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PROCEEDINGS

Computer simulation of the space charge dominated beam dynamics for external injection into the JINR Phasotron

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Abstract A project of increasing the beam intensity of the 660 MeV JINR proton Phasotron up to 50 μA by an external injection of the H^- beam with energy of 5 MeV is now under design. Computer simulation of the space charge dominated beam dynamics in Phasotron is reported. As follows from the simulation, the capture efficiency does not change too much when the beam space charge is taken into account.

Key words phasotron • external injection • space charge • beam dynamics

Introduction

To increase the intensity of the JINR synchrocyclotron (Phasotron) from 5 to 50 μA, a project [2, 5, 6, 8] of the external injection of beam is developed. It is supposed that the beam with current of 6–8 mA and energy of 5 MeV, delivered from the cyclotron, after additional bunching and neutralization ($H^- \rightarrow H^0$), is injected into the central region of the Phasotron. A carbon foil will be used in order to get a proton beam ($H^0 \rightarrow p$). Some parameters of the Phasotron central region for the scheme of external injection (Fig. 1) are given in Table 1.

Some preliminary results concerning the efficiency of beam capture into acceleration not taking into account space charge effects, were described earlier in [5, 6]. But, at such high intensity of the injected beam it is necessary to know detailed information about space-charge effects (SCE) on the particle dynamics. The methodology of two-dimensional numerical simulation [1] of SCE developed in PSI for the cyclotron with sectioned magnetic system is well known. However, we were faced with the task to fulfill three-dimensional SCE simulation with the minimum of simplifying assumptions. For studying of SCE in synchro-cyclotron, code PHASCOL was created in which the method of large (macro) particles is realised. Two methods are possible to be used in the code for calculating electric field of the beam: the method of pairwise interactions and the method of particle in cell. In the first method, electric field in the location of macroparticle is calculated by summation Coulomb's field which acts from the remaining particles. In the second method, with the aid of rapid Fourier's transform three-dimensional Poisson's equation is solved numerically on a grid, which covers beam. The code is written in Microsoft Visual Fortran and is supplied with an on-line graphics, which illustrates the set of initial conditions and the results of calculations.

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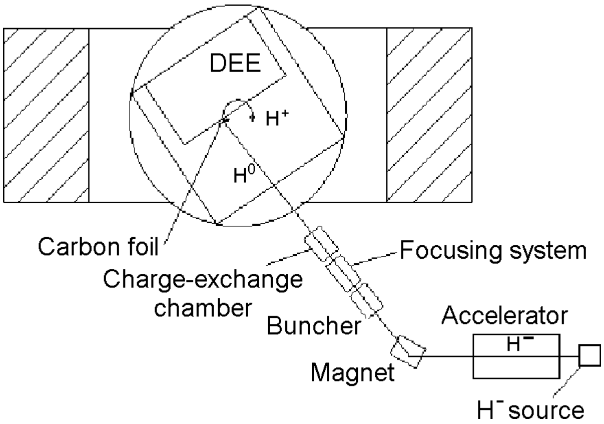

Fig. 1. Scheme of the external injection.

Using the code PHASCOL some computations that cover first 2000 turns of the beam have been fulfilled. These calculations have made it possible to determine the SCE influence on the distribution of particle free oscillations as well as on the effectiveness of their capture into acceleration.

Brief description of the code PHASCOL

The code PHASCOL is intended for calculating particle dynamics in cyclotrons and synchrocyclotrons taking into account the three-dimensional distribution of beam electric field. For numerical simulation of the effects of space charge the beam is divided into a series of bunches injected into an accelerator, each of which consists of a set of particles. The sum charge of the particles corresponds to the current being simulated (method of large particles). In PHASCOL the following complete equations of motion [4] of the charged particle in the cylindrical coordinate system are used:

(1) $$\ddot{r} = r\dot{\varphi}^2 + \frac{qc^2}{E}\left[\varepsilon_r - r\dot{\varphi}B_z + \dot{z}B_\varphi - \frac{\dot{r}}{c^2}\left(\dot{r}\varepsilon_r + r\dot{\varphi}\varepsilon_\varphi + \dot{z}\varepsilon_z\right)\right]$$

(2) $$\ddot{z} = \frac{qc^2}{E}\left[\varepsilon_z + r\dot{\varphi}B_r - rB_\varphi - \frac{\dot{z}}{c^2}\left(\dot{r}\varepsilon_r + r\dot{\varphi}\varepsilon_\varphi + \dot{z}\varepsilon_z\right)\right]$$

Table 1. Data of the Phasotron central region.

