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SIMULATING FAST BEAM-ION INSTABILITY IN FFAG-BASED ERHIC RINGS*

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Abstract

Recirculating electron rings based on Fixed Field Alternating Gradient (FFAG) technique are capable of transporting multiple electron beams with different energies through a common beam pipe, leading to more compact and cost-effective electron accelerator designs. However, the very nature of simultaneously transporting multi-energy beams adds complexities in analysing collective effects in such machines.

In this work, we present our simulation studies of the fast beam-ion instability (FBII), which is caused by electrons resonantly interacting with ions generated from residue gas molecules, in FFAG-BASED eRHIC rings.

INTRODUCTION

In an electron transport line, high-energy electrons in the beam ionize residue gas molecules along their passages, leaving the positively charged ions in the vacuum chamber. Under unfavourable conditions, these residue gas ions can resonantly interact with the successive traversing electrons, causing the coherent oscillation amplitude of both the electrons and the ions to grow. This phenomenon, named 'fast beam-ion instability' (FBII), was predicted by T.O. Raubenheimer and F. Zimmermann in 1995 [1] and experimentally observed at Advanced Light Source (ALS) two years later [2]. Raubenheimer and Zimmermann gave an analytical treatment based on the assumption of linear coherent space charge force between a longitudinal slice of electrons and a slice of ions at the same longitudinal location. The analysis predicted a quasi-exponential growth of electrons' coherent oscillation amplitudes with longitudinal location as they travelling along the accelerator, which was confirmed by the simulation results presented in the same article. Since their simulation assumed the electron beam had Gaussian spatial density distribution in the transverse planes, the interactions between electrons and ions were non-linear and consequently the quasi-exponential growth saturated as the coherent oscillation amplitude approaching the R.M.S. width of the electron beam. The non-linear nature of the electrons' space charge field also introduces frequency spread in ions' oscillations, which can alleviate the FBII through ion de-coherence. The effects were later analysed by G.V. Stupakov et al.[3]. Their analytical results, together with confirmations from numerical simulations, showed that the instability growth rate was indeed reduced as a result of ion de-coherence. A following study by S.A. Heifets revealed that the amplitude of the beam centroid oscillation kept growing linearly after being saturated from the quasi-exponential growing regime [4].

In this contribution, we present our preliminary studies of FBII in the two FFAG rings of eRHIC by numerical simulations. The current design of a Linac-ring type electron ion collider (EIC), eRHIC, is based on Energy Recovery Linac (ERL) and Fixed Field Alternating Gradient (FFAG) rings. After being generated from the polarized electron source with 9.4 MHz repetition frequency and 12 MeV of initial energy, the bunched electron beam is injected into the 1.322 GeV ERL where it recirculates for 16 times through the 413 MHz Superconducting Radio Frequency (SRF) linac to obtain its top energy, 21.164 GeV[5]. The electron beam is then brought to collision and recirculates for another 16 times through the SRF linac to recycle its energy. The recirculating beam line consists of two FFAG rings, a low energy ring where electron beam recirculates 5 times on its accelerating passes to reach 7.944 GeV and a high-energy ring where it completes the rest of its accelerating passes to reach the top energy. Including all passes, the electron beam travels 21 times in the high-energy FFAG ring and 10 times in the low-energy FFAG ring. As electrons with different energies follow different trajectories, they are usually separated in the transverse planes. Depending on the transverse separation of their trajectories, ions generated by electrons with certain energy may interact with electrons with different energies, which make FBII in a FFAG ring more complicated than that in a traditional storage ring or linac.

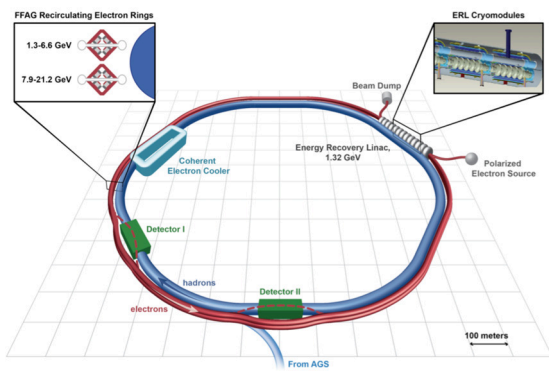

Figure 1: lay out of FFAG-based eRHIC design.

THE SIMULATION CODE

We start from the code FII, which was originally written to study FBII in the storage ring of Beijng Tau-

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Charm Factory (BTCF)[6]. FII is based on a weak-strong algorithm developed by Ohmi et al. [7]. In the simulation, ions are represented by a group of macro-particles while electron bunches are rigid with given transverse profile and only their centroids are tracked. The electron bunches creates and interacts with residue gas ions at multiple interaction points along the accelerator. TWISS functions at each interaction point and betatron phase advances between two adjacent interactions points are specified. The transverse profile of electron bunches is assumed to be Gaussian and hence Bassetti-Erskine formula is used to calculate the space-charge force perceived by each macro-ion [8]. Changes of the transverse momentum of an electron bunch are obtained by taking the opposite value of the summation of the transverse momentum kicks received by all macro-ions from the electron bunch.

