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BEAM-BREAKUP STUDIES FOR THE 4-PASS CORNELL-BROOKHAVEN ENERGY-RECOVERY LINAC TEST ACCELERATOR

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Abstract

The Cornell Brookhaven Energy-Recovery-Linac (ERL) Test Accelerator (CBETA) [1] is currently under construction at the Cornell Wilson Laboratory. The primary structures in CBETA for beam recirculation include the Main Linac Cryomodule (MLC) and the FFAG beamline. As the electron bunches pass through the MLC cavities, Higher Order Modes (HOMs) are excited. The recirculating bunches in-turn excite HOMs further, and this feedback loop can give rise to beam-breakup instability (BBU). We will first explain how BBU occurs and how we simulate the effect. Then we present the simulation results on how BBU limits the maximum achievable current of CBETA, and the potential ways to improve the threshold current.

INTRODUCTION

BBU occurs in recirculating accelerators when a recirculated beam interacts with HOMs of the accelerating cavities. The most dominant HOMs are the dipole HOMs which give transverse kick to the beam bunches. The off-orbit bunches return to the same cavity and excite more dipole HOMs which, if in phase with the existing dipole HOMs, can kick the bunches further in the same direction. The effect can build up and eventually result in beam loss. With a larger beam current the effect becomes stronger, so BBU is a limiting factor on the maximum achievable current, the threshold current I_{th}. With more recirculation passes, bunches interact with cavities for more times, and I_{th} can significantly decrease [4]. The low and high target currents of CBETA are 1 mA and 40 mA respectively, for both the 1-pass mode and 4-pass mode. Simulations are required to check whether I_{th} is above this limit.

BBU SIMULATION OVERVIEW

Cornell Wilson Laboratory has developed a simulation software called Bmad to model relativistic beam dynamics in customized accelerator lattices [3]. Subroutines have been established to simulate BBU and find the I_{th} for a specific design. The lattice provided to the program must include at least one multipass (recirculated) cavity with HOM(s) assigned to it. The following section will explain in detail how HOMs of the MLC cavities are obtained.

The goal of BBU simulation is to find the I_{th}. The program starts with a test current and records the voltage of all assigned HOMs over time. As the beam pass through the cavities, the momentum exchange between the bunches and wake fields are calculated, and HOM voltages are updated. If all HOM voltages are stable over time, the test current is considered stable, and a greater current will be tested. In contrast, if at least one HOM voltage is unstable, the test current is regarded unstable, and a smaller current will be tested. Usually I_{th} can be pinned down within numerical accuracy under 30 test currents.

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HOM SIMULATION AND ASSIGNMENT

To run BBU simulation we must first obtain the HOM characteristics. Each HOM is characterized by its frequency f, shunt impedance (R/Q), quality factor Q, order m, and polarization angle θ. Since the MLC has been built and commissioned, one would expect directly measurement of HOM spectra from the cavities. Unfortunately, the measured spectra contains hundreds of HOMs, and it is difficult to isolate each individual HOM and compute their characteristics. Instead, since the cavity shapes are modelled before constructed, we can simulate the HOM profiles using the known cavity structures. This has been done using the Horizontal Test Cryomodule (HTC) program, and the HOM characteristics can be directly computed.

In reality each cavity is manufactured with unknown precision errors. The errors in the ellipse parameters of the cavity shape are typically within ±125 µm (in short, $\epsilon = 125\,\mu m$). Accounting for such random errors in the HTC simulation results in different HOM spectra for a single cavity. Since MLC has 6 cavities with different manufacture errors in general, for each BBU simulation we assign each cavity a different set of HOM spectrum from HTC. With multiple BBU simulations we can therefore obtain a statistical distribution of I_{th} of CBETA. The results are shown in the next section.

In general we could assign each cavity many HOMs of different HOM orders m, but this can be computationally heavy. To save simulation time we include only the 10 most dominant dipole-HOMs ($m = 1$) from a spectrum. A dipole-HOM is more dominant if it has a greater figure-of-merit $\xi = (R/Q)\sqrt{Q}/f$ [4]. For the rest of this paper, HOM refers to dipole-HOM unless further specified.