Type of accelerated particle		p
Initial energy	(MeV)	5.0
Radius of injection	(cm)	27.0
Average magnetic field	(T)	1.2
Betatron frequencies		
ν_r		1.01
ν_z		0.12
Orbital frequency	(MHz)	18.124
Phase width of the bunch	(°RF)	20–30
Harmonic number		1
Number of acceleration gaps		2
Accelerating voltage	(kV)	37

(3) $$\ddot{z} = \frac{qc^2}{E}\left[\varepsilon_z + r\dot{\varphi}B_r - rB_\varphi - \frac{\dot{z}}{c^2}\left(\dot{r}\varepsilon_r + r\dot{\varphi}\varepsilon_\varphi + \dot{z}\varepsilon_z\right)\right]$$

where (r, φ, z) – coordinates of particle; (B_r, B_φ, B_z) $(\varepsilon_r, \varepsilon_\varphi, \varepsilon_z)$ – components of magnetic and electric fields; q – particle charge; c – speed of light; E – total energy of particle, the point above the coordinates indicates differentiation with respect to time. The method of Runge–Kutta of 4-order is used for integrating the equations. All calculations are fulfilled in the regime of double precision.

Magnetic field is introduced into the program in the form of the table of radial dependencies of average values, amplitudes and phases of Fourier's harmonic in the median plane. The magnetic field created by the beam current is not considered in the code. Electric field are represented in the form of the sum of the components of the accelerating field and of the space charge field:

(4) $$\varepsilon_{r,\varphi,z} = \varepsilon^{\mathrm{RF}}_{\varphi,z} + \varepsilon^{\mathrm{SC}}_{r,\varphi,z}.$$

At each step of integration a particle gets, or loses energy in accordance with the sign of the expression:

(5) $$\Delta w = q(\dot{r}\varepsilon_r + r\dot{\varphi}\,\varepsilon_\varphi + \dot{z}\varepsilon_z)\Delta t$$

where Δt – step of integration. Accelerating field is described by the expression:

(6) $$\varepsilon^{\mathrm{RF}}_{\varphi,z} = \varepsilon^{\max}_{\varphi,z}\cos\left(2\pi\int_0^t (t)dt + \psi\right)$$

where: $f(t)$ – frequency program of synchrocyclotron (for the case of cyclotron this is constant); ψ – starting phase of particle. The analytical description [3] is used for calculating the amplitudes $\varepsilon^{\max}_\varphi$, $\varepsilon^{\max}_z$:

(7) $$\varepsilon^{\max}_\varphi = \frac{U}{S\sqrt{2\pi}}\exp\left(-0.5\cdot(y/S)^2\right)$$

(8) $$\varepsilon^{\max}_\varphi = \frac{yz}{S^2}\varepsilon^{\max}_\varphi\left\{1 + \frac{1}{6}\left(\frac{z}{S}\right)^2\left[\left(\frac{y}{S}\right)^2 - 3\right]\right\}$$

where: $S = 0.2\,H + 0.4\,W$ (see Fig. 2); U – accelerating voltage.

Two methods were realised for calculating the field of space charge: the method of pairwise interactions (particle-to-particle, PTP) and the method of particle in cell (particle-in-cell, PIC). More detailed description of both methods is represented in another our article [7] submitted to this Workshop. All computations described below were

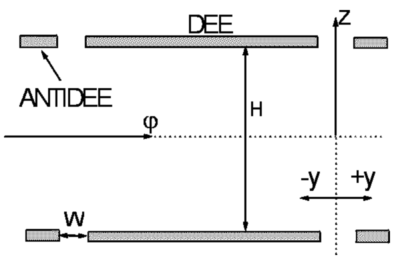

Fig. 2. Dee cross section geometry.

