A SMALL ISOCHRONOUS RING FOR EXPERIMENTAL STUDY OF THE LONGITUDINAL SPACE CHARGE EFFECT IN ISOCHRONOUS CYCLOTRONS

Eduard Pozdeyev, NSCL, MSU, East Lansing, USA *

Abstract

We intend to build a small, low-cost, low-energy isochronous ring for experimental study of the space charge effect in isochronous cyclotrons and synchrotrons at the transition gamma. The paper describes the main physics issues to be addressed by the ring and the ring design. It also presents results of beam dynamics simulations in the ring.

1 INTRODUCTION

The longitudinal-radial space charge effect is the main cause of current limitation in high intensity isochronous cyclotrons. The space charge force increases the energy spread within beam bunches and tends to destroy turn separation. This leads to beam losses and extraction deflector overheating and activation.

There is very little theoretical and experimental knowledge of high-intensity beam dynamics in isochronous accelerators. To study the space charge in the isochronous regime experimentally we intend to build a low-cost, low-field, low-energy isochronous ring. This ring is a small-scale experiment that requires low beam intensities to simulate dynamics of intense ion beams in large scale accelerators. The important issues to be addressed by the ring are the space charge induced vortex motion specific to the isochronous regime, formation of the self-consistent, stable charge distribution by short bunches, the longitudinal break-up of long bunches, formation of weak beam tails and the beam halo. Besides direct experimental study of the space charge effect the ring will be used for validation of multi-particle codes that are/will be used for simulation of the space charge effect.

This paper describes the proposed Small Isochronous Ring (SIR). Section 2 outlines the ring design. Section 3 concentrates on single-particle dynamics in SIR. High-intensity phenomena in the ring are described in Section 4.

2 DESIGN OF THE RING

The requirement of low cost of the project has determined the choice of beam parameters: a low energy H_2^+ or H^+ beam. The low beam energy and the high rest mass of the ions give a low particle velocity. Because the space charge effect scales as $1/\beta^3$ [1], the beam of low intensity is required for the experiment. Besides, the low particle velocity relieves timing requirements on the diagnostics and on the injection-extraction system.

The low beam energy allows us to use low-field, simple-design magnets. Simulations show that the field in the magnets should be at the level of 1000 Gauss to avoid severe problems from stray fields.

Figure 1 shows the perspective view of SIR. Table 1 gives the main parameters of the ring. A 20 keV, 25 μA_{peak}, 100-1000 nsec H^+ or H_2^+ beam is injected into SIR by means of a fast pulsed electrostatic inflector. The voltage on the inflector is regulated by a fast semiconductor switch. The output of the switch is matched to the capacitive load of the inflector. The ring itself consists of four 90° flat-field magnets with the edge focusing. The edge focusing provides both the vertical focusing and the isochronism in the ring. The extraction system, which is similar to the injection one, sends the beam to a diagnostics station, which consists of a beam size meter and a fast coaxial Faraday Cup. The longitudinal beam profile of the beam is measured by the Faraday Cup with time resolution 1 ns that corresponds to spatial resolution 1.5 mm for H_2^+ and 2 mm for H^+.

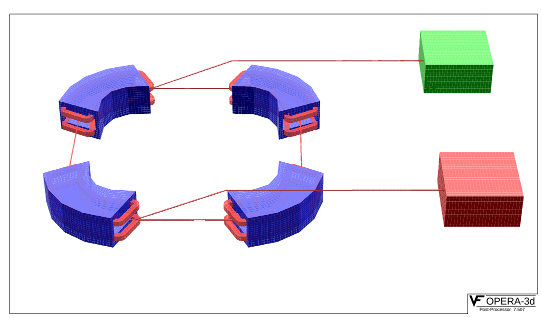

Figure 1: A schematic perspective view of SIR with the ion source and the external diagnostics. Injection and extraction electrodes, as well as steering electrodes in the ring, are not shown. The size of the ring without the source and the diagnostics is 1.5 x 1.5 m

3 SINGLE-PARTICLE DYNAMICS

The ring is isochronous within the hard-edge approximation and the low energy limit if

$$\tan(\alpha) = \frac{L/2}{L/2 + R} \quad (1)$$

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Table 1: Main beam and machine parameters

Particles	H_2^+ or H^+
Energy	20 keV
Peak beam current	50 μA
Magnetic field	1000 Gauss
Injection-extraction	Pulsed electrostatic kickers, $\tau = 30$ nsec
Diagnostics	Fast coaxial Faraday cup, $\tau = 1$ nsec
Circumference	4.68 m
Total weight	400 kg
Total power	4 kW

where α is the magnet edge angle, R is the radius of the magnets, and L is the distance between the magnets. A ratio of L and R with the edge angle given by (1) determines the betatron tunes ν_x and ν_y. We have chosen R equal to 35 cm and L equal to 62 cm. This choice gives the betatron tunes ν_x and ν_y equal to 1.14 and 1.17 respectively with the edge angle α equal to $25.1°$. Figure 2 shows the optical functions for a single period of the ring calculated by DIMAD [2] vs. distance.

