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ACCELERATOR PHYSICS LESSONS FROM CBETA, THE FIRST MULTI-TURN SRF ERL*

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Abstract

The Cornell-BNL ERL Test Accelerator (CBETA) has been designed, constructed, and commissioned in a collaboration between Cornell and Brookhaven National Laboratory (BNL). It focuses on energy-saving measures in accelerators, including permanent magnets, energy recovery, and superconductors; it has thus been referred to as a green accelerator. CBETA has become the world's first Energy Recovery Linac (ERL) that accelerates through multiple turns and then recovers the energy in superconducting radiofrequency (SRF) cavities though multiple decelerating turns. The energy is then available to accelerate more beam. It has also become the first accelerator that operates 7 beams in the same large-energy aperture Fixed Field Alternating-gradient (FFA) lattice. The FFA is constructed of permanent combined function magnets and transports energies of 42, 78, 114, and 150 MeV simultaneously. Accelerator physics lessons from the commissioning period will be described and applications of such an accelerator from hadron cooling to EUV lithography and from nuclear physics to a compact Compton source will be discussed.

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, ZX, 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. 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. In the SX section, the splitter lines are labeled S1, S2, S3, and S4, with the lowest line energy being

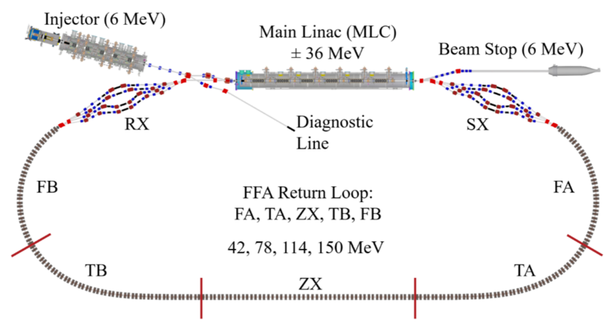

Figure 1: The four-turn configuration of CBETA.

transported in S1 which is located closest to the interior of the loop. Consequently, S4, the highest energy line, is located furthest from the interior. A similar numbering scheme and orientation is applied for the RX section [1, 2].

Select successes of the commissioning period include single-turn high-transmission energy recovery [3], four-turn energy recovery, orbit correction of multiple beams at different energies using a common set of corrector magnets, and measuring seven different beams simultaneously through the FFA arc [1]. CBETA could be used to study a number of critical beam dynamics effects, including beam-breakup instability, halo development and collimation, microbunching, and energy spread growth due to coherent synchrotron radiation (CSR). All of these, among others, are critical areas of study as ERLs are pushed to higher currents for various applications [1].

GREEN ACCELERATORS

As specifications of new facilities are being developed, the trend is for beams of increasingly high energy and current. In many cases, the quality desired may preclude storage rings from being an acceptable design; however, these high-power beams, if produced in linear accelerators, would have infeasible power requirements, especially as sustainability becomes an increasingly important aspect of accelerator design [5, 6].

ERLs operate by recovering the kinetic energy of previously accelerated bunches during deceleration and using that recovered energy to accelerate subsequent bunches. Not only does this minimize the amount of energy required by the SRF cavities, the amount of beam power delivered can actually exceed the installed power supplies. ERL operation does impose some restriction on the application - for example, delivering the beam into a target at an end station would preclude energy recovery; however, ERLs have previously

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operated as drivers for Free Electron Lasers (FELs), which can produce some energy loss in the beam while still being successfully energy recovered, provided the return line has sufficient energy acceptance [5].

Permanent magnet FFA transport lines reduce both power and space requirements for multi-turn operation while providing wide energy acceptance. For both multi-turn ERLs and recirculating linacs, transporting the beam through multiple passes of the accelerating section reduces the number of SRF cavities required, minimizing purchase cost [6].

APPLICATIONS

The applications for these design approaches are wide ranging, but they can loosely be categorized by using either an ERL or a recirculating linac with FFA transport. Multi-turn ERLs may prove beneficial when compared to single-turn ERLs in many applications, given the reduced power and space requirements, but any given design depends on the specific requirements [6].