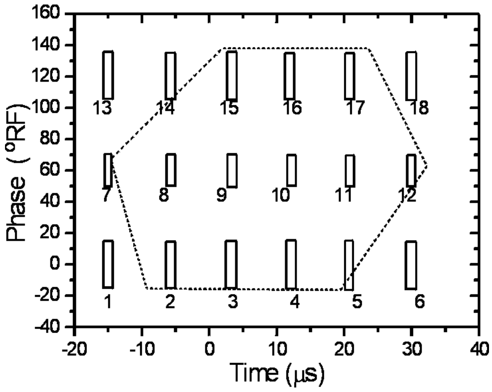

Fig. 3. Position of the injected bunches on plane (time, RF phase). Each of 18 rectangular contains (25 bunches, 5000 particles). Dashed line shows a boundary of the capture region determined by earlier computation without SCE.

done making use of the PIC method because it takes less time than the PTP method.

Initial conditions

Earlier, in the calculations of particle capture into the acceleration without SCE it was shown that the time of capture of the beam of energy 5 MeV is equal to ~ 46 μs in the range of frequency of accelerating field (18.150–18.075) MHz. Computations, taking into account SCE, were carried out for 18 collections of the bunches, whose starting position on the plane time – RF phase is shown in Fig. 3. One starting bunch consisted of 200 particles. The charge of one macroparticle was composed of 0.36×10^7 proton charges. The position of particles in the phase space ($r, r'z, z'\varphi$) was matched with the acceptance of synchrocyclotron in the region of stripping foil. The transverse emittances of beam were equal to 100π mm·mrad and 15π mm·mrad for the radial and axial motion, respectively. The phase width of bunches was equal to ~20° for the central type of bunch (average phase 60°), and ~30° for the extreme bunches (average phases 0° and 120°). Energy of each of 200 particles of the bunch was determined via the random sampling from the range (5 ± 0.15) MeV.

As soon as first starting bunch completed sequential turn, the instantaneous (at one step of integration) injection of the following bunch was produced and the number of calculated particles increased by 200. Thus, this continued until reaching the total number of particles 5000 (25 starting bunches). Further, the number of injected particles remained constant. In Figs. 4–6 the particle positions on planes (z, P_z), (r, z) and (φ, r) are compared for two types of computation at the moment when the last (25th) bunch is injected. In all pairs of figures below the left panel shows the results with SCE ignored, and the right panel shows the results with the SCE taken into account.

Dynamics on each of 18 bunch sets was simulated separately two times: when SCE are on and when SCE are off. The time step of integration corresponded to the azimuth step 1°. Maximal value of particle turns was equal to 2000. The resources of PC (2 GHz, 1 Gb) made it possible to get the results for one bunch set in 20 h if SCE was on, and in 10 h if SCE was off.

