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CBETA, THE 4-TURN ERL WITH SRF AND SINGLE RETURN LOOP*

G.H. Hoffstaetter, N. Banerjee, J. Barley, A. Bartnik, I. . Bazarov, D.C. Burke, J.A. Crittenden, L. Cultrera, J. Dobbins, S. Full, F. Furuta, R. Gallagher, M. Ge, C. Gulliford, B. Heltsley, D. Jusic, R. Kaplan, V. Otakar Kostroun, Y. Li, M. Liepe, W. Lou, C. Mayes, J.R. Patterson, P. Quigley, D. Sabol, D. Sagan, J. Sears, C.H. Shore, E. Smith, K.W. Smolenski, V. Veshcherevich, D. Widger
Cornell University, Ithaca, New York, USA
J. Scott Berg, S. Brooks, C. Liu, G. Mahler, F. Meot, R. Michnoff, M. Minty, S. Peggs, V. Ptitsyn, T. Roser, P. Thieberger, D. Trbojevic, N. Tsoupas, J. Tuozzolo, F.J. Willeke, H. Witte
Brookhaven National Laboratory, Upton, New York, USA
D. Douglas, Thomas Jefferson National Accelerator Facility, Newport News, Virginia, USA
B. Kuske, M. McAteer, J. Völker, Helmholtz-Zentrum Berlin, Germany
J. Jones, D. Kelliher, Daresbury Laboratory, Daresbury, UK

Abstract

A collaboration between Cornell University and Brookhaven National Laboratory has designed and is constructing CBETA, the Cornell-BNL ERL Test Accelerator on the Cornell campus. The ERL technology that has been prototyped at Cornell for many years is being used for this new accelerator, including a DC electron source and an SRF injector Linac with world-record current and normalized brightness in a bunch train, a high-current linac cryomodule optimized for ERLs, a high-power beam stop, and several diagnostics tools for high-current and high-brightness beams. BNL has designed multi-turn ERLs for several purpose, dominantly for the electron beam of eRHIC, its Electron Ion Collider (EIC) project and for the associated fast electron cooling system. Also in JLEIC, the EIC designed at JLAB, an ERL is envisioned to be used for electron cooling. The number of transport lines in an ERL is minimized by using return arcs that are comprised of a Fixed Field Alternating-gradient (FFA) design. This technique will be tested in CBETA, which has a single return for the 4-beam energies with strongly-focusing permanent magnets of Halbach type. The high-brightness beam with 150 MeV and up to 40 mA will have applications beyond accelerator research, in industry, in nuclear physics, and in X-ray science. Low current electron beam has already been sent through the most relevant parts of CBETA, from the DC gun through both cryomodules, through one of the 8 similar separator lines, and through one of the 27 similar FFA structures. Further construction is envisioned to lead to a commissioning start for the full system early in 2019.

INTRODUCTION

CBETA is being constructed at Cornell University. It will be the first ever multi-turn Energy Recovery Linac (ERL) with superconducting RF (SRF) acceleration. And it will be the first ERL based on Fixed Field Alternating-gradient (FFA) optics. It will be a unique resource to carry out accelerator science and enable exciting research in nuclear physics, materials science and industrial applications. Initially it will prototype components and evaluate concepts that are essential for Department of Energy (DOE) plans for an Electron-Ion Collider (EIC), in particular for the electron cooling systems of the hadron beams in BNL's as well as in JLAB's EIC design. Two DOE labs, BNL and JLAB, have EIC projects and both need an ERL as an electron cooler for low-emittance ion beams. For eRHIC at BNL, a new electron accelerator would be installed in the existing RHIC tunnel, colliding polarized electrons with polarized protons and ^{3}He ions, or with unpolarized ions from deuterons to Uranium. The current baseline design produces a polarized electron beam in a photo-emitter gun and accelerates it by a short linac and a spin transparent rapid-cycling synchrotron into a polarized storage ring, where the electron beam collides in two interaction regions with the hadron beam. Because experiments are performed for all combinations of helicity, electron bunches with opposing polarization directions are stored simultaneously. Electron bunches injected polarized and are replaced before they have depolarized too far. It is envisioned to replace an electron bunch every second, leading to store times of about 6 minutes for each bunch. The ion bunches cannot be replaced similarly fast but should be stored as long as possible. Fast electron cooling is therefore needed to counteract stochastic emittance growth of the hadrons. Currently it is expected that these cooler beams are provided by a multi-turn SRF ERL. CBETA will establish the operation of a multi-turn ERL as well as that of an FFA lattice with large energy acceptance. Many effects that are critical for designing the EIC will be measured, including the Beam-Breakup (BBU) instability, halo-development and collimation, growth in energy spread from Coherent Synchrotron Radiation (CSR), and CSR micro bunching. In particular, CBETA will use a non-scaling FFA lattice that is very compact, enabling multiple passes of the electron beam in a single recirculation beamline, using the SRF linac 8 times, 4 times for acceleration and 4 times for deceleration. Because the prime accelerator-science motivations for CBETA are essential for an EIC, and address items that are perceived as the main risks of eRHIC, its construction is an important milestone for the NP division of DOE and for BNL.

