ERL WITH NON-SCALING FIXED FIELD ALTERNATING GRADIENT LATTICE FOR ERHIC*

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Abstract

The proposed eRHIC electron-hadron collider uses a "non-scaling FFAG" (NS-FFAG) lattice to recirculate 16 turns of different energy through just two beam lines located in the RHIC tunnel. This paper presents lattices for these two FFAGs that are optimised for low magnet field and to minimise total synchrotron radiation across the energy range. The higher number of recirculations in the FFAG allows a shorter linac (1.322GeV) to be used, drastically reducing cost, while still achieving a 21.2 GeV maximum energy to collide with one of the existing RHIC hadron rings at up to 250GeV. eRHIC uses many cost-saving measures in addition to the FFAG: the linac operates in energy recovery mode, so the beams also decelerate via the same FFAG loops and energy is recovered from the interacted beam. All magnets will be constructed from NdFeB permanent magnet material, meaning chillers and large magnet power supplies are not needed. This paper also describes a small prototype ERL-FFAG accelerator that will test all of these technologies in combination to reduce technical risk for eRHIC.

INTRODUCTION

A possible future Electron Ion Collider (EIC) at Brookhaven National Laboratory will be placed in the existing tunnel of the superconducting Relativistic Heavy Ion Collider (RHIC→eRHIC) [1-5]. This is a design for the additional electron accelerator to provide polarized electrons with an energy range from 5 to 21 GeV. Electrons will collide with existing polarized protons or ^{3}He, or with other heavy ions from deuterons to Uranium.

The existing RHIC has been producing fascinating results so far with extraordinary performance above any expectations. RHIC represents a complicated chain of many accelerators, starting with the Electron Ion Beam Source (EBIS) with Radio Frequency Quadrupole (RFQ) and the polarized proton source (development of polarized ^{3}He has already started). It is the only collider in the world with the ability to collide unequal species and polarized protons. RHIC was the first to measure the formation of a "perfect liquid" consisting of quark gluon plasma (QGP). This system of accelerators and one of the two superconducting rings in RHIC will be reused in the future EIC while electrons will be provided by a new accelerator. Electron acceleration comes from a single superconducting linac with an energy gain of 1.322 GeV, as shown in the upper right corner in Fig. 1. The accelerator design for producing electrons with energies up to 21.2 GeV is based on up to 16 passes through the linac with energy recovery (ERL). After polarized electrons are accelerated to the top energy (eRHIC has 15.9 or 21.2 GeV modes) and collided with the polarized protons or ions, their energy is recovered in the same linac. There are the same number of decelerating passes through the linac as accelerating passes, but at negative voltage (180° phase) so the energy is recovered. They reach the initial injection energy during the last pass. The "blue" hadron ring is shown schematically above the two electron beam lines (upper left corner in Fig. 1). Orbit offsets in the NS-FFAG electron rings are shown in Fig. 2. The hadron Interaction Region (IR) magnets are shown at the bottom of Fig. 1 with electrons and ions crossing with a 10 mrad angle.

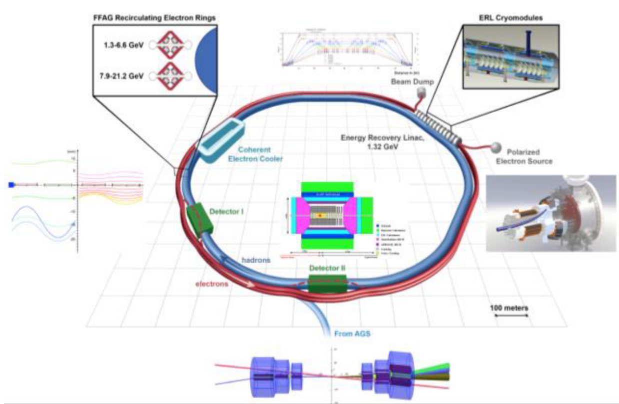

Figure 1: Layout of eRHIC: Existing "blue" superconducting hadron ring (centre); Two electron NS-FFAG beam lines (top left, with beam orbits on left); Polarized electron Gatling gun (right); Combiners and separators (top centre); Interaction region schematic (bottom) at the 6 o'clock point; and the superconducting linac (top right).