ERLs are an appropriate design when the accelerated beam is required to be high power and high quality with some perturbation. One well known example is the Jefferson Lab FEL, which operated successfully for a number of years and still holds the record for highest beam power and current of an SRF ERL [7–9]. Other examples of similar applications include hadron coolers, EUV lithography for chip production, nuclear physics colliders, x-ray and gamma-ray sources through Inverse Compton scattering (ICS), medical isotope production, transmutation of nuclear waste, and high-energy physics colliders [5, 10–13]. In many of these cases, the accelerator design could be very similar to CBETA, with the beam being repeatedly accelerated and transported through an FFA arc, before a separate transport line steers the highest energy beam away from the FFA, starting in SX, through the interaction of interest, back through RX, before decelerating through multiple passes and ending in the beam stop. A representative cartoon can be seen in Fig. 2, with the bypass line for ICS, collision, cooling, etc. shown by the red line.

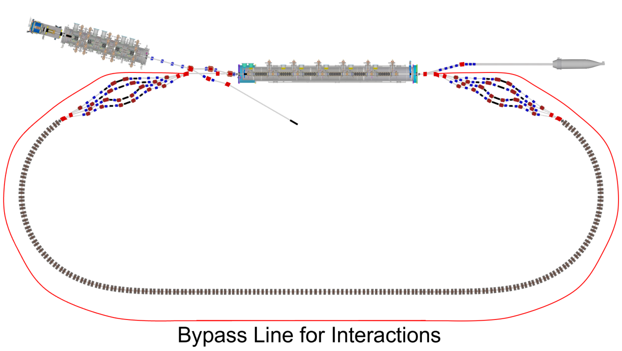

Figure 2: A cartoon layout of a multi-turn SRF ERL with an FFA arc and a bypass line for various applications, based on CBETA.

While recirculating linacs are unable to take advantage of the efficiency of energy-recovery, there are some applications which are not suitable for ERLs. However, with recirculation through FFA transport, fewer SRF cavities are necessary and power supplies for magnets are reduced through the use of permanent magnets for the FFA.

HARD X-RAYS AT CBETA

Inverse Compton scattering (ICS) is the process of producing radiation through the scattering of photons and relativistic electrons at an interaction point (IP). These relativistic electrons can be produced by a linac, ERL, or storage ring, though most ICS sources recently designed have been focused on “compact” sources, typically driven by linacs or ERLs. These compact Compton sources typically have x-ray energies similar to those found at synchrotron radiation facilities, while producing x-ray beams of lower flux and brilliance; however, the trade off is the significantly reduced size and cost [14].

As CBETA in the 4-turn configuration produces 150 MeV electrons, an ICS source at CBETA demonstrates a paradigm shift to this understanding of light sources. This design, shown in Fig. 3, has a bypass for the 150 MeV electrons, beginning in S4, which starts with a vertical dogleg to transport the bypass line to 30 cm above the existing accelerator plane. After being transported through the IP and a path corrector chicane, the bypass line transports the beam back into R4, where it matches into the existing CBETA optics and proceeds to decelerate into the beam stop [13]. The space constraint of the existing building necessitates a vertically separated bypass line, instead of the horizontally separated concept seen in Fig. 2.

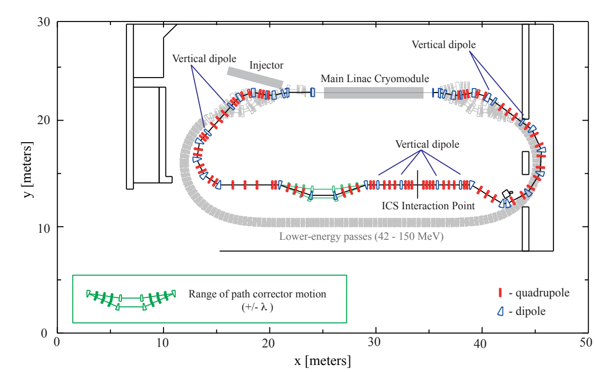

Figure 3: Layout of the ICS bypass in CBETA; grayed beamline elements are already installed in the existing accelerator; originally published as Fig. 6 from [13].

