EXTERNAL INJECTION INTO THE JINR PHASOTRON. COMPUTER SIMULATION OF THE BEAM DYNAMICS TAKING INTO ACCOUNT THE SPACE CHARGE

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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 beam dynamics in Phasotron taking into account the beam space charge effects (SCE) is reported. As follows from the simulation, the capture efficiency decreases from ~70 to ~48% under influence of the SCE. At the same time maximal particle axial amplitude increases from 0.7 cm to 1.3 cm.

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1. INTRODUCTION

To increase the intensity of the JINR synchrocyclotron (Phasotron) from 5 to 50 μA, a project [1,2,5,6,8,9] of the external injection of the H^- 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 [9] and neutralisation ($H^- \rightarrow H^o$) is injected into the central region of the Phasotron. A carbon foil will be used in order to get a proton beam ($H^o \rightarrow p$). Some parameters of the Phasotron central region for the scheme of external injection (Fig. 1) are given in Table.

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 on the particle dynamics. For studying of SCE in synchrocyclotron, code PHASCOL was created. A method of large (macro) particles is realised in this code. Two methods are possible to be used in the code for calculating electric field of the beam: the particle-to-particle (PTP) method and particle-in-cell (PIC) one. 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 fast Fourier's transform three-dimensional Poisson's equation is solved numerically on a grid, which covers beam. The code is supplied with an on-line graphics, which illustrates the set of initial conditions and the results of calculations. The code PHASCOL was described in detail in [7]. Comparison PTP and PIC methods showed that PIC method calculated the space charge electric field by ~20 times faster than PTP one when number of macroparticles was of about 10000.

Using the code PHASCOL some computations that covered first 2800 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 efficiency of particle capture into acceleration.

2. INITIAL CONDITIONS

Earlier, in the calculations [5,6] of particle capture into the acceleration without SCE it was shown that the time capture of the beam with 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 positions on the plane time -RF phase are shown in Fig. 2. One starting bunch consisted of 200 particles. The charge of one macroparticle was equal $0.36 \cdot 10^7$ proton charges.

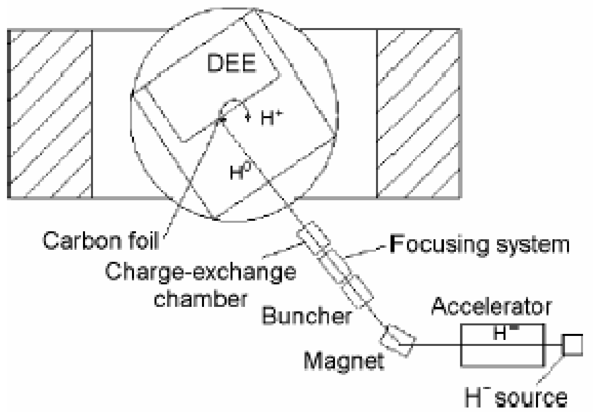

Fig.1. Schematic diagram of the external injection

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; ν_z	1.01; 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)	37.0

The position of particles in the phase space (r, r', z, z') was matched with the acceptance of synchrocyclotron in the region of stripping foil. The transverse emittances of beam were equal to 100 π mm·mrad and 15 π·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.

At first stage of calculations only 25 bunches were injected in each rectangle in Fig. 2 (results of this simulation see in [1]). This limitation was imposed by insufficient computer operational memory. The almost full rejection of the on-line graphics from the PHASCOL has increased by 10 times the operational memory available for calculation. As a result an opportunity has been appeared to use full injection time 46 μs for each phase range.

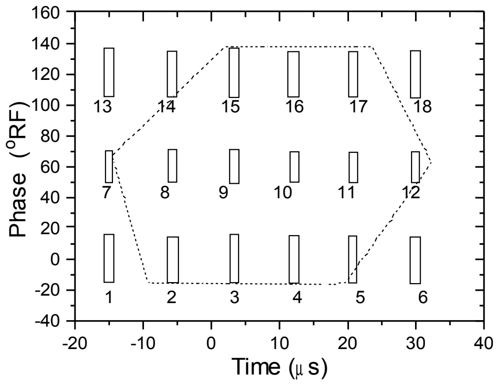

Fig.2. Position of the injected bunches on plane (time, RF phase). Each of 18 rectangles contains 25 bunches, 5000 particles. Dashed line shows a boundary of the capture region determined by earlier computation without SCE

