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TECHNOLOGY SPINOFF AND LESSONS LEARNED FROM THE 4-TURN ERL CBETA

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Abstract

The Cornell-BNL ERL Test Accelerator (CBETA) developed several energy-saving measures: multi-turn energy recovery, low-loss superconducting radiofrequency (SRF) cavities, and permanent magnets. With green technology becoming imperative for new high-power accelerators, the lessons learned will be important for projects like the FCC-ee or new light sources, where spinoffs and lessons learned from CBETA are already considered for modern designs.

CBETA

CBETA is the first successful demonstration of an SRF multi-turn ERL [1–3]. Shown in Fig. 1, it features a non-scaling fixed-field alternating-gradient (FFA) return loop constructed using permanent magnets [4], which transport the four beam energies (42, 78, 114, and 150 MeV) simultaneously in a common beam pipe [1, 2]. The accelerator has a 6 MeV injector, the main linac cryomodule (MLC), SX and RX splitter sections, FFA return loop (FA, TA, ZA, TB, FB), and the beam stop line.

CBETA can be configured for one to four turns, with the top energies of each configuration corresponding to 42, 78, 114, and 150 MeV, respectively; the design parameters are given in Table 1. For a configuration of Y turns, the beam completes $2Y$ passes through the MLC and $2Y - 1$ passes through the FFA return loop. In the SX and RX sections, each beam energy has a corresponding splitter line; this allows for independent control for $\alpha_{x,y}$, $\beta_{x,y}$, horizontal dispersion and its derivative, R_{56}, and orbit; the path length is controlled by moving stages installed in the center of the splitter lines.

Table 1: Design Machine Parameters of CBETA in the Four-Turn Configuration [1]

Parameter	Quantity	Unit
Bunch charge	125	pC
Bunch rate	325	MHz
Beam current	40	mA
Beam energy, injector	6	MeV
Beam energy, peak	150	MeV

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MULTI-TURN ENERGY RECOVERY USING SRF CAVITIES

The simplest example of a single-turn energy recovery linac has a low-energy beam injected into a string of cavities, accelerated, transported back around to pass through the cavity string again, decelerating the beam, before being transported into the beam stop line. While this approach does absorb a significant amount of the beam energy, which helps to reduce the amount of radiation deposited into the beam stop, the most significant benefit comes when the cavity string consists of SRF cavities. When superconducting cavities are used, the energy recovered by decelerating the beam is used to accelerate subsequent bunches with very little to no loss; however, when normal conducting cavities are used, this energy dissipates before it can accelerate new bunches [1, 5]. This reallocation of energy allows for the beam power in an ERL to greatly exceed the RF power, reducing the overall power consumption of the machine.

A multi-turn ERL, as the name implies, has the beam accelerate multiple times before decelerating into the beam stop. While this can be a more difficult machine to commission, it has the benefit of requiring fewer SRF cavities than a single-turn ERL of the same energy. Fewer SRF cavities reduces the initial purchase cost, power requirements, and necessary floor space, while also reducing the ongoing operations cost in terms of power consumption and cryogenics [5].

PERMANENT MAGNETS

While previous accelerators have used FFA optics for transport in the past [6], CBETA has successfully demonstrated a single FFA transport that accepts an energy from 42 to 150 MeV [1]. The production of permanent Halbach type magnets for the CBETA FFA has also demonstrated that a very high field quality can be achieved through “tuning” the permanent magnets after production [4].

Despite reasonable concerns about radiation associated with normal operation of CBETA damaging the permanent magnets, sufficient machine protection through beam loss monitors along the FFA return loop helped to address this concern. By estimating the dose of radiation the permanent magnets could receive while still functionally transporting beam and taking into account the desired lifetime of the machine, an administrative limit of radiation in the FFA

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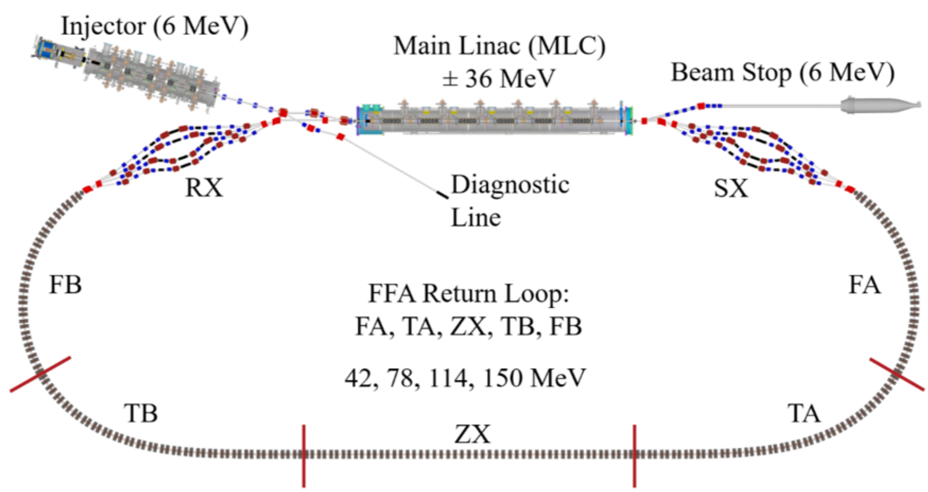

