INJECTION LINE STUDIES FOR THE SPC2 CYCLOTRON AT ITHEMBA LABS

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Abstract

The transmission efficiency of some ion beams through the second solid-pole injector cyclotron (SPC2) at iThemba LABS requires improvement. In order to understand the beam optics in the injection line, and match the beam to the acceptance of the cyclotron, the beam envelope behaviour from the beginning of the vertical injection-line to SPC2 was investigated with different simulation programs. The transverse effects were taken into account by the beam transport codes TRANSOPTR and TRANSPORT, while the multi-particle simulation code OPAL was used to include space-charge effects. Simulations of the effect of an additional buncher, operating at the second harmonic, on the transmission of the beam through the cyclotron were made.

INTRODUCTION

A K=8 MeV second solid-pole injector cyclotron at iThemba LABS, shown in Fig. 1, is used to pre-accelerate light and heavy ions, as well as polarized protons, before injection into the separated-sector cyclotron (SSC) for final acceleration [1]. The beams are mainly used for nuclear physics experiments. To accelerate both light and heavy ions, SPC2 was designed to utilize three constant orbit patterns. Depending on the final energy required and type of ion species to be accelerated, ions make 8, 16, or 32 turns before extraction. The transmission efficiency for the 8 turn pattern, however, requires improvement.

Figure 1: A photograph of SPC2.

The beams from the ion sources, which are situated in the SPC2 vault basement, are injected axially into the cyclotron. The DC beam is bunched using a double-gap buncher operating at the fundamental frequency before being deflected onto the median plane of the cyclotron with a spiral inflector. The beam is bunched in order to increase the number of ions that can be accelerated within the phase acceptance of the cyclotron.

In an attempt to improve the transmission efficiency of SPC2, beam dynamics simulations studies of the vertical beam line were performed using three codes. For the transverse optics of the beam along the injection line the beam transport code TRANSPORT [2] was used. The second-order beam transport code TRANSOPTR [3] was used because of its capability to include an arbitrary matrix for the spiral inflector. The Object Oriented Parallel Library (OPAL) code [4], which includes 3D space-charge effects, was utilized to investigate the bunching efficiency of an additional buncher, operating at the second harmonic, on the number of ions that can be grouped within the phase acceptance of SPC2.

TRANSVERSE OPTICS

Beams of heavy ions produced by the electron cyclotron resonance (ECR) ion sources are deflected into the vertical beam line using a 90^0 dipole magnet. The vertical beam line, shown in Fig. 2, consists of two triplets (Q1–Q6) and two solenoids magnets (SL1 and SL2). Also available are steering magnets that steer the beam in both X and Y directions [5].

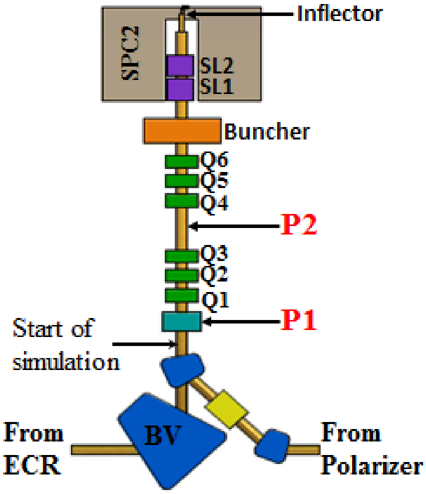

Figure 2: The axial beam line leading into the median plane of SPC2.

It is assumed that the deflection of the beam from the horizontal beam line into the vertical beam line is axisymmetric. Thus, for the present study only the beam dynamics through the vertical beam line was investigated. In the current study $^{20}Ne^{3+}$ ions with an energy of 48.50 keV were considered. The initial phase space parameters

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are listed in Table 1. Here, x is the horizontal radius of the envelope, θ is the angle in the x-z plane, y is the vertical radius of the envelope, ϕ is the angle in the y-z plane, l is the bunch length, and δ relates to energy spread in the bunch. The bunch length (l) was chosen to correspond to one bunch spacing $\beta\lambda = 56$ mm.