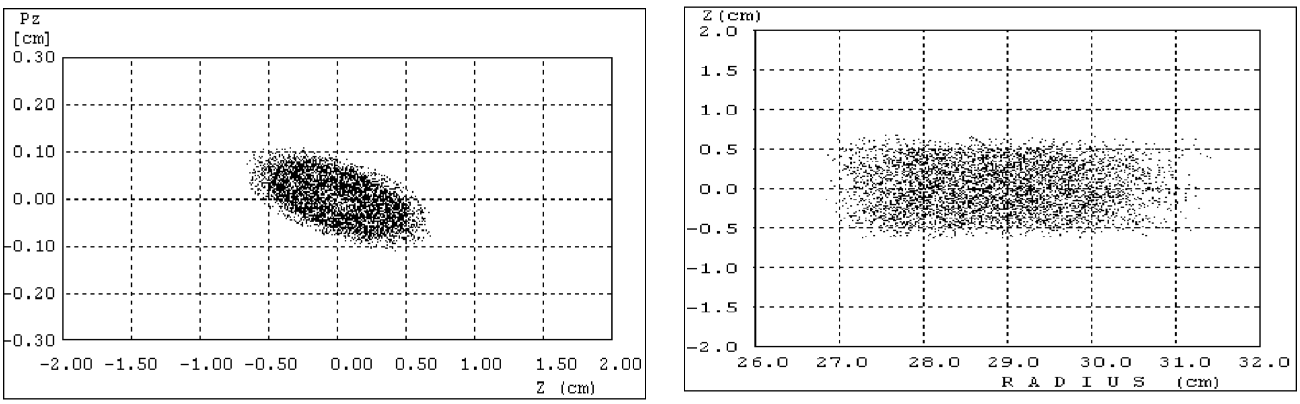

Fig. 4. Position of 5000 particles on axial phase plane (25 bunches from rectangular No. 9, Fig. 3).

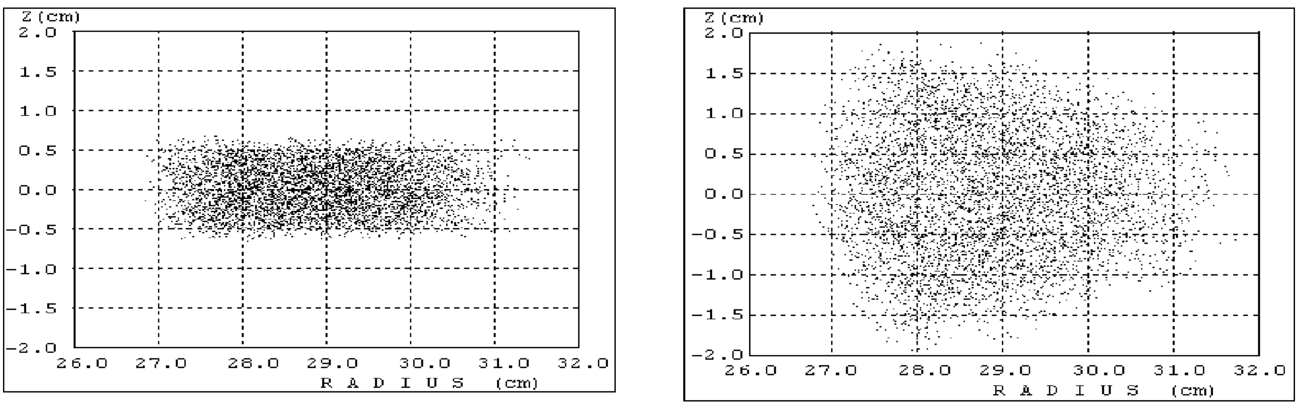

Fig. 5. Position of 5000 particles on plane (r, z) (25 bunches from rectangular No. 9, Fig. 3).

Table 2. Distribution of particle losses for two variants of simulation.

Type of losses	Space charge is on (%)	Space charge is off (%)
Withdrawal to the center	21.9	24.4
Axial losses	7.5	0.05
Phase losses	19.1	20.9
Sum of losses	48.5	45.35

