A NOVEL USE OF FFAGS IN ERLS - IN COLLIDERS: ERHIC, LHEC AND A PROTOTYPE AT CORNELL UNIVERSITY*

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Abstract

We propose a novel use of Non Scaling Fixed Field Alternating Gradient beam line (NS-FFAG) to replace multiple beam lines in existing Energy Recovery Linacs (ERLs) (4-pass at Novosibirsk, ERL of CEBAF, ERL at KEK, etc.) with NS-FFAG beam lines connected with spreaders and combiners to the linac. We present two designs for the Electron Ion Colliders one at CERN-LHeC and one at Brookhaven National Laboratory-eRHIC to be placed in the tunnel of the existing Relativistic Heavy Ion Collider (RHIC) called eRHIC. The proof of principle electron accelerator with the NS-FFAG arcs is to be built at Cornell University Wilson Hall where there are already available injector, superconducting linac accelerator and the dump. There are very new developments in the NS-FFAG design never accomplished before: arc-to straight adiabatic matching with merged multiple orbits into one, permanent magnet design for the arc and straights with ability of four times in energy, etc.

INTRODUCTION

There are many ways for accelerating particles in the non-relativistic region: the neutron generators or for Accelerator Driven Subcritical System (ADS) and they could be the superconducting linacs, fast cycling synchrotrons, superconducting cyclotrons, FFAG's etc. The isochronous circular accelerator, where the beam arrives for all energies at the same time to the RF and operates in the CW mode is very advantageous. A preferred solution is a straight superconducting linac but it requires large power, long length and it is very expensive. Cyclotrons might be the preferred solution. This presentation shows examples of savings in the linac lengths in relativistic electrons acceleration for the LHeC, eRHIC, and an ERL at Cornell University (eRHIC prototype) with isochronous condition. It is not suggested that this solution could be applied for non-relativistic particles but it provides an input for new possibilities in this case. The energy recovery in all three examples is possible as the electron time of flight during acceleration is properly adjusted on the top of the RF sinusoidal wave, while during the deceleration or energy recovery it is shifted close to the minimum of the RF wave. There are multiple advantages in using ERL's in the electron ion colliders: electrons are colliding only once with hadrons, due to energy recovery the enormous power of the electron beam is brought down to the dump with initial very low energy and with the overall linac efficiency very close to 100%.

Electron Energy Colliders LHeC and eRHIC

The electron ion collider LHeC goal is to study of deep inelastic scattering (DIS) into unknown areas of physics and kinematics. "The physics program also includes electron-deuteron and electron-ion scattering in a (Q^2, 1/x) range extended by four orders of magnitude as compared to previous lepton-nucleus DIS experiments for novel investigations of neutron's and nuclear structure, the initial conditions of Quark-Gluon Plasma formation and further quantum chromo-dynamic phenomena"[1].

LHeC:

The LHeC collider will collide 60 GeV maximum energy electrons with 7 TeV protons or heavy ions. The LHeC collider main parameters are shown in Table 1.

Table 1: Beam Parameters LHeC

	Protons	Electrons
Energy (GeV)	7000	60
γ	7460	11740
$\varepsilon_{x,y}$ (nm)	0.4	0.43
Beam	>430 mA	6.4 mA

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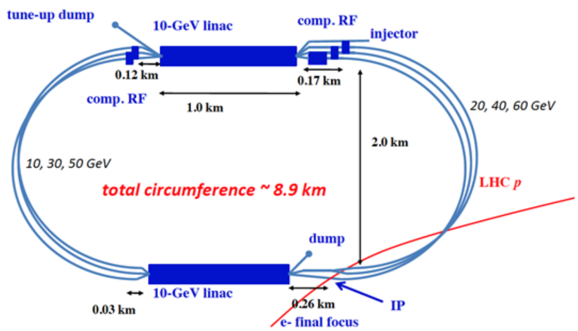

Figure 1: LHeC ERL layout including dimensions.

The LHeC ERL design layout is shown in Fig. 1. The radius of the curvature, a parameter important for the synchrotron oscillations energy loss, is R=1000 m. The limit on the total amount of synchrotron radiation loss is set to be 15 MW.

