COMPUTER SIMULATIONS OF THE BEAM DYNAMICS IN THE SMALL ISOCHRONOUS RING

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Abstract

A Small Isochronous Ring (SIR), whose main objective is the experimental study of the space charge effects in the isochronous regime, is under development at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU). To study the beam dynamics in the ring we tracked particle trajectories in a realistic magnetic field generated by Tosca. The single-particle tracking shows that the horizontal and vertical dynamic apertures of the ring are 7 cm and 5 cm respectively at the injection energy. With the inclusion of an energy spread of ±4.4%, the dynamic aperture is still greater than 5 cm. To simulate the multi-particle beam dynamics in the ring, we have developed a three-dimensional PIC code that accurately calculates particle trajectories in a specified magnetic field. A field solver based on Fast Fourier Transformations calculates the space charge field of the beam. Multi-particle simulations show that the energy spread within a bunch circulating in the ring grows from 0 to ±4.4% in 15 turns. In addition, the bunch breaks into a set of small round clusters. Detailed investigation reveals that particles within each cluster are involved in a vortex motion induced by the space charge force.

1 INTRODUCTION

The SIR lattice, shown in Figure 1, consists of four dipole magnets that are specifically designed to accommodate the beam with a large energy spread. Facets provided on both sides of the 19 cm wide pole tips increase the flat field region to ±5 cm. Both entrance and exit pole faces of each dipole are rotated 26°. The edge focusing provides both vertical focusing and isochronism in the ring. More details on the design of the dipole magnets and the rest of the ring can be found in [1], [2]. In this paper we report results of simulation of the beam dynamics in SIR. Section 2 presents results of single-particle tracking. Section 3 presents an example of high-intensity, multi-particle phenomena in SIR.

2 SINGLE-PARTICLE DYNAMICS

2.1 The optical functions, bare tunes, and isochronism in SIR

We have used the code Genspeo [3] developed at NSCL to calculate the optical functions, bare tunes, and isochronism in SIR. The magnetic field, which was also used for all other simulations presented in this paper, was generated by Tosca [4] and had the maximum value of 640.0 Gauss in the dipoles. This field level was an arbitrary choice and can be changed to any other value with the only limitation that the the beam energy should be below 30 keV. The maximum beam energy is limited by the design of the ion-source setup.

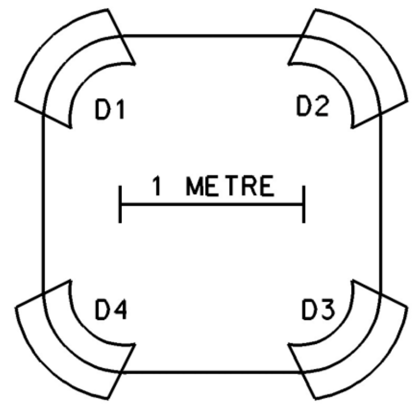

Figure 1: Bare SIR lattice, shown without steering, inflector and deflector plates.

Figure 2 shows the optical functions for a deuteron beam with a kinetic energy of 22.8 keV. Bare tunes vs. beam energy are presented in Figure 3. The bare betatron tunes ν_x and ν_y of the 22.8 keV, mono-energetic deuteron beam are 1.143 and 1.111 respectively. According to multi-particle

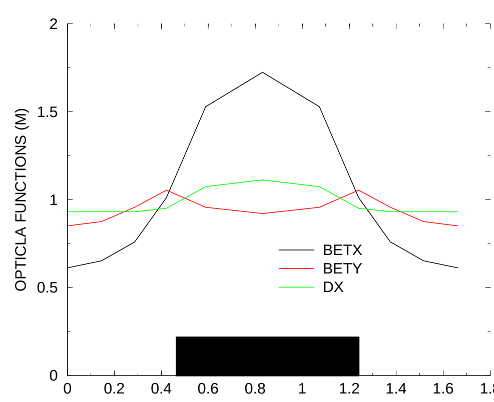

Figure 2: The optical functions for a single period of SIR vs. distance. The solid rectangle schematically shows one of the 90° dipole magnets.

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simulations the energy spread within the injected beam quickly grows up to ±1.0 keV. This causes the vertical and radial tune spreads to grow up to ±0.015 and ±0.01 respectively. Although the use of sextupoles in the ring reduces the tune spread related to the energy spread, we are planning no sextupole correction at the current stage of the project.

