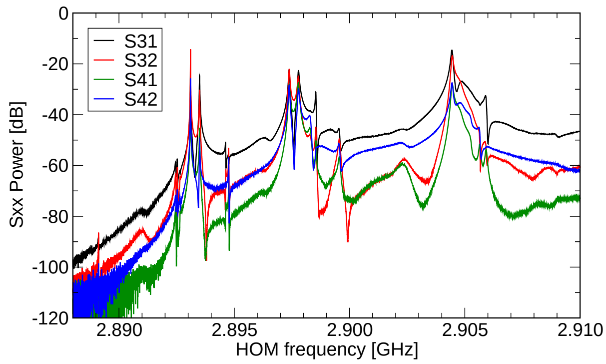

Figure 2: Example Sxx TM111 mode transfer functions measured in the CEBAF tunnel for cryomodule C100-1, cavity 6. The most dangerous modes are at the lower frequencies in the TM111 $\pi/7$ mode; evidence of a narrow, high Q can be seen near 2893 MHz.

and Q values to automatically and accurately extract Q values of all HOMs in our sampled frequency ranges by using an enhanced version of the Mathematica program *polfit*, developed at Universität Rostock and Jefferson Lab [10]. *polfit* also compensates for cable phase shifts in its analysis. Fitted HOMs were spot-checked with detailed at sample high Q HOMs to confirm *polfit* accuracy.

An overview of the most important TE111, TM110, and TM111 modes for all cavities in C100-1 and C100-2 cryomodules is shown in Fig. 3. Dipole mode impedances were calculated from measured Q values, and R/Q values as modeled by CST/Microwave Studio. Surveyed Q values are quite consistent over all cavities, which makes outliers such as those in C100-1 cavity 4 TM110 (π) and 5/7 ($5\pi/7$) modes quite apparent. The circled impedances are of the most concern for CEBAF BBU performance, though when extrapolated they are still far below the 5-pass 400 μA baseline impedance threshold of 10^{10} Ω/m.

Although multi-pass BBU is a threshold phenomenon, it is not necessary to exceed the threshold current in order to measure it. This can be measured by the beam transfer function (BTF) measurement. The accessibility to the HOM ports of the cavities enabled us to directly excite the beam through an HOM port of the cavity. The response signal was measured from the other HOM port of the same or an adjacent cavity.

We planned to extract the threshold current I_{th} by measuring the effective Q_{eff} as a function of average beam current I and using

$$Q_{\text{eff}} = \frac{I_{\text{th}}}{I_{\text{th}} - I} Q_L, \tag{3}$$

where Q_L is the quality factor with no beam

Unfortunately we could not detect the difference in Q_{eff} as a function of current because the experimental beam currents (up to 180μA) were much smaller than the expected threshold current ($\approx$26 mA). Alternatively, by measuring the ratio of the stored energy with beam off to the stored

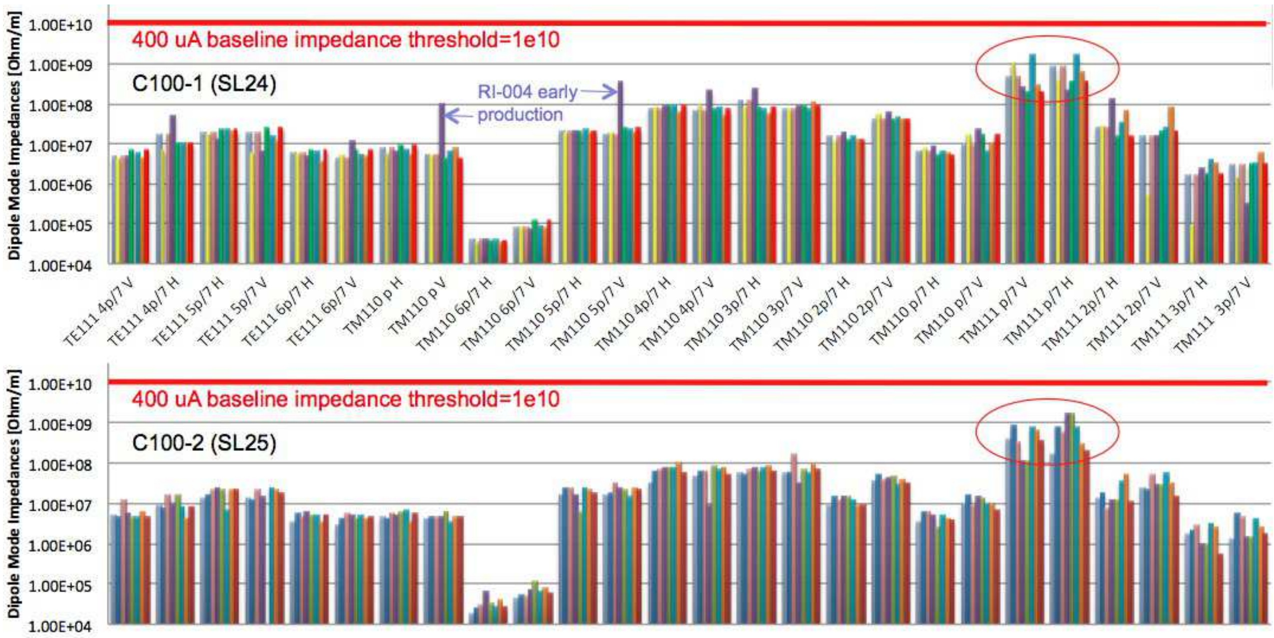

Figure 3: Measured Dipole HOM impedances for the first two production C100 cryomodules, C100-1 and C100-2, installed in the CEBAF south linac locations SL24 and SL25. The 5-pass 400 μA 12 GeV baseline impedance threshold is 10^{10} Ω/m. The highest surveyed impedances are TM111 $\pi/7$ modes near 2893 MHz.

energy with beam on, the threshold current can be obtained [11] from

$$I_{\rm th} = \frac{I}{1-\sqrt{\frac{P(0)}{P(I)}}} \tag{4}$$

Here $P(0)$ and $P(I)$ are the HOM powers radiated with beam currents of zero and I respectively. The data analysis using this approach is in progress. This requires detailed characterization of attenuation of C100 HOM cables used in the study, which will occur in June 2011. To characterize the case of $m^{\star}\sin(\omega T_r) > 0$, the analysis using second order perturbative solution will be performed.

CONCLUSIONS

We have characterized the HOM and BBU performance of two CEBAF 12 GeV upgrade C100 cryomodules, each containing eight 7-cell 1497 MHz C100 cavities. Full HOM surveys across TE111, TM110, and TM111 modes were performed in a test facility and the CEBAF tunnel. These surveys, supported by simulation and experiment, show that the lowest 1-pass BBU thresholds for C100-1/2 cryomodules are over 20 mA; 5-pass thresholds are likely well over the 5-pass 400 μA 12 GeV spec. Detailed analysis of extrapolated BBU experiment data to lower measured BBU threshold lower bound uncertainties is ongoing.

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