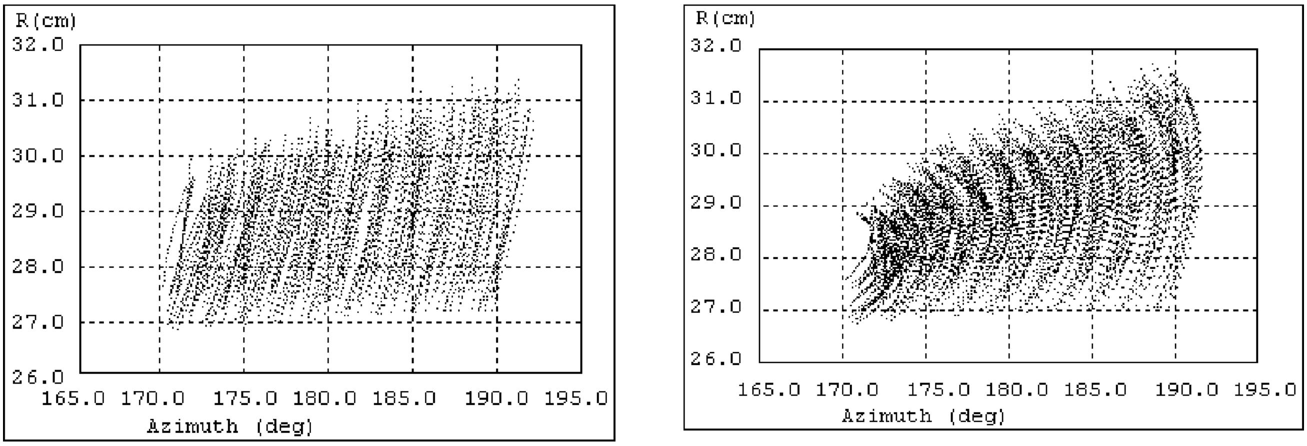

Fig. 6. Position of 5000 particles on plane (r, φ) (25 bunches from rectangular No. 9, Fig. 3).

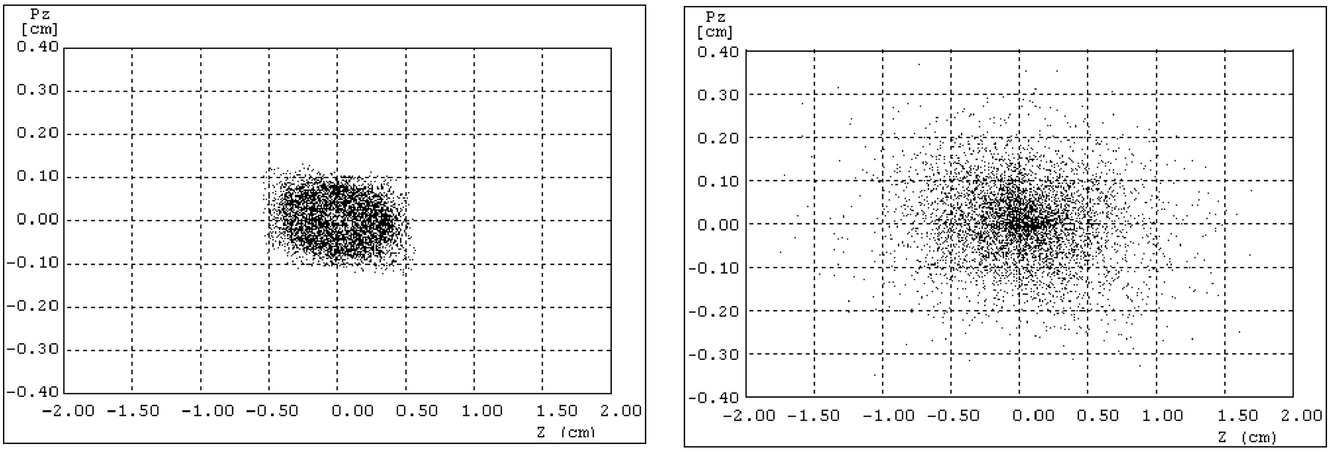

Fig. 7. Position of 5000 particles from rectangular (No. 9, Fig. 3) on axial phase plane after 2000 turns.

