

## ACCELERATION OF ELECTRONS WITH THE RACETRACK NON-SCALING FFAG FOR e-RHIC\*

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### Abstract

The future relativistic electron hadron collider: e-RHIC requires acceleration of electrons to 10 GeV with a possible upgrade to 20 GeV. In the case that the superconducting linac is selected for acceleration, an energy recovery scheme is required. We propose to study a possibility of using the non-scaling Fixed-Field Gradient-Accelerator (NS-FFAG) for different energies. The beam will be accelerated by the superconducting linac at the top of the sine function, brought back to the front of the linac by the non-scaling FFAG and repeating this a few times until the total energy of 20 GeV is reached. After collisions the beam is brought back by the non-scaling FFAG and decelerated (on the lower RF phase) in the same sequence but in the reverse order. Conventional and non-conventional beam dynamic issues will be discussed, like the transit time matching effect and the time of flight adjustments.

### INTRODUCTION

A development of the NS-FFAG started from the very same problem in muon acceleration – a high cost of the superconducting linac. The NS-FFAG [1] is made of two kinds of combined function magnets with the fixed linear variation of the magnetic field along the transverse aperture. Two smaller opposite bends with the focusing gradient surround large major bending magnet. The most important property of the NS-FFAG is a small aperture requirement for the large energy acceptance. It comes from extreme focusing and a use of opposite bending. Small beam offsets in a large energy range are due to a very small dispersion function of few cm. In addition the amplitude functions are also small due to small magnet size. The e-RHIC will be an electron-hadron collider. The present e-RHIC proposal assumes the maximum electron energy of 10 GeV. If the energy recovery superconducting linac is selected for acceleration, this energy could be doubled in future with a larger linac and limited number of additional passes. This report is a study of possible use of the single NS-FFAG ring inside of the RHIC tunnel with ability to accept electrons with momentum (energy) range of  $\delta p/p = \pm 60\%$ . Five acceleration passes of electrons are presently assumed through the linac and the NS-FFAG ring, with the last one used for collisions. Reusing the cavities during acceleration reduces the cost of the superconducting Energy Recovery Linac (ERL). In addition, after the collisions, a removal of enormous power of very large energy electrons represents a very serious problem. This is eliminated by de-acceleration, using the lower crest of

the sine RF wave in the cavities. This report, on a first design of the NS-FFAG ring inside of the RHIC tunnel represents just a first step in exploring use of ERL in e-RHIC with possible cost reduction. The magnet properties and a lattice design of the NS-FFAG inside of existing RHIC tunnel are reported. This report contains only a NS-FFAG design through the RHIC tunnel. It is just the first step towards a complete solution with additional chicanes to allow time of flight adjustments and to avoid the interaction regions (IR) with large detectors. The lattice with momentum acceptance of  $\delta p/p = \pm 60\%$  in the RHIC tunnel represents an energy range between 5 to 20 GeV, or 2.5 to 10 GeV, or from 1 to 4 GeV. This could also be considered as a staging process where the superconducting linac could start with lower energies.

### RHIC GEOMETRY

Two RHIC superconducting rings accelerate protons and heavy ions up to the 250 GeV/u. Along the 3833.845 m circumference there are six  $\sim 313$  m long straight sections the six fold symmetry layout as presented in Fig.1. At the 6<sup>th</sup> and 8<sup>th</sup> o'clock two large detectors "STAR" and PHENIX" are placed. An additional detector at the 12 o'clock IR is being developed for the electron-proton/heavy ion collisions. Positions of the NS-FFAG magnets are selected to be between the existing cryostats of the present two superconducting ring. This is represented in Fig. 1 by the "magenta" ring a radius of  $R_1 = 380.4943$  m.

