CBETA - CORNELL UNIVERSITY BROOKHAVEN NATIONAL LABORATORY ELECTRON ENERGY RECOVERY TEST ACCELERATOR*

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Abstract

Cornell's Lab of Accelerator-based Sciences and Education (CLASSE) and the Collider Accelerator Department (BNL-CAD) are developing the first Superconducting RF multi-turn energy recovery linac with Non-Scaling Fixed Field Alternating Gradient (NS-FFAG) racetrack. The existing injector and superconducting linac at Cornell University are installed together with a single NS-FFAG arcs and straight section at the opposite side of the linac to form an Electron Energy Recovery (ERL) system. The 6 MeV electron beam from the injector is injected into the 36 MeV superconducting linac, and accelerated by four successive passes: from 42 MeV up to 150 MeV using the same NS-FFAG structure made of permanent magnets. After the maximum energy of 150 MeV is reached, the electron beam is brought back to the linac with opposite Radio Frequency (RF) phase. Energy is recovered and reduced to the initial value of 6 MeV with 4 additional passes. There are many novelties: a single NS-FFAG structure, made of permanent magnets, brings electrons with four different energies back to the linac. A new adiabatic NS-FFAG arc-to-straight section merges 4 separated orbits into a single orbit in the straight section.

General Layout

This report will explain first the CBETA [1] role as a prototype for the future Electron Ion Collider (EIC) in the present Relativistic Heavy Ion Collider eRHIC, as an ERL proof of principle for accelerating electrons with energy recovery. Next, few novelties in the project are explained: this will be the first time that a total of eight passes of electrons, four during acceleration in the superconducting linac and four during the energy recovery will occur. This is also a first time that the NS-FFAG will be used as a single beam line to transfer electrons with four times in energy through the same magnet structure. The magnets are being built with permanent magnet material. After the principle of NS-FFAG is shown the expected CBETA deliverables are presented. The progress report and summary follows.

Why to Build Electron Ion Collider?

Several fundamental questions in nuclear physics are posed: can the quark and gluon contribution to the proton spin be determined at last, what is the spatial distribution of quarks and gluons in nucleon/nuclei, understand deep aspects of gauge theories, and quantitatively probe the universality of the strong color fields in the electron/proton ion collisions. The study of the high-density gluon fields requires a high energy, high luminosity polarized EIC, a microscope for gluons an ultimate QCD laboratory.

What is CBETA

The ERL at Cornell University is being built not by coincidence: the first proposal for ERL came from Maury Tigner 1965 [2] with a long and very successful R&D in building and developing of the superconducting linacs. A combination of the ERL with NS-FFAG comes from a team of experts in this field from BNL: D. Trbojevic, S. Berg, F. Meot, S. Brooks and E.D. Courant [3,4]. A schematic of the CBETA is shown in Fig. 1.

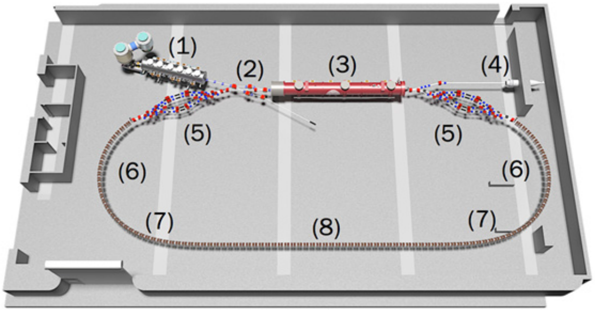

Figure 1: CBETA-Existing Injector (1), merger (2) with the Main Linac Cryo-module (MLC) (3). The rest of the accelerator is being built: spreaders (5), FFAG arcs (6), transitions to the straight (7), and the straight section (8).

The gun HV power supply for 750 kV at 100 mA is based on proprietary insulating core transformer technology. The gun is shown in Fig. 2. This gun holds the world

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(3) Left Cornell University and the CBETA project

record in sustained current of up to 75mA. The high-power CW SRF injector linac is fully operational and has just being used for commissioning with the beam the MLC. The injector delivered up to 500 kW of RF power to the beam at 1300 MHz is shown in Fig. 3.