Table1: Initial phase space parameters of the 48.50 keV neon beam in the vertical beam line

x (mm)	θ (mrad)	y (mm)	ϕ (mrad)	l (mm)	δ (%)
2	20	2	20	56	0.075

The beam envelopes were calculated using TRANSPORT and TRANSOPTR. For benchmarking purpose, the envelopes were also calculated by multi-particle simulation, using OPAL, with no space-charge effects. Figure 3 shows the calculated beam envelopes in the transverse direction for $^{20}Ne^{3+}$ ions. Also shown in the figure are the calculated beam envelopes using OPAL, taking space-charge effects into account for a 100 eμA beam current. It should be noted that for simulations with space-charge forces, the currents in the beam line elements were increased. These results show that the injection beam line is capable of handling high intensity beams.

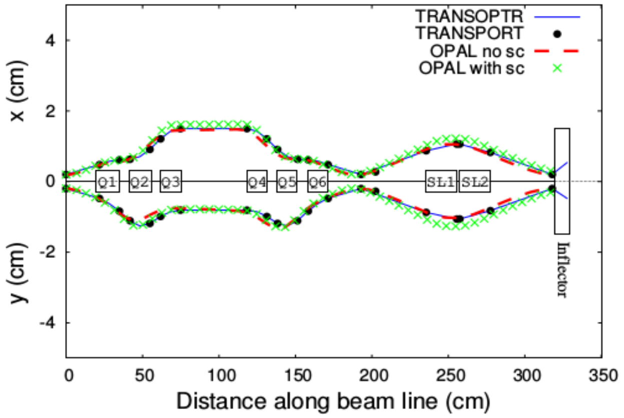

Figure 3: The calculated beam envelopes for the vertical beam line obtained from three different codes, namely, TRANSPORT, TRANSOPTR, and OPAL.

It is understood that the process of deflecting the beam onto the median plane through the spiral inflector leads to coupling in the transverse phase space. This affects the matching of the beam to the cyclotron acceptance. TRANSOPTR was used to investigate the emittances at the exit of the spiral inflector. To do this, emittances at the entrance and the exit of the inflector were compared. The emittances were optimized for lowest emittance growth by varying the settings of the solenoids SL1 and SL2. The emittances obtained for the final settings are $\varepsilon_x = 40\ \pi$ mm.mrad, $\varepsilon_y = 40\ \pi$ mm.mrad at the entrance of the inflector and $\varepsilon_x = 70.2\ \pi$ mm.mrad, $\varepsilon_y = 40.7\ \pi$ mm.mrad at the exit of the inflector. These values are considered acceptable for SPC2.

LONGITUDINAL OPTICS

The longitudinal beam dynamics were simulated using the OPAL code. The code tracks the charged particles including 3D space-charge effects. This code computes space-charge forces by solving the 3D Poisson equation with the open boundary conditions using a standard or integrated Green function method [4]. The external electromagnetic fields are obtained by means of field maps or by analytical models.

DC beams from the polarized and ECR ion sources require bunching in order to increase the number of particles within the cyclotron's phase acceptance. Currently the beam to the SPC2 is bunched using a double-gap buncher operating at the fundamental frequency. The buncher is installed in the vertical beam line between the second triplet and the solenoids as indicated in Fig. 2. The phase acceptance of SPC2 is 40^0 and 55% bunching efficiency can be achieved with this buncher as shown in Fig. 4. It is expected that by using bunchers operating at the 1st and 2nd harmonic frequency the bunching efficiency of particles can be increased.

Therefore, it is planned to install a second buncher, operating at the 2nd harmonic, in the injection beam line. In order to find the optimal position of the buncher, two available positions, labelled P1 and P2 in Fig. 2, were investigated and compared. To use position P2 the settings on the quadrupoles Q1-Q3 were changed such that the focal point would be at P2. Because of the limited space in the vertical beam line only these two positions are realistic options that can be considered.

