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CBETA – NOVEL SUPERCONDUCTING ERL*

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Abstract

We are successfully commissioning a unique Cornell University and Brookhaven National Laboratory Electron Recovery Linac (ERL) Test Accelerator 'CBETA' [1]. The ERL has four accelerating passes through the superconducting linac with a single Fixed Field Alternating Linear Gradient (FFA-LG) return beam line built of the Halbach type permanent magnets. CBETA ERL accelerates electrons from 42 MeV to 150 MeV, with the 6 MeV injector. The novelties are that four electron beams, with energies of 42, 78, 114, and 150 MeV, are merged by spreader beam lines into a single arc FFA-LG beam line. The electron beams from the Main Linac Cryomodule (MLC) pass through the FFA-LG arc and are adiabatically merged into a single straight line. From the straight section the beams are brought back to the MLC the same way. This is the first 4 pass superconducting ERL and the first single permanent magnet return line.

CBETA AND ELECTRON ION COLLIDERS (EIC)

We emphasize importance of the project with respect to the future EIC's as an EIC prototype and as an electron source for the necessary strong hadron cooling. The CBETA role for EIC's is best described by the recent report from the US National Sciences [2] the quote: 'The CBETA project will serve as prototype of the fixed-field alternating gradient-ERL concept. The design incorporates several highly innovative concepts and could achieve higher performance at lower cost'…'The large momentum acceptance of the NS-fixed-field alternating gradient optics could substantially reduce the number of return arcs and the cost of the 18 GeV injector of the eRHIC electron storage ring (or the 18 GeV ERL itself, in the case of the linac-ring design concept). Several beams of different energies could pass through the same arc structure on different orbits. Like eRHIC, the Jefferson Laboratory Electron Ion Collider (JLEIC) design of an EIC also employs an ERL as an electron cooler to achieve low-emittance ion beams. These, and other future ERLs or recirculating linac accelerators, could also benefit from the fixed-field alternating gradient focusing principle'.

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CBETA LAYOUT

The previous proposal of the Cornell Energy Recover Linac [3] and a long and very successful R&D in building and developing the superconducting linacs produced a proof of principle 6 MeV injector, with 750 kV 100 mA gun, superconducting injector linac, and of the Main Linac Cryomodule (MLC). The first idea of ERL came from Maury Tigner at Cornell University [4]. The ERL combined with FFA-LG comes from the previous EIC proposal at BNL based a team of experts in this field from BNL: D. Trbojevic, S. Berg, F. Meot, S. Brooks and E.D. Courant [5, 6]. A schematic of the CBETA is shown in Figure 1.

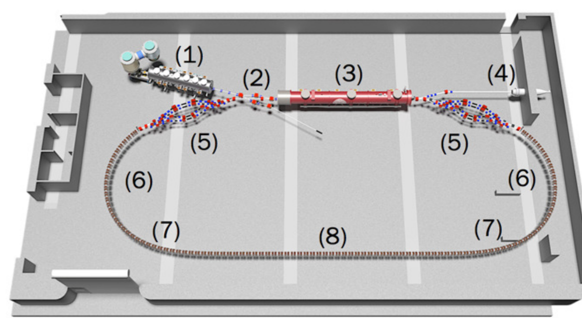

Figure 1: CBETA Injector (1), merger (2) with the Main Linac Cryo-module (MLC) (3), spreaders (5), FFA arcs (6), transitions to the straight (7), and the straight section (8).

The injector starts with the electron gun: the HV power supply for 750 kV at 100 mA is based on proprietary insulating core transformer technology. A five-cavity injector cryomodule was designed and fabricated in Cornell University with the 2-cell SRF cavity, input coupler, HOM absorbers, LLRF system, and cryomodule it is designed to support 100 mA beam currents. The high-power CW SRF injector linac is fully operational and commissioned previously with the CBETA Fractional Arc Test (FAT). The injector previously delivered up to 500 kW of RF power to the beam at 1300 MHz. The Cornell digital LLRF system

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for CBETA is tested extensively with a wide range of parameters. The field stability meets and exceeds CBETA specifications. All digital components and control codes are on hand. The 42 MeV electron beam from the MLC. This cryomodule houses six SRF 1.3 GHz, 7-cell cavities, powered via individual 5 kW CW RF solid state amplifiers, providing a total single-pass energy gain of up to 75 MeV, although only 36 MeV is required for the 4 pass acceleration to the maximum energy of 150 MeV, shown in Fig. 2.

