EXPERIMENTAL RESULTS OF THE SMALL ISOCHRONOUS RING*

J. Rodriguez†, F. Marti, R. York, NSCL, Michigan State University, Michigan, USA
E. Pozdeyev†, Jefferson Lab, Newport News, Virginia, USA

Abstract

The Small Isochronous Ring (SIR) has been in operation since December 2003. The main purpose of this ring, developed and built at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU), is to simulate the dynamics of intense beams in large accelerators. To observe the same effects, the beam power needed in SIR is orders of magnitude lower and the time scale is much longer than in the full scale machines. These differences simplify the design and operation of the accelerator. The ring measurements can be used to validate the results of space charge codes. After a variable number of turns, the injected hydrogen bunch (with energies up to 30 keV) is extracted and its longitudinal profile is measured using a fast Faraday cup. We present a summary of the design, the results of the first six months of operation and the comparison with selected space charge codes.

INTRODUCTION

Validation of multi-particle space charge computer codes is difficult in existing large scale accelerators. Time resolution requirements combined with high beam power make diagnostics for this kind of experiments complicated and expensive. A shortage of time available for beam studies farther complicates the problem.

SIR has been designed and built to model space charge effects in large scale cyclotrons and synchrotrons at the transition gamma. The ring simulates a small portion of an isochronous cyclotron. 1 mm accuracy of longitudinal profile measurements can be achieved using low energy proton beams and simple and inexpensive diagnostics.

The ring also provides a unique opportunity to study experimentally the beam dynamics in space charge regimes that cannot be achieved in existing machines. A beam current of only 30 μA is required to simulate the beam dynamics of a 3 mA beam in the PSI Injector 2 cyclotron (50% higher that the maximum achieved so far).

Table 1: SIR parameters

Particles	H_2^+
Energy	15-30 keV
Peak beam current	0-20 μA
Compaction factor, α_p	1.0 ± 0.05
Bare tunes	ν_x=1.14, ν_y=1.1
Laslett tune shift (20 μA)	0.05
Circumference	6.58 m
Lap time (20 keV, H_2^+)	5 μsec
Number of turns	100

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† rodriguez@nscl.msu.edu, pozdeyev@jlab.org

DESIGN OF SIR

SIR consists of four 90°, flat-field magnets with edge focusing that provides both the vertical focusing and the isochronism in the ring. The main parameters of SIR are listed in Table 1.

H_2^+ beam is produced by a multi-cusp ion source that can be biased up to 30 kV. An analyzing magnet, located under the ion source, is used to separate charge-to-mass states and to steer the beam towards the ring. The selected beam is chopped by a chopper and matched to the ring by a triplet of electrostatic quadrupoles in the injection line. The bunch length can be changed from 10 cm to 5-6 m. The beam is injected into the ring using a fast pulsed electrostatic inflector.

After a variable number of turns, the bunch is deflected from the median plane and sent towards either a coaxial fast Faraday Cup (FFC) located below the median plane or a phosphor screen above the median plane. The phosphor screen is used to observe the transverse beam profile of the extracted beam. The FFC measures the longitudinal beam profile of the beam with a time resolution of 1 ns corresponding to a spatial resolution of 1.4 mm for 20 keV H_2^+. Using this diagnostics, we can take "snapshots" of the transverse and longitudinal beam profiles after a different number of turns.

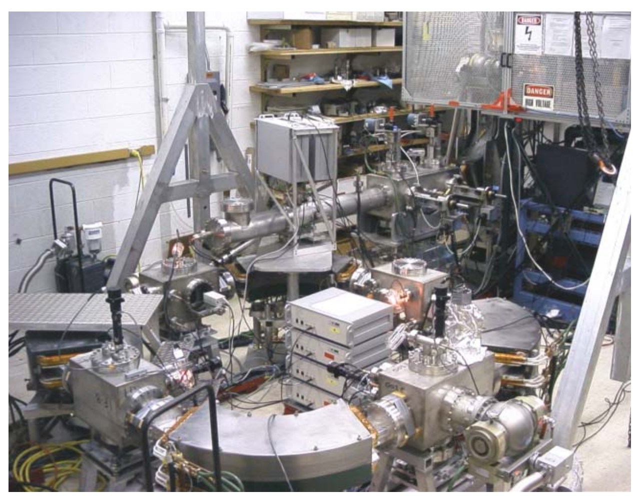

Figure 1: Picture of SIR (11/02/03).

Construction of the ring began in summer of 2001. Assembly of the vacuum chamber and other major components of the ring was finished in October of 2003.

Refer to [1], [2], [3] and [4] for additional details on the project. Results of simulations of the beam dynamics in the injection line and in the ring can be found in [5] and [6] respectively. Details about the electronics and the control system are described in [7] and the different diagnostic elements are described in [8].