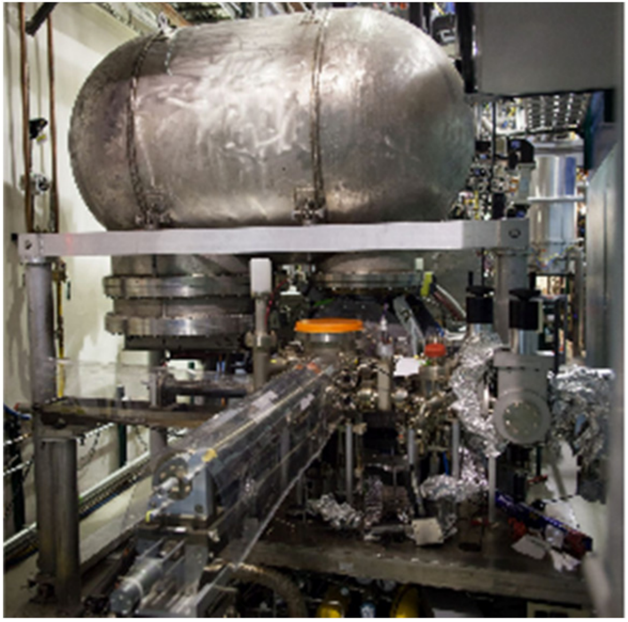

Figure 2: The 750 keV Cornell DC electron gun.

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.

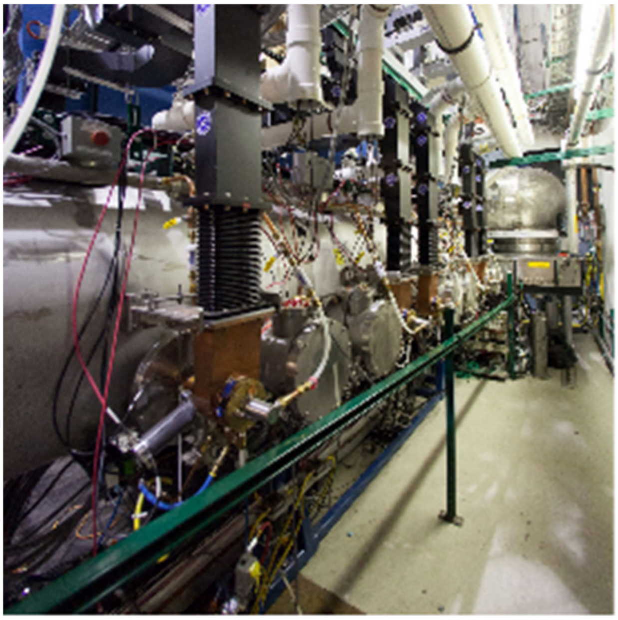

Figure 3: Injector cryomodule.

More results from the Injector previous and present runs are shown in Fig. 4.

The accelerator module in the ERL loop will be the MLC, which has been built as a prototype in Cornell. 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. 5.

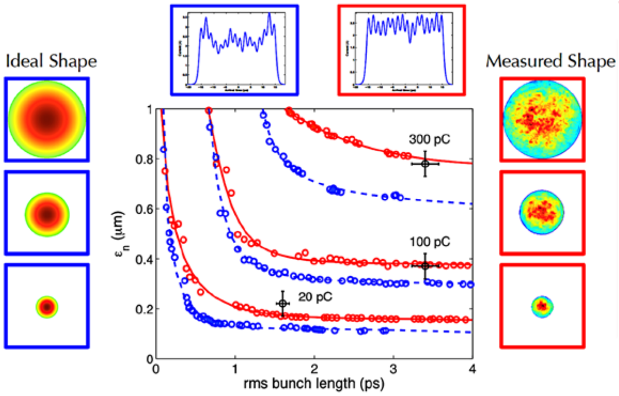

Figure 4: The injector beam emittance measurements.

Figure 5: Present commissioning (May 2017) of the MLC.

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 module is installed and it is now being commissioned for CBETA project.

The Cornell digital LLRF system 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 microphonics in few of the MLC cavities are above the normal values. That also would have some impact on the field stability achievable. The CBETA requirements are quite tight, so dedicated LLRF studies are proceeding. A part of the recent commissioning results are shown in Fig. 5, while the first beam through the linac is measured on May 4, 2017 as shown in Fig. 6.

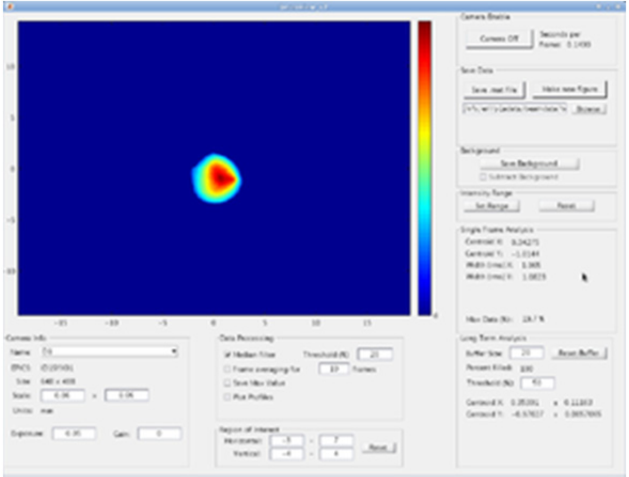

Figure 6: First beam through the MLC (May 4, 2017)