The CBETA ICS design assumes a laser energy of 1.17 eV and when the four discrete energies of CBETA (42, 78, 114, and 150 MeV) are evaluated, the scattered x-rays have an anticipated energy range of 32 to 402 keV. When the expected flux, which is on the order of 10^7 photon/(sec 0.1% bandwidth) for all four configurations, is compared to synchrotron radiation facilities, the lower three energies conform to the expectation that Compton sources are outperformed. However, past ~300 keV, undulator radiation production is diffi-

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cult due to high harmonics and undulator phase errors; this behavior is seen in Fig. 4, which plots flux reported at various facilities and the anticipated performance of the CBETA ICS. When extending the CBETA electron beam parameters to higher energies, the expected collimated flux values remain roughly constant and demonstrate, with 300 and 600 MeV electrons, that MeV-scale photons can be produced [13].

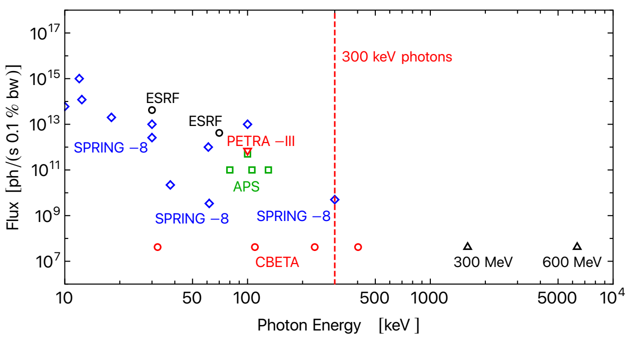

Figure 4: Flux per 0.1% bandwidth of the CBETA ICS (red) against a collection of the major high energy storage ring undulators across the globe; originally published as Fig. 12 from [13].

FFA@CEBAF

The Continuous Electron Beam Accelerator Facility (CEBAF) is a continuous-wave recirculating linac at Jefferson Lab [15, 16], shown in Fig. 5. The electron beam makes multiple accelerating passes through the linacs, with transport between the linacs performed with electromagnetic arcs. While CEBAF delivered 6 GeV electron beam for many years, an upgrade was recently performed by installing additional SRF cavities to increase the beam energy to 12 GeV at Hall D [15, 16].

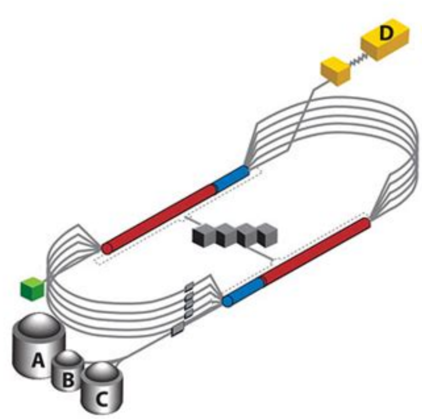

Figure 5: The 12 GeV layout of CEBAF.

Energy increases of recirculating linacs can be handled by either installing more SRF cavities or making additional more passes through the linac. Looking at Fig. 5, it becomes clear that there is no free space to install additional cavities to increase the energy past 12 GeV without changing the footprint of the overall accelerator, making more turns around the racetrack necessary to increase the beam energy. With the current size of the accelerator tunnel, however, there is limited room for additional electromagnetic arcs. Fortunately, FFA arcs provide the transport of multiple beam energies through a single transport arc.

The FFA@CEBAF Energy Upgrade study examines the optics and performance of removing 1-2 electromagnetic arcs at the highest energies and replacing them with FFA arcs and corresponding splitters (time of flight chicanes). While the design work of this study is ongoing, the anticipated energy may be increased to 20 GeV or greater [17].

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 of future accelerators. As the CBETA photo-injector design 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.

Potential applications of CBETA's technologies include medical isotope production by electron bombardment of matter, cancer therapy with FFA gantries, compact Compton photon sources, and industrial applications such as microchip production through EUV lithography beams from an ERL-FEL, as well as more energy-efficient machines for basic research in physics, materials science, and many other fields.

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