In order to simulate FBII in FFAG rings, we modified the original code. We treat electron bunches from all energy passes as a single electron beam and calculate the bunch pattern for a given injection pattern. The bunch pattern has the same period as the injection pattern that we denote with T_{rev}. We propagate electron bunches from all energy passes with $t \le T_{rev}$ through all interaction points where they interact with existing macro-ions and create new macro-ions according to the vacuum pressure and ionization cross-section. The pre-specified Twiss functions and phase advances are used to bring electron bunches from one interaction point to the next point. Since electron bunches with different energies have different orbits and lattice functions, the designed orbits and lattice functions are specified for all energy passes at the interaction points.

After tracking for one period of the bunch pattern, T_{rev}, the pass number and longitudinal location of each electron bunch are updated, with one train of electron bunches dumped and one fresh train injected.

As electrons with different energies have different designed orbit, ions created by electron bunches from different energy usually have different initial transverse location. Depending on the bunch pattern, beam widths, and separations of designed orbits of electron bunches, ions may either stay around where they are created or move towards other regions.

Another modification of FII comes from the dependence of the ionization cross section on the electron's energy. To account for this effect, different scaling factors are assigned to macro-ions created by electrons from different energy passes, and consequently, the number of ions contained in one macro-ion is proportional to the ionization cross section, which is given by

$$\sigma_{ionization} = 4\pi\lambda_c^2\beta^2\left\{C + 2M^2(\ln\beta\gamma - \frac{1}{2})\right\},$$

where C and M are constants depending on ion species, and $\lambda_c \equiv \hbar/(m_e c)$ is the Compton wavelength of an electron. For the species considered here, CO, the coefficientsare $C = 35.1$ and $M = 3.7$.

As described in the previous section, multiple FFAG rings may be employed to fulfil the required energy passes of an ERL. In order to simulate FBII in such an accelerator, ions are grouped according to which FFAG ring they are created and, naturally, electrons and ions only interact when they are within the same ring.

SIMULATION RESULTS OF FBII IN ERHIC FFAG RINGS

As a preliminary study, we assume the beta function is 5 m in all ten interaction points [9] that are evenly distributed around the rings. We also assume that the designed orbits are the same in all interaction points. Table 2 lists parameters that we used in the simulation and the bunch pattern is shown in Fig. 2.

Table 1: Parameters Used In The Simulation

Electron bunch charge	1.9 nC
Electron rf frequency	413 MHz
Electron RMS emittance, norm.	20 μm
Beta function at interaction points	5 m
Electron repetition frequency	9.38 MHz
Residue gas species	CO
Residue gas pressure	1 nTorr
Ring temperature	273 K

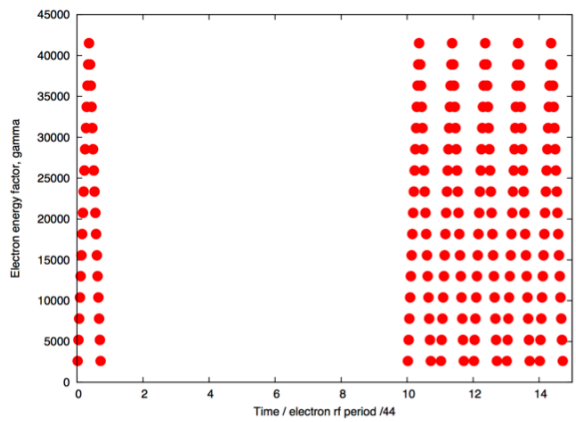

Figure 2: eRHIC bunch pattern as calculated internally from MFII code. The abscissa is the arriving time in unit of injection period, which is 44 buckets of the 413 MHz electron rf system, and the ordinate is the relativistic energy factor, γ, of the electron bunches.

Figure 3 shows the macro-ion distribution after 1 train of 111×31 bunches passed by the two FFAG rings, i.e. one RHIC revolution period. Figure 4 shows the offsets of electron bunches with respect to their designed orbit as they passing by the last interaction point. As shown in Fig. 4, whilst the coherent beam-ion instability is completely suppressed by introducing clearing gaps of 950 ns into the bunch pattern (green), without ion clearing gaps (red), the coherent oscillation of electron bunch centroid grows to ~3.5% of the R.M.S. beam width in 1.6 ms.