SIMULATIONS

Computer simulations have been performed with a particle in cell code developed at the NSCL called CYCO. Refer to [1] and [6] for details.

Figure 2 shows top views of a 20 keV H_2^+ bunch extracted after a variable number of turns. The length of the bunch is 22cm and the peak current is 7 μA. Several features have been observed in this and other simulations:

- Due to space charge effects, particles in the head of the bunch gain energy (i.e. radius increases) and particles in the tail lose energy yielding to an apparent growth of the transverse size of the beam.
- After a number of turns the beam breaks up into clusters. Simulations show that the higher the peak beam current is, the faster this break up occurs. On the other hand the break up process seems to be independent of the length of the initial bunch.
- After the initial break up, clusters tend to collapse with each other. The number of clusters per unit length reaches an asymptotic value. CYCO includes metallic boundary conditions to simulate the vacuum chamber. The asymptotic value is reached when the distance between clusters is comparable to the size of the chamber (i.e. clusters are shielded from each other).
- High sensitivity to initial ensemble. Relatively small changes in the initial distributions of ions yield to slightly different cluster patterns.

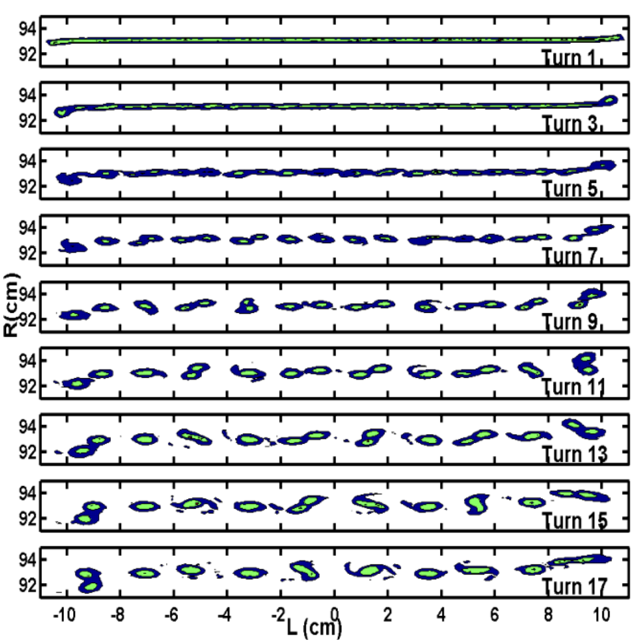

Figure 2: Top view of a 20 keV H_2^+ bunch extracted after a variable number of turns. Peak current is 7μA and length is 22cm. Simulation performed with CYCO.

FIRST EXPERIMENTAL RESULTS

After the vacuum chamber of the ring was assembled and pumped down to 10^{-8} Torr, the H_2^+ beam was injected in the ring. The betatron tunes were measured by means of observation of the beam spot precession on the phosphor screen [8]. The measured horizontal and vertical betatron tunes were 1.14 and 1.1 respectively. These numbers were very close to the designed values: 1.14 and 1.12.

The phosphor screen that is used for observation of the extracted beam can also be used as a current monitor. Measuring the extracted current, we were able to determine the beam life-time. The measured beam life-time was approximately 120 turns that corresponded to an average pressure of $2 \cdot 10^{-7}$ Torr. This pressure was a factor of 20 higher than the residual gas pressure in the ring and was mostly due to a gas flux from the ion source.

Transverse Beam Dynamics with Space Charge

By increasing the arc discharge current in the multi-cusp ion source, the peak current of the 20 keV H_2^+ beam was increased to 20 μA. According to [1], space charge effects in the isochronous regime and low energy limit scale as

$$\frac{qI}{m\omega^3}$$

Using this formula one can easily find out that space charge effects in the beam with the mentioned above parameters were equivalent to those in a 2 mA, 5 MeV beam in the PSI Injector II cyclotron. The length of bunches was approximately 1 μsec and the injection/extraction frequency was 1 kHz. Figure 3 shows the beam spot on the phosphor screen for different extracted turns.

The radial beam size increases with the turn number. The beam spot also shows a tilt with respect to the horizontal plane. The tilt of the of the bunch arises from a correlation between the radial particle position that depends on the particle energy as $\eta(\delta p / p)$ and the vertical deflection angle that also depends one the energy as $-2\alpha(\delta p / p)$, where α is the deflection angle of a particle with δp=0.