In OPAL a buncher is modelled by a double-gap RF cavity. Geometrical parameters of the buncher cavities are listed in Table 2. The user can vary the voltage and the phase of the sinusoidal voltage produced by the cavity. Currently the effect of the buncher in the vertical beam line is measured by observing the beam intensity on the probe situated just after the 1st acceleration gap in SPC2. This technique was utilized in our simulation. By calculating the number of particles that can be bunched to within the phase acceptance of the cyclotron the buncher efficiency can be obtained. Figure 4 shows the bunching efficiency of the 1st harmonic buncher obtained by varying the voltage of the buncher while the phase is kept constant. The simulations were performed with and without space-charge effects.

Table 2: Geometrical parameters of the buncher drift tubes

Buncher	Length of Centre Electrode (mm)	Gap (mm)	Aperture Radius (mm)
1st Harmonic	26	2	12.5
2nd Harmonic	39	2	12.5

For simulations with space-charge effects, a beam current of 10 eμA was used. The results show that 50%

bunching efficiency can be achieved with this buncher for both cases.

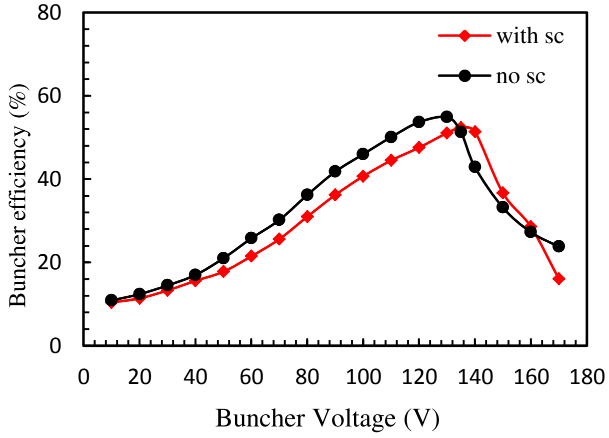

Figure 4: The bunching efficiency of the 1st harmonic buncher as a function of buncher voltage, with and without space-charge effects.

For the inclusion of the 2nd harmonic buncher the two positions P1 and P2 were investigated separately. Figure 5 shows the bunching efficiency for the two bunchers operating at the 1st and 2nd harmonic. The 2nd harmonic buncher was placed at position P1 for Fig. 5(a) while in Fig. 5(b) it was placed at P2. The 1st harmonic buncher was set to its optimal parameters and the voltage of the 2nd harmonic buncher was varied while the phase was kept constant.

For the buncher placed at P1, bunching efficiencies of 76% and 62% could be achieved, respectively for simulations without and with space-charge effects included. Whereas 77% and 73% were obtained with the buncher placed at P2 with and without space-charge effects, respectively. When space-charge is taken into account the shorter drift space between the 1st and the 2nd harmonic buncher contribute to better bunching efficiency with the 2nd harmonic buncher at position P2 compared to position P1. Due to these results, a 2nd harmonic buncher will be installed at position P2 in the near future.

INFLUENCE OF RADIAL ELECTRIC FIELD ON BUNCHING EFFECTS

The electric field experienced by the particles when passing through the buncher gaps is not homogeneously distributed radially. As a result, if one is dealing with beams with large emittances, the inhomogeneity of the electric field deteriorates the bunching effect, as is demonstrated in Fig. 6. Here, the OPERA-3d [6] code was used to investigate the bunch length at the position of the 1st harmonic buncher by tracking the particles through the 2nd harmonic buncher situated at P1. Three particles with phase of -20^0, 0^0 and $+20^0$, representing a bunch with length of 40 RF degrees, were tracked through the electric field at different radial positions between 0 and 10 mm from the axis. Figure 6 shows that when the particles are situated at radii larger than 8 mm, a phase deviation between 55^0 and 100^0 was obtained. As a result, the bunching effect of the 2nd harmonic buncher is destroyed before the particles arrive at the 1st harmonic buncher position.

