SPACE CHARGE EFFECTS IN A HIGH-CURRENT CYCLOTRON INJECTOR

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Abstract

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 beam H^- first into H^0 and then into H^+[1].

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

Table 1.

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 (°)	30
Gap between poles (cm)	3
Radial length of pole (cm)	15 ÷ 65
Mean magnetic field (kGs)	5.0÷5.07
Maximum flutter	1.45
Particle dynamics	
Revolution frequency (MHz)	8.25
Harmonic number	6
Frequency of free oscillations: radial axial	1.1÷1.2 1.0÷1.1
Injection	
Amplitude of radial oscillations (mm)	6
Amplitude of axial oscillations (mm)	6
Phase width of bunch (° RF)	30
Radial emittance (π*mm*mrad)	30
Axial emittance (π*mm*mrad)	30
Longitudinal emitt. (π*deg*permille)	75
Extraction (I = 30 mA)	
Amplitude of radial oscillations (mm)	10
Amplitude of axial oscillations (mm)	4
Phase width of bunch (° RF)	32
Radial emittance (π*mm*mrad)	100
Axial emittance (π*mm*mrad)	22
Longitudinal emitt.(π*deg*permille)	150

1 INJECTOR CYCLOTRON BEAM DYNAMICS

Acceleration of H^- - ions with intensity 10÷30 mA to the energy 5 MeV was calculated. The parameters for the calculation are given in Table 1.

Transverse beam emittances at injection were taken to be equal to initial emittances from the H^- -sources, 1π*mm*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 center of the accelerating gap. A flat-top cavity can be installed. 100÷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.

2 NUMERICAL SIMULATION

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

Note that at the center 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÷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 50 μA. 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 18.114MHz (at energy 5 MeV). If we increase the revolution frequency of particles in the cyclotron to 9.057MHz, 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.

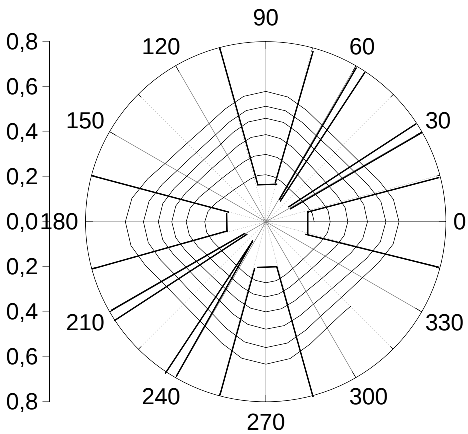

Fig. 1. Path of the central particle

2.1 Center

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 center 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.

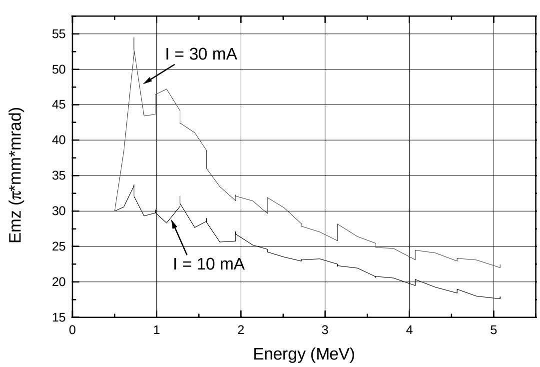

Fig. 2. Dependence of effective axial emittances on the ion energy for I = 10 mA and I = 30 mA

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 accelerate 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 3cm.

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.

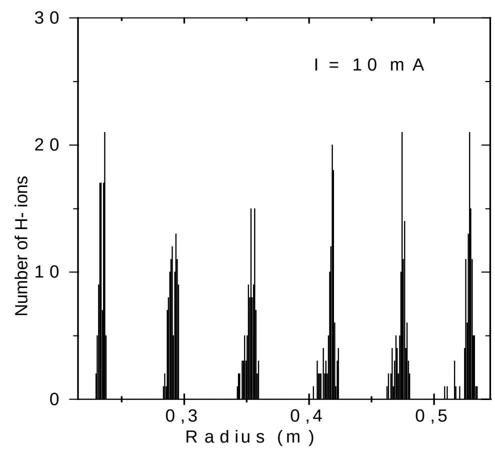

Fig. 3.Radial distribution of particles at I=10mA

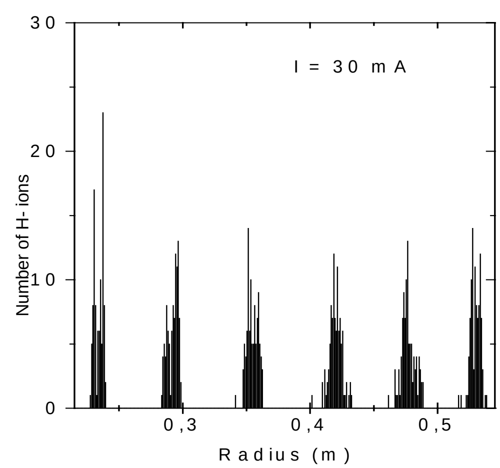

Fig. 4. Radial distribution of particles at I = 30mA

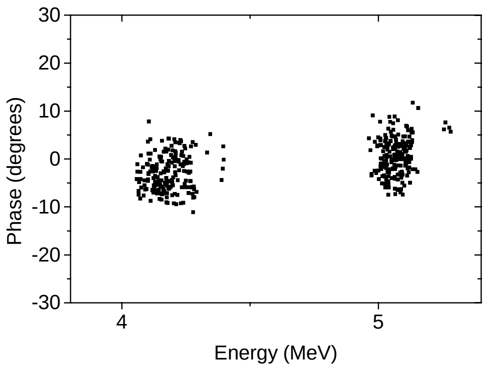

Fig. 5. Phase portraits.

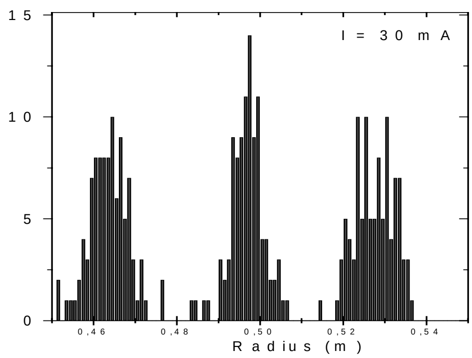

Fig. 6.Radial distribution of particles (I = 30 mA, the last three turns) in the accelerator with 11 orbits

3 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 5MeV.
- 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.

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