OBSERVATION AND MITIGATION OF MULTIPASS BBU IN CEBAF*

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Abstract

The Continuous Electron Beam Accelerator Facility (CEBAF) recirculating accelerator at Jefferson Lab consists of two linacs carrying beam for up to five passes of acceleration. The design of this accelerator anticipated the onset of multipass beam break-up (BBU) at a beam current of approximately 20 mA, far above the operational peak current of 200 μA. For more than a decade of operation, no sign of BBU was ever observed. However, a specially designed acceleration cavity in a cryomodule installed in the summer of 2007 has been observed to cause BBU instability with as low as 40 μA of injected beam current. This presented an opportunity to study BBU in a five-pass accelerator. In this paper we will discuss multipass BBU, present observational data, and discuss the ways we have developed to maintain the instability threshold current to values above those required for operation.

INTRODUCTION

At sufficiently high currents, BBU becomes an issue for any recirculating accelerator, such as the superconducting CEBAF at Jefferson Lab. BBU can also set an upper limit to the operating current for energy recovery linac drivers proposed for synchrotron light sources and free electron lasers [1]. The advantage of superconducting cavities is a high quality factor (Q) for the fundamental (accelerating) mode, but SRF cavities also have Higher Order Modes (HOMs) with possibly very high Q values. These high Q HOMs can enable BBU.

In the BBU mechanism, the HOM excited in the cavity perturbs the first pass beam. When the beam returns to the same cavity, the recirculated beam can provide gain for the HOM, providing positive feedback. With high enough Q and current, the gain can overwhelm the passive losses and cause BBU. The higher the Q of a particular HOM, the lower the instability threshold current will be. Therefore, damping of HOMs (lowering their Qs) is of great concern.

In the original CEBAF design, the cavity HOM damping results in a stability threshold current more than a factor of one hundred larger than the operational peak current. A replacement cryomodule, "*Renascence*,"[2,3] was recently added near the entrance of the first CEBAF linac (North Linac, Figure 1). Because of some weaknesses in the quality control during production (since identified and corrected), the Q for two of the HOMs of one of the cavities exceeded the design value, creating the possibility of BBU within the operating current range of the accelerator. In this paper, we will first describe the BBU mechanism, reviewing the important formulae. Then we present our measured data, calculate the important parameters of the offending HOMs, and discuss possible causes of the problem. We close with a summary of possibilities for mitigating the problem.

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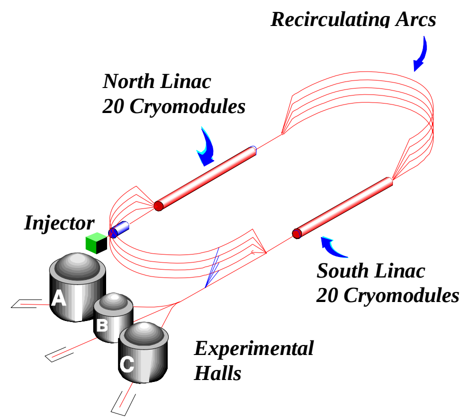

Figure 1: Layout of CEBAF.

MULTIPASS BBU

In order to describe the BBU mechanism, let us assume that a dipole HOM is present in one of the cavities in the first linac in Figure 1. The dipole mode has a nonzero transverse magnetic field. Without loss of generality, let us assume that only the horizontal component B_x is present, deflecting the first pass beam vertically. The accompanying vertical gradient in E_z couples to the recirculated beam, amplifying or damping the mode depending upon the optics and time of flight. The overall gain depends upon how much power is coupled out of the beam versus how much damping is present in the cavity for this dipole mode. When the overall gain exceeds unity, the dipole HOM fields increase exponentially and eventually drive the beam too far off-orbit. The beam current above which the BBU mode has net gain is called the threshold current and is given by the formula in Eq. (1) for a single dipole HOM in a two-pass machine:

$$I_{th} = \frac{-2p_1 c}{ek(R/Q)QM\sin(\omega T_r)} \qquad (1)$$

where p_1 is the first pass beam momentum at the cavity, c is the speed of light, e is electron charge, k is the wave number ω/c of the HOM, $(R/Q)Q$ is the shunt impedance of the HOM, T_r is the recirculation time, and M is the transfer matrix element 12 (horizontal) or 34 (vertical) from the cavity back to itself [4].

In multiple pass machines like CEBAF, there may be BBU contributions from all higher passes [5]. For example, instead of only pass 1 to 2, pass 2 to 3 or pass 2 to 5 can also contribute. To include all those cases, the expression $M\sin(\omega T_r)$ in Eq. (1) needs to be replaced by the more general expression:

$$M\sin(\omega T_r) \rightarrow \sum_j^N \sum_{i<j} M^{ij} \frac{p_1}{p_i} sin(\omega T_r^{ij}) \qquad (2)$$

where N is the number of passes, M^{ij} is the appropriate transfer matrix element from pass i to pass j, with transit time T_r^{ij}.

