ELECTRON ACCELERATION FOR E-RHIC WITH NON-SCALING FFAG*

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Abstract

A *non-scaling* FFAG lattice design to accelerate electrons from 3.2 to 10 GeV is described. This is one of possible solutions for the future electron-ion collider (eRHIC) at Relativistic Heavy Ion Collier (RHIC) at Brookhaven National Laboratory (BNL). The e-RHIC proposal requires acceleration of the low emittance electrons up to energy of 10 GeV. To reduce a high cost of the full energy super-conducting linear accelerator an alternative approach with the FFAG is considered. The report describes the 1277 meters circumference *non-scaling* FFAG ring. The Courant-Snyder functions, orbit offsets, momentum compaction, and path length dependences on momentum during acceleration are presented.

INTRODUCTION

We introduced the idea of *non-scaling* FFAG at the Montauk [1] Muon Collider meeting 1999. The US neutrino collaboration accepted this concept and a design for the higher energy muon acceleration. We followed the basic idea of the *scaling* FFAG [2] with a combination of the previously known "minimum emittance lattice" concept for the electron storage rings [3]. Several disadvantages of the original FFAG design like large aperture requirements are reduced. The required aperture in the *non-scaling* FFAG is significantly smaller. The transverse magnetic field in the alternating gradient magnets is linear and particles with different momenta follow orbits oscillating around the ring. The average radius corresponds to the value of the momentum. The basic lattice cell consists of the two combined function elements: the large bending magnet with a defocusing gradient, and two smaller opposite bends, with focusing gradient, placed at both sides. There is a drift space large enough for the accelerating cavity between two focusing magnets. The principle of the *non-scaling* FFAG is based on the basic relation between the radial offset and dispersion function: $\Delta x = D_x\ \delta p/p$. The *non-scaling* design does not have zero chromaticity during acceleration. The tunes in the cell vary within a range $\nu_{x,y} \sim 0.4 - 0.1$.

FFAG LATTICE FOR E-RHIC ELECTRON ACCELERATION

A proposal for the Electron-Ion Collider, presented at this conference [4], assumes electron beam with energy of 10 GeV colliding with protons and heavy ions. The *non-scaling* FFAG represents a possibility of accelerating electrons up to 10 GeV preserving the low emittance and reducing the price of the linear accelerator.

The Courant-Snyder functions of the basic cell are presented in Figure 1. The functions are calculated for the central energy of E_o = 6.7 GeV. Electron acceleration is provided from energy of E_o=3.2 GeV up to E_{max}=10 GeV (or in the momentum range of from $\delta p/p$ = -52% to $\delta p/p$ = +50%):

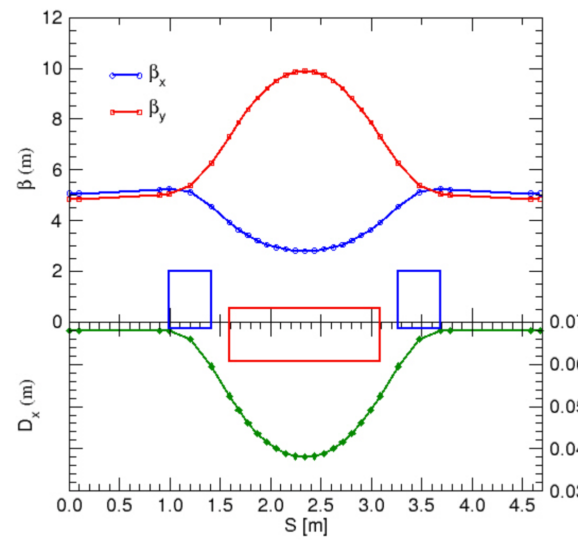

Figure 1. Betatron functions within two basic cells. Dispersion function D_x is presented in the lower part of the picture box.

The central, 1.5 meter long, magnet has a bending angle of θ=45.56 mrad, and it is a combined function magnet with a defocusing gradient of G_d =–11.7 *T/m*. The opposite bend is 0.42 meter long with the bending angle of θ=–11.27 *mrad*, with a focusing gradient of G_f = 23 *T/m*. The cell length is 4.678 m. The available drift length for the RF cavity is 2.335 m. There are 273 cells. The required aperture in a transverse direction depends on the orbit offsets during acceleration. The synchrotron radiation from electron depends on the value of the bending angle $(\rho = l/\theta)$. The bending angle of the major bend in this example is θ=0.045 *rad*. The bending radius is estimated as $\rho = l/\theta \sim 33$ m.

ORBITS, TUNES, AND PATH LENGTH DURING ACCELERATION

At the start of acceleration, the energy is equal to E_o =3.22 GeV, corresponding momentum offset from the central energy of 6.7 GeV is $\delta p/p$ = –52%. The maximum orbit offset at the beginning of acceleration, presented in figure 2, is equal to Δx = -15.5 mm. It is passing parallel to the central circular orbit through a drift space assigned to the cavity. As acceleration proceeds, the orbits move towards the central path. When the momentum offset becomes positive orbits move outside of the central path reaching the maximum value of Δx = +49.27 mm. The aperture of the beam pipe should be wider than ~70 mm. The magnetic field strength of the major bending magnet is B_p=0.679 T while the opposite bending field, of the 42 cm long combined function magnet, is B_{neg} = -0.6 T.