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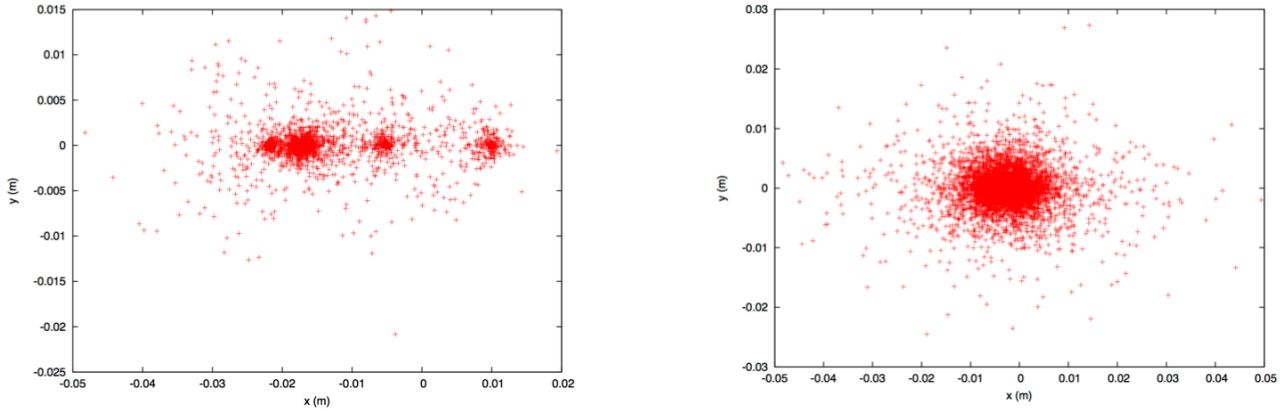
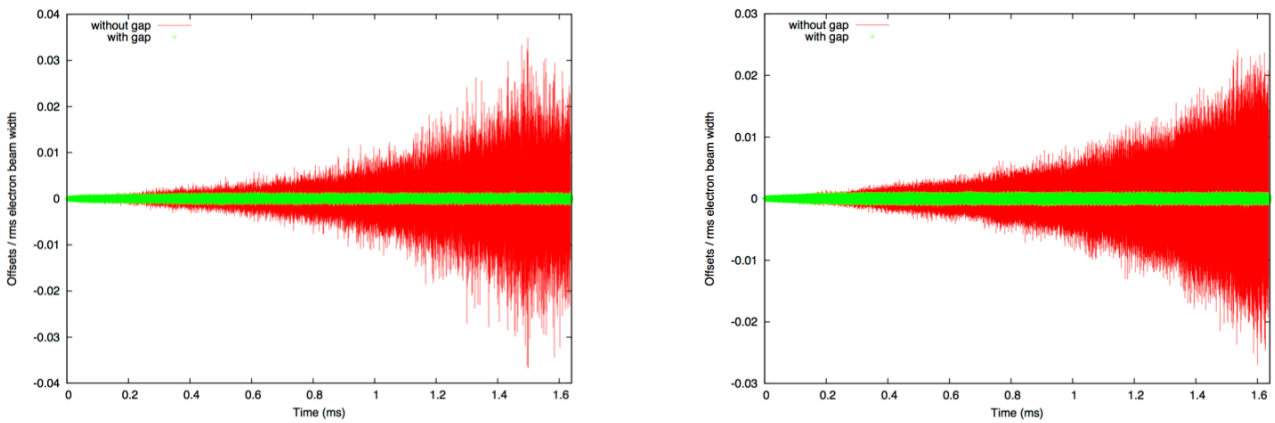


(a) (b)

Figure 3: macro-ion distribution at the last interaction point. (a) macro-ions in the low-energy ring; (b) macro-ions in the high-energy ring. From lowest energy to top energy, the designed orbits are at -2.2 cm, -1.8 cm, -1.6 cm, -0.5 cm, 1cm, -0.75 cm, -0.7 cm, -0.6 cm, -0.5 cm, -0.4 cm, -0.3 cm, -0.1 cm, 0 cm, 0.1 cm, 0.3 cm and 0.5 cm, where the first five orbits are in the low-energy ring and the rest passes are in the high-energy ring. The snapshot is taken after 1 train of 111×31 bunches passes through the FFAG rings.



(a) (b)

Figure 4: simulation results of FBII in two eRHIC FFAG rings with 31 passes. The abscissa is time in unit of millisecond and the ordinate is the offset of electron bunches, observed at the last interaction point. The red data show the bunch offsets when there is no gaps between bunch trains and the green data points show the offsets when gaps of 950 ns are introduced. (a) bunch offsets in the low-energy FFAG ring; (b) bunch offsets in the high-energy FFAG ring.

SUMMARY

As shown in the previous section, our preliminary simulation results of FBII in eRHIC FFAG rings suggests that the ion clearing gap of 950 ns in the present eRHIC design is adequate in suppressing the fast beam-ion instability. It is also observed from the simulation that, without the clearing gaps, the coherent oscillation amplitude of electron beam persistently grows to 3.5% of their R.M.S. beam width in 1.6 ms.

The simulation presented here assumes identical beta function and designed orbits in all interaction points. However, it is straightforward to set realistic lattice functions once the lattice design is stabilized.

More realistic estimation of the vacuum level and the content of the residue gases are required to improve the simulation. One limitation of our simulation code is that it only deals with a single species of residue gases. If the residue gas is not dominated by one major heavy species, the code needs to be further extended.

Another limitation comes from the weak-strong approach of our simulation. In reality, both the electron beam size and shape evolve with time due to beam-ion interaction, which, in turn, may lead to high-order instabilities as well as substantial changes in the growth rate of the dipole-mode instabilities. In such cases, a more sophisticated, and likely computing resource demanding, simulation code is needed for more accurate FBII analysis.

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