A MICROSCOPE FOR GLUONS

An EIC will be used to study the "spin puzzle" to determine quark and gluon contributions to the total proton spin, including the spatial distribution of quarks and gluons inside nuclei – a "microscope for gluons".

eRHIC Parameters

The new EIC collider eRHIC should achieve very high luminosities of the order of 10^{34} due to the expected small emittance of both electron and proton/ion beams. A new coherent electron cooling scheme is proposed for the

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hadrons and will be tested in the existing RHIC collider. A crossing angle of 10 mrad will be used in the two IRs with no electron bending upstream to avoid generating synchrotron radiation in the detector. Crab cavities will be used to preserve the same luminosity achieved in collisions without an angle. Due to the small emittance, very strong focusing of the beam at the interaction point can be applied with β^*= 5 cm. The angle of 10 mrad between electrons and protons/ions will be achieved using very specialised magnets for protons/ions close to the interaction point with zero magnetic field bore holes for electrons to pass through without synchrotron emission.

Table 1: BNL eRHIC Beam Parameters and Luminosities

	e	P	$^{3}He^{2+}$	$^{197}Au^{79+}$
Energy (GeV)	15.9	250	167	100
CM energy (GeV)		122.5	81.7	63.2
Bunch freq. (MHz)	9.4	9.4	9.4	9.4
Bunch Int. (nucl.), 10^{11}	0.33	0.3	0.6	0.6
Bunch charge (nC)	5.3	4.8	6.4	3.9
Beam current, mA	50	42	55	33
Hadron *rms* ε_N (μm)		0.27	0.20	0.20
Electron *rms* ε_N (μm)		31.6	34.7	57.9
β^* (cm) (both planes)	5	5	5	5
Hadron beam-beam ξ		0.015	0.014	0.008
Electr. Beam disruption		2.8	5.2	1.9
Space charge par. ξ		0.006	0.016	0.016
rms bunch length, cm	0.4	5	5	5
Polarization, %	80	70	70	none
Peak $\mathcal{L}$, 10^{33} cm^{-2}s^{-1}		1.5	2.8	1.7
Improve $\mathcal{L}$, 10^{34} cm^{-2}s^{-1}		1.5	2.8	1.7
Ultimate $\mathcal{L}$, 10^{35} cm^{-2}s^{-1}		1.5	2.8	1.7

NS-FFAG Recirculating Loops in eRHIC

Significant simplification and cost reduction of the multi-pass electron ERL is possible by using Non-Scaling Fixed Field Alternating Gradient (NS-FFAG) recirculating loops. Two NS-FFAG beam lines placed in the existing RHIC tunnel allow 16 passes though the linac with only small "splitter" sections where all 16 are separate. This reduces the linac size but enhances the load on the superconducting cavities. The advantage of NS-FFAG lines is their large energy acceptance with linear fixed field magnets (NdFeB in eRHIC). The first proof of principle NS-FFAG electron ring (EMMA) was built at Daresbury Laboratory in England [6] but the combination of NS-FFAG loop(s) with an ERL has not yet been tried. The NS-FFAG lines provide the following advantages: a large energy range of up to 5× with small orbit offsets (dispersion less than 5 cm), leading to small magnet size and physical aperture; linear magnetic fields, giving large dynamical aperture; less opposite bending than scaling FFAGs; and very strong focusing and small beam sizes.

eRHIC NS-FFAG Cell Lattice Designs

The superconducting linac accelerates electrons by 1.322 GeV per pass and is connected to the two NS-FFAG recirculating loops by splitters (top centre in Fig. 1) at both ends. Each chicane-shaped line in the splitters has to match the linac betatron functions and zero dispersion to one of the NS-FFAGs, which have much smaller betas and a small but finite D_x. There are two NS-FFAG arc beam lines: one accepting electron beams with energies from 1.334 to 6.622 GeV (turns 1-5), and the second one for energies between 7.944 to 15.876 [or 21.164] GeV (turns 6-12 [or 16]). The injector provides polarized electrons with 12 MeV initial energy at the start of the linac, which is the same energy accepted by the dump. Orbits in both NS-FFAGs are shown in Fig. 2.