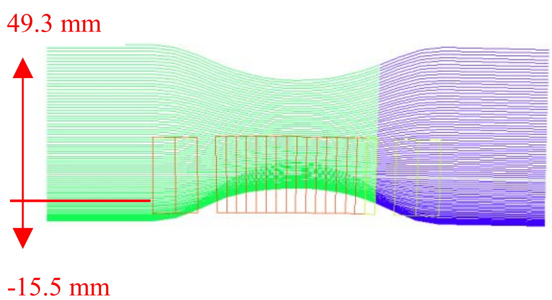

Figure 2. Particle orbits during acceleration. The magnets are presented by the red and yellow boxes.

Betatron Tunes during acceleration:

The betatron tunes in the *non-scaling* FFAG vary with energy, contrary to that of the scaling FFAG. It is important to avoid half and full integer tunes within the single cell because accelerating particles might be lost due to repetition of the same cells along the circumference path. The vertical and horizontal tune dependence on energy or momentum is presented in figure 3.

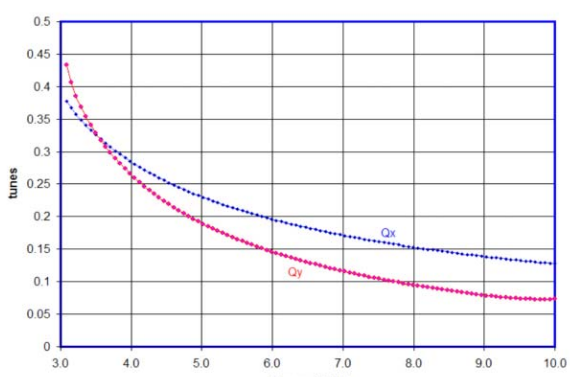

Figure 3. Betatron tunes per cell dependence on energy.

The Path Length dependence on energy:

The path length dependence on energy is very close to a parabolic function. At the lowest energy the momentum compaction α is a negative number (the transition energy γ_t is an imaginary number). During acceleration from a value of the momentum offset of $\delta p/p$ =–0.52 up to the central value, the absolute value of the transition energy gradually increases. The path length difference is equal to zero at the central momentum. The path length difference follows the parabolic function and reaches the maximum at the $\delta p/p$ = +0.52 of ΔL ~21.7 cm. This path dependence was used to simulate the longitudinal motion of the electrons during acceleration.

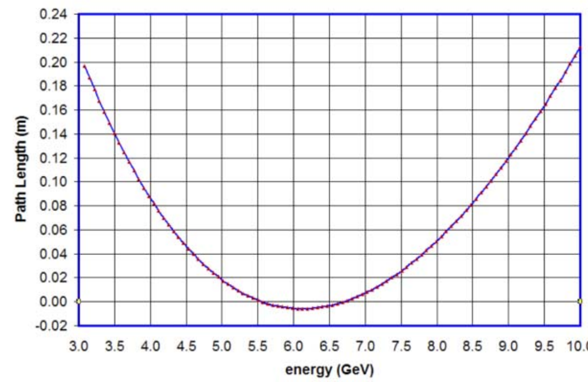

Figure 4. Path length dependence on momentum.

ACCELERATION

The major problem of applying the FFAG concept for the high electron energy acceleration is the loss of energy due to synchrotron radiation. Energy loss for a single electron per turn in the circular orbit is defined as:

$$\frac{\Delta E}{m_o c^2} = \frac{4\pi}{3}\left(\frac{r_o}{\rho_d}\right)\beta^3\,\gamma^4\,, \quad (1)$$

Where r_o is the classical electron radius, ρ_d is the bending dipole angle, and β and γ are the relativistic factors. The average radius of the 1/3 of the RHIC circumference is of the order of 200 m, but within the FFAG magnets electrons would be bend much harder even in the opposite way and the radius of curvature is much smaller. The energy loss of electron at the last turn, reaching the highest energy of 10 GeV, is calculated for this example to be 12.891 MeV. This energy needs to be compensated by the RF system. It is assumed that the cavity voltage in the *non-scaling* FFAG should be at least twice higher at the last turn (energy reaches the largest value equal to 10 GeV). This implies that the total required RF voltage is ~24 MV. If cavities to be used are similar to the RHIC storage cavities, were each reaches a voltage of 2 MV, then twelve cavities are necessary to fulfill the acceleration requirement. This also shows that from 3.2 up to 10 GeV there are required ~1500 turns. The parabolic dependence of the path length difference on momentum requires adjustment of the RF voltage in time. The 20 cm path length difference corresponds to a fractional frequency difference of $1.5e^{-4}$ or a quality factor of Q=6000 for no cavity tuning. This is a fairly small Q so we will need to tune the cavity. The synchrotron tune with 20 MV/turn with a 700 MHz cavity frequency is shown in Fig. 5.