Bmad SIMULATION RESULT

Hundreds of simulations with different HOM assignments were run to obtain a statistical distribution of I_{th} for each specific CBETA design. Three distributions are presented as histograms in this section:

Case 1: CBETA 1-pass with $\epsilon = 125\,\mu m$
Case 2: CBETA 4-pass with $\epsilon = 125\,\mu m$
Case 3: CBETA 4-pass with $\epsilon = 250\,\mu m$

The third case with manufacture precision errors within ±250 µm is investigated for academic interest.

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Case 1) CBETA 1-Pass with $\epsilon = 125\ \mu m$

The design current of CBETA 1-pass is 1 mA (the lower goal) and 40 mA (the higher goal). Figure 1 shows that all 500 simulations results exceed the lower goal of 1 mA, and 499 of them are above 40 mA. The result is quite promising.

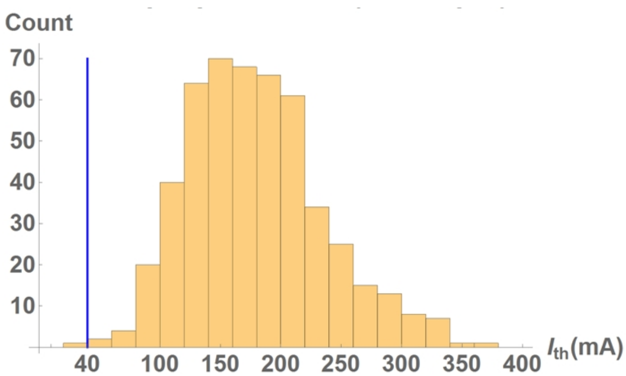

Figure 1: 500 BBU simulation results of I_{th} for the CBETA 1-pass lattice. Each cavity is assigned with a random set of 10 dipole HOMs ($\epsilon = 125\,\mu$m). The blue line indicates the higher current goal of 40 mA.

Case 2) CBETA 4-Pass with $\epsilon = 125\ \mu m$

The design current of CBETA 4-pass is the higher goal of 40 mA. Figure 2 shows that out of 500 simulations, 494 of them exceed the 40 mA goal. This implies that with certain undesirable combinations of HOMs in the cavities, the beam current can not reach the 40 mA goal due to BBU.

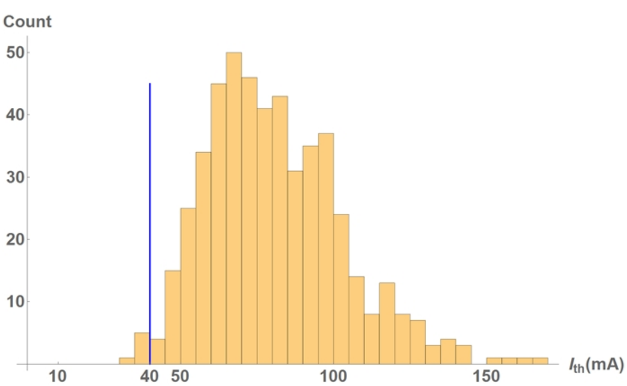

Figure 2: 500 BBU simulation results of I_{th} for the CBETA 4-pass lattice. Each cavity is assigned with a random set of 10 dipole HOMs ($\epsilon = 125\,\mu$m). The blue line indicates the higher current goal of 40 mA.

Case 3) CBETA 4-Pass with $\epsilon = 250\ \mu m$

It is interesting to see how I_{th} distribution changes with a different manufature error (ϵ) for the 4-pass lattice (see Fig. 3). For $\epsilon = 250\,\mu$m, all 500 simulations are above 40 mA, which is better than the ϵ= 125 µm case. Some might thus wonder if a greater ϵ could statistically improve the threshold current. In fact, greater deviation in cavity shapes results in greater spread in the HOM frequencies. This allows the HOMs across cavities to act less coherently when kicking the beam, thus potentially increases the I_{th}. However, a greater deviation also tends to undesirably increase the Q (and possibly R/Q) of the HOMs, which usually lowers I_{th}. Compensation between the frequency spread and HOM damping implies that a greater manufacture error in cavity shapes can not reliably improve I_{th}.