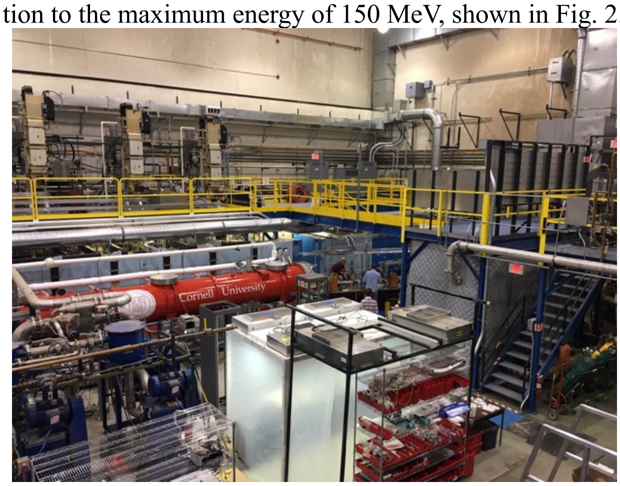

Figure 2: The superconducting six module linac MLC the major part of CBETA project.

The HOM beam line absorbers are placed in-between the SRF cavities to ensure strong suppression of HOMs, and thus enable high current ERL operation. The 6 MeV comes from the injector and while 36 MeV is the 6 module MLC acceleration is transferred by the splitter line S1 (5) into the FFA-LG arc. The arc is connected by the adiabatic transition of the FFA cells to the straight section, as shown in Fig. 3, made of the same FFA cells but without bending. In the adiabatic transition the bending angles of the combined function magnets are adiabatically reduced to zero. Different energy beams are merged into a single orbit in the middle of straight section.

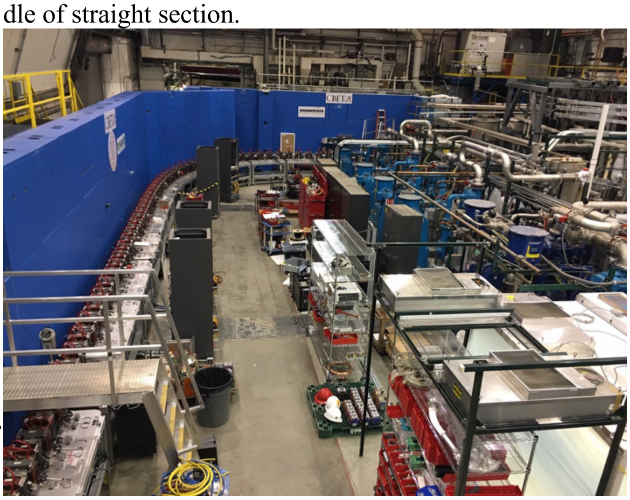

Figure 3: Straight section and the FFA arc of CBETA.

They continue through the opposite transition part (7) as shown in Fig. 1, and again in the FFA arc with separated orbits. The last element of the FFA arc (shown in Fig. 4) is a half size combined function magnet creating a triplet configuration and allowing beam to exit with parallel orbits into the common dipole magnet; the same solution is applied at the opposite splitter side.

Figure 4: Details of one the FFA arc magnets.

The splitters on both sides of the linac have a role to match the betatron functions, angles and positions at the entrance of the FFA-LG of each beam (as shown in Fig. 5).

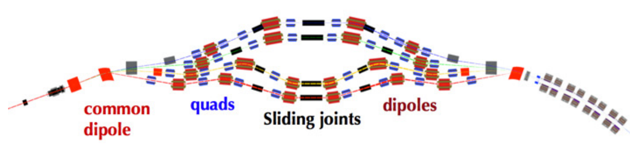

Figure 5: Splitter beam lines with four chicanes to match the MLC linac to the FFA arc.

The path length in the S1 and R1 splitter lines are presently set-up to be equal to ½ of the RF period. The time of flight for each beam line needs to be correct to arrive to the linac at the correct phase. The highest energy beam time of flight requires a condition $T_4 \cdot f_{RF} = 343+1.5$ to arrive at the linac with opposite sign of the RF. The splitters adjust the momentum compaction factor *r56,* as well. The energy recovery continues for all lower energies the same way making the ERL to be 99.9 efficient.