DESCRIPTION OF BEAM TESTS

In normal operations, beam loss triggers the machine protection interlocks at a very reproducible beam current threshold. This is easily corrected. But when beam loss events occurred in the fall of 2007 at currents lower than previous experience, no overloaded cavity could be identified, and the current threshold was insensitive to RF settings. When we fixed the current just under the threshold, we observed that as spontaneous current fluctuations raised the beam current, the beam spot visible on a synchrotron light monitor (SLM) would distend vertically (Figure 2). We immediately recognized this as a vertically polarized HOM generating BBU. In this "near unity gain" configuration, the BBU growth rate was sufficiently low that with manual control of beam current, we were able to maintain large HOM excitation for minutes at a time, allowing beam measurements.

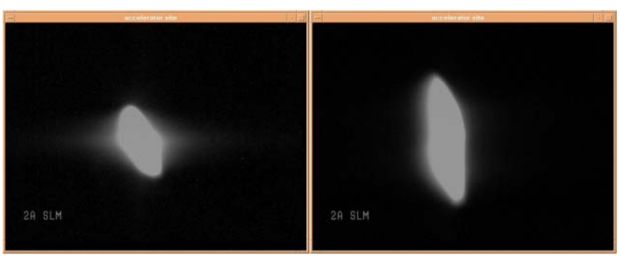

Figure 2: Beam spot well below BBU limit (left) and very close to BBU limit (right) on the SLM.

The most suspect modes were in the cavities of the zone 4 cryomodule, newly installed during the summer of 2007 near the beginning of the North Linac. The first observed frequency of the beam fluctuation was 2156 MHz, a known dipole HOM frequency detected from a beam position monitor (BPM) downstream from the North Linac. In a survey of zone 4 cavities, we observed this frequency on a probe of cavity 5 in coincidence with the real-time visual indication of BBU on the SLM, flagging this cavity as the source of the instability. The magnitude of this HOM grew out of the noise floor, increasing exponentially as the current approached the beam loss threshold.

The BBU phenomenon recurred during operations at various beam energies, sometimes due to an HOM at 2149 MHz, but was always avoidable by slight changes in linac focusing to alter the recirculation transfer function elements. Facility development time was scheduled to determine whether this behavior matched classic BBU mechanisms. During this dedicated time, we were able to induce and observe BBU behavior with multiple machine configurations, measuring the beam current threshold and transfer functions.

The 908 MeV/pass acceleration configuration in use at the start of these tests delivered three-pass beam with optics configured such that the second pass was driving the 2149 MHz BBU mode, but the third pass was almost non-participating (the magnitude of the transfer matrix M^{12} was significantly larger than M^{13}). The phase factors $\sin(\omega T_r)$ for passes 1 to 2 and 1 to 3 were of approximately unit magnitude at this frequency. The instability started at a threshold current of 108 μA. Dwelling at the threshold current, we measured the fluctuation frequency on the beam using a BPM at the end of the North Linac. The beam fluctuation shows up as sidebands of the bunch frequency of the beam. Figure 3 explains this measurement.

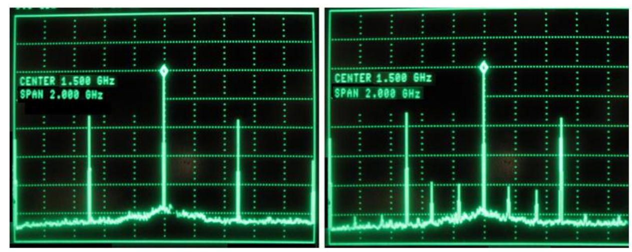

Figure 3: Spectrum of beam position signal at the end of North Linac well below the BBU limit (left) and very close to BBU limit (right). The left trace shows the beam bunch frequency at 0.5 GHz plus its harmonics at 1.0, 1.5, 2.0, and 2.5 GHz. The right trace shows the same frequencies as the left trace plus side bands due to beam motion at 2.149 GHz, the HOM frequency.

Next, we changed the third pass optics so that the M^{13} was much larger than before, with both positive and negative values, keeping M^{12} and all other BBU related parameters unchanged. With both M^{13} and M^{12} negative, the threshold current decreased to 66 μA. With positive M^{13} the threshold current rose to above the then-current administrative limit of 140 μA. The frequency of the beam fluctuation and cavity HOM were unchanged. Looking at Eq. (1), the effective value of M was changed and therefore I_{th} was inversely changed by the same factor. The recirculation times between passes do not change, so the phase factor $\sin(\omega T_r)$ remains unchanged (still close to unity for passes 1 to 2 and 1 to 3).

We then stopped the third pass beam altogether and operated a 2-pass machine. This gave us a $I_{th} = 98\,\mu A$ similar to our very first configuration, confirming that the third pass was non-participating (or slightly damping).

