RECENT PROGRESS ON BEAM-BREAKUP CALCULATIONS FOR THE CORNELL X-RAY ERL

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Abstract

Beam-breakup calculation algorithms have been developed in the general framework of the Cornell X-ray ERL design software, enabling their extension to multi-pass optics design for ERLs. A status report of this work is presented, together with initial results comparing the instability thresholds calculated for single- and two-turn optics with recently developed RF cavity designs.

INTRODUCTION

The potential for excellent quality of X-ray beams from low-emittance electron beams produced by a 5-GeV superconducting energy-recovery linac (ERL) is motivating an extensive development study at Cornell. Figure 1 shows the present status of the design layout on the Cornell campus.

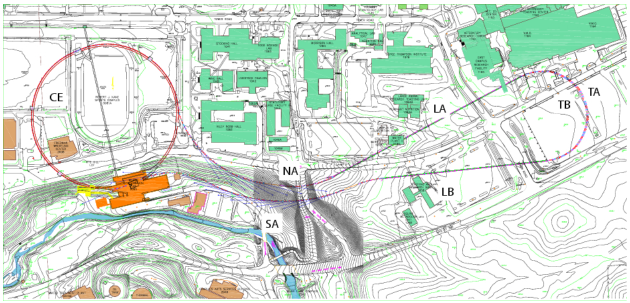

Figure 1: Layout of the Cornell X-ray ERL.

The 10 MeV electron beam produced by the injector is accelerated to 2.8 GeV in the first linac (LA), transported to the second linac (LB) by the high-energy turnaround (TA), where it is accelerated to 5 GeV. The south arc (SA) provides X-ray beamlines, the present CESR ring (CE) is used to transport the beam to the North Arc (NA) beamlines, then the first linac decelerates the 5 GeV beam to 2.2 GeV, and the inner turnaround (TB) transports the beam to the second linac where it is decelerated to 10 MeV and stopped.

Beam-breakup (BBU) instabilities arising from the excitation of higher-order modes in the superconducting RF cavities in the main linacs are important contributions to the operational current limit [1]. The original quantitative estimates of the instability threshold limits in the case of continuous wave recirculators have been extended to energy-recovery linacs [5] and generalized to coupled optics and polarized higher-order modes (HOMs) [6]. More recently, detailed numerical estimates for the Cornell one-turn ERL design have been obtained [7]. This paper reports on the implementation of such calculations in Bmad, the lattice analysis and design software package developed at Cornell for the ERL, CESR and other projects [3]. Primary motivation for this work is the extension to multi-pass ERLs.

BEAM-BREAKUP CALCULATIONS IN THE CORNELL ACCELERATOR-DESIGN SOFTWARE BMAD

Beam-breakup instabilities arising from higher-order-mode (HOM) power induced in the linac RF cavities have been modeled using Bmad tracking calculations by choosing an initial beam current with all RF buckets filled, tracking an off-axis beam to load HOM power, then testing for the time dependence of the highest HOM amplitude over a predetermined number of turns. A binary search for the threshold current then provides the instability limit to any chosen accuracy.

Solutions for the threshold current can be accurately approximated by simple formulas for the case of a single HOM in a single cavity where the HOM decay time is short or long relative to the return time [5]. Figure 2 shows the comparison of the Bmad tracking calculation to the analytic approximation of the threshold current for the toy model described in Ref. [5]. The HOM parameters are $R/Q = 100\ \Omega$, $f_\lambda = 2.0$ GHz, and $Q_\lambda = 10^4$. For the purposes of validating the model, the return time to the cavity was scanned through the period of the BBU sensitivity determined by the HOM parameters and the bunch spacing. The result for the threshold current as a function of the ratio of the return time t_r to the time between bunches t_b (0.77 ns for the 1.3 GHz cavities) is compared to the analytic approximation.

Having demonstrated the accuracy of the BBU thresholds in the short-return-time limit, we apply the model to the full Cornell ERL optics with the same single HOM parameters modeled in a single cavity. This case exemplifies the limit of return times much greater than the HOM decay time. Figure 3 shows the result of the scan, demonstrating that the Bmad tracking reproduces the analytic approximation. The higher order mode parameters employed for this study are those of the first HOM of Ref. [6]: $R/Q = 71\ \Omega$, $f_\lambda = 1.861$ GHz, and $Q_\lambda = 4968$.