Figure 1: The four-turn configuration of CBETA.

was set. The slow beam loss monitors around the ring kept the radiation dose at appropriate levels and indicated that the majority of radiation received by the FFA was within the first FFA girder. Assuming similar operating conditions throughout the lifetime of the machine, the lifetime of the FFA could be significantly increased by replacing one of twenty-seven girders – increasing the lifetime of the machine at a fraction of the purchase cost. Alternatively, the first girder could be rebuilt with SmCo magnets, which have a much better radiation lifetime at a higher cost.

For accelerators with significant synchrotron radiation, some thought has been given to designing permanent magnets with horizontal gaps to allow this radiation to exit without irradiating the permanent magnet material [2, 4, 7]. This would increase the applicability of permanent magnets, either by themselves or as part of an FFA transport.

APPLICATIONS

The future applications of multi-turn SRF ERLs is wide ranging – any application requiring high energy, beam current, and quality may feasibly benefit from using a multi-turn SRF ERL. Lattices incorporating FFA transports made of permanent magnets can be useful in any application requiring a wide range of energy acceptance or wanting to reduce energy usage. Taking these concepts together or separately, some potential applications for the future include:

- Proton cancer therapy gantries – use of permanent magnets would reduce the cost associated with delivering beam to the patient and help make proton radiation therapy more accessible by making facilities more affordable and thus, more common [8].
- Small synchrotons using permanent magnets for proton therapy applications – as in the previous example, use of permanent magnets reduces operating costs by reducing the power cost of operating.
- Isotope production machines using ERLs – lost electron energy through isotope production can be accepted by a suitable FFA transport with $\delta p/p < \pm 60\%$.
- Multi-turn ERL designs for x-ray and γ-ray production through inverse Compton scattering – using a multi-turn ERL helps reduce the number of SRF cavities required and reduces the power requirement for a high current beam, while a permanent magnet FFA has a wide energy acceptance after the photon-electron interaction and low energy cost [9].

CONCLUSION

The successful commissioning of CBETA has demonstrated the feasibility of multi-turn energy recovery with superconducting cavities and permanent magnets for beam transport for future accelerators – both technologies which may be critical to the effort to reduce power requirement and consumption of future accelerators. As the CBETA photo-injector has already been successfully transferred to other facilities and applications, it seems reasonable that other technology from CBETA also finds uses in a wide range of applications and to help advance the next generation of accelerators.

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REFERENCES

[1] A. Bartnik *et al.*, "CBETA: First Multipass Superconducting Linear Accelerator with Energy Recovery", *Physical Review Letters*, vol. 125, p. 044803, Jul. 2020. doi:10.1103/PhysRevLett.125.044803

[2] G. H. Hoffstaetter *et al.*, "CBETA Design Report, Cornell-BNL ERL Test Accelerator", 2017. arXiv:1706.04245

[3] C. Gulliford *et al.*, "Measurement of the per cavity energy recovery efficiency in the single turn Cornell-Brookhaven ERL Test Accelerator configuration", *Physical Review Accelerators and Beams*, vol. 24, p. 010101, Jan. 2021. doi:10.1103/PhysRevAccelBeams.24.010101

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB007

[4] S. Brooks, G. Mahler, J. Cintorino, J. Tuozzolo, and R. Michnoff, "Permanent magnets for the return loop of the Cornell-Brookhaven energy recovery linac test accelerator", *Physical Review Accelerators and Beams*, vol. 23, p. 112401, Nov. 2020. doi:10.1103/PhysRevAccelBeams.23.112401

[5] L. Merminga, D. R. Douglas, and G. A. Krafft, "High-Current Energy-Recovering Electron Linacs", *Annual Review of Nuclear and Particle Science*, vol. 53, pp. 387-429, Dec. 2003. doi:10.1146/annurev.nucl.53.041002.110456

[6] S. Machida *et al.*, "Acceleration in the linear non-scaling fixed-field alternating-gradient accelerator EMMA", *Nature Physics*, vol. 8, pp. 243-247, 2012. doi:10.1038/nphys2179

[7] S. J. Brooks, "Modified Halbach Magnets for Emerging Accelerator Applications", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper TUXC07, this conference.

[8] D. Trbojevic, S. J. Brooks, T. Roser, and N. Tsoupas, "Superb Fixed Field Permanent Magnet Proton Therapy Gantry", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper TUPAB030, this conference.

[9] K. Deitrick *et al.*, "Intense monochromatic photons above 100 keV from an inverse Compton source", *Physical Review Accelerators and Beams*, vol. 24, p. 050701, May 2021. doi:10.1103/PhysRevAccelBeams.24.050701