NUMERICAL SIMULATION OF THE $^{48}Ca^{5+}$ IONS TRANSPORT ALONG THE U-400 CYCLOTRON'S INJECTION LINE

V.S. Aleksandrov, G.G. Gulbekian, N.Yu. Kazarinov, V.F. Shevtsov, A.V. Tikhomirov
Joint Institute for Nuclear Research, Dubna, Moscow Region, Russia

Abstract

The numerical simulation of the $^{48}Ca^{5+}$ ions beam transport along the U-400 cyclotron's injection line has been carried out. Space charge effects of multi-charged ions spectrum extracted from ECR-source and the longitudinal beam compression influence of two bunchers (sine and line types) on the transverse beam dynamics have been taken into consideration in the process of the beam transport optimization. The simulation results are compared for two injection line schemes: of presently utilized line and its reconstructed variant. The injection line reconstruction does not require any new ion-optic elements. It assumes the exception of the 102° horizontal bending magnet from the present injection line. Eventually this reconstruction will give meaningful transport line shortening. According to produced simulation the expected transmission efficiency from the ECR-source to the cyclotron's spiral inflector entrance along the reconstructed injection line will be essentially increased, as well as appreciably more $^{48}Ca^{5+}$ beam intensity level will be provided.

1 INTRODUCTION

Numerical study of the injection of the $^{48}Ca^{5+}$ ions from the ECR ion source into the U-400 cyclotron is presented. The influence of the space charge transverse forces of the multi-charged ions spectrum extracted from the ECR-source on particle motion is taken into account. All calculations are based on the program library for numerical simulation of the dynamics of the multi-component ion beams in the transport lines[1].

2 INITIAL BEAM DATA

The simulation of ion beam dynamics was carried out for the beam of calcium of 7 species $^{48}Ca^{2+}$ - $^{48}Ca^{8+}$ and 2 species of helium – $^{4}He^{1+,2+}$. The experimental beam current distribution of ion species was used as initial one. It's shown in Fig. 1. The ion beam emittance at the entrance of the channel was assumed to be equal to 160 π mm · mrad, the initial radius of the beam – 4 mm. Particles in the transverse phase space were distributed in accordance with Kapchinsky-Vladimirsky model. The number of macro-particles in the simulation was equal to 1500. The initial kinetic energy of ions was chosen Z×15 keV (Z is ion charge). The total initial current of the beam was varied from 0 till 1.7 mA. In this case the maximal current of the $^{48}Ca^{5+}$ ions was equal to 272 μA. The current distribution was not changed during variation of the total current.

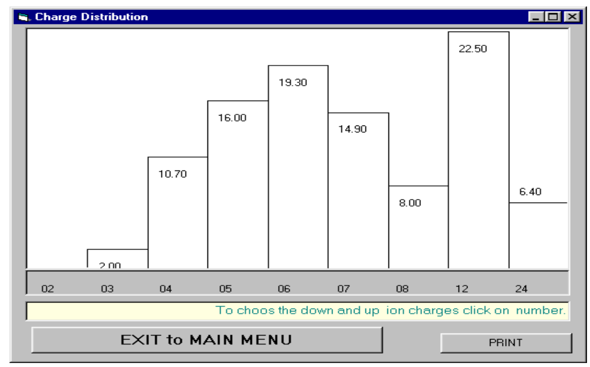

Figure 1: Initial beam current distribution.

3 PRESENT INJECTION BEAM LINE

The scheme of the present injection beam line (total length – 9.28 m) is shown in Fig. 2. In this beam line two bunchers are used to achieve the matching of the bunch longitudinal dimension with RF acceptance of the cyclotron – the linear type buncher U1 placed at 4.4 m and the sine type buncher U2 placed at 1.25 m from the middle plane of the cyclotron. The voltage on the linear buncher V_1 = 240 V and on the sine buncher V_2 = 350 V. For the initial longitudinal momentum spread Δp/p = 0.25% the final longitudinal bunch size at the acceleration gap of the cyclotron dee is decreased by five time in comparison with initial one. The final value of the momentum spread is equal to 1.25%. The dependence of the bunching coefficient (that is the ratio of the maximal bunch current I to the initial beam current I_0) on the

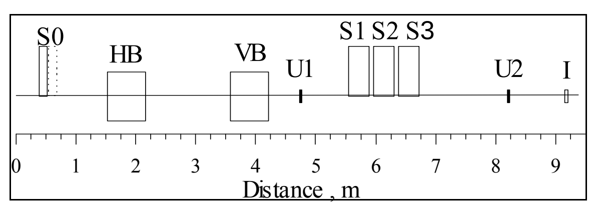

Figure 2: Present injection line. S0-S3 – focusing solenoids, HB – 102_0 horizontal bending magnet, VB – 90_0 vertical bending magnet, U1,2 – bunchers, I – cyclotron inflector.

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distance from linear buncher U1 is shown in Fig. 3, (curve 1).