### Design Procedure

There are only two types of NS-FFAG arcs in the RHIC tunnel: the NS-FFAG arcs with smaller radius follow the six RHIC arcs in the existing tunnel. The NS-FFAG arcs with very large radius in the middle of the IR's are connected to the two neighboring NS-FFAG arcs. The smaller NS-FFAG arc has already defined radius  $R_1$  while its length is to be defined by an angle  $\alpha$  ( $L_{arc} = 2\alpha R_1$ ). The length of the larger radius  $R_2$  is defined from the crossing of as the line with  $R_1$  with the line connecting IR point to the center RHIC. Angle  $\alpha$  has to be smaller than  $\pi/6$  to allow this crossing to happen. A relationship between the angles as  $\alpha + \beta = \pi/6$  a consequence of the RHIC six fold symmetry and its way of the straight sections layout. The radius of the larger ring  $R_2$  is defined in equation (1). A procedure requires first designs of first two NS-FFAG rings: one with the smaller radius  $R_1$  and

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second ring with a very large radius  $R_2$ .

$$R_2 = R_1 \frac{\sin(5\pi/6)}{\sin \beta} \tag{1}$$

The number of cells in the two arcs has to fulfill the geometrical constraints and a relation:

$$N_1 L_{arc-cell} = 2\alpha R_1, \text{ and } N_2 L_{IR-cell} = 2\beta R_2 \tag{2}$$

A circumference of the first ring is  $C_1=2\pi R_1$ . If the total number of cells in the “arc” NS-FFAG ring is  $N_{arc}=648$  and in the IR ring  $N_{IR}=2232$  everything becomes very simple: the circumference of the “arc” ring is  $C_{arc}=2\pi R_1=648*L_{arccell}$ , while of the “IR” ring is  $C_{IR}=2\pi R_2=2232*L_{IR-cell}$ . The “arc” ring length cells is  $L_{arc-cell}=3.6894$  m. Number of cells in the arcs are  $N_1=81$  and  $N_2=93$ , for “arc” and “IR”, respectively. The relationships between the number of cells in the arcs ( $N_1, N_2$ ) with respect to the total number of cells in the rings ( $N_{arc}, N_{IR}$ ) are:  $N_1/N_{arc}=81/648=1/8=2\alpha/2\pi$  for the “arc” ring  $\alpha=\pi/8$ , while for the “IR” ring  $N_2/N_{IR}=93/2232=1/24=2\beta/2\pi$ , the angle  $\beta=\pi/24$ . Then the sum of two angles is  $\alpha+\beta=\pi/8+\pi/24=\pi/6$  and the first condition for the RHIC geometry is fulfilled.

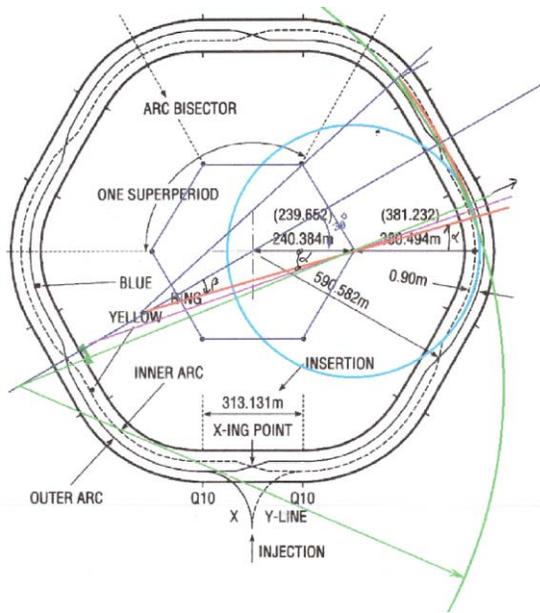


Figure 1: RHIC geometry with additional NS-FFAG arcs: one in the arc region presented by a part of the “magenta” circle and the other green colored within the IR region.

*NS-FFAG Lattice Design*

The lattice properties of the smaller radius NS-FFAG ring are described first: The magnets and the electron beam orbits at different energies in one repeatable cell are shown in the Fig. 2. The larger 1.2 meter long magnet, labeled as *BD*, is divided in the figure into two parts as shown at the left and the right end of the picture. The minimum of the orbit offsets are shown in the middle of this defocusing combined function magnet. The largest offsets are in the middle of the cell between the two

smaller 0.6 meter long opposite bend magnets with a focusing field labeled as *BF*.