LHeC NS-FFAG ERL Proposal

The electron beam from the 17 MeV injector is transferred to the two 5.435 superconducting linacs connected with a five spreaders lines and one separate line to the collision point with the protons/ions marked as IP in Fig. 2. After passing through the two linacs the 10.87 GeV electron beam arrives to the low energy NS-FFAG arc continues from the adiabatic arc-to-straight section transition reaching to the opposite NS-FFAG arc through the same kind of adiabatic transition. The lower energy NS-FFAG arcs, arc-to-straight, straight section, straight-to-arc and opposite arc transfers three energies: 10.906, 21.829 and 32.735 GeV. The higher NS-FFAG line transfers two energies 43.644 and 54.547 GeV.

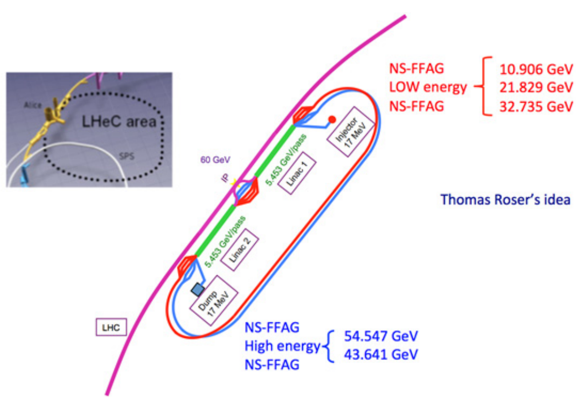

Figure 2: NS-FFAG proposal for the LHeC.

There are few significant advantages of the NS-FFAG proposal, shown in Fig. 2:

- A smaller value of the 54.547 GeV highest electron beam energy going to through the arc, not 60 GeV as in the official design reduces significantly the synchrotron radiation loss, as the dependence on energy is γ^4. Enhancement of the luminosity is equal to 1.34 as the electron current could become 8.87 mA instead of 6.6 mA to correspond to total synchrotron radiation power loss of 15 MW.
- The three separate beam lines shown in Fig. 1 are replaced with the two NS-FFAG lines.
- Not only that the number of beam lines is reduced but the size of the linacs as well: from the previous 2x10 GeV linacs to 2x5.455 GeV or 54.547% of the previous 10 GeV. This would represent a significant saving of total linac size.

The betatron functions for the central momentum energy basic NS-FFAG arcs cell of the higher energy range are shown in Fig. 3, while the orbit offsets in the same arcs cell are shown in Fig. 4. The combined function focusing and defocusing magnets are shown in both figures with detail characteristics: gradients and bending angles. The synchrotron radiation losses for the whole energy range in the NS-FFAG ERL design, with 6.6 mA (electron current of the LHeC design) and with 8.87 mA, are shown in Table 2.

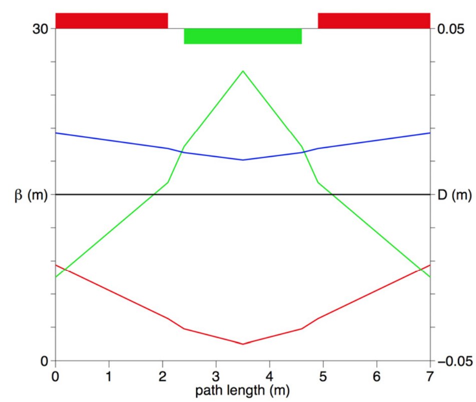

Figure 3: Betatron functions for the central energy of the higher NS-FFAG ERL design, with the combined function magnets.