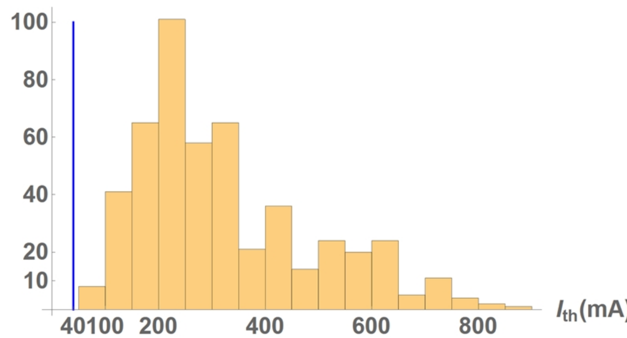

Figure 3: 500 BBU simulation results of I_{th} for the CBETA 4-pass lattice. Each cavity is assigned with a random set of 10 dipole HOMs ($\epsilon = 250\,\mu$m). The blue line indicates the higher current goal of 40 mA.

AIM FOR HIGHER I_{th}

To achieve a higher I_{th}, three ways have been proposed, and their effects can be simulated. The first way is to change the bunch frequency f_b (from injector) by an integer multiple. Simulations on a CBETA 1-pass and 4-pass lattice show a change of I_{th} fewer than 5% over several choices of f_b, implying that varying f_b is not effective in improving CBETA I_{th}. Rigorous calculation [4] has shown that I_{th} depends on f_b in a non-linear way for a multi-pass ERL, and it will be interesting to experiment this effect on the realistic CBETA. The other two ways involve either varying the phase advances or introducing x-y coupling between the cavities. The simulation results with these two methods are presented in the following sections.

EFFECT ON I_{th} BY VARYING PHASE ADVANCE

I_{th} can potentially be improved by changing the phase advances (in both x and y) between the multi-pass cavities. This method equivalently changes the T_{12} (and T_{34}) element of the transfer matrices, and smaller T_{12} values physically correspond to a greater I_{th} in 1-pass ERLs [4]. To vary the phase advances in Bmad simulations, a zero-length matrix element is introduced right after the first pass of the MLC LINAC. In reality the phase advances are changed by adjusting the quad strengths around the accelerator structure. In simulation the introduction of the matrix may seem arbitrary, but this gives us insight on how high I_{th} can reach as phase advances vary.

For each simulation, each cavity is assigned with three "$\epsilon = 125\,\mu$m" HOMs in x, and three identical HOMs in y

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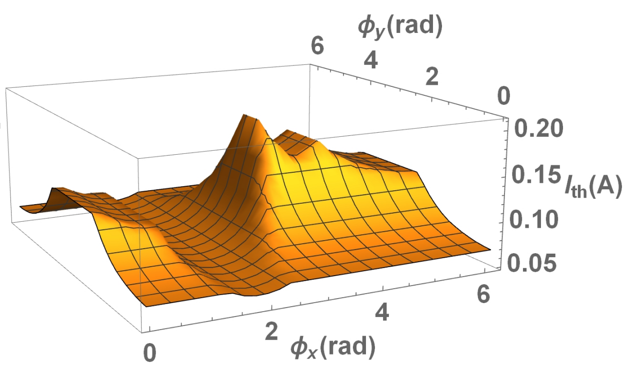

Figure 4: A scan of BBU I_{th} over the two phase advances for the CBETA 4-pass lattice. Each cavity is assigned with a random set of 3 dipole HOMs in both x and y polarization. (ϵ = 125 µm). For this particular HOM assignment, I_{th} ranges from 61 mA to 193 mA.

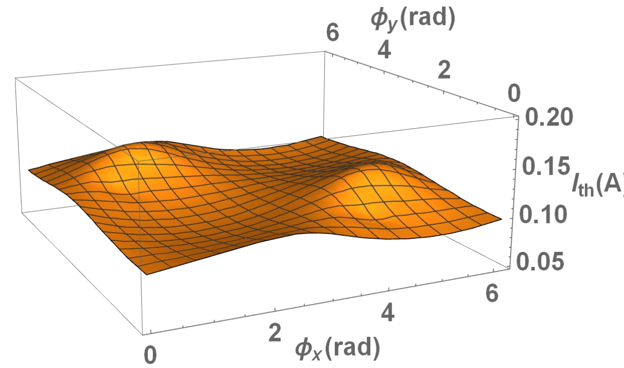

Figure 5: A scan of BBU I_{th} over the two free phases for the CBETA 4-pass lattice with x-y coupling. Each cavity is assigned with a random set of 3 dipole HOMs in both x and y polarization. (ϵ = 125 µm). For this particular HOM assignment, I_{th} ranges from 89 mA to 131 mA.