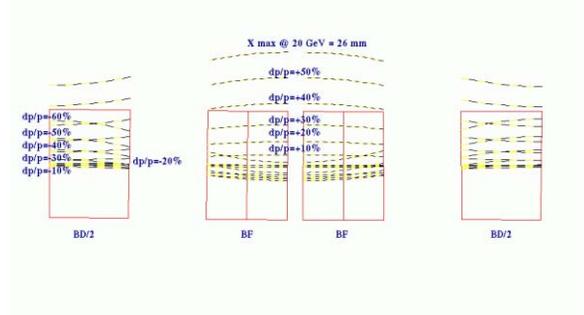


Figure 2: Magnets and orbit offsets in the “arc” cell.

The minima of the  $\beta_x$  and  $D_x$  dispersion functions in the NS-FFAG triplet lattice are at the middle of the larger defocusing magnet. The square root of the horizontal betatron function  $\beta_x^{1/2}$  dependence on energy together with magnets of the “arc” cell is presented in Fig. 3.

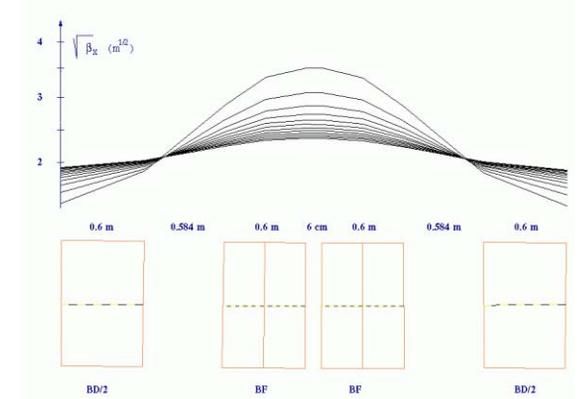


Figure 3: The horizontal betatron function in the “arc” cell.

Properties of the “IR” ring cells are shown next. The betatron  $\beta_x^{1/2}$  and the dispersion functions are shown in the Fig. 4.

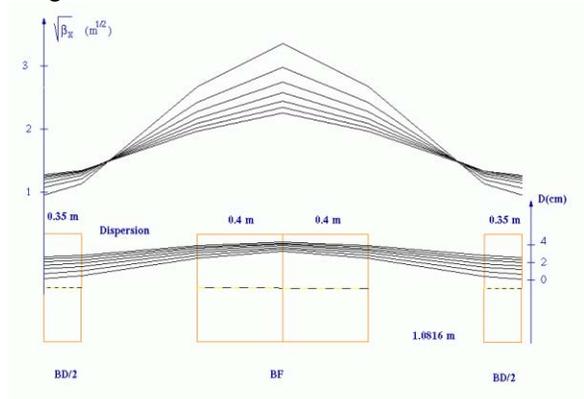


Figure 4: The horizontal betatron function and dispersion in the “IR” cell together with 0.7 m long *BD* and 0.4 m *BF*.

The betatron tunes dependence on momentum in “arc” and “IR” cells are shown in Fig. 5 and 6, correspondingly.

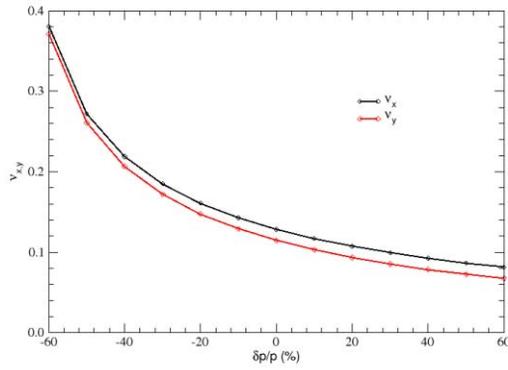


Figure 5: Betatron tunes versus momentum in the “arc” cell.

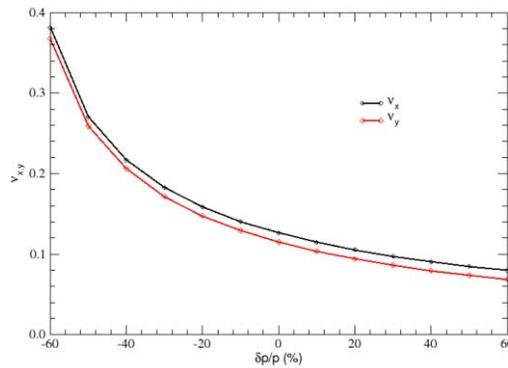


Figure 6: Betatron tunes versus momentum in the “IR” cell.