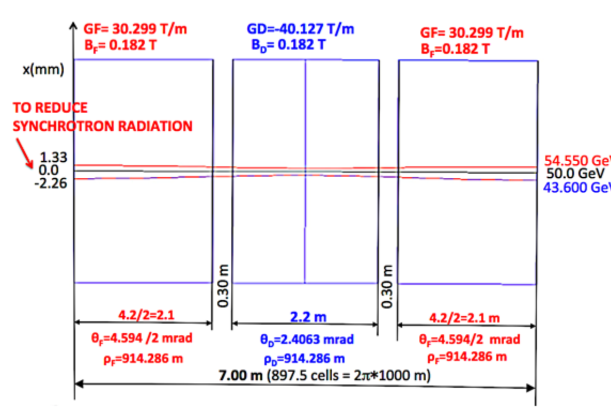

Figure 4: Orbit offsets in the higher energy range LHeC NS-FFAG ERL proposal with magnet properties: gradients and bending angles.

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Table 2: Synchrotron Radiation Losses in LHeC NS-FFAG Design (electron currents of 6.6 mA and 8.87 mA)

Energy (GeV)	**8.87 mA**	**6.6 mA**
55.547	7.578	5.638
43.644	4.208	3.131
32.735	1.390	1.034
21.829	1.288	0.959
10.923	0.536	0.399
Total loss	15.000	11.161

eRHIC:

The high energy, high luminosity, polarized EIC eRHIC should: determine quark and gluon contributions to the proton spin at last, should determine what is the spatial distribution of quarks and gluons in nucleons /nuclei and understand in detail the transition to the non-linear regime of strong gluon fields and the physics of saturation in the electron ion collisions [2]. This should be a microscope for gluons and will the study the high-density gluon fields. The basic parameters of the eRHIC collider are shown in Table 3, while the layout is shown in Fig. 5. There are two NS-FFAG beam lines connected to the linac with combiners and spreaders: former at the entrance and latter at the linac exit, accordingly.

Table 3: eRHIC Beam Parameters

	e	p	$^2He^3$	$^{79}Au^{197}$
Energy, GeV/u	15.9	250	167	100
CM energy		126	103	80
Bunch f, (MHz)	9.4	9.4	9.4	9.4
Intensity, 10^{11}	0.07	3.0	3.0	3.0
B. Charge (nC)	1.1	48	32	19.6
Beam (mA)	10	415	275	165
$\varepsilon_{x,yN}$ (μm) hadron		0.2	0.2	0.2
$\varepsilon_{x,yN}$ (μm) e	23		35	58
β^* (cm)	5	5	5	5
Beam-beam		0.004	0.003	0.008
rms bunch (cm)	0.4	5	5	5
Polarization	80	70	70	none
Luminosity, 10^{33}		4.1	2.8	1.7

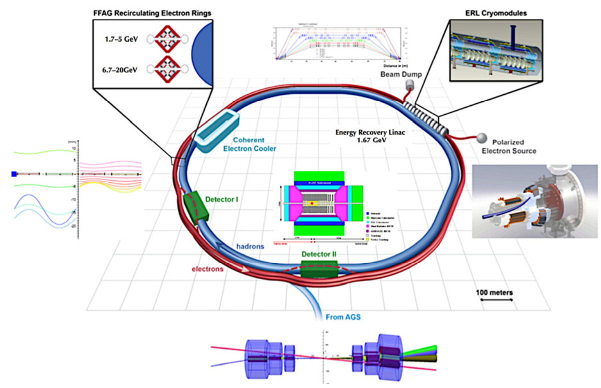

Figure 5: eRHIC layout with major components.

Two NS-FFAG beam lines are designed with the displaced focusing and defocusing quadrupoles as shown in Fig. 6 for the higher NS-FFAG beam line.

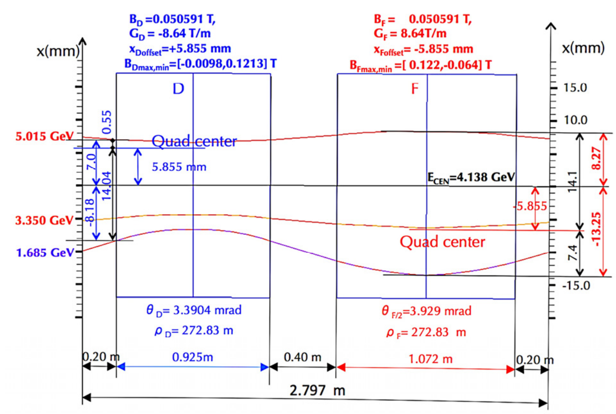

Figure 6: Orbit offsets in the basic cell for the NS-FFAG design for the larger energy range 6.68-20 GeV.