The expected deliverables from the CBETA project are shown in Table 1, like 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

The LINAC-RING solution for eRHIC uses two FFAG beam lines to do multiple recirculations (FFAG-I: 1.7-5.0 GeV, FFAG-II: 6.7-18.3 GeV). All sections of a FFAG beam line are formed using a same FODO cell. Required bending in different sections is arranged by proper selection of the offsets between cell magnets (or, alternatively, with dipole field correctors). Permanent magnets can be used for the FFAG beam line magnets (no need for power supplies/cables and cooling). There are few very important topics to be shown in the CBETA with respect to the Linac-Ring solution for the EIC: 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.

NS-FFAG Arcs and Transition

The last couple of decades have seen a remarkable revival of interest in Scaling Fixed Field Alternating Gradient (S-FFAG) accelerators. Originally developed in the 1950s [5-7], S-FFFAGs have very large momentum acceptances, with a magnetic field that varies across the aperture as $B \sim B_o\ (r/r_o)^k$, where the scaling exponent $k\sim150$ is as large as possible. Similarly, ERLs cannot use synchrotron-like arcs, because it is not possible to rapidly change the magnetic field during electron acceleration. Except for CBETA, all proposed and operational multipass ERLs (and recirculating linacs) use multiple beamlines - one beamline for every electron energy. The NS-FFAG optics reduces the number of beamlines required in a multipass ERL to one, while preserving centimeter-scale apertures. The aperture reduction is enabled by ensuring very small values of horizontal dispersion D_x, because according to: $\Delta x=D_x \cdot \Delta p/p$, where D_x is the orbit offset, and p is the electron momentum. For example, if the dispersion is $D_x\sim40$ mm, then the orbit offsets are only $\Delta x\sim20$ mm for a momentum range $\Delta p/p\sim50\%$ that corresponds to an energy range of 3 for relativistic particles. The magnetic field in NS-FFAG optics is purely linear, with $B_y=B_o+G \cdot x$, and $B_x=G \cdot x$. The basic NS-FFAG cell orbits together with the combined function magnets are shown in Fig. 7. The energy range in the CBETA FFAG lattice is 4 times the initial energy: 36+6 MeV→ 42→78→114→ 150 MeV.

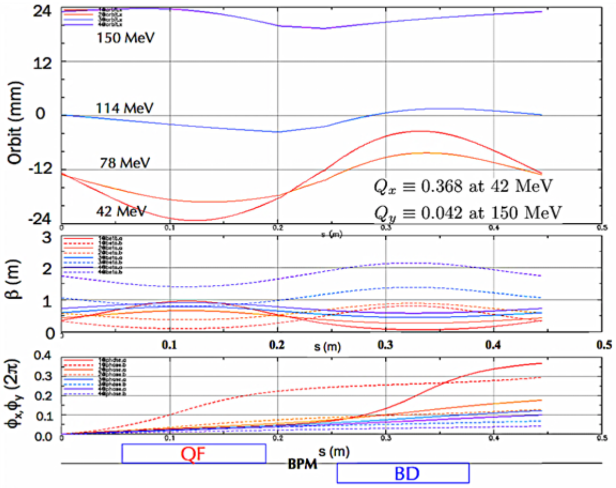

Figure7: Orbits and betatron functions in the NS-FFAG cell.

Splitters

The splitters on both sides of the linac have a role to match the betatron functions, angles and positions at he entrance of the FFAG of each beam. After the commissioning of the first pass with the lowest energy (bottom beam line) the path length of this line needs to be adjusted for 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 be able to arrive at the linac with opposite sign of the RF. The splitters adjust as well as the momentum compaction factor *r56* as well. One of the splitters is shown in Fig. 8.

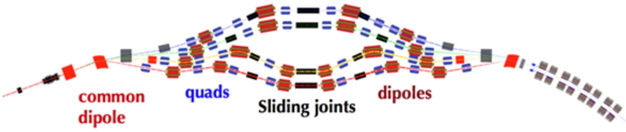

Figure 8: Details of one of two splitters, marked by (5) above in Fig. 1, to match the MLC to the NS-FFAG arc.

The full tracking of the electron beam with acceleration and energy recovery of the eight passes, done by Chris Mays is shown in Fig. 9.