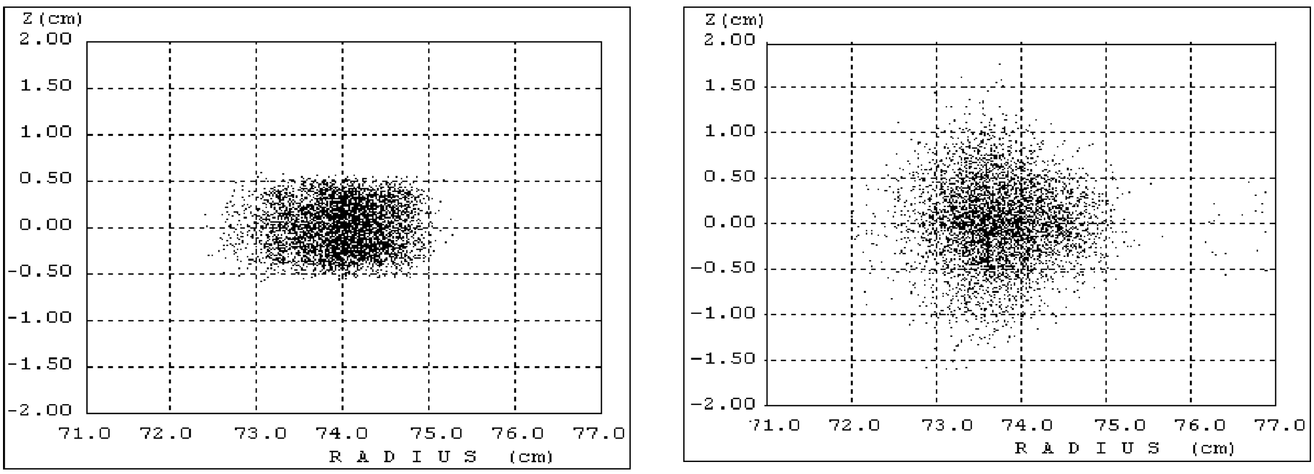

Fig. 8. Position of 5000 particles from rectangular (No. 9, Fig. 3) on plane (r, z) after 2000 turns.

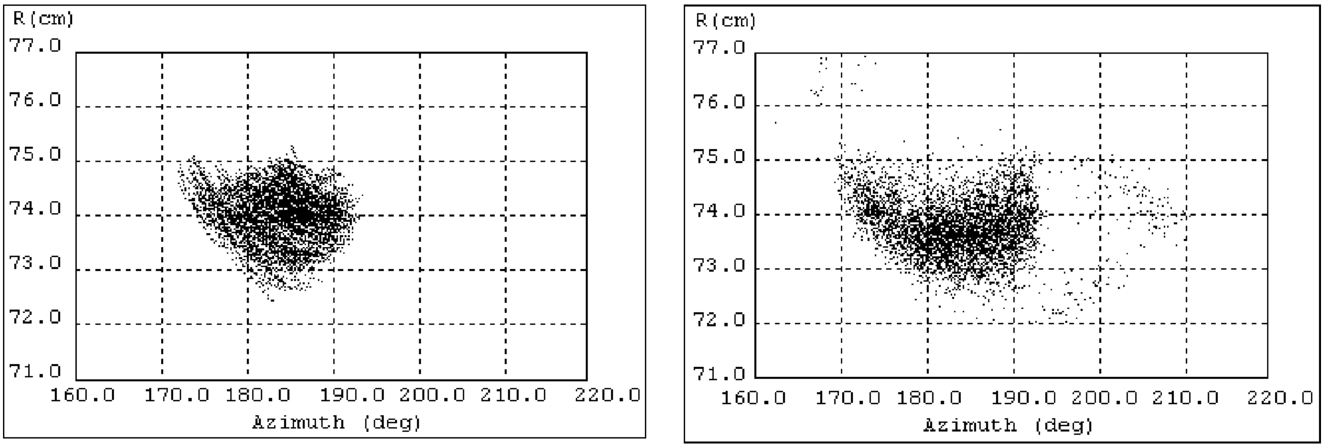

Fig. 9. Position of 5000 particles from rectangular (No. 9, Fig. 3) on plane (φ, *r*) after 2000 turns.

