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HIGH ORDER MODE ANALYSIS IN ENERGY RECOVERY LINAC BASED ON AN ENERGY BUDGET MODEL

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Abstract

Energy Recovery linear accelerator (ERL) light source facilities based on superconducting radiofrequency (SRF) are deemed of the most resplendent techniques in the future of accelerator physics. Running in a continuous waves mode with a high repetition rate for a long timescale, we discuss High order modes (HOMs) analysis in a two-pass two-way ERL scheme where acceleration and deceleration of electron bunches are supported by a standing wave structure of the RF cavity. The analysis reported in this paper is based on differential equations that describe the beam dynamics (BD) to overcome the limitations imposed by high currents and insure energy recuperation over millions of interactions.

INTRODUCTION

ERLs have a relatively fascinating history in the field of particle accelerator physics [1–3]. The concept of energy recovery in accelerators has been around for a long time since 1965 [4], with the first successful implementation of energy recovery occurring in the late 80s with the construction of the TRISTAN collider in Japan [5]. However, the ERL concept takes this idea one step further by recovering the energy of the beam in a more efficient way. The first ERL facility; the IR-FEL, was constructed at the Thomas Jefferson National Accelerator Facility (Jefferson Lab) in the early 2000s and demonstrated the feasibility of the ERL concept for the generation of intense high-quality electron beams [3, 6]. Since then, several other ERL facilities have been built, including the ERL Test Facility (ERLTF) at Brookhaven National Laboratory and the Cornell-BNL ERL Test Accelerator (CBETA) [7–10]. ERL technology has many advantages over traditional linear accelerators. For example, ERLs can provide continuous-wave (CW) operation, which means that the accelerator can run for extended periods of time, enabling a wide range of experiments [11]. Additionally, ERLs can create beams of variable energy, making them ideal for a wide range of applications in fields such as nuclear physics, materials science, and particle detection [12–14].

In accelerators, Electron bunches gain energy at the cost of an electromagnetic (EM) field resonant in the linac during acceleration; when utilized as a decelerator, the EM field gets energy from the bunch. In the case of ERL, electrons are not reused but only their energy. As a consequence, the electron generating light at the current point is not the same as it was on the previous turn. This is advantageous since a stable electron beam was not established enabling the generation of a beam that is used only one time with a lower emittance. The difference between a linear accelerator and a decelerator is just a matter of a bunch spot with respect to the phase of the resonant moving EM wave.

Our study focuses on the BriXSinO ERL model [15–22]. This machine is an ERL based on SC technology incorporating three coupled cavities and hosts two light sources, generating X-RAY based on inverse Compton scattering and a THz radiation source based on classical undulators and optical cavities, respectively. Notably, SC cavities are of great importance in this study due to their ability to accelerate beams with high repetition rates and large average currents. However, SC technology can lead to the presence of HOMs that exhibit a significant level of shunt impedance. In this paper, we will focus on two major parts, the stabilization of the process of energy recovery within the ERL operation during beam acceleration and deceleration; and second, the impact of HOMs on beam degradation using the HOMEN model [23].

STORED ENERGY LOSS IN ENERGY RECOVERY LINAC

In ERL, the beam is accelerated and then decelerated in the same linac, with the energy recovered and reused for acceleration in subsequent passes. However, not all of the beam's energy can be recovered during the deceleration process, leading to a loss of energy and a reduction in the overall efficiency of the ERL. There are several approaches to mitigate the energy loss in ERLs and we can cite here four main mechanisms. Optimization of the energy recovery efficiency by adjusting the beam parameters such as the beam current, energy, and bunch length. By optimizing the beam parameters, the energy loss during deceleration can be reduced, leading to higher energy recovery efficiency. Beam recirculation through the linac, allowing for additional opportunities to recover energy that was not recovered during the initial deceleration. Passive energy recovery, where the beam is decelerated by passing through a series of magnetic fields, which convert the kinetic energy of the beam into electrical energy that can be fed back into the power grid. The last mechanism would be the use of SRF cavities to improve energy recovery efficiency by providing a high accelerating gradient and minimizing the beam losses due to wakefields [24]. By combining these approaches, the energy loss during

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deceleration in an ERL can be minimized, leading to higher overall efficiency and greater energy recovery.