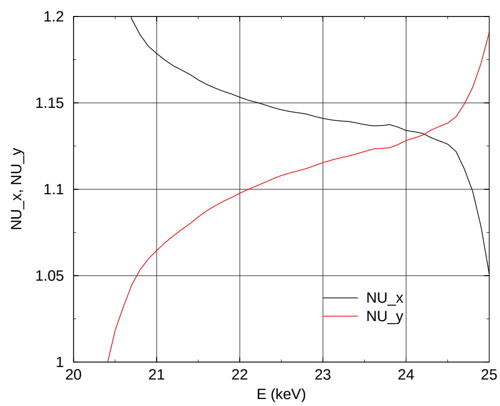

Figure 3: Bare tunes vs. energy.

Figure 4 shows the particle longitudinal lag per turn behind a reference ion of the kinetic energy of 22.8 keV vs. particle energy. As follows from the picture, the ring is almost ideally isochronous within the 22.8 ± 0.5 keV (±2.2%) range. Particles whose energy deviates by ±1.0 keV (±4.4%) will lag behind the reference particle with the rate of approximately 1.5 mm/turn. It is worth noting that the edge field effect has a big impact on the shape of the lag curve. The edge magnetic field extends farther out at the center of the pole tip than at the sides, closer to the return yoke. Thus, the field integral differs for particles entering a dipole magnet at different radii.

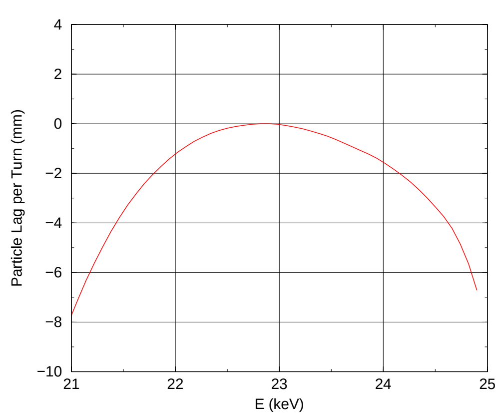

Figure 4: Particle lag per turn behind a reference particle vs. energy. The kinetic energy of the reference particle is 22.8 keV.

2.2 Dynamic aperture

To estimate the size of the dynamic aperture in SIR we have developed a code that calculates trajectories of ions in a realistic 3D magnetic field map generated by Tosca. The code uses the classical 4^{th} order Runge-Kutta integration method. The number of turns was pre-set to 1023. This number of turns exceeds the expected beam lifetime, which is determined by the residual gas pressure, by a factor of 10. (To find out more about vacuum and beam lifetime in SIR, see [1]).

Figure 5 shows the X-X' phase space plot at the mid-point of a drift between two dipoles. As follows from the picture, deuterons with the kinetic energy of 22.8 keV are stable inside of a phase space area of the size of 35x55 π·mm·mrad. The size of the stable region for particles with an energy deviation of ±1.0 keV (±4.4%) is still larger than 26x40 π·mm·mrad.

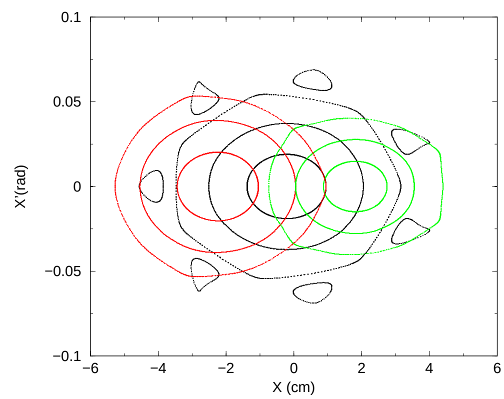

Figure 5: X-X' phase space plot at the mid-point of a drift between magnets. Different colors correspond to different particle energies: red to 21.8 keV, black to 22.8 keV, and green to 23.8 keV.

Figure 6 shows the Y-Y' (vertical) phase space plot at the mid-point between the magnets. The size of the stable Y-Y' region almost does not depend on energy and is approximately equal to 24x29 π·mm·mrad.

Both the radial and vertical stable regions are big enough to easily accommodate the beam from our ion source, which has the emittance of less than 50 π·mm·mrad. (To find out more about the ion source and the beam emittance measurement system, see [1], [2]).

