CBETA: THE CORNELL/BNL 4-TURN ERL WITH FFAG RETURN ARCS FOR ERHIC PROTOTYPING*

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Abstract

The Cornell-BNL ERL Test Accelerator (CBETA) is a 4-turn Energy Recovery Linac with a FFAG return arc that is being built at Cornell University in collaboration with BNL.

Cornell University has prototyped technology essential for any high brightness electron ERL. This includes a DC gun and an SRF injector Linac with world-record current and normalized brightness in a bunch train, a high-current CW cryomodule, a high-power beam stop, and several diagnostics tools for high-current and high-brightness beams, e.g. slit measurements for 6-D phase-space densities, a fast wire scanner for beam profiles, and beam loss diagnostics. All these are now available to equip a one-cryomodule ERL, and laboratory space has been cleared out and is radiation shielded to install this ERL at Cornell. BNL has designed a multi-turn ERL for eRHIC, where beam is transported more than 20 times around the RHIC tunnel. The number of transport lines is minimized by using two non-scaling (NS) FFAG arcs.

A collaboration between BNL and Cornell has been formed to investigate eRHIC's NS-FFAG optics and its multi-turn ERL by building a 4-turn, one-cryomodule ERL at Cornell. It has a NS-FFAG return loop built with permanent magnets and is meant to accelerate 40mA beam to 150MeV.

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 (FFAG) optics [1]. 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).

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 electron beam can either be stored in a ring for a ring-ring collider or it can be provided by an ERL for a linac-ring collider. Because experiments have to be performed for all combinations of helicity, bunches with alternating polarization have to be provided for the collisions. An electron ring can provide these conditions only when it is regularly filled by a linac. The ring-ring as well as the linac-ring design therefore have a recirculating linac with return loops around the RHIC tunnel. Significant simplification and cost reduction is possible by configuring these loops with non-scaling (NS-FFAG) optics of large momentum aperture.

CBETA will establish the operation of a multi-turn ERL as well as that of an FFAG 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 an NS-FFAG lattice that is very compact, enabling multiple passes of the electron beam in a single recirculation beamline, using the SRF linac four times.

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.

CBETA brings together the resources and expertise of a large DOE National Laboratory, BNL, and a leading research university, Cornell. CBETA will be built in an existing building at Cornell, using many components that have been developed at Cornell under previous R&D programs for a hard x-ray ERL [2] that were supported by the National Science Foundation (NSF), New York State, and Cornell University. These components are a fully commissioned world-leading photoemission electron source, a high-power injector, and an ERL accelerator module, both based on SRF systems, and a high-power beam stop. The only elements that require design and construction from scratch are the FFAG magnet transport lattices of the return arc.

THE CBETA HALL 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

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hall for extracted-beam experiments with Cornell's 12 GeV Synchrotron. It is equipped with a high ceiling and an 80 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 Table 1.

The DC photo-emitter electron source, the injector linac, the ERL merger, the high-current ERL linac module, and the ERL beam stop are already installed in this hall and are connected to their cryogenic systems and to other necessary infrastructure.

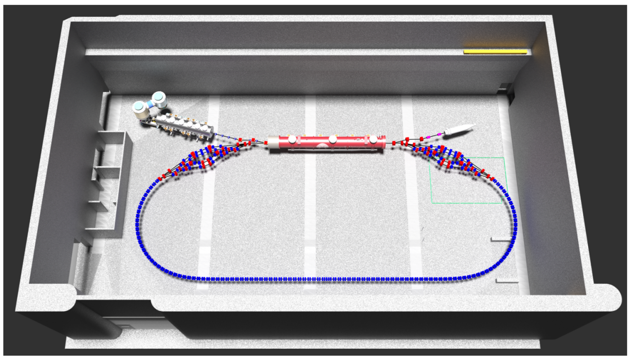

Figure 1: Floor plan of the Cornell-BNL ERL Test Accelerator in the L0E experimental hall at Cornell's Wilson laboratory.

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	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

EXISTING COMPONENTS AT CORNELL

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 photoinjector requires a high voltage power supply (HVPS) supplying hundreds of kV to the high voltage (HV) surfaces