The two combined function magnets of the lower energy ring (energy range 1.6-5 GeV) are made of ±5.3 mm displaced quadrupoles in opposite radial direction, with equal but opposite sign gradients of ±8.6 T/m, with maximum orbit offsets of ±10.8 mm from the central momentum. The NS-FFAG basic cell of the larger energy range (6.68-20 GeV) is shown in Fig. 6. The values of the gradients are shown at the upper side of the figure: $G_{F,D}$ = ±8.5 T/m with the same orbit offsets from the central momentum of ±5.855 mm. One of the novelties in the proposed NS-FFAG design is the adiabatic matching from the arc-to-straight section as shown in Fig. 7.

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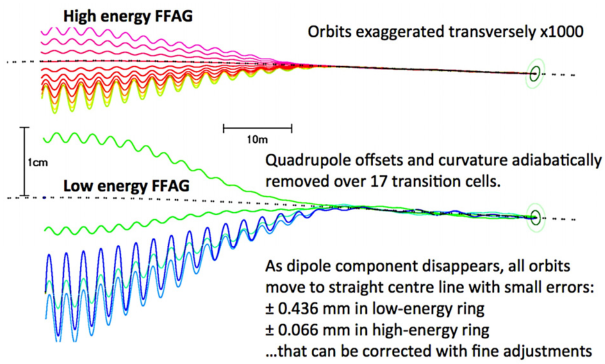

Figure 7: New property of the NS-FFAG lattice: Adiabatic removal of the quadrupole offsets and matching to the straight section.

As the arc-to-straight matching is resolved the by pass of the NS-FFAG detectors around detectors solution obtained by the same method as shown with 1000 times enlarged orbit offsets in Fig. 8:

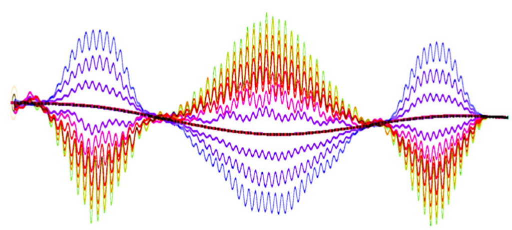

Figure 8: The by-pass of the NS-FFAG around detectors.

The basic cell design as well as selection of the central momentum is always connected towards reduction of the synchrotron radiation losses, as the synchrotron radiation loss power is proportional to $\sim B^2E^2$. It is desirable to have the smallest magnetic field for the highest energies in the focusing element as the magnetic field could be presented as $B_F = B_{Fo} + G_F * x_{max}$. This indicates that it is preferable to have longer focusing than the defocusing magnet as the maximum if the magnetic field of the defocusing magnet is at the radially inward part of the orbits as: $B_D = B_{Do} + G_D * x_{max}$ as the G_D has a negative sign.

The time of flight dependence in the NS-FFAG is a parabolic function. The maximum value of the time of flight difference at the higher energy NS-FFAG for six arcs is ~7 cm. This needs to be corrected in the spreaders and combiners, as well as ability to adjust the M_{56}. Numerous tracking studies of the electron beam emittance growth effect due to misalignment have been performed. It is very clear that the transverse misalignment and gradient magnet errors induce the emittance growth especially due a large number of cells required in NS-FFAG (as the strong focusing requires small cell length bringing large number of cells). The misalignment errors have to be corrected with the horizontal and vertical dipole correctors as well as with the gradient correctors.

The eRHIC NS-FFAG magnets will use permanent magnet material. There was previous experience with permanent magnets used for the anti-proton storage ring placed in the Main Injector at Fermi National Laboratory. They had used passive temperature compensation of the permanent magnet with a material with opposite temperature dependence [3].

NS-FFAG ERL CBETA

As there are no either present ERL's with superconducting RF with larger number of passes or a NS-FFAG ERL combination so far it is very important to test the eRHIC prototype. The Cornell University Physics Department represents an ideal place for such a combination, as there are already available:

- The 6 MeV injector has already been built and commissioned producing world record good quality electron beam.
- The superconducting RF cavities able to produce 60-70 MeV.
- The beam dump for 6 MeV electrons
- Available space in the Wilson interaction Hall.

