УДК 621.384.633.5/.6

BEAM SPACE CHARGE EFFECTS IN HIGH-CURRENT CYCLOTRON INJECTOR CI-5

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Separated sector cyclotron-injector CI-5 has been studied in the framework of the external injection into phasotron project. The calculations of beam dynamics characteristics of Cyclotron CI-5 for H^- beam of 5 MeV energy are presented. Space charge limits (both transverse and longitudinal) have been investigated. Analytical estimations and numerical simulations of particle motion taking into account space charge effects confirm that it is possible to achieve 10 mA in a 5 MeV separated sector H^- Cyclotron.

Проводились расчеты по ускорению H^--ионов до энергии 5 МэВ в секторном циклотроне ЦИ-5, предназначенном для инжекции в фазотрон ОИЯИ. Исследовалось влияние пространственного заряда (поперечного и продольного) на динамику частиц. Аналитические и численные расчеты движения ионов с учетом эффектов пространственного заряда показали возможность создания циклотрона с рабочей интенсивностью 10 мА.

1. CYCLOTRON-INJECTOR BEAM DYNAMICS

To overcome the maximum intensity limitations in the central zone of the JINR Phasotron caused mainly by weak vertical focusing, it was proposed to increase the proton beam intensity by about an order of magnitude via external injection and sequential charge exchange of the H^- beam first into H^0 and then into H^+ [1].

In the present paper, acceleration of H^- ions with the intensity of $10 \div 30$ mA to the energy of 5 MeV in a sector cyclotron, designed to be an injector for the JINR Phasotron, is calculated and space charge effects are estimated.

The parameters for the calculation are given in the Table.

Transverse beam emittances at injection were taken to be equal to initial emittances from the H^- sources, $1\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$ [2] (normalized), on the assumption that they did not vary in the preaccelerator.

The software [3] based on the code NAJO [4] for calculation of particle dynamics in GANIL sector cyclotrons was used. The basis for the code is integration of differential equations by the Runge–Kutta method (integration step $0.5°$). Acceleration is treated in the thin-lens approximation (constant velocity and coordinate), kicks are in the centre of the accelerating gap, a flat-top cavity can be installed. $100 \div 200$ particles obeying the random distribution are used to simulate the beam. The space charge effect is taken into account eight times per turn. The equivalent continuous method is used. The subroutines to calculate the isochronous field by the Gordon method [5], to correct the calculated field, and to calculate betatron frequencies have been added to the code. The code ORBITA [6] was used to check single-particle calculations.

Type of cyclotron	Sector cyclotron
Accelerated particle	H^-
Injection energy, MeV	0.5
Final energy, MeV	5.0
Intensity, mA	10, 30
Magnetic system	
Number of sectors	4
Angular length of sector, degrees	30
Gap between poles, cm	3
Radial length of pole, cm	$15 \div 65$
Mean magnetic field, kGs	$5.0 \div 5.07$
Maximum flutter	1.45
Particle dynamics	
Revolution frequency, MHz	8.25
Harmonic number	6
Frequency of free oscillations:	
radial	$1.1 \div 1.2$
axial	$1.0 \div 1.1$
Injection	
Radial emittance, $\pi \cdot$ mm $\cdot$ mrad	30
Axial emittance, $\pi \cdot$ mm $\cdot$ mrad	30
Longitudinal emitt., $\pi \cdot$ deg $\cdot$ permille	75
Extraction ($I = 30$ mA)	
Radial emittance, $\pi \cdot$ mm $\cdot$ mrad	100
Axial emittance, $\pi \cdot$ mm $\cdot$ mrad	22
Longitudinal emitt., $\pi \cdot$ deg $\cdot$ permille	150

2. NUMERICAL SIMULATION

Energy gain takes place over six turns. Figure 1 displays the path of a central particle.