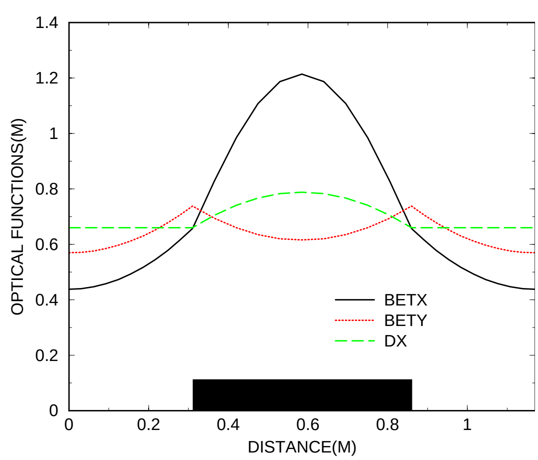

Figure 2: The optical functions for a single period of the ring vs. distance.

4 HIGH-INTENSITY PHENOMENA IN SIR

4.1 *Transverse space charge effect in a KV beam*

The equations for the beam envelopes X(s) and Y(s) are given by the formulas [1]:

$$X'' + k_{x0}X - \frac{2K}{X+Y} - \frac{\epsilon_x^2}{X^3} = 0 \qquad (2)$$

$$Y'' + k_{y0}Y - \frac{2K}{X+Y} - \frac{\epsilon_y^2}{Y^3} = 0 \qquad (3)$$

where k_{x0} and k_{y0} are the periodic external focusing functions and K is the generalized perveance. A numerical solution of the system (2-3) for a 20 keV 50 π·mm·mrad H_2^+ beam is shown in Figure 3. The figure shows the beam envelopes for peak beam currents 0, 40 μA, and 80 μA. Table 2 shows the betatron tunes as a function of peak beam current.

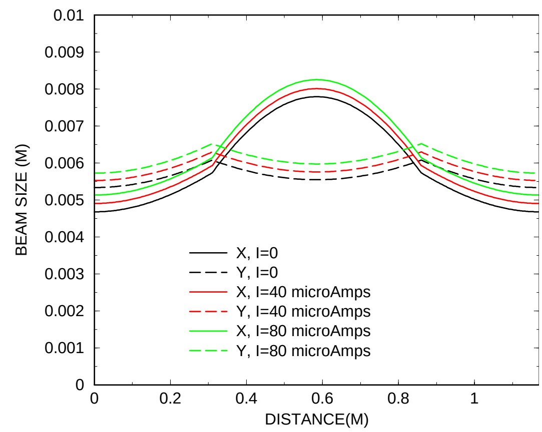

Figure 3: The beam envelopes X and Y vs. distance for peak beam currents 0, 40 μA, and 80 μA.

Table 2: The betatron tunes as a function of peak beam current.

I(μA)	ν_x	ν_y	**I(μA)**	ν_x	ν_y
0.0	1.142	1.169	**50.0**	1.037	1.069
10.0	1.120	1.149	**60.0**	1.017	1.050
20.0	1.099	1.128	**70.0**	0.998	1.032
30.0	1.078	1.108	**80.0**	0.979	1.013
40.0	1.057	1.088			

The linearized equations for oscillations of the mismatched beam envelopes are [1]

$$\xi'' + a_1(s)\xi + a_0(s)\eta = 0 \qquad (4)$$

$$\eta'' + a_2(s)\eta + a_0(s)\xi = 0 \qquad (5)$$

where ξ and η are small deviations from the matched beam envelopes X and Y. a_0, a_1, and a_2 are periodic coefficients that depend on the external focusing, beam current, and X and Y. The system (4-5) can be unstable in case of SIR because the betatron phase advance per a period of the ring is larger than $90°$. The stability analysis of the system (4-5) is mathematically identical to stability analysis of the betatron motion in a periodic beam line with the linear coupling. Numerical integration of four characteristic functions with initial conditions $(\xi, \xi', \eta, \eta')_{1,2,3,4}$= (1,0,0,0),(0,1,0,0),(0,0,1,0),(0,0,0,1) yields the matrix of the transformation described by (4-5). Figure 4 shows the absolute value of the four matrix eigen values vs. peak beam current for the 20 keV 50 π·mm·mrad H_2^+ beam. As follows from the figure the oscillations of the mismatched beam are stable ($|\lambda_{1,2,3,4}| = 1$) if peak beam current does not exceed 90 μA. This current limit is approximately four times higher than the current required for the experiment.