In our study, by implementing SC cavities, we numerically solved this energy loss problem using the set of differential equations provided by the HOMEN model [15, 23, 25, 26]. We can recall the stored energy expression of the fundamental mode ($n = 0$) which can be written as follows:

$$\frac{dU_n}{dt} = P_{\mathrm{Kly}} - \frac{\omega_n U_n}{Q_n} \pm \frac{qV_{acc,n}}{\tau} \tag{1}$$

where P_{Kly} is the klystron power, ω_{n} is the angular frequency of the mode n, Q_{n} is the intrinsic quality factor of the cavity in the order of 10^{10}, q is the bunch charge, τ is the cavity flight time and $V_{\mathrm{acc,n}}$ is the overall accelerating voltage. The values related to these parameters are listed in Table 1.

In ERL, the process of acceleration and deceleration must be stabilized in time in order to achieve the principle of energy recovery, in other words, the stored energy inside the cavity must always be the same at the entrance and exit of the cavity over a long time-scale. Supposing 1J of initial stored energy, we accelerate the first electron bunch (point-like bunch) in time $t = \tau$, then decelerate the coming back bunch in the same cavity with opposite phase injection. According to eq. 1, the initial stored energy will decrease during the acceleration of the bunch, while it will increase in order to reach back the initial energy during the deceleration of the beam for energy recovery. We found that this principle can't be achieved (see Fig. 1) based on the assumption we made. Due to superconductivity, the quality factor is very high which will result in a small dissipation power $P_{diss} \approx 0.3$W, this can give us an idea about the amount of power needed in the system for the operation of beam acceleration, therefore, we suppose that $P_{\mathrm{Kly}} = P_{\mathrm{diss}}$ to compensate the power loss.

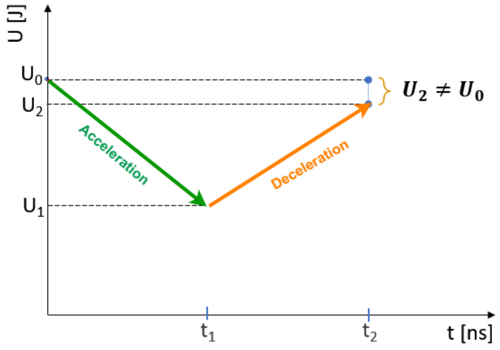

Figure 1: Missing energy in one cavity cycle. U_0 is the initial stored energy of the cavity. U_1 is the stored energy remaining after the acceleration and U_2 is the final energy of the cavity after deceleration.

After the passage of one electron bunch in accelerating mode, the initial stored energy decreases from $1J$ to $U_1 = 0.999875$ J. By decelerating the coming back bunch from the bubble arc, and starting from the opposite cavity direction, we recovered an amount of energy $U_2 \neq U_0(1J)$. The fact that theoretically, we want to recover back all the energy to be used as a power source instead of the Klystron. Based on the assumptions we made above, the missed energy per each cycle will shatter the principle of energy recovery for power sustainability. By injecting approximately 2×10^5 bunches in the ERL. The computation results show the stored energy inside the system will vanish in time as presented in Fig. 2.

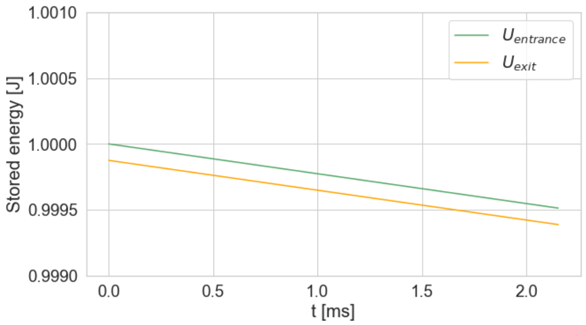

Figure 2: Stored energy loss in ERL based on one 7-cell SC cavity.