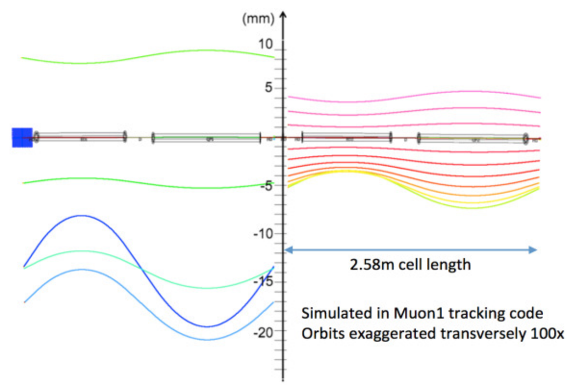

Figure 2: Electron orbits in the eRHIC arc cells, magnified 1000× transversely: lower energy loop 1.3-6.6 GeV (left); and high-energy loop 7.9-21.2 GeV (right).

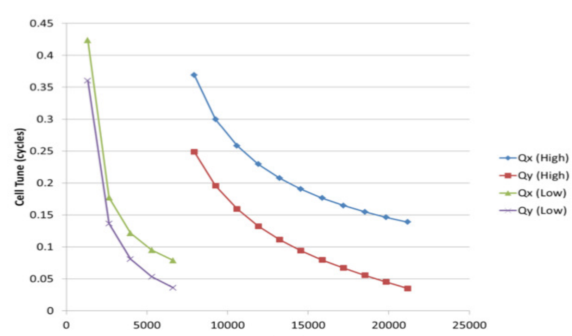

Figure 3: Tunes variation with energy in the two NS-FFAG arc cells.

The tunes' variation with energy in the two eRHIC NS-FFAG cells are shown in Fig. 3, while the time of flight for the two NS-FFAG beam lines is shown in Fig. 4. In the design procedure of the NS-FFAG arc cells, the major concern was optimization of synchrotron radiation losses. The lattices were modified until the lowest possible radiation was achieved. A total synchrotron radiation limit of 10 MW was set for the losses in all the arcs of both FFAGs in eRHIC. The synchrotron radiation from each turn in the two NS-FFAG loops is presented in

Fig. 5. The two cases shown are: accelerating electrons to 15.9 GeV with the full current of 50 mA (blue); and accelerating to the full energy of 21.2 GeV (green) with a reduced current chosen to remain within the 10 MW limit. The RHIC tunnel also has six ~200 m long straight sections the FFAG arcs have to match with (Fig. 6).

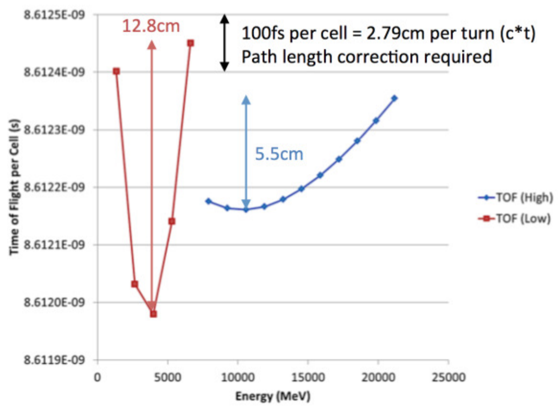

Figure 4: Time of flight dependence of the two eRHIC NS-FFAG arc cells.

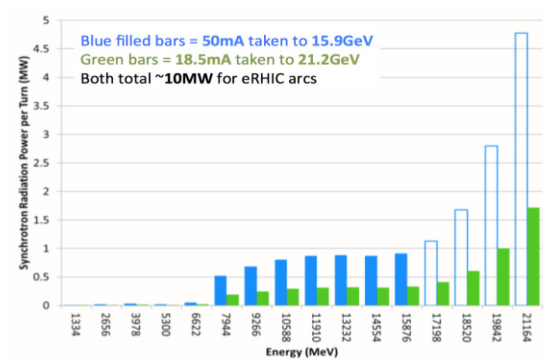

Figure 5: Synchrotron radiation loss for the two cases of acceleration: up to 15.9 GeV with 50 mA beam, and to 21.2 GeV with 18.5 mA beam.