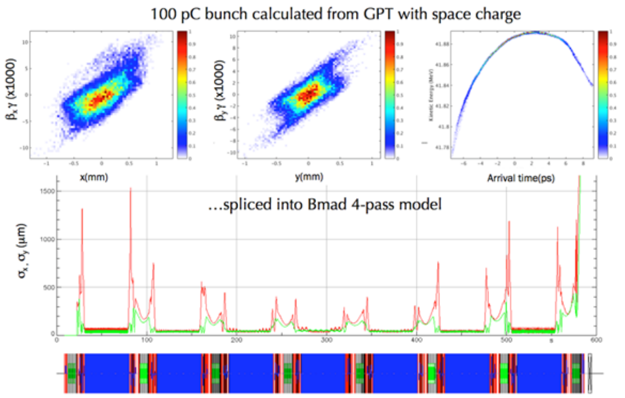

Figure 9: The electron beam tracking GPT and Bmad during acceleration and energy recovery in the CBETA NS-FFAG lattice.

The 8 passes beam tracking with a very small emittance growth is shown in Fig 10.

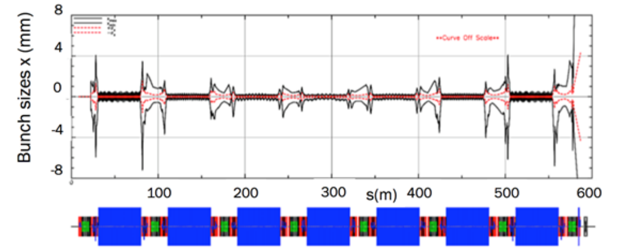

Figure 10: Beam size during acceleration and energy recovery.

The First NS-FFAG Girder

The NS-FFAG CBETA permanent magnets of the Halbach type are being built and assembled in the first girder. The magnet design is based on the Halbach quadrupole and dipole magnet design but with an innovative approach for obtaining magnetic material efficient defocusing magnet. This magnet cross section designed by S. Brooks [8] is shown in Fig. 11. There are two kinds of magnets in the NS-FFAG: the focusing quadrupole(s), and the defocusing combined function magnet placed between the two focusing quadrupoles if the optimum triplet structure was used.

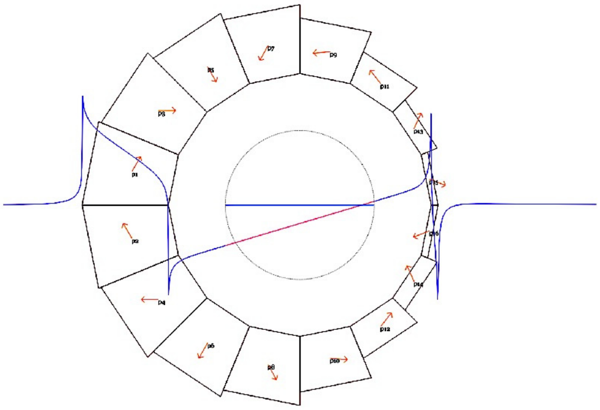

Figure 11: S. Brooks innovative permanent combined function magnet design. The magnetic field is linear with gradient G_D= 11.07 T/m and bending field of 0.306 T.

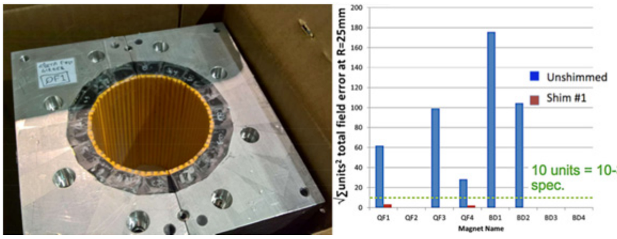

Figure 12: Halbach magnet with correction wires with results before and after the corrections applied.

In the middle of the defocusing magnet, as in the light source lattice, there is a minimum of the horizontal betatron function β_x and horizontal dispersion D_x, the same condition for the smallest value of the dispersion action function H. The beam offsets of the highest and lowest energy are equally displaced from the center of the focusing quadrupole, 0.133 m long, with a gradient of $G_F=-11.49$ T/m. The integral gradient of the defocusing combined function magnet, 0.122 m long, is $G_D=11.07$ T/m, with the bending field of 0.306 T. Because of the limited space available in the Cornell University experimental area a doublet structure was chosen. The drift spaces between the magnets with lengths of 6.6 cm and 12.3 cm, the shorter and longer one respectively, with a total FFAG cell length of 0.444 m.