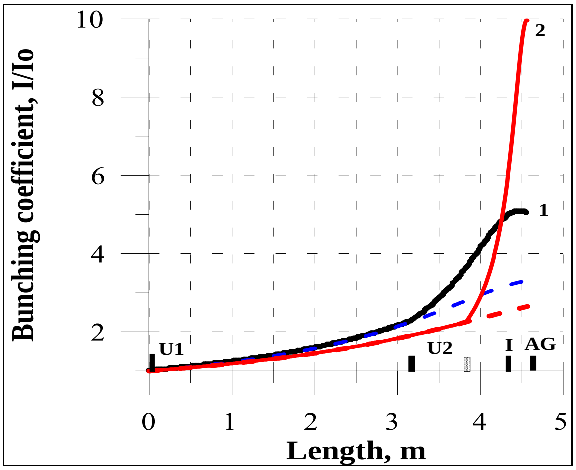

Figure 3: Changing of the bunching coefficient along the beam line. Curve 1 – present position (right) of the buncher U2 , curve 2 – proposed position(left), dashed lines correspond zero voltage on sine buncher.

The increasing of the bunched beam current leads to the growth of the beam self field. In the simulation this effect was taking into account only for transverse self forces.

The envelopes of the beam near the inflector of the cyclotron in this case are shown in Fig. 4. For small initial total beam current (less than 0.31 mA which corresponds to the 50 μA current of the separated $^{48}Ca^{5+}$ ions) the losses of the $^{48}Ca^{5+}$ ions during transportation are absent.

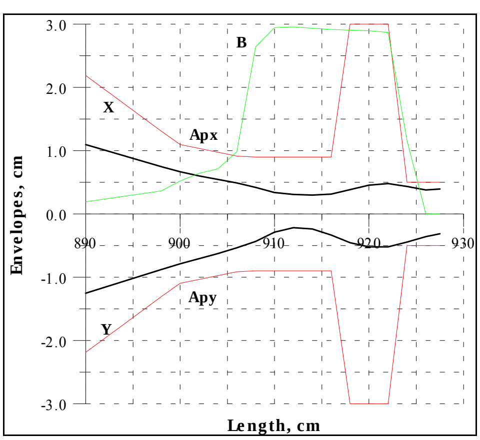

Figure 4: Envelopes of the beam near inflector. Curves X, Y – beam envelopes, Apx,y – apertures of the vacuum chamber, B – longitudinal magnetic field of the cyclotron (arbitrary units).

For greater initial beam current the losses firstly take place in the inflector only and for the total beam current greater than 0.94 mA ($^{48}Ca^{5+}$ current – 150 μA) also on the wall of the vacuum chamber before separator. This may be seen in Fig. 5.

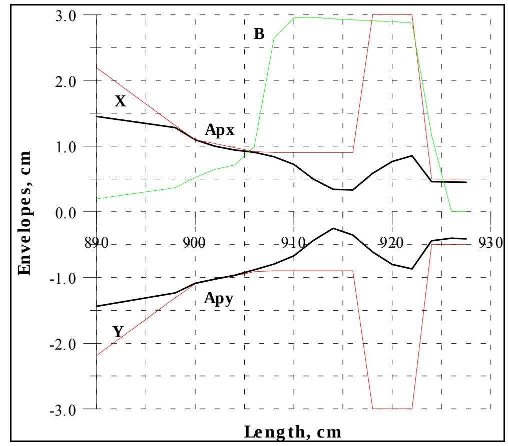

Figure 5: Envelopes of the beam near inflector.

The particle losses may be explained by the significant growth of the beam emittance with increasing the total initial beam current.

The value of the emitttance of the separated $^{48}Ca^{5+}$ ion beam (after the bending magnets) as a function of the total initial beam current is shown in Fig. 6.

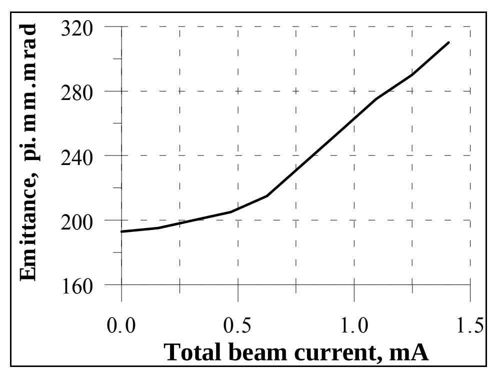

Figure 6: Emittance of the $^{48}Ca^{5+}$ beam *vs* total beam current.

The optimization of the induction of the fields in the solenoids S0 – S3 was carried out to achive the maximum capture of the $^{48}Ca^{5+}$ beam current into inflector acceptance. The dependence of the captured current of the ions $^{48}Ca^{5+}$ on its initial current is shown in Fig. 7 (curve 1, solid line).