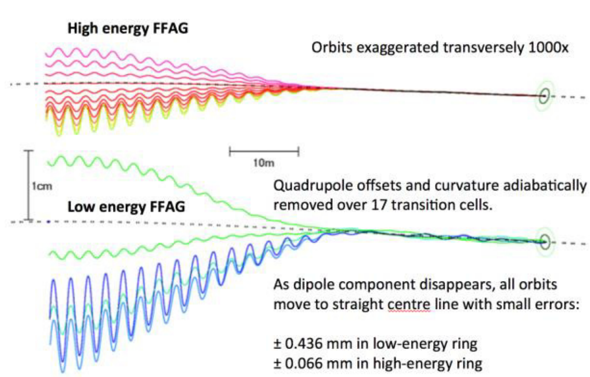

Figure 6: Straight section design for the eRHIC NS-FFAG beam lines.

The combined function magnets in the eRHIC FFAG arcs are made by misplaced permanent magnet quadrupoles. S. Brooks found a method to match the NS-FFAG arc cells with the straight sections by reducing the quadrupole offsets (dipole component) and bending angles in the cells adiabatically towards zero, while keeping all the gradients and beta functions constant. This “flexible FFAG” design also provided the basis for the detector by-pass (Fig. 7), where the NS-FFAG beam lines have to reroute around the existing detector areas in the tunnel, as only the highest energy is split off to collide with the hadrons.

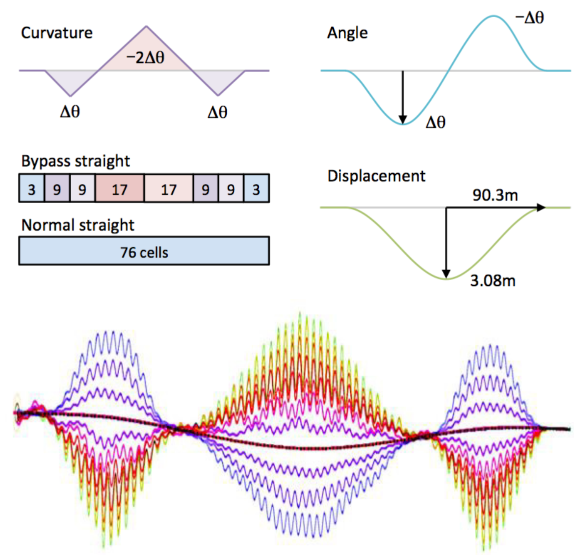

Figure 7: NS-FFAG by-pass design around the detectors.

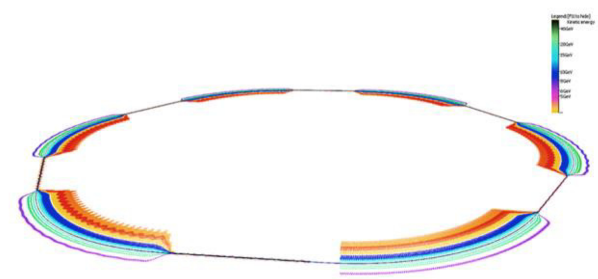

Figure 8: Electron beam trajectories for both NS-FFAGs around the whole RHIC tunnel (without by-passes) magnified transversely 5000×.

Figure 8 shows a Muon1 simulation of the whole ring containing both eRHIC FFAGs stacked on top of each other, for all electron energies.

CONCLUSION

The NS-FFAG concept has been very successfully combined for the first time with an ERL in the design of the new EIC at eRHIC, leading to large cost savings. As technologies such as 16-pass superconducting ERLs and FFAGs have not been deployed in collider-sized accelerators before, a technology demonstrator for ERL-FFAGs [7] is proposed to test all these features in combination at a smaller scale. This is anticipated to build experience and reduce the project risk greatly.

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