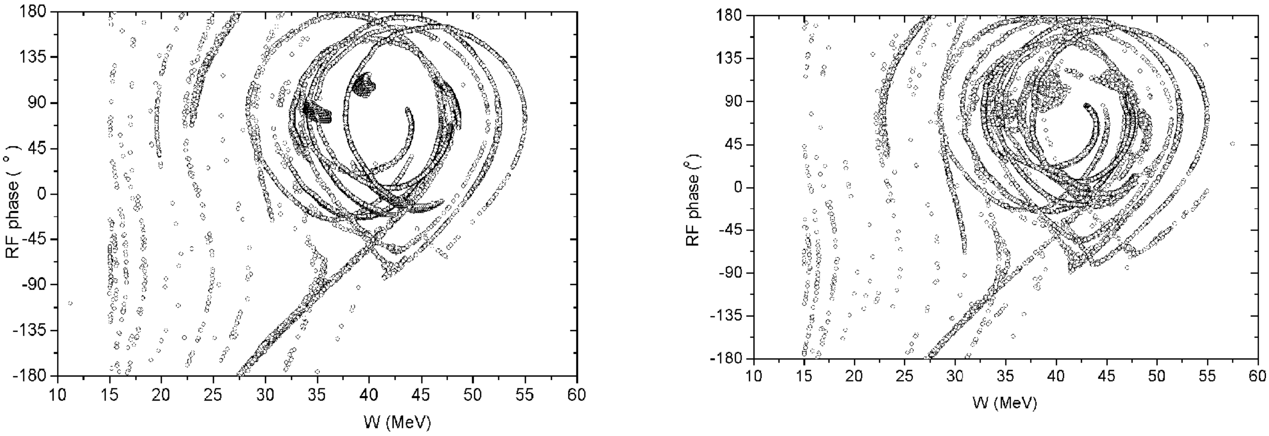

Fig. 10. Position of all captured particles from rectangulars (No. 1–18, Fig. 3) on plane (W–RF phase) after 2000 turns.

Results of computations

A particle whose radius in the process of calculation became less than 5 cm was considered lost because of the withdrawal to the center of the accelerator, therefore it was excluded from further calculation. A particle is also considered lost, when its amplitude of axial oscillations reached 2.3 cm. (The aperture of the dee is equal to 4.5 cm in the central region of the Phasotron.) Those particles which after 2000 turns did not fall under these conditions of the losses, but with energy less than 15 MeV were pointed out at the end of calculation, and were considered lost as not fallen inside the separatrix (phase losses). The remaining particles were considered as being captured into acceleration. The obtained results of particle losses for two variants of computations are shown in Table 2.

One can see that SCE increases particle losses by ~3% mainly due to enlargement of the axial size of the beam. Both withdrawal to the center and phase types of the losses become smaller under the influence of space charge forces.

The influence of SCE on axial, radial and phase motion is illustrated in Figs. 7–11.

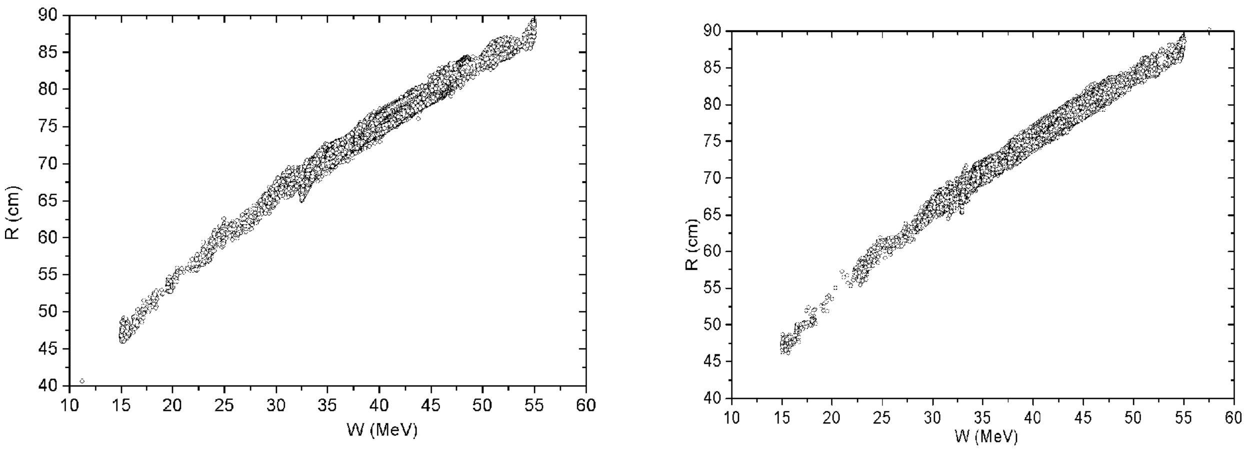

Fig. 11. Position of all captured particles from rectangulars (No. 1–18, Fig. 3) on plane (W–R) after 2000 turns.