Note that at the centre acceleration occurs in the close vicinity of the resonance $Q_z = 1$. Therefore, the magnetic system of the accelerator should be changed either to increase the axial focusing to $Q_z = 1.2 \div 1.3$ or to decrease it to $Q_z < 1$. The $Q_z < 1$ version leads to slightly lower limiting current, but the injector cyclotron current of 20 mA at the capture efficiency of 50 % is enough to increase the average current of the internal Phasotron beam to 50μA. The capture efficiency can be increased to 66 % by matching the injector and Phasotron frequencies. The revolution frequency of particles in the Phasotron is known to be 18.114 MHz (at an energy of 5 MeV). If we increase the revolution frequency of particles in the cyclotron to 9.057 MHz, two of three bunches (remember that the harmonic number of the cyclotron is 6) will be captured. Thus, the necessary cyclotron current will decrease to 15 mA.

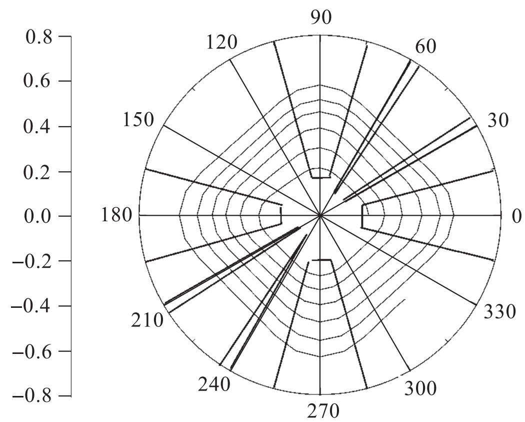


Fig. 1. Path of the central particle

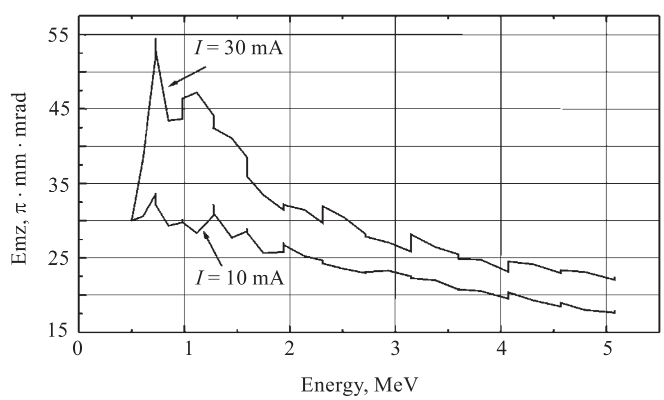
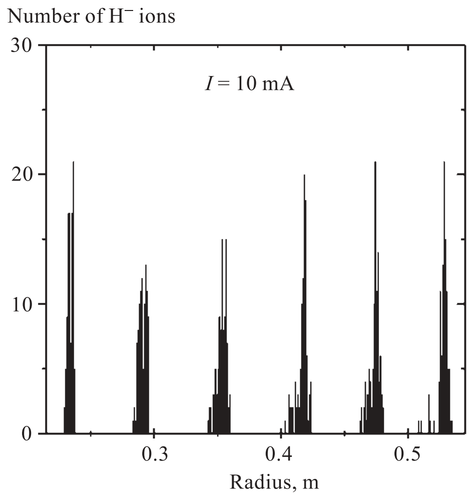


Fig. 2. Dependence of effective axial emittances on the ion energy for $I = 10$ mA and $I = 30$ mA

2.1. Centre. Figure 2 displays axial emittances as a function of the ion energy for currents of 10 and 30 mA. It is evident from the figure that transverse forces of the space charge cause a sharp increase in the effective axial emittance at the centre of the accelerator while the axial spread does not exceed the accelerator aperture. Thus, a current of 30 mA is tolerable, which agrees with analytical estimation. Note, however, that the emittance was calculated as a function of the root-mean-square deviation, i.e., not all particles fall within the emittance and thus the real transverse space charge limit is slightly below 30 mA.

2.2. Extraction Area. To minimize the effect of the longitudinal space charge, high energy gain per turn should be provided and proper beam quality should be maintained in the course of acceleration. In our calculations the energy gain allowed the beam of H^- ions to be accelerated to 5 MeV after six revolutions while the maximum energy gain linearly varied from 0.56 to 1.2 MeV. Figures 3 and 4 display the radial distribution of particles at $I = 10$ mA and $I = 30$ mA respectively. The turn separation in the extraction area is about 5 cm, some beam broadening is observed, which decreases the particle-free area to 3 cm.