Finally, we restored the 700 MeV/pass configuration with the 2156 MHz HOM generating BBU that we observed earlier. The threshold current was 54 μA in the same cavity, NL4-5. In this four-pass configuration, the recirculation times stayed the same but now ω was different. The $\sin(\omega T_r)$ for pass 1 to 2 was about -1, pass 1 to 3 was about +1, and pass 1 to 4 was about -1. The selection between the two BBU modes, 2149 MHz and 2156 MHz, is determined by M and $\sin(\omega T_r)$. The reason we did not see the 2156 MHz mode in some of the machine configurations described above was that the $\sin(\omega T_r)$ values for the 2156 MHz mode give a negative threshold current in Eq. (1). Negative threshold indicates that the beam damps the mode.

EXPERIMENTAL RESULTS

Both HOMs we have observed were in the same cavity, NL4-5, and extensive RF measurements were done on the cavity with and without beam to measure the RF parameters of these modes. The most important parameters are the frequencies and Qs of the modes, listed in Table 1. The Q was measured via decay time after beam trips and through direct RF network analyzer measurements using the cavity couplers.

Table 1: Measured Frequency and Q of the HOMs

Mode Frequency	**Loaded Q (decay time)**	**Loaded Q (Network Analyzer)**
2149.1503 MHz	1.1e8	1.2e8
2156.1212 MHz	0.92e8	1.0e8

Once the threshold current, transfer matrix, frequency, and Q were all measured, R/Q for the modes could be calculated using Eq. (1). Table 2 shows the resulting R/Q values together with experimental results of the beam

Table 2: Beam Test Results

Mode	I_{th}	M^{12}	M^{13}	M^{14}	**R/Q**
2149 3-pass	108 μA	-35.4	2.1	~	14.4
2149 3-pass added Gain	66 μA	-36.6	-17.8	~	15.4
2149 2-pass	98 μA	-36.5	~	~	15.3
2156 4-pass	54 μA	21.1	-34.0	34.9	9.7

tests as described in the previous section. Note that R/Q represents the geometry of the cavity and the HOM fields. The other way of measuring this parameter is by bead pull measurement, which is not an option for a cavity already installed in the machine. Please note that for transfer matrix calculations, we have not listed the contributions between higher passes because in Eq. (2) all those higher passes have a factor p_1/p_i in them and that diminishes the magnitude of their contributions. For example, the contribution of pass 3 to 4 has a factor of p_1/p_3 which is (100/1500). Table 3 lists the $p_1/p_i \sin(\omega T_r^{ij})$ for both HOMs and it shows relatively small contributions of higher passes ($i > 1$).

Table 3: Value of $\boldsymbol{p_1/p_i}$ $\boldsymbol{\sin(\omega T_r^{ij})}$ for Different Passes

Freq	**1-2**	**1-3**	**1-4**	**2-3**	**2-4**	**3-4**
2149	0.92	0.94	0.87	0.01	0.1	0.05
2156	-0.93	0.91	-0.97	0.01	-0.05	0.09

POSSIBLE CAUSE

Using the measured RF parameters as input, software developed at SLAC was used to understand why these Q values are so much higher than the design for cavity 5, the source of our BBU. This software predicts the shape of the cavity based on RF data and it has predicted that cavity 5 is shorter by 8 mm than design. This deformation has drastically tilted the fields of several dipole modes, isolating them from the intended HOM loads and raising their Qs. It has also changed the value of R/Q for some modes [6]. Table 4 shows these results for our modes. That cavity 5 was shorter than design, was noted in our pre-installation quality check data, but at the time it was thought that it would cause no problem [7].

Table 4: Ideal and Deformed Cavities vs. Beam Test

Mode	**Ideal Cavity**		**Deformed Cavity**		**Beam test**	
	Q	**R/Q**	**Q**	**R/Q**	**Q**	**R/Q**
2149	2.9e6	20	2.2e8	19	1.2e8	15
2156	3.7e6	37	8.9e8	10	1.0e8	9.7

MITIGATION

Knowing that the problem of high Q cavities is localized, limited to one cavity in one module, makes mitigation of the problem much easier. Our principal technique has been to adjust the optics to reduce the transfer matrix element to this particular location thereby raising the threshold current. This has been sufficient effort for our needs to date. We have also considered moving the module to the end of the South Linac raising the values of p_1 and consequently I_{th}. The last option, since this problem is localized to one module only, is to replace or rework the problem cavity in that module.

CONCLUSION

We made the first observation of BBU with multi-recirculated beam at CEBAF. Our results agreed well with the classical BBU and it was the first experimental test for the formula presented in Eq. (2). The beam and RF test results of R/Q and Q of the abnormal cavity matched well by the simulation data for a shortened cavity. Our investigation demonstrated that the problem is localized to a few cavities in one cryomodule, mainly due to a manufacturing variance thought to be insignificant at the time. Now that we understand the situation, we are confident it will not be a serious problem for the future operation of CEBAF.

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