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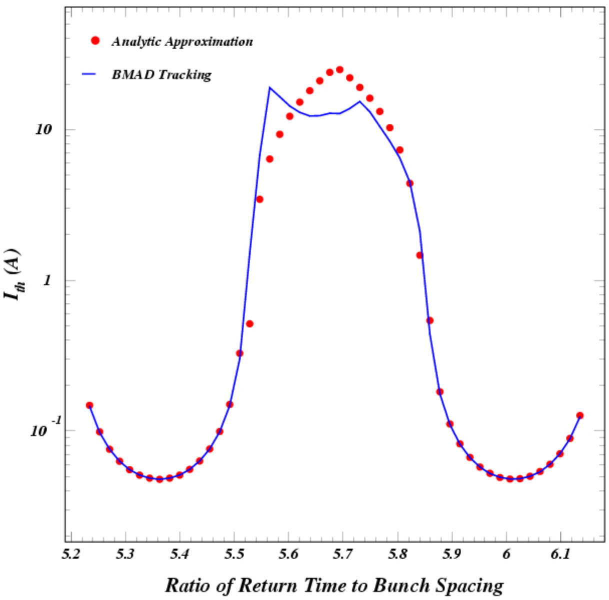

Figure 2: Comparison of the Bmad tracking result for the BBU instability threshold current for the case where of a single HOM in a single cavity where the return time is much less than the HOM decay time. The result is compared to the analytic approximation for this case.

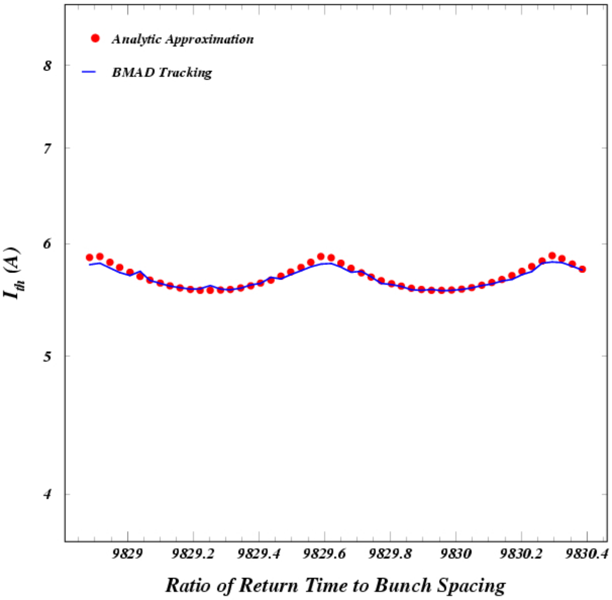

Figure 3: Comparison of the Bmad tracking result for the BBU instability threshold current for the full Cornell X-ray ERL optics with a single HOM in a single cavity, where the return time is much greater than the HOM decay time.

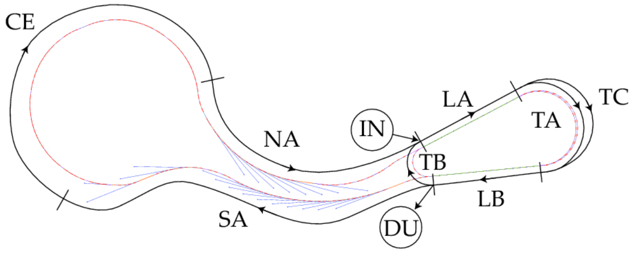

Figure 4: Layout of the two-turn ERL design.

TWO-TURN ERL DEVELOPMENT

Figure 4 shows the layout of the two-turn ERL for which optics has been designed. The linacs are half as long and a third turnaround (TC) has been added to provide the first of two accelerating turns through the linacs.

Figure 5 compares the BBU threshold calculation for the one-turn optics shown in Fig. 3 with the result for the same HOM parameters in the two-turn optics. The worst-case threshold for the two-turn ERL is about 100 mA, about a factor of 50 lower than that for the one-turn optics in this simplified case. A full calculation is expected to yield a threshold for the two-turn optics which is about a factor of six smaller [5]. The Bmad BBU threshold calculation algorithm remains under active development.