Transition Cells from FFAG Arc to the Straight

The eRHIC linac-ring design of the EIC has an ERL with two NS-FFAG arcs to bring the multi-pass electron beam back to the linac. The CBETA follows the same innovative solution and a special adiabatic dependence (1) found by S. Berg is:

$$f_T(x)=\frac{1}{2}+\left(x-\frac{1}{2}\right)=\sum_{k=0} a_k\binom{2k}{k}x^k(1-x)^k \quad (1)$$

It is presented by a graph in the Fig. 13.

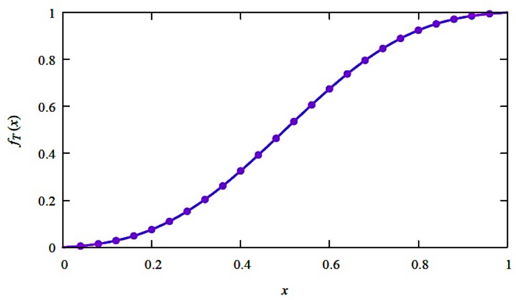

Figure 13: Function used for the transition from the NS-FFAG arc to the straight section.

The RHIC tunnel is made by the six-fold symmetry with long straight sections. The NS-FFAG arcs need to follow the shape of the tunnel.

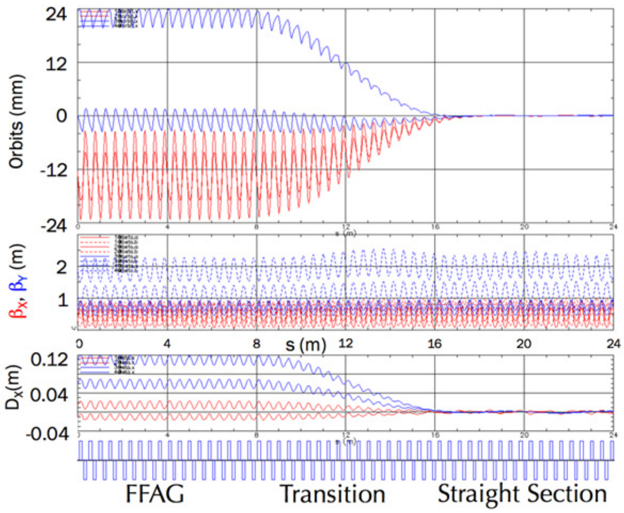

Figure 14: Orbits merging from the NS-FFAG arc to the straight section.

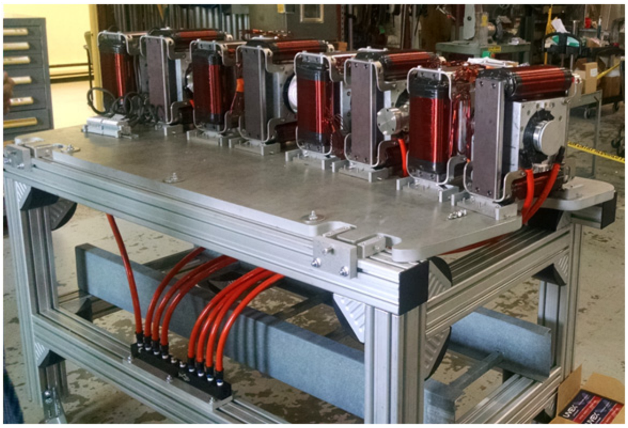

Figure 15: Eight NS-FFAG permanent Halbach type magnets.

A problem of matching the multi beam FFAG arc with the straight section was solved by adiabatically reducing the bending of the FFAG magnets until all different energy electron beam orbits merged into a single one in the straight section. Merging orbits from the NS-FFAG arc to the straight section are shown in Fig. 14. The first girder with 8 magnets making the four NS-FFAG cells is built and shown in Fig. 15: nets surrounded by the dipole correction coils are shown assembled in the girder.

Summary

The project CBETA Cornell University Brookhaven National Laboratory collaboration in building the Energy Recovery Linac ERL with the Non Scaling Fixed Field Alternating Gradient single bypass is in progress. The funding by New York State Research and Development Authority-NYSERDA started in November 2016. The CBETA project has multiple purposes and showing every day noticeable developments and success. Novelties in CBETA are: the first superconducting linac with four accelerating and four energy recoveries passes; the first time that a single NS-FFAG 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 NS-FFAG transition from the arc-to-straight section merges four different orbits into a single one. The permanent magnets based on Halbach design are built and successfully tested with extremely good field quality after the correction is applied. This successful test of the first permanent magnet girder is also important for other applications like the proton cancer therapy gantry. The 6 MeV electron beam has been transferred from the injector through the Main Linac Cryo – module MLC on May 4, 2017. The first test with the beam is planned at the beginning of 2018th.

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