FIRST COMMISSIONING RESULTS

After the Fractional Arc Test in May 2017, the CBETA continued with installation. All fixed field with correction magnets, the beam position monitors [7] and the remaining splitter magnets, vacuum system, beam profile monitors, the dump line and the rest of the systems were installed the final commissioning started in March 2019. The 6 MeV beam is brought to the dump line. The first attempt to prop-

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agate the 42 MeV beam through the FFA-LG was attempted on May 7, 2019. The correction magnets of the FFA beam line this time have not been connected to the power supplies, but the beam went to the end of the beam line without any corrections as shown in Fig. 6.

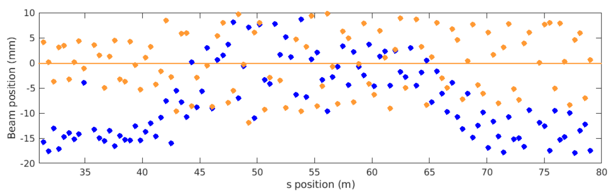

Figure 6: First 42 MeV orbits through the FFA without any correction (colour blue horizontal and yellow vertical).

The responses to the horizontal and vertical kicks with respect to the model predictions are shown in Fig. 7, and Fig. 8, respectively. More commissioning results are presented at this conference [8, 9].

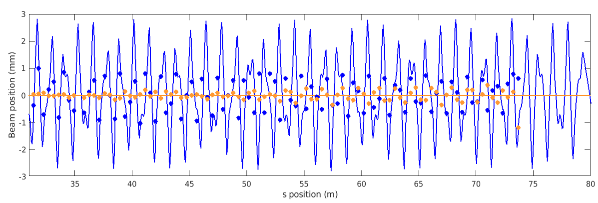

Figure 7: Horizontal response result.

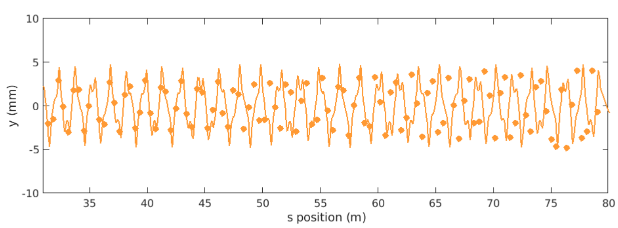

Figure 8: Vertical response results.

CBETA Deliverables

The expected deliverables from the CBETA project are shown in Table 1: The maximum beam energy, electron bunch change, electron gun current, RF frequency, the CW operational mode etc.

Table 1: CBETA Key Performance Parameters (KPP)

Parameter	**Unit**	**KPP**	**UPP**
Electron beam energy	MeV	150	150
Electron bunch charge	pC		123
Gun current	mA	1	40
Bunch rep. rate	MHz		325
RF frequency	MHz	1300	1300
Injector energy	MeV	6	6
# of turns		1	4
Energy aperture of arc		2	4

There are few very important topics to be shown in the CBETA with respect to the future EIC especially for the strong hadron cooling required for the very high luminosities: Injector and ERL studies as almost every proposal includes an ERL. Multi-turn ERL operation with a large number of turns (important reduction of the High Operating Modes (HOM's), explore the Bunch Beam break-up limits (BBU's), FFAG loop operation with the multiple passes with 4 times in energy.

SUMMARY

The CBETA commissioning is showing excellent progress. The funding by New York State Research and Development Authority-NYSERDA started in November 2016. The CBETA project has multiple purposes showing the results already. Novelties in CBETA are: the first superconducting linac with four accelerating and four energy recoveries passes; the first time that a single FFA-LG beam line is transferring four times different electron energies energy back to the linac; the first time that permanent magnets are used in ERL's, and the first time a FFA-LG transition from the arc-to-straight section merges four different orbits into a single one. The permanent magnets based on Halbach design are built [10] and successfully tested with extremely good field quality after the correction is applied [11]. This successful test of the first permanent magnet girder is also important for other applications like the proton cancer therapy gantry. The 42 MeV beam has already been transported through the MLC, S1 splitter line and the whole FFA-LG on May 7, 2019.

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