The influence on the particle motion of the transverse magnetic fields induced by the cyclotron leads to the significant decreasing of the captured current. The constant vertical component B_y of the transverse magnetic field were introduced in the calculation of the particle trajectory in the region between ECR-source and horizontal bending magnet. The value of B_y was equal to 10 Gauss. The result of this simulation is shown also in Fig. 7 (curve 1, dashed line). The maximum captured current is about three times smaller than in the previouse case.

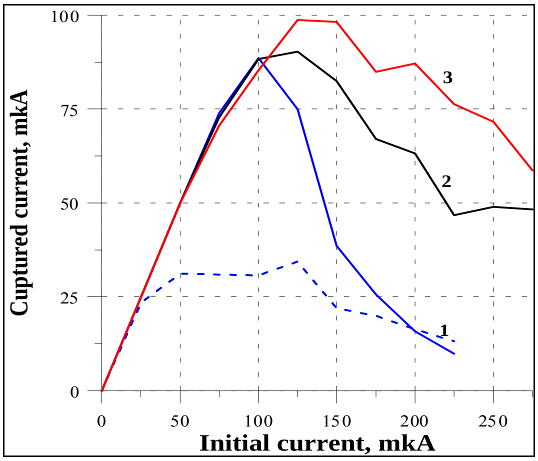

Figure 7: Captured $^{48}Ca^{5+}$ current.

4 RECONSTRUCTED INJECTION BEAM LINE

The scheme of the reconstructed injection beam line (6.46 m of total length) is shown in Fig. 8. The reconctruction supposes the exeption of the 102^0 horizontal bending magnet from the present injection line. To avoid the beam center of mass displacement caused by transverse magnetic field of the cyclotron in the region after 90^0 vertical bend two steering dipole magnet C must be installed before and after magnet VB. This reconstraction will give meaningful transport line shortening.

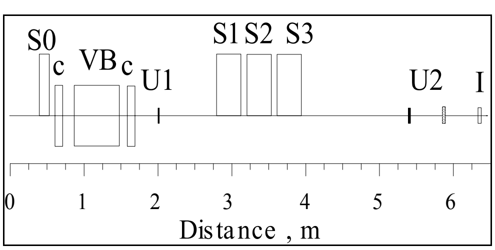

Figure 8: Schematic view of the reconstructed injection line. Symbols are described in Fig. 2.
C – steering dipole magnet.

The position of the sine type buncher U2 at 125 cm from the middle plane of the cyclotron is not optimal for achieving the good matching of the bunch length with the cyclotron RF acceptance. The sine type buncher placed at 57.5 cm from the middle plane (left position in Fig. 8) gives the opportunity to get the necessary value of the bunching coefficient at the acceleration gap of the cyclotron dee for the same initial bunch length and the longitudinal momentum spread. The voltage on the linear buncher V_1 = 204 V and on the sine buncher V_2 = 1.33 kV, the final momentum spread is equal to 2.5%. This is illustrated in Fig.3 (curve 2, solid line).

As for present beam line the small initial total beam current (less than 0.31 mA, $^{48}Ca^{5+}$ current – 50 μA) is transportated into cyclotron without losses of the $^{48}Ca^{5+}$ ions.

The simulation of the particle motion was carried out for two possible values of the bunching coefficient at the acceleration gap of the cyclotron as it was discussed earlier (see solid curves 1 and 2 in Fig. 3). The influence of the transverse magnetic field was not taken into account because of the possibility to correct the center of mass displacement.

The current captured into inflector acceptance is essentially increased in comparison with the present beam line. The dependence of the captured current of the ions $^{48}Ca^{5+}$ on its initial current is shown in Fig. 7.

Curves 1 in Fig. 7 correspond the absence (solid line) and presence (dashed line) of the transverse magnetic field induction in the present injection beam line. Curve 2 gives the captured current in the reconstructed beam line for the maximum value of bunching coefficient to be equal to 5. Curve 3 corresponds the maximum value of the bunching coefficient to be equal to 10.

5 CONCLUSION

The transverse magnetic field induced by the cyclotron significantly decreases the transmission efficiency of the present injection beam line.

The proposed reconstruction of the injection beam line gives the meaningful beam line shortening in the initial part of the line (before vertical bending magnet) where the transverse cyclotron magnetic field may be large. The residual displacement of the beam center of mass may be corrected with the help of the two dipole steering magnet.

The removing of the sine type buncher to the middle plane of the cyclotron will give the possibility to get the best matching condition of the longitudinal beam dimension with RF acceptance of the cyclotron.

According to the produced simulation the expected current transmission from ECR-source to the exit of the cyclotron inflector will be considerably increased in comparison with present injection beam line.

6 REFERENCES

[1] V.Alexandrov, Yu.Batygin, N.Kazarinov, V.Shevtsov, G.Shirkov, Workshop on Space Charge Dominated Beam Physics For Heavy Ion Fusion ECR Sources, RIKEN, Saitama, Japan, December 1998.