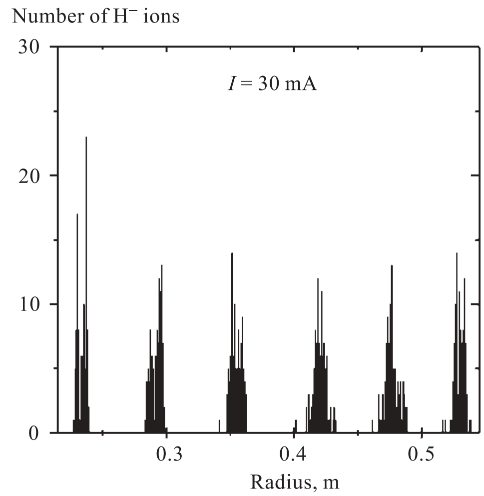
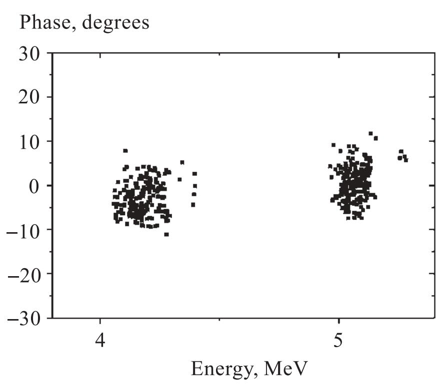


Fig. 3. Radial distribution of particles at $I = 10$ mA

Fig. 4. Radial distribution of particles at $I = 30$ mA



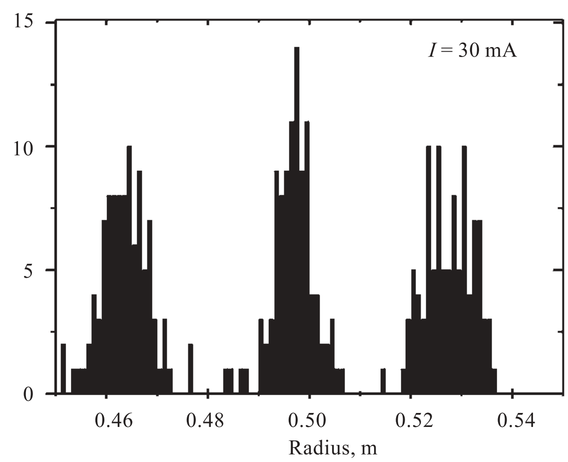


Fig. 5. Phase portraits

Fig. 6. Radial distribution of particles ($I = 30$ mA, the last three turns) in the accelerator with 11 orbits

Figure 5 displays phase portraits of the beam (the last three turns) at the intensity $I =$ 30 mA. Figure 6 shows radial distributions of particles (the last three turns) for a smaller energy gain in the cyclotron (the maximum energy gain linearly varied from 0.28 to 0.56 MeV). In this case the acceleration process occurred for 11 turns. It is seen that the orbit separation is retained though the particle-free area decreases to 8 mm, which is quite enough for effective extraction.

CONCLUSION

• The transverse space charge effects substantially shift free oscillation frequencies of particles in the injector cyclotron.

• With a given particle energy gain, the orbit separation at the final radius at the intensity below 30 mA is enough to provide 100% beam extraction. The required energy gain per turn may probably somewhat decrease while the high beam extraction efficiency is retained.

• Transverse beam emittances at the exit from the cyclotron are such that the cyclotron beam can be matched to the transverse projections of the Phasotron acceptance at the injection energy of 5 MeV.

• To match longitudinal emittances, a system for appropriate beam preparation (buncher) should be included in the line of particle injection from the cyclotron to the Phasotron and the chosen particle revolution frequency in the cyclotron should be a multiple of that in the Phasotron.

• The analytical and numerical calculations point to a possibility of particle beam acceleration with a limiting intensity not higher than 30 mA. The intensity of 10 mA can be considered a working intensity.

The authors are grateful to Dr. E.M.Syresin for his support and to Prof. A.A.Glazov for the accelerating system data.

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Received on February 16, 2001.