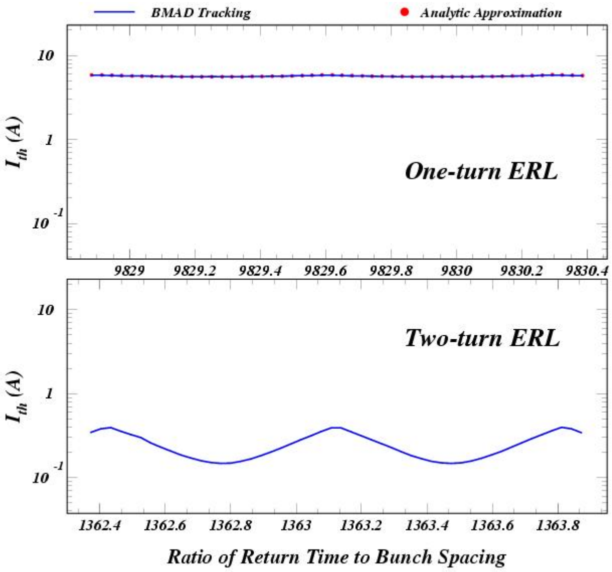

Figure 5: Comparison of the Bmad BBU threshold calculation for the simple HOM parameters in the one-turn optics to the result for the two-turn optics.

CAVITY DESIGN OPTIMIZATION

We are currently in the process of optimizing the cell shape of two main linac cavity designs with differences in the cavity end sections: a 7-cell cavity with a 39-mm radius beam tube end section on one end and a 55 mm beam tube end section on the other end, and a 7-cell cavity with 55-mm radius beam tubes on both ends [4]. The cavity designs use the same center-cell shape, which has been optimized to minimize dynamic cryogenic losses for a given iris radius of 35-mm, a maximum wall angle of $85°$, and limiting the ratio of peak electric field to accelerating field to a maximum value of 2. In each case, the end cell shapes are optimized to minimize the BBU HOM factor $(R/Q)Q/f$ of the worst higher order mode(s). The worst case HOM in these designs has a value of $(R/Q)Q/f \approx 3 \cdot 10^4$. Future optimization is likely to reduce this value.

BBU tracking results for a one-turn ERL with cavities based on the design with 55 mm beam tubes on both ends are summarized in Table 1. In addition, results obtained for the same ERL lattice, but with cavity HOM parameters as given in [7] are shown. BBU threshold currents have been calculated with and without HOM frequency spread from cavity to cavity for a given type of HOM.

	Cavity parameters from [7]			55-55 mm cavity parameters		
HOM	f [MHz]	Q	(R/Q) [Ω/cm^2]	f [MHz]	Q	(R/Q) [Ω/cm^2]
1	1861.37	4968	5.4403	2512.896	8867	2.1180
2	1873.94	20912	8.4409	2513.556	1472	7.6777
3	1881.73	13186	2.1629	2514.671	8557	8.1083
4	2579.66	1434	15.7821	3068.192	186198	0.0632
5				3073.245	64567	0.3971
Turns			No frequency spread			
1		12 mA			36 mA	
2		6 mA			8 mA	
			$\sigma_f/f = 0.4\%$			
1		235 mA			307 mA	
2		53 mA			87 mA	

Table 1: BBU tracking results for 7-cell cavity designs. In each case, the HOMs with highest values of $(R/Q)Q/f$ have been included in the Bmad tracking calculations, as listed below.

These results provide a first estimate of the improvement in the BBU instability threshold provided by the cavity redesign. They also give an early indication of the reduced thresholds in a two-turn optics. However, a more systematic study including the effects of varying HOM parameters and mitigation techniques such as HOM polarization will be required before conclusions can be drawn. Note also that the spread over many recalculations in the calculated threshold values for the case of HOM frequency spread is about 20% [7].

SUMMARY

Beam-breakup instability calculation algorithms have been implemented in the framework of the accelerator design software tool Bmad, enabling their extension to multipass ERLs. They have been validated by comparison to analytic approximations and to prior numerical estimates. These calculations will serve an important purpose in the further development of the Cornell X-ray source design. The design of the lattice optics and that of the superconducting RF cavities are interdependent. First results on the threshold currents for two cavity designs for one-turn and two-turn optics have been obtained. Further work on mitigating considerations such as HOM frequency spread and coupling with HOM polarization will be necessary.

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