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CBETA brings together the resources and expertise of a large DOE National Laboratory, BNL, and a leading research university, Cornell. During recent beam commissioning of a significant part of the system, additional contributions were made by visitor from JLAB in Virginia, Daresbury in the UK, and the Helmholtz-Zentrum Berlin. The visitors by these teams demonstrate the significant global impact of the CBETA project. The location of CBETA is on the campus of Cornell University, in an existing building of Fig. 1, using many components that have been developed at Cornell under previous R&D programs for a hard x-ray ERL [1] that were supported by the National Science Foundation (NSF), New York State, and Cornell University. These components are a fully commissioned world-leading DC photoemission electron source, a high-power superconducting injector cryomodule (ICM), and an SRF module for ERL operation - the main linac cryomodule (MLC), and a high-power beam stop. The only elements that required design and construction from scratch were the FFA magnet transport lattices of the return arc, with their corrector coils, water cooling, support and alignment structure, their vacuum and diagnostics system, and their mulipole correction procedure. These systems have now been fully designed, tested, and are currently produced by industry and will be fully assembled during the next year [2].

INFRASTRUCTURE AT CORNELL

Cornell's Wilson laboratory has the experimental hall L0E that has already largely been freed up for the installation of CBETA. It was originally constructed as the experimental hall for extracted-beam experiments with Cornell's 12 GeV Synchrotron. It is equipped with a high ceiling and an 40 ton crane, with easy access and a suitable environment, mostly below ground level. The dimensions of CBETA fit well into this hall, as shown in Fig. 1 with the parameters of Tab. 1. The DC photo-emitter electron source, the injector linac, the ERL merger, the high-current ERL linac module, the first spreader line, the first FFA table, and the ERL beam stop are already installed in this hall and are connected to their cryogenic systems and to other necessary infrastructure.

DC photo-emitter electron source High voltage DC photoemission electron guns offer a robust option for photoelectron sources, with applications such as ERLs. A DC gun for a high brightness, high intensity photo-injector requires a high voltage power supply (HVPS) supplying hundreds of kV to the high voltage (HV) surfaces of the gun. At Cornell, the gun HV power supply for 750 kV at 100 mA is based on proprietary insulating core transformer technology. This technology is schematically shown in Fig. 2 for Cornell's DC photoemitter gun. This gun holds the world record in sustained current of up to 75 mA.

High-Power CW SRF injector linac The photoemission electron injector shown in Fig. 3 is fully operational, and requires no further development. It has achieved the