The layout of the future NS-FFAG beam with a spreader and collider is shown in Fig. 9.

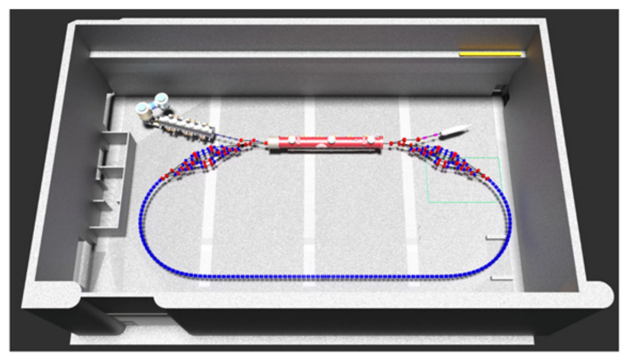

Figure 9: Layout of the eRHIC prototype at Cornell University (CBETA). The upper left corner shows the injector, followed by the Linac (red colour), following with a dump. On both sides of the linac there are a combiner (on the left side) and spreader on the right side. The NS-FFAG arc and straight section is shown by blue color.

During the last three years an excellent collaboration between the BNL and Cornell University have been established and numerous designs and studies have been performed: two type of permanent magnet have not only been designed but the prototypes have been built and measured, the vacuum chamber with the beam position monitors, spreaders-combiner, correction magnets for both types of permanents magnets, layout, Conceptual Design Report-CDR, the White paper report [3], Detail layout, studies of tolerances in misalignment using the correction magnet design, effect of the coherent synchrotron radiation on the beam longitudinal emittance, etc.

The picture of the commissioned CBETA injector is shown in Fig. 10. The simulations are shown in Fig. 11.

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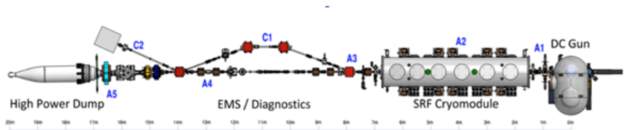

Figure 10: The fully commissioned 6 MeV injector at Cornell University.

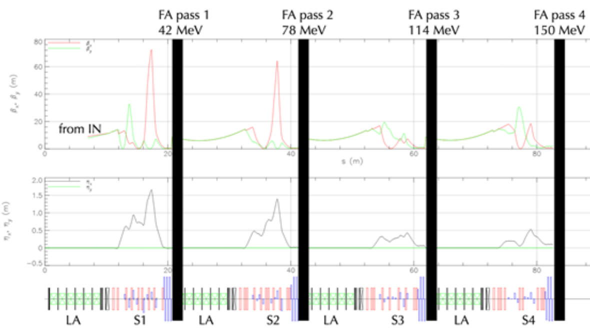

Figure 11: Simulation of the 8 passes trough the CBETA linac, spreader and combiner, NS-FFAG with the energy recovery.

CONCLUSION

A cost effective LHeC (almost twice reduction of the proposed linac size with enhanced luminosity) and eRHIC designs with 1.6 GeV linac and maximum energy of 20 GeV, as well as the 150 MeV ERL with NS-FFAG at Cornell University, are shown. At LHeC a proposal for replacement of the 2x10 GeV linacs and three arcs, with 2x5.453 GeV linacs and two NS-FFAG arcs, respectively. This would be a cost-effective solution with lower synchrotron radiation, hence with 34% larger luminosity for the same limit on the value of 15 MW for the total loss from synchrotron radiation. The ERL with NS-FFAG arcs at Cornell University will be a first ERL of that type. Advantages at Cornell University are already existing the 6 MeV injector, superconducting linac 45-70 MeV making possible to obtain with the NS-FFAG maximum energies of 150-250 or higher MeV. This will be a proof of principle for the new concept: merging FFAG beam lines with the Energy Recovery Principle.

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