To overcome this disequilibrium of the ERL working mode, one can rely on the solutions cited above where the most feasible solution can be to implement an active beam feedback. Active beam feedback can be used to adjust the beam position based on the actual acceleration and deceleration rates, which can lead to better energy recovery rates. In this study, we solved this problem numerically. The energy difference within one cavity cycle in our case is $\Delta U = 7.822345 \times 10^{-09} J$. Taking into account the repetition rate frequency of the machine, this equates to approximately 0.7W of additional power that must be supplied to the system to maintain its stability. Specifically, the HOMEN model was developed to ensure that the ERL can sustain its operating mode over billions of interactions and for long periods of time. Following this new assumption, it has been found that the method utilized to guarantee the regularity of the ERL is effective for 1 million electron bunches being injected. The results show that the initial stored energy inside the linac remains stable at the cavity entrance, ensuring that the bunch in the fundamental mode always sees a consistent amount of energy. Similarly, at the cavity exit, after the beam has been accelerated, U_n(t) is in equilibrium, even after the passage of 2 million bunches.

Fig. 3, shows The path of an electron bunch inside the ERL based on three coupled SC cavities. Considering the length of BriXSinO's arc, the bunch is injected in this case with $\gamma = 10$ (5 Mev); during the acceleration inside the first cavity, the bunch gains an amount of 13.4 MeV arriving at $\gamma = 36.2$. After a time $t_s \approx 2.68$ ns, which corresponds to the time to cross and reach the second cavity, the bunch will be accelerated again reaching γ=62.5 and so on until going out from the third cavity with γ=88.7 ($\approx$ 45.33MeV). After crossing the bubble arc of length L_{arc}= 80 m, the

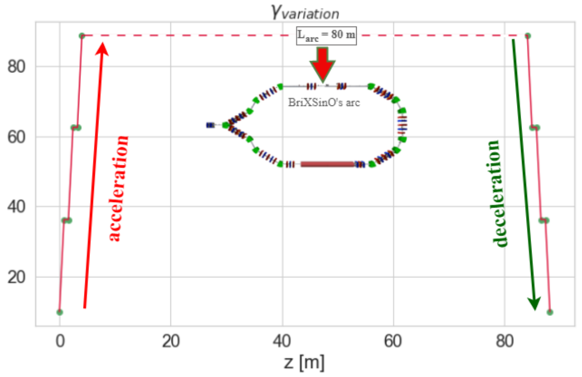

Figure 3: Variation of the bunch energy gain taking into account an initial energy of 5 MeV (γ=10). The ERL is composed of 3 coupled 7-cell SC cavities.

Table 1: ERL Beam Parameters

Target parameter	Unit	Value
Injection energy	MeV	10
Average beam current	mA	5
repetition rate	MHz	100
Bunch charge	pC	50
Flight time	ns	5
Cavity length	m	1.5
RF frequency	MHz	1300
Quality factor Q_0		3.78×10^{10}
Duty factor		CW

bunch will be decelerated for energy recovery. Based on our simulations, we have successfully demonstrated the principle of energy recovery in the ERL and achieved a total energy gain of approximately 42.7 MeV. This finding showcases the potential of energy recovery technology in improving the efficiency of particle accelerators and highlights its relevance for various research areas.

BUNCH ENERGY GAIN IN THE PRESENCE OF HOM IN ERL

The bunch energy gain refers to the change in the kinetic energy of a beam. In the presence of HOMs, the bunch energy gain in ERLs can be affected leading to a loss of the beam energy due to the energy transfer from the beam to the resonant modes [27]. This can cause an increase in the energy spread of the beam and a reduction in the beam quality and stability. To mitigate the effects of HOMs, ERLs use various techniques, such as HOM damping, beam conditioning, and feedback systems. HOM damping system uses RF components to remove unwanted modes from the system. The beam conditioning system uses an elliptical cavity to suppress the HOMs, while the feedback system monitors the beam quality and adjusts the parameters accordingly to suppress the HOMs. In order to visualize HOMs effects on beam quality, accurate simulations of the wakefield have been done to achieve a reliable evaluation of the variation of stored energy in the cavity as well as of the bunch energy distribution. Depending on previous studies in these Refs [23, 25, 26], we add the loss factor k_{loss} contribution to Eq. 1. We evaluate back the system of equations of HOMEN with k_{loss}=0.6V/pC and f=2.43GHz. Based on these data, the stored energy and the bunch energy gain will both vary until achieving an equilibrium after few ms.