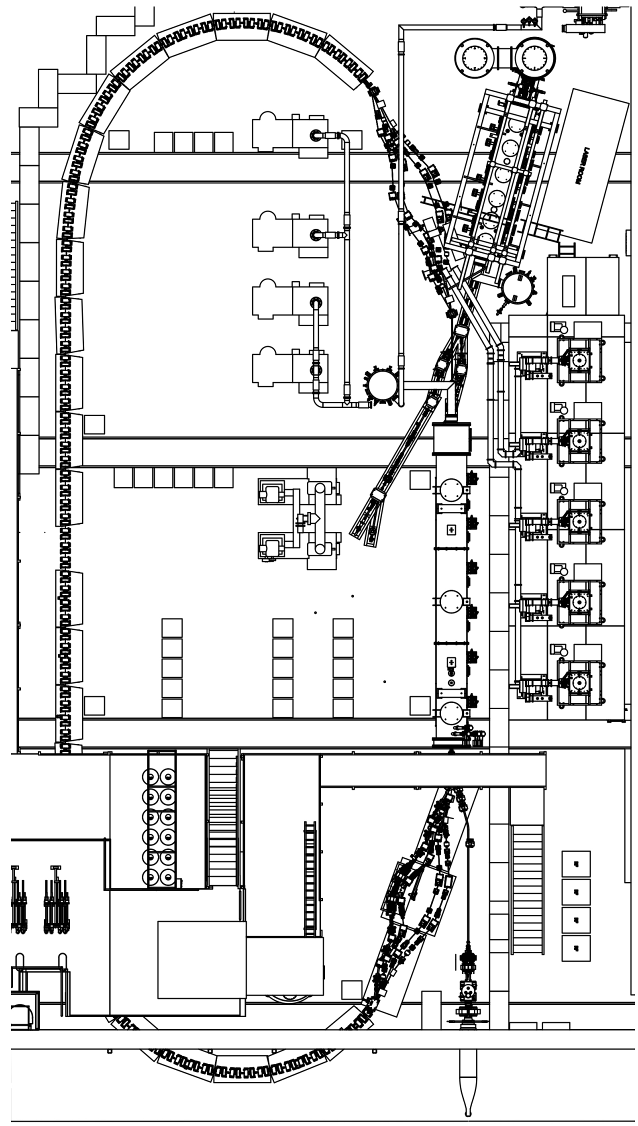

Figure 1: Floor plan of CBETA in the L0E experimental hall at Cornell's Wilson laboratory, showing a roughly 20 m × 45 m section of floor space. The beam transports starts with the DC gun in the top right corner and then goes downward through the ICM and the 10m long MLC. The table with spreader lines for the 4 different energies then leads the beam into the single return loop with FFA optics to a table with 4 re-combiner lines that lead the beam back through the MLC, either for further acceleration or for deceleration. The beam diagnostics line left of the MLC and the line to the beam stop below the MLC are also shown.

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Table 1: Primary Parameters of CBETA

Parameter	Value	Unit
Top energy	150	MeV
Injector energy	6	MeV
Energy gain	36	MeV
Injector current	≤40	mA
Linac passes	4 accel. + 4 decel.	
Arc energies	42, 78, 114, 150, 114, 78, 42	MeV
RF frequency	1300	MHz
Bunch frequency	≤325	MHz
Harmonic number	343	
Rms x/y emittances	2	µm
Bunch length	3	ps
Typical arc $\beta_{x/y}$	0.4	m
Typical splitter $\beta_{x/y}$	50	m
Rms bunch size	52 to 2806	µm
Bunch charge (min)	1 to 123	pC

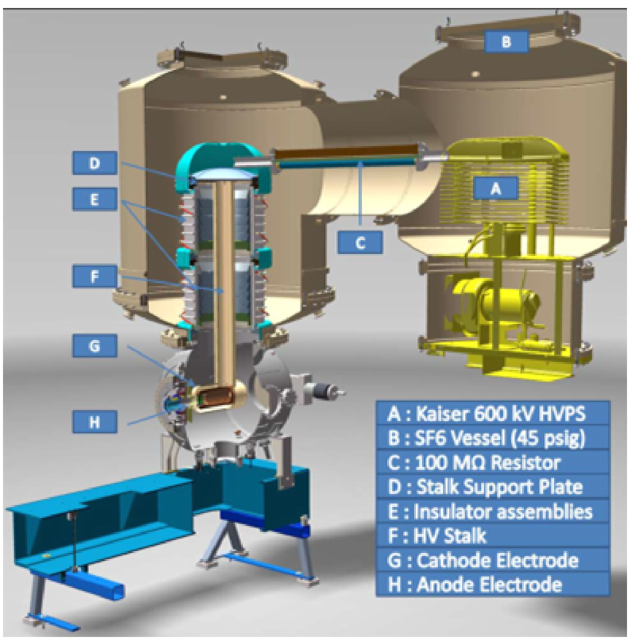

Figure 2: A cutaway view of the DC photoemission gun. Photocathodes are prepared in a load lock system mounted on the large flange at the left, and transported through the cathode cylinder to the operating position in the Pierce electrode shape on the right. The beam exits through the small flange to the right.