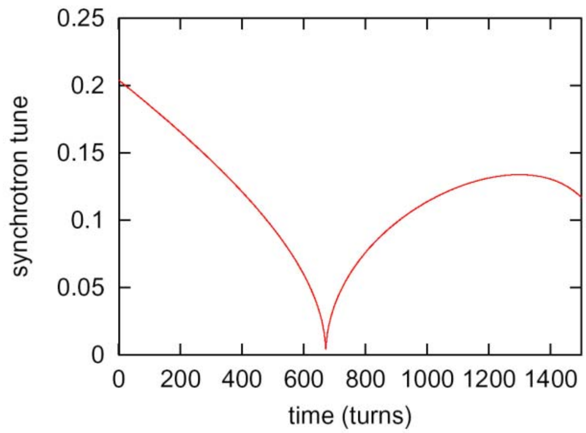

Figure 5. Synchrotron tunes versus time for 3-10 GeV electron acceleration with 20 MV/turn and 700 MHz cavity frequency.

The large tunes imply adiabaticity except near transition. Figure 8 shows the initial and final longitudinal phase space distributions for an initial (full) emittance of 1.e-3 eV-s per bunch.

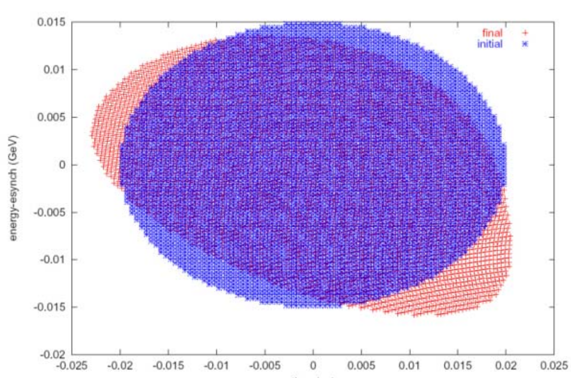

Figure 6. Initial (blue) and final (red) longitudinal phase space for 3-10 GeV acceleration with 20 MV/turn and 700 MHz cavity frequency.

The longitudinal emittance is preserved (growth is not larger than 5%) as presented in Figure 7.

SUMMARY

An initial proposal for the Electron ion collider at RHIC e-RHIC has already been documented [5]. A *non-scaling* Fixed Field Alternating Synchrotron FFAG has been considered as an option to accelerate electrons and reduce the cost of the super-conducting or warm long linear accelerator, preserving the electron beam low emittance and polarization.

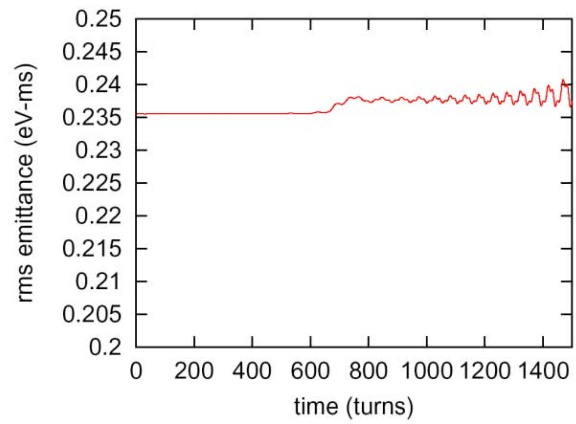

Figure 7. Longitudinal emittance during acceleration.

The polarization should be preserved due to a relatively short acceleration time and fast crossing through the resonances. A major problem in electron acceleration up to the energy of 10 GeV is the synchrotron radiation especially at the largest energies. Although the RF has to compensate the lost energy, a number of required cavities would be substantially lower with respect to the linear accelerator option. We have shown that the *non-scaling* FFAG represents a real possibility. Properties of the lattice and required size of the combined function magnets are presented. Orbit, tune, and path length dependence on momentum are presented, as well as the acceleration study.

REFERENCES

[1] D. Trbojevic, D. Courant, and A. Garren, "FFAG lattice without Opposite bends", Muon Colliders at 10 TeV and 100TeV HEMC '99 Workshop, Colliders and Collider Physics at the Highest Energies, Montauk, September 27-October 1, 1999, pp. 333-338, AIP Conference Proceedings, Volume 530, American Institute of Physics, Melville, New York (2000), Editor B. J. King.

[2] K. R. Symon, "The FFAG Synchrotron – MARK I", MURA-KRS-6, November 12, 1954, pp. 1-19.

[3] Trbojevic, D., Courant, E., Low emittance lattices for electron storage rings revisited, 4th European Particle Accelerator Conference, London, England, June 27-July 1, 1994, pp. 1000-1002.

[4] V. Ptitsyn et. all,'eRHIC Future Electron-Ion Collider at BNL', this conference.

[5] "eRHIC Zeroth Order Design Report", BNL C-AD Note 142, 2004. http://www.agsrhichome.bnl.gov/eRHIC/eRHIC_ZDR.htm