The six arcs are glued together at the point of minimum betatron and dispersion function as previously described [2]. The end of the row of each “arc” or “IR” cells is always the middle of the large bending magnet *BD*.

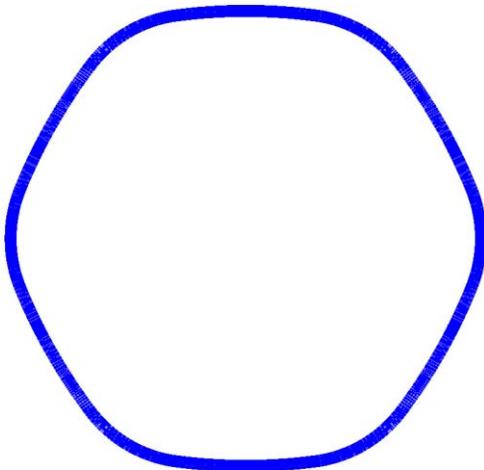


Figure 7: The NS-FFAG ring placed in the RHIC tunnel.

The whole NS-FFAG ring placed in the RHIC tunnel is shown in Fig. 7. The time of flights or the path lengths differences during acceleration is a very important parameter in the ERL. At energies close to 20 GeV the energy loss due to synchrotron radiation is large and

adjustments of the time of flight will be necessary. The NS-FFAG’s are not asynchronous and the path length dependence is a parabolic function on momentum. The path length dependence on momentum in the “IR” cell is shown in the Fig. 8. There are 6x93 IR cells in the ring.

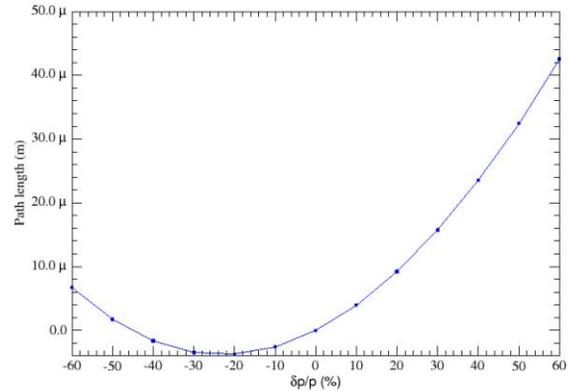


Figure 8: Path length dependence on momentum in the “IR” cell. (40μs corresponds to 0.133 ps ).

### Magnet Properties

The magnet sizes and magnetic fields are presented in Table 1.

Table 1: Magnet Specifications

Mag	L(m)	B <sub>0</sub> (T)	G (T/m)	A <sub>x</sub> (mm)	B <sub>max</sub> (T)
BD	1.2	0.937	-18.94	-0.1-+25	0.94-0.4
BF	0.6	-0.60	19.56	-0.4-33	-0.7-0.0
BD2	0.7	0.1677	-27.83	0.0-10	0.2—0.1
BF2	0.4	0.0001	25.1	-0.01-12	0.0-0.3

### SUMMARY

An attempt to design of the NS-FFAG inside of the present RHIC tunnels has been presented. The ring has an energy acceptance of  $\delta p/p = \pm 60\%$ . It was constructed from two different radii FFAG rings matched at the central energy and placed between the two existing superconducting “blue” and “yellow” RHIC rings. Stable orbits in the whole energy range were found. Betatron and dispersion functions of two rings are presented. Future work on designing matching chicanes for each energy pass for the time of flight adjustment and to avoid the large detector areas, as well as matching to the superconducting linac is necessary. Also, we would like to minimize the synchrotron radiation due to reverse bends making the orbit more flat at the top energy.

### REFERENCES

- [1] D. Trbojevic, E. Courant, and M. Blaskiewicz, Phys. Rev. ST Accelerator Beams 8, 050101 (2005).
- [2] D. Trbojevic, “Racetrack non-scaling FFAG for muon acceleration”, published in the proceedings of the EPAC06, Edinburgh, Scotland, June 2006, TUPLS025.