Assuming that the size of the beam spot after 2.5 turns is mostly due to the beam emittance, we can estimate the energy spread after 16.5 turns as

$$\frac{\delta E}{E} = 2\frac{\sigma_{16.5} - \sigma_{2.5}}{\eta} = 5\%$$

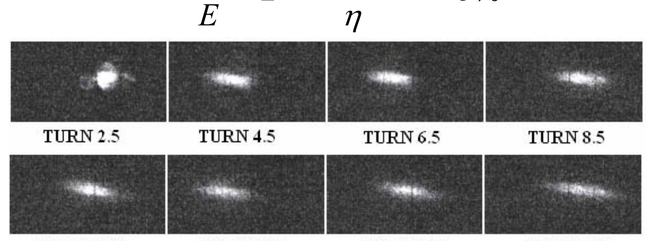

Figure 3: Beam spot produced by the extracted H_2^+ beam on the phosphor screen situated above the median plane. The peak beam current was approx 20 μA, beam energy 20 keV, and a pulse length 1 μsec. Each frame is approximately 60 mm by 30 mm.

Longitudinal Beam Dynamics with Space Charge

As an example of the longitudinal beam dynamics in SIR, Figure 4 shows evolution of the longitudinal bunch profile measured by the fast Faraday cup. The energy of the H_2^+ beam was 20 keV, the peak current was 23μA.

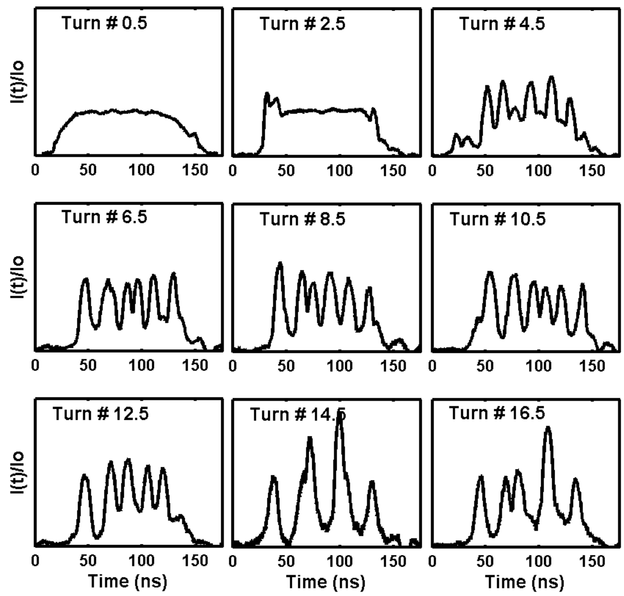

Figure 4: Longitudinal bunch profile measured by the fast Faraday Cup. E_b=20 keV, I_{peak}=23.5 μA.

Figure 5 shows the number of cluster per unit length vs. turn number for different bunch lengths. The bunch length was varied from 18 cm (132 nsec) to 57 cm (414 nsec) while the peak current was kept the same. Each line is a result of averaging over 100 bunches of a given length. The standard deviation for the 414 nsec long bunches is also plotted.

It can be observed that the bunch break up does not depend on the initial length of the bunch and occurs throughout the entire bunch at the same time.

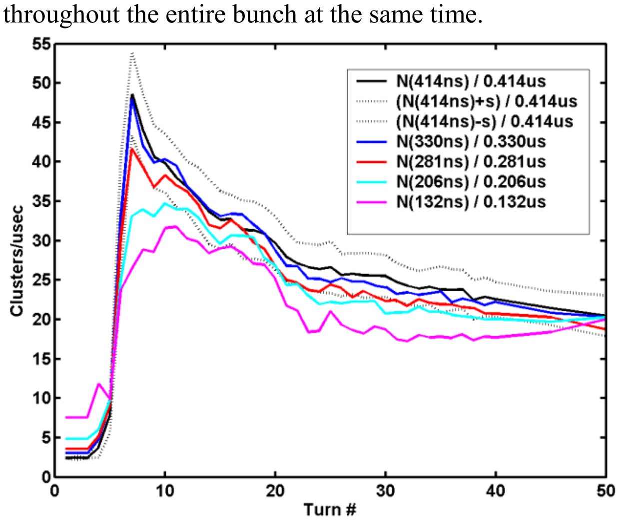

Figure 5: Longitudinal density of clusters vs. turn # for different bunch lengths.

It can also be observed that after the initial break up, the number of clusters goes down approaching a constant value asymptotically.

CONCLUSION

The Small Isochronous Ring has been assembled and commissioned. Main machine and beam parameters including vacuum in the ring, beam life-time, and betatron tunes are close to designed values.

First experimental results show that the space charge force in the isochronous regime causes a longitudinal bunch breakup accompanied by a fast growth of the energy spread. The collected data indicates that the distortion of the bunch distribution induced by the space charge force develops almost simultaneously throughout the length of the bunch, causing an abrupt breakup of the bunch into smaller clusters. The number of clusters and their size do not change much from bunch to bunch for the same turn number while the exact position of clusters within the bunch varies. Similar behavior is observed in other beam instabilities when the growth rate of instability depends on the average charge density while the shape of the final distribution depends on the shape the distortion of the initial distribution.

The experimental results are in qualitative agreement with results of simulations calculated by the code CYCO. Thorough quantitative analysis of the experimental data and simulation results is currently under way.

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