world-record current of 75 mA [3,4], and record low beam emittances for any CW photoinjector [5], with normalized brightness that outperforms other sources by a substantial factor. Cornell has established a world-leading effort in photoinjector source development, in the underlying beam theory and simulations, with expertise in guns, photocathodes, and lasers. The injector delivers up to 500 kW of RF power to the beam at 1300 MHz. The buncher cavity uses a 16 kW IOT tube, which has adequate overhead for all modes of operation. The injector cryomodule is powered through ten 50 kW input couplers, using five 130 kW CW klystrons. The power from each klystron is split to feed two input couplers attached to one individual 2-cell SRF cavity. An additional klystron is available as a backup, or to power a deflection cavity for bunch length measurements.

Figure 3: The high voltage DC gun left of the center, followed by an emittance compensation section, the RF buncher, and the SRF injector cyomodule ICM, located in the location needed for CBETA in the experimental hall LE0.

High-current ERL cryomodule For CBETA, the main accelerator module will be the Main Linac Cryomodule (MLC) [6], which was built as a prototype for the NSF-funded Cornell hard-X-ray ERL project. This cryomodule houses six 1.3 GHz SRF cavities, powered via individual CW RF solid state amplifiers. Higher order mode (HOM) beamline absorbers are placed in-between the SRF cavities to ensure strong suppression of HOMs, and thus enable high current ERL operation. The module, shown in Fig. 4 was finished by the Cornell group in November 2014 and successfully cooled-down and operated starting in September 2015. First electron beam was sent through the module and was accelerated by individual cavities in May 2017. The MLC was powered individual solid-state RF amplifiers, some of 5 kW and some of 10 kW. Each cavity has one input coupler. The full RF system with amplifiers and LLRF control has been installed. With simultaneous operation of the cavities, the beam energy of the first turn, 42 MeV, have been achieved.

ERL merger and ERL beam stop In Fig. 1, three merger magnets are shown between the Injector Cryomodule (ICM) and the MLC. These merger magnets steer the injected beam with 6 MeV from the ICM into the MLC, bypassing the recirculated beams of higher energy. This merger has already been tested after the ICM, and it was shown that its influence on the beam emittances can be minimized. The beam stop at the bottom of that picture also already exists, and with a power limit 600kW it can absorb all beams that are specified for CBETA.

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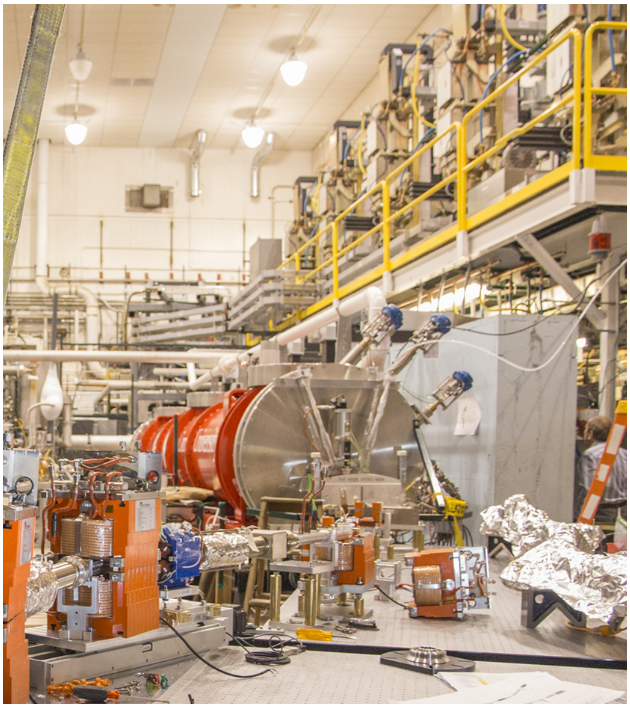

Figure 4: The Cornell Main Linac Cryomodule (MLC) to the left to the cabinets of its Solid-State Amplifiers and under the ICM's bench of klystrons.