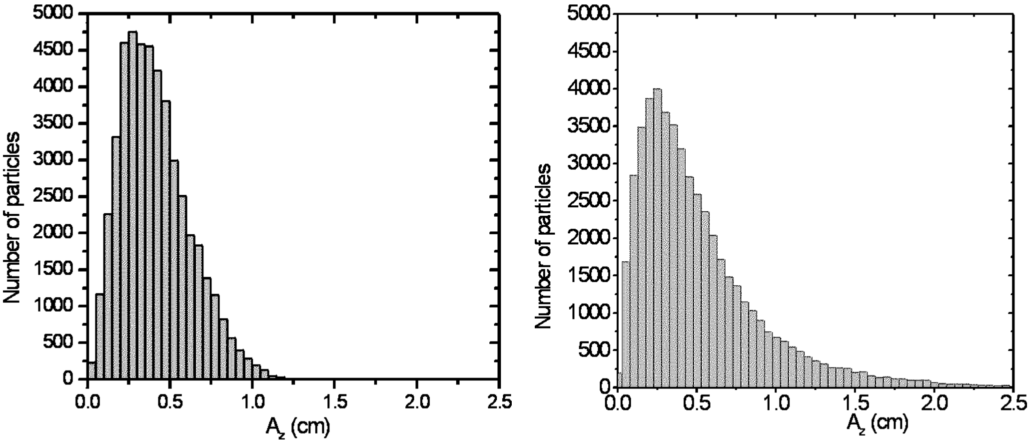

Fig. 12. Distribution of particle axial amplitudes after 2000 turns.

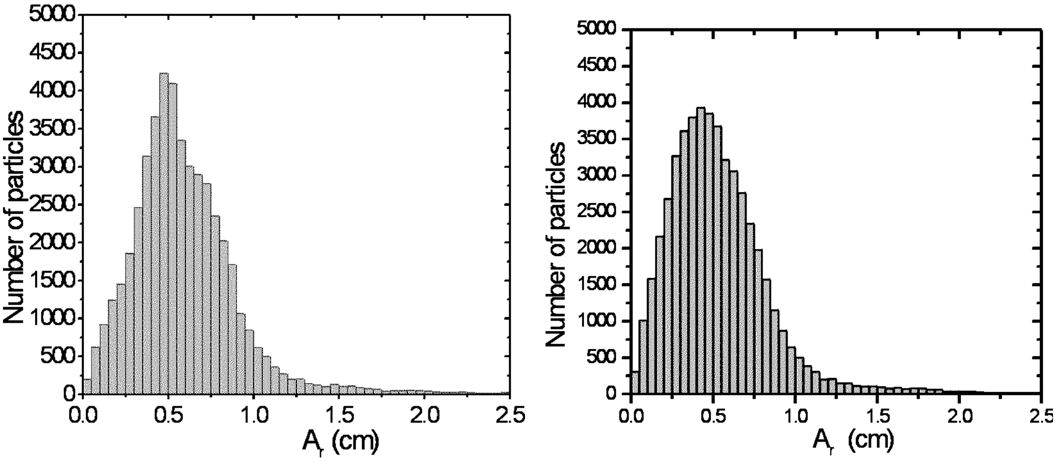

Fig. 13. Distribution of particle radial amplitudes after 2000 turns.

Distribution of all captured particles on amplitudes of free oscillations are shown in Figs. 12 and 13. The space charge forces causes mainly enlargement of the axial amplitudes, while the radial oscillations did not get any visible increase of their value. When SCE are off, for 95% of the particles the axial amplitudes are smaller than 0.85 cm, but if SCE are on, then this value increases to 1.35 cm. An analogous value for radial oscillations is equal to 1.3 cm in both types of the particle dynamic simulation.

Conclusions

The performed simulations have shown that the space charge effects reduced (for accepted beam model) the capture efficiency from 55% to 51% and increased the axial amplitudes from 0.85 cm to 1.35 cm for 95% of the captured particles. The influence of space charge on the radial amplitudes is rather small. We plan to study the capture efficiency dependence on the beam initial parameters (axial emittance, energy spread, number of injected bunches) and on the number of turns (5000 instead of 2000).

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