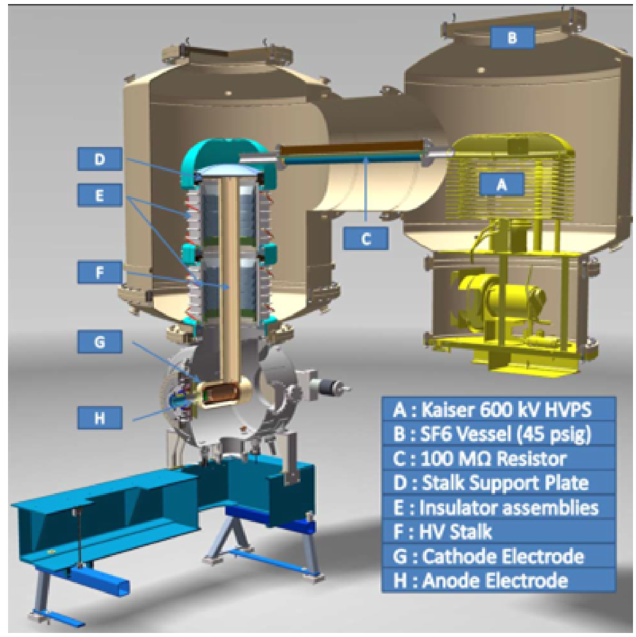

Figure 2: A cutaway view of the DC photoemission gun. Photocathodes are prepared in a load lock system mounted on the large flange at the left, and transported through the cathode cylinder to the operating position in the Pierce electrode shape on the right. The beam exits through the small flange to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

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 75mA.

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 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.

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.

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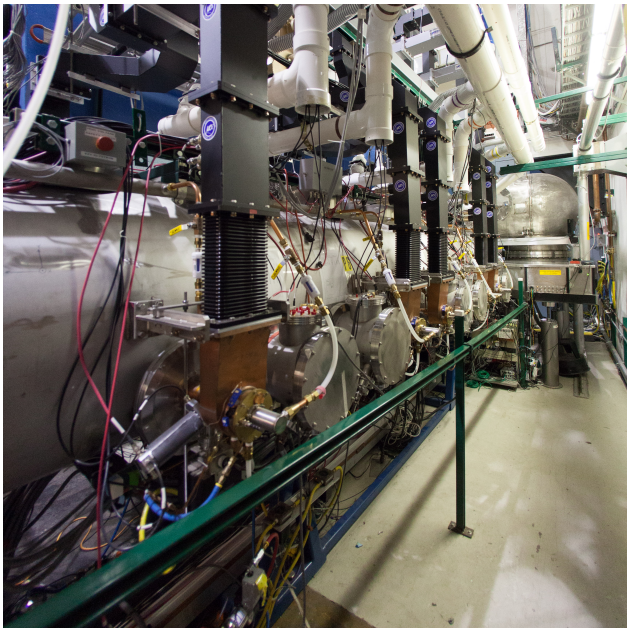

Figure 3: The high voltage DC gun at the right, followed by an emittance compensation section, the RF buncher, and the SRF cryomodule.

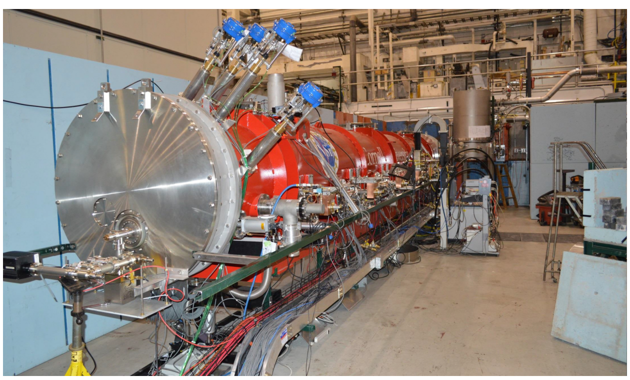

Figure 4: The Cornell Main Linac Cryomodule (MLC) installed for RF testing in the experimental hall L0E.

This cryomodule houses six 1.3GHz 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. The MLC will be powered by 6 individual solid-state RF amplifiers with 5 kW average power per amplifier. Each cavity has one input coupler. One amplifier is currently available for testing purposes, so an additional 5 amplifiers are needed for this project.

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 in the top left of that picture also already exists, and with a power limit 600kW it can absorb all beams that are specified for CBETA.

COMPONENT UNDER DEVELOPMENT

While the splitter and recombiner sections to the right and the left of the MLC in Fig. 1 are equipped with conventional electro magnets, the magnets of the FFAG arc are made of permanent magnets. The field of these quadrupoles is shaped by iron poles, but the magnetic flux is produced by cubes of permanent magnet material. A prototype of this design is shown in Fig. 5 on a field-measuring bench at BNL.

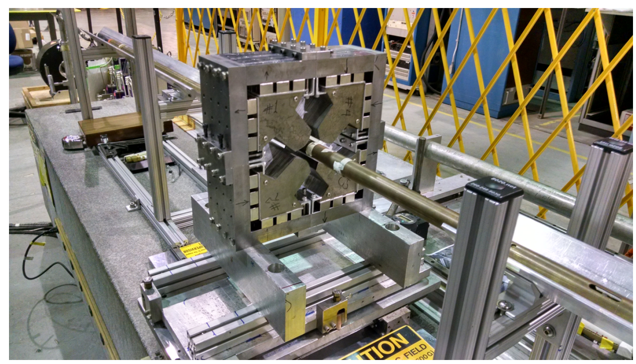

Figure 5: The FFAG magnet QD on a rotating coil test bench.

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