Spreaders and FFA return loop While the splitter and re-combiner sections before and after the MLC in Fig. 1 are equipped with conventional electro magnets, the magnets of the FFA arc are made of permanent magnets. The field of these quadrupoles produced by permanent magnet material that is arranged in a Halbach geometry to produce quadrupoles and combined function magnets. The first table with 8 such Halbach magnets and dipole corrector windings is shown in Fig. 5. Water-cooled permanent Halbach magnets and their dipole corrector coils for 25 of such 8-magnet tables have been ordered and are currently under construction, to be installed before spring 2019. Commissioning of the full system can then start to establish ERL operation.

BEAM COMMISSIONING

Beam commissioning periods have been used to set up the DC gun, the diagnostics line, the MLC with all cavities, the first spreader line, and the first table of FFA magnets. The lowest-energy splitter line before the MLC in Fig. 1 is fully operational, including the movement of dipoles to adjust the path length. The 8 permanent Halbach magnets of the fist FFA table are aligned and equipped with view screens and BPMs. Beam from the SRF ERL chain has been sent through this full arrangement at several energies between 36 and 42 MeV. The beam spot after the first transport through the FFA section is shown in Fig. 6. The ease with which the beam could be steered through this FFA section in the tested energy range of 36–42 MeV are an encouragement for the operation of the full multi-turn ERL.

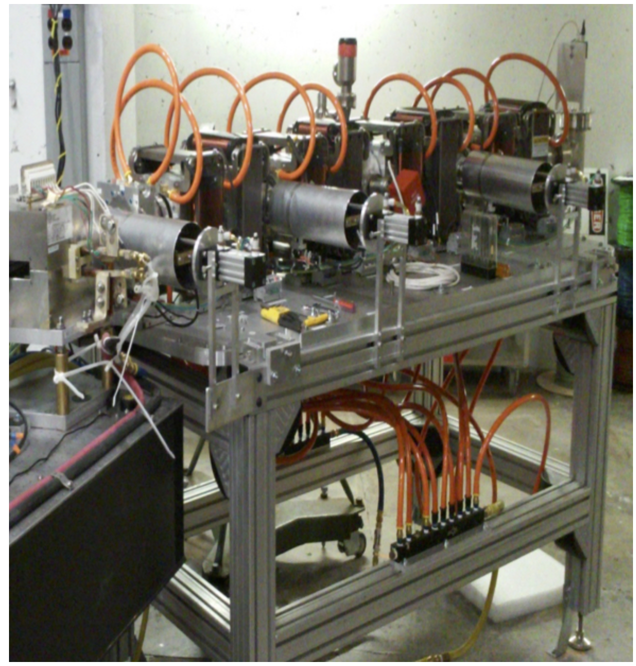

Figure 5: The first table of permanent FFA magnets. The Halbach magnets around the beampipe are so small that they cannot been seen inside the correction coils.

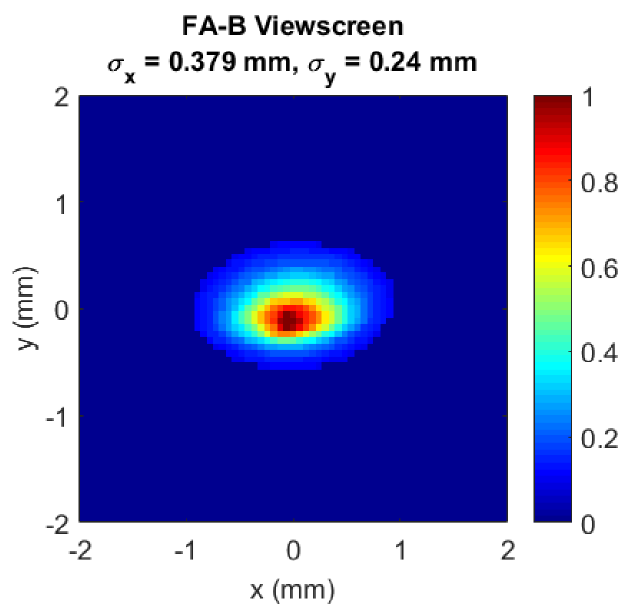

Figure 6: The first beam spot after the first spreader line and the first FFA table. This is an encouraging systems test for the full accelerator, which contains 8 spreader lines and 27 FFA tables.

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