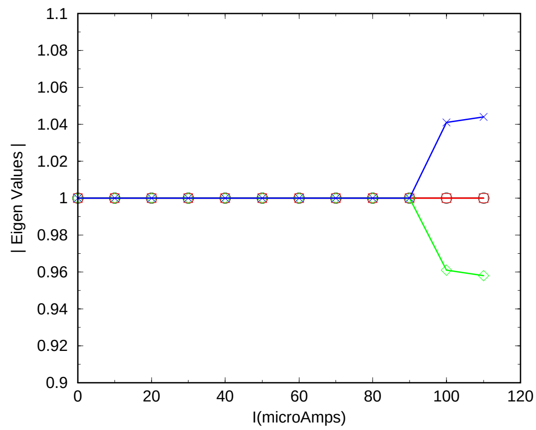

Figure 4: The absolute value of the four eigen values of the mismatched beam envelope oscillations vs. peak beam current. The oscillations are stable if the current is below 100 μA

4.2 3D simulation of the space charge effect in SIR

A 3D Particle-In-Cell code was developed to simulate the space charge phenomena in SIR. The code calculates particle trajectories in the ring elements using transfer matrices and includes the effect of the space charge force as an integrated kick at the end of every integration step. The field of the beam is calculated by a fast field solver developed specifically for the code and based on Fast Fourier Transformations.

The longitudinal-radial space charge force induces a vortex motion within beam bunches [3]. The vortex motion deforms a short bunch into a single round self-consistent distribution which changes little after it has formed. Longer bunches show more complicated behavior. Figure 5 shows simulated dynamics of a 20 keV, 25 μA H_2^+ bunch in SIR. The bunch initially had an almost rectangular longitudinal distribution with the length of 10.5 cm. As follows from the figure the vortex motion cases the edges of the bunch to bend. As beam continues circulating in the ring the disturbance propagates into the bunch, and the bunch breaks into small round clusters. Particles within each cluster are involved in the vortex motion around the cluster center. Figure 6 shows the longitudinal charge density profile of the beam after 0 (initial distribution), 5, 10, and 15 turns.

5 ACKNOWLEDGMENT

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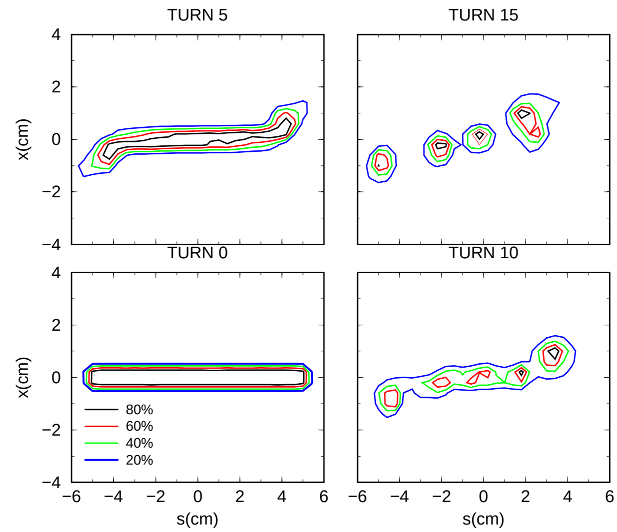

Figure 5: Median-plane charge density contour plot of the 20 keV, 25 μA H_2^+ bunch in SIR after 0 (initial distribution), 5, 10, and 15 turns.

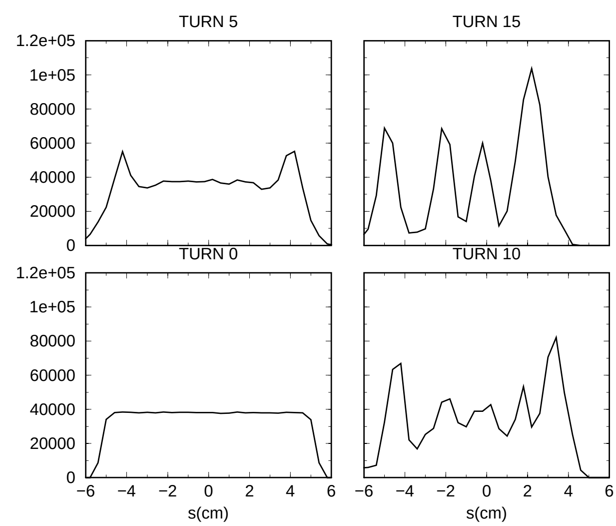

Figure 6: The longitudinal charge density profile of the 20 keV, 25 μA H_2^+ bunch in SIR after 0 (initial distribution), 5, 10, and 15 turns. The charge density is in arbitrary units.

6 REFERENCES

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