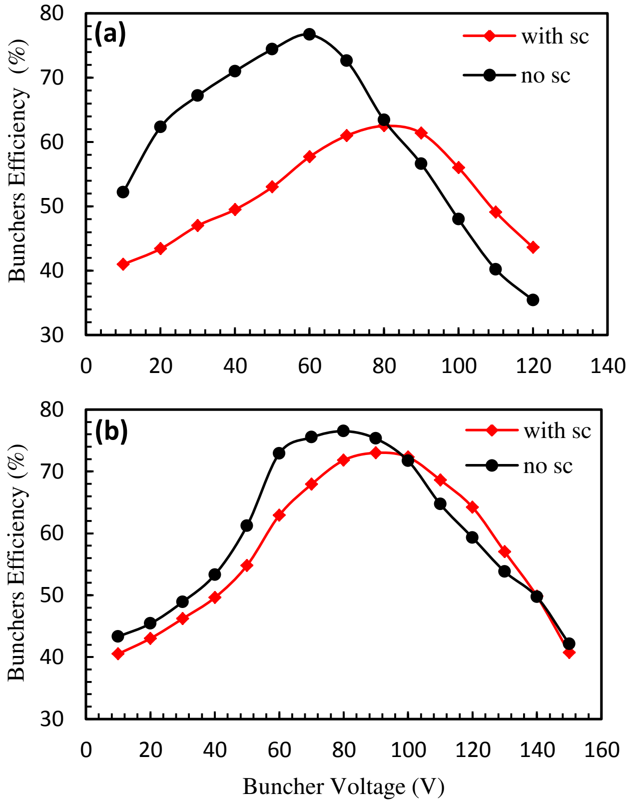

Figure 5: The bunching efficiency as a function of buncher voltage of the 2nd harmonic buncher, (a) with the buncher P1 and (b) with the buncher at P2.

To reduce this effect, grids of two by two crossed conducting wires were placed at each end of the gaps of the 2nd harmonic buncher. By using the grid, the electric field experienced by particles is more homogenous radially, hence the phase deviation is drastically reduced from 100^0 to 30^0 at a radius of 10 mm, as shown in Fig. 6.

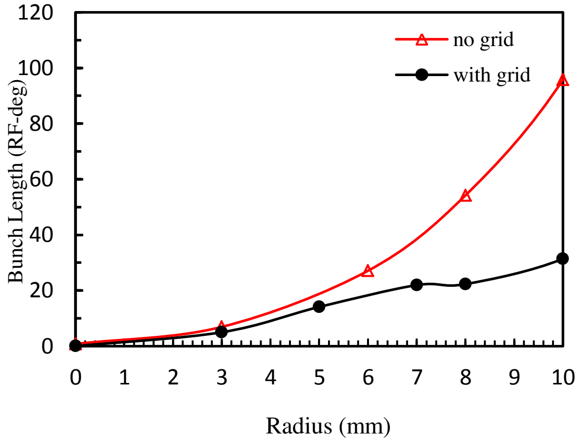

Figure 6: Bunch length of particles at the position of the 1st harmonic buncher as a function of off-axis radial position at the entrance of the 2nd harmonic buncher.

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SUMMARY

The beam optics of the vertical beam line for beam injection into SPC2 were investigated. The transverse optics were studied using TRANSPORT, TRANSOPTR as well as OPAL. The inclusion of space-charge effects showed that the injection beam line is capable of handling high-intensity beams. The inclusion of the inflector transfer matrix made it possible to calculate the transverse emittances at the entrance and exit of spiral inflector. The multi-particle simulation code OPAL was used to study the longitudinal behaviour of the beam. Calculations of the buncher efficiency with two bunchers operating at 1st and 2nd harmonics show that the distance between the two bunchers is an important parameter. When the distance between the bunchers is 1.83 metres a buncher efficiency of 62% could be obtained. This increased to 73% when the distance is reduced to 1.01 metres. The OPERA-3d code were used to investigate the bunching effects on the radial dependence of the electric field.

FUTURE PLANS

Since the beam emittance considered in the present study is small, one-dimensional electric field maps were utilized to model the RF bunchers. For large emittances, three-dimensional field maps need to be considered. The next step of the simulation study will utilize the 3D electric field maps.

In order to improve the accuracy of the beam matching process in the central region of SPC2, the deflection of ions as well as the acceleration along the first few turns will be included in future simulations. The simulations will be accompanied by measurements.

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