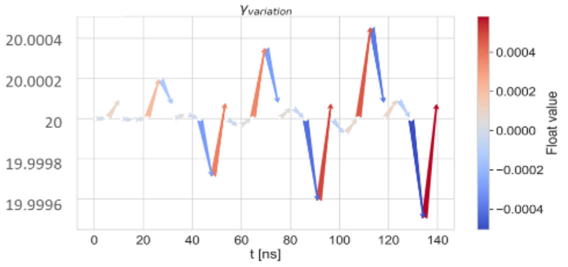

Figure 4: Bunch energy gain for HOM in the ERL (Float value is the net value). Red arrows indicate the bunch acceleration and energy gain, and blue arrows indicate deceleration and energy loss.

Fig. 4 illustrates the variation of the first 14 bunches in the ERL with 10 MeV of initial energy. The first bunch at the cavity entrance experiences no energy gain due to the absence of stored energy required to evaluate HOMs. However, subsequent bunches begin to accelerate and gain energy (as indicated by red arrows) or decelerate and lose energy (as indicated by blue arrows), depending on their injection phase.

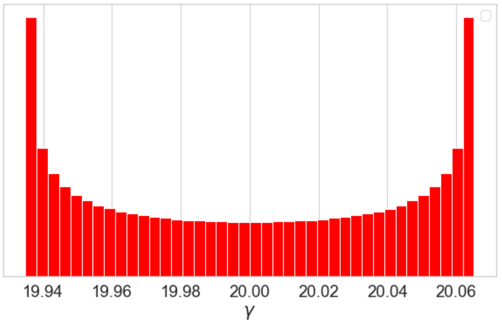

Figure 5: Accumulated bunch energy gain at the cavity exit after the passage of 3 million bunches in the ERL.

To evaluate the quality of the beam, it is necessary to conduct simulations that cover a long period of time to accurately capture any energy fluctuations. In Fig. 5, we present the probability distribution of relative energy fluctuations for the bunch at the cavity exit after passing over 3 million electron bunches, assuming an initial energy gain of γ=20. The energy fluctuates around the fundamental mode, resulting in a beam degradation of approximately $\pm 3 \times 10^{-3}$. This value was obtained under the worst-case scenario, where an undamped HOM with the highest k_{loss} value in a 7-cell SC cavity was considered.

CONCLUSION

HOM analysis in a two-pass two-way ERL scheme has addressed the challenge of missing energy during Linac's recovery operation. Through simulations based on the HOMEN model, which enhances beam dynamics while supporting energy recuperation over millions of interactions despite high current limitations, this research represents a significant step forward in developing efficient ERL light sources for various applications. This technology has strong potential for significantly improving the output and efficiency of particle accelerators and paves the way for even more advanced developments in accelerator physics and related fields.

REFERENCES

[1] S. Bogacz and G. A. Krafft, “Recirculated linacs and energy-recovered linacs, book chapter in particle physics reference library-vol. 3. accelerators and colliders, stephen myers and herwig schopper, eds., 2020,” Thomas Jefferson National Accelerator Facility (TJNAF), Newport News, VA …, Tech. Rep., 2019.

[2] W. Lou and G. H. Hoffstaetter, “Beam breakup current limit in multiturn energy recovery linear accelerators,” *Phys. Rev. Accel. Beams*, vol. 22, p. 112 801, 11 2019. `doi:10.1103/PhysRevAccelBeams.22.112801`

[3] L. Merminga, “Energy recovery linacs,” in *Synchrotron Light Sources and Free-Electron Lasers: Accelerator Physics, Instrumentation and Science Applications*. 2020, pp. 439–477. `doi:10.1007/978-3-030-23201-6_11`

[4] M. Tigner, “A possible apparatus for electron clashing-beam experiments,” *Nuovo Cim.*, vol. 37, pp. 1228–1231, 1965. `doi:10.1007/BF02773204`

[5] G. B. Lubkin, “Tristan e+e– Collider in Japan Yields 50 GeV of Mass,” *Physics Today*, vol. 40, no. 1, pp. 21–23, 1987. `doi:10.1063/1.2815292`

[6] S. Benson *et al.*, “First lasing of the jefferson lab ir demo fel,” *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 429, no. 1, pp. 27–32, 1999.

[7] H. Hahn, V. Litvinenko, D. Kayran, and E. Pozdeyev, “Energy recovery linac test facility at bnl,” *Phys. Rev. Spec. Top. Accel Beams*, vol. 12, no. 6, p. 063 501, 2009.