(polarization angle = $\pi/2$). The I_{th} is obtained for a choice of (ϕ_x, ϕ_y), each from 0 to 2π. Several simulations were run for both the 1-pass and 4-pass CBETA lattice, and mainly 4-pass results are presented below.

Figure 4 shows a typical way I_{th} varies with the two phase advances. Depending on the HOM assignment, the I_{th} can reach up to 200 mA with an optimal choice of (ϕ_x, ϕ_y). This implies that changing phase advances does give us advantages in improving I_{th} for the 1-pass CBETA lattice (the improvement can range from +200 mA to +400 mA depending on the HOMs assigned). Note that ϕ_x and ϕ_y affect I_{th} rather independently. That is, at certain ϕ_x which results in a low I_{th} (the "valley"), any choice of ϕ_y does not help increase I_{th}, and vise versa. It is also observed that I_{th} is more sensitive to ϕ_x, and the effect of ϕ_y becomes obvious mostly at the "crest" in ϕ_x. Physically this is expected since many lattice elements have a unit transfer matrix in the vertical direction, and the effect of varying T_{12} is more significant than T_{34}. In other words, HOMs with horizontal polarization are more often excited. As we will see this is no longer true when x-y coupling is introduced.

It is also observed that the location of the "valley" remains almost fixed when HOM assignments are similar. Physically the valley occurs when the combination of phase-advances results in a great T_{12} which excites the most dominant HOM. Therefore, the valley location depends on which cavity is assigned with the most dominant HOM, and is consistent with the simulation results.

EFFECT ON I_{th} WITH X-Y COUPLING

Another method potentially improves I_{th} by introducing x-y coupling in the transverse optics, so that horizontal HOMs excite vertical oscillations and vise versa. This method has been shown very effective for 1-pass ERLs [5]. To simulate the coupling effect in Bmad simulation, a different non-zero length is again introduced right after the first pass of the LINAC. The matrix couples the transverse optics with two free phases (ϕ_1, ϕ_2) to be chosen. These two phases are not the conventional phase advances, but can also range from 0 to 2π.

Figure 5 shows a typical way I_{th} varies with the two free phases for the 4-pass lattice. Depending on the HOM assignment, the I_{th} can reach up to 131 mA with an optimal choice of (ϕ_1, ϕ_2). Because the transverse optics are coupled, the two phases no longer affect I_{th} in an independent manner. That is, there is no specific ϕ_1 which would always result in a relatively high or low I_{th}. Both phases need to be varied to reach a relatively high I_{th}. Therefore introducing x-y coupling can still improve I_{th} for the 4-pass lattice (about +60 mA), but not as significantly as varying phase advances.

SUMMARY

Bmad BBU simulation has shown that for the current CBETA design lattice, both the 1-pass and 4-pass machine can always reach the low design current (1 mA), and can surpass the high goal of 40 mA over 98% of the time depending on the HOMs assigned.

To potentially increase the I_{th}, we can either adjust the injector bunch frequency, or vary the lattice optics (by introducing additional phase advances or x-y coupling). While the former is shown ineffective by simulation, the later provides room for improvement. For the 1-pass lattice, both optic-varying methods allow great improvement in I_{th} (about +200 mA to +400 mA). For the 4-pass lattice, the method of varying phase advances allow more improvement (about +150 mA) than x-y coupling (about +60 mA).

In realty, introducing x-y coupling requires installation of skew qudrupole magnets, so varying phase advances remains the most effective method to improve the I_{th} of CBETA.

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REFERENCES

[1] G.H. Hoffstaetter, D. Trbojevic *et al.*, *CBETA Design Report*, https://arxiv.org/abs/1706.04245

[2] G.H. Hoffstaetter *et al.*, *CBETA: The Cornell/BNL 4-Turn ERL with FFAG Return Arcs for ERHIC Prototyping* in *LINAC16:Proceedings of the 28th Linear Accelerator Conference, East Lansing, Michigan, USA* (2016), paper TUP02.

[3] D. Sagan, *Bmad Simulation Software*, https://www.classe.cornell.edu/bmad/

[4] G.H. Hoffstaetter and I.V. Bazarov, Phys. Rev. ST Accel. Beams 7, 054401 (2004).

[5] G.H. Hoffstaetter *et al.*, Phys. Rev. ST Accel. Beams 10, 044401 (2007).