3 HIGH-INTENSITY PHENOMENA IN SIR

Estimation of the beam current limit imposed by the transverse space charge effect was presented before in [5]. We have also presented results of simulations of multi-particle beam dynamics in SIR in the same paper. The program we have developed for those simulations used transfer matrices to calculate particle trajectories and included the effect of the space charge force as an integrated kick at the

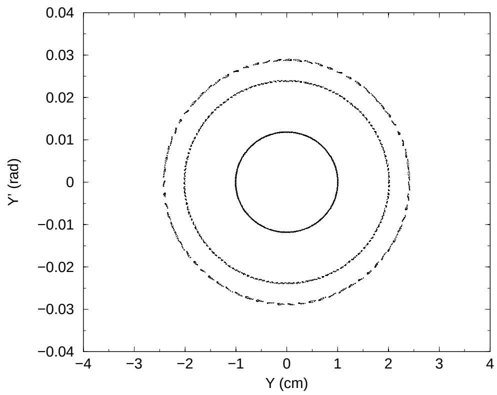

Figure 6: Y-Y' phase space plot at the mid-point of a drift between magnets.

end of each step. As followed from the paper [5] the longitudinal space charge effect was strongly pronounced at beam currents well below the limit imposed by the transverse space charge effect.

To improve accuracy and credibility of space charge simulations we have developed a new 3D Particle-in-Cell code. The code calculates particle trajectories in a realistic 3D field generated by Tosca, solving a full, unsimplified system of six equations of motion of an ion in a 3D electro-magnetic field. The code uses the classical 4^{th} order Runge-Kutta integration method to numerically solve the system. The space charge field of the beam is calculated by a fast field solver developed by the authors. The solver is based on the Fast Fourier Transformation technique described in [6].

Figure 7 shows simulated dynamics of a 22.8 keV, 16 μA deuteron bunch in SIR. As follows from the figure the vortex motion causes the bunch to break into a set of small round clusters. Detailed investigation reveals that particles within each cluster are involved in the vortex motion around the cluster center. The energy spread within the bunch as a function of the turn number is shown in picture 8. The result is in good qualitative and quantitative agreement with the result presented in [5]. Regardless the dramatic change of the energy spread and the shape the beam stays well confined and no particle loss is observed.

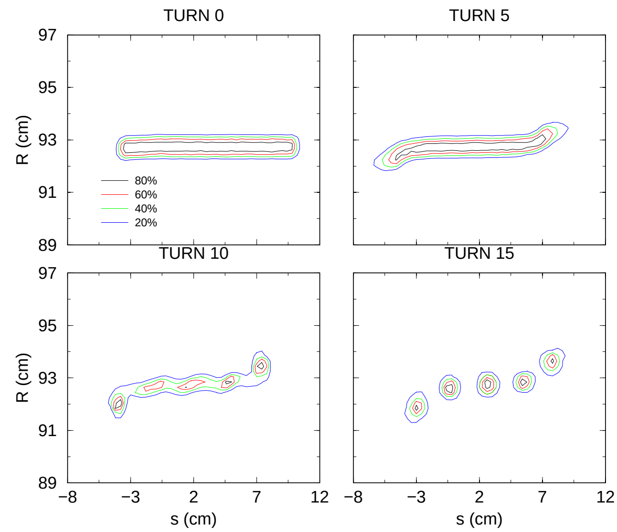

Figure 7: Median-plane charge density contour plot of the 22.8 keV, 16 μA deuteron bunch in SIR after 0 (initial distribution), 5, 10, and 15 turns.

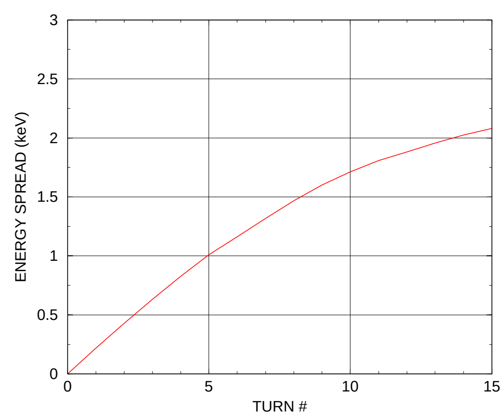

Figure 8: Energy spread with the bunch as a function of the turn number.

4 ACKNOWLEDGMENT

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