[8] A. Höfler *et al.*, “Experimental commissioning of the cornell-bnl erl test accelerator (cbeta),” *Physical Review Accelerators and Beams*, vol. 23, no. 6, p. 063 401, 2020.

[9] J. Gulliford *et al.*, “Experimental results from the cornell-bnl erl test accelerator (cbeta),” *Physical Review Accelerators and Beams*, vol. 23, no. 7, p. 073 401, 2020.

[10] X. Liu *et al.*, “Simulation studies of the cornell-bnl erl test accelerator,” *Physical Review Accelerators and Beams*, vol. 22, no. 4, p. 043 401, 2019.

[11] J. H. David Gaskell and G. Biallas, “A continuous-wave superconducting erl at jefferson lab,” *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 877, pp. 66–70, 2017. `doi:10.1016/j.nima.2017.09.017`

[12] I. Ben-Zvi, Y. Derbenev, V. Litvinenko, and L. Merminga, “Energy recovery linacs in high-energy and nuclear physics,” *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 557, no. 1, pp. 28–35, 2006.

[13] W. A. Barletta and M. Borland, “Report of the basic energy sciences workshop on compact light sources,” USDOE Office of Science (SC)(United States), Tech. Rep., 2010.

[14] C. Adolphsen *et al.*, “The development of energy-recovery linacs,” *arXiv preprint arXiv:2207.02095*, 2022.

[15] L. Serafini *et al.*, *BriXSinO - Technical Design Report*, 2022. `https://marix.mi.infn.it/brixsino-docs/`

[16] L. Serafini *et al.*, *MariX Conceptual Design Report*, `https://repodip.fisica.unimi.it/marix/MariX_CDR.pdf`, 2019.

[17] *The MariX Initiative official website*, `https://marix.eu`.

[18] I. Drebot *et al.*, “Brixsino High-Flux Dual X-Ray and THz Radiation Source Based on Energy Recovery Linacs,” in *Proc. IPAC'22*, Bangkok, Thailand, 2022, pp. 2407–2410. `doi:10.18429/JACoW-IPAC2022-THOXSP2`

[19] V. Petrillo *et al.*, “Coherent, high repetition rate tender x-ray free-electron laser seeded by an extreme ultra-violet free-electron laser oscillator,” *New Journal of Physics*, vol. 22, no. 7, p. 073 058, 2020. `doi:10.1088/1367-2630/ab9bbf`

[20] A. Bacci *et al.*, “Two-pass two-way acceleration in a superconducting continuous wave linac to drive low jitter x-ray free electron lasers,” *Phys. Rev. Accel. Beams*, vol. 22, p. 111 304, 11 2019.

[21] A. Bacci *et al.*, “GeV-class two-fold CW linac driven by an Arc-Compressor,” en, *Instruments*, vol. 3, no. 4, 2019.

[22] C. Koral *et al.*, “Multi-pass free electron laser assisted spectral and imaging applications in the terahertz/far-ir range using the future superconducting electron source brixsino,” *Frontiers in Physics*, p. 127, 2022.

[23] S. Samsam *et al.*, “The HOMEN Model: An Estimator of High Order Modes Evolution in an Energy Recovery Linac,” in *Proc. IPAC'22*, Bangkok, Thailand, 2022, pp. 2342–2345. `doi:10.18429/JACoW-IPAC2022-WEPOMS042`

[24] A. Nassiri, “Review of cryomodules and srf challenges for light source energy recovery linacs.,” Argonne National Lab.(ANL), Argonne, IL (United States), Tech. Rep., 2007.

[25] S. Samsam *et al.*, “Hom damping in multi-cell superconducting cavities for the future electron source brixsino,” 2022.

[26] S. Samsam, “Beam breakup and high order modes instabilities studies for energy recovery linear acceler,” Ph.D. dissertation, Sapienza University of Rome, 2023.

[27] E. Johnson, I. Ben-Zvi, H. Hahn, L. Hammons, and W. Xu, “Higher-order mode analysis at the bnl energy recovery linac,” Brookhaven National Lab.(BNL), Upton, NY (United States), Tech. Rep., 2011.