3. SIMULATION AND RESULTS

The next scheme of calculations was used for full time injection. The 812 bunches were injected for each of the above mentioned ranges of the initial phases, altogether 3 $\times$ 812=2436 bunches. Full number of the injected particles (200 macro particles inside each bunch) was equal to 487200, injected current was equal 6.6 mA during the injection time 46 μs. Some particles were lost during injection time due to two next reasons:

- particle went to the center (radius less than 5 cm)
- particle hit the dee plate(axial amplitude larger than 2.3 cm)

Each injected particle had its own number from 1 to 487200. At the end of injection only 10000 particles from all injected ones were chosen by the random sampling for future examination. At this moment some of them were turned out due to the above mentioned reasons. The rest particles (~6200) got the initial electric charge multiplied by 48.72 and then accelerated for next 2000 turns. Hence, the final turn's number for the particles from the first injected bunch was equal 2812 and from the last bunch was equal 2000. Calculations were provided with and without space charge. For calculation of the space charge electric field the 3D grid with 128$\times$ 128$\times$ 16 cells was used by means of PIC method

As it was mentioned above, the particles, that had the axial amplitude larger than 2.3 cm and also those, which had the radius less than 5 cm were considered as lost ones. In addition, the particles with the energy less than 15 MeV after 2812 turns also were considered as lost ones. The main results of simulation are shown in fig. 3-6.

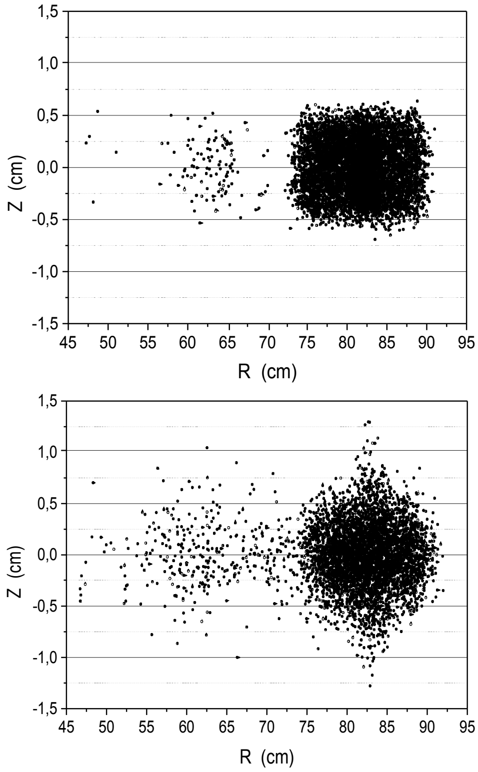

Fig.3. Final particle position on plane (R-Z) after 2812 turns. Above – without SCE, below – with SCE

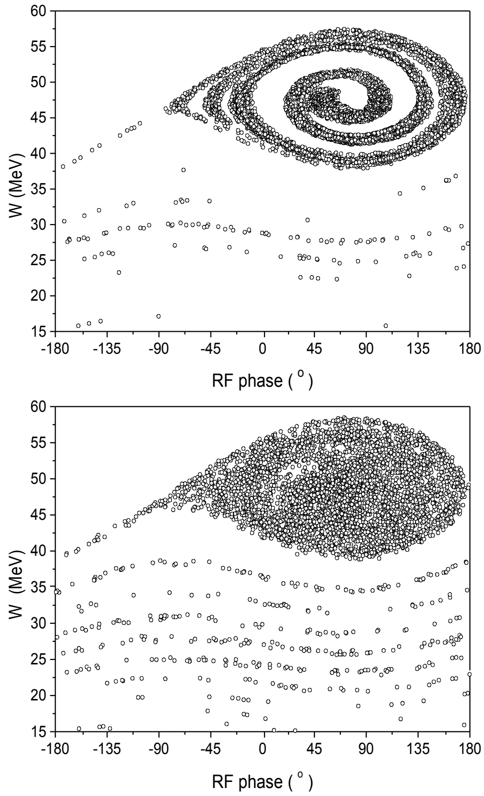

Fig.4. Final particle position on the plane (RF phase -W) after 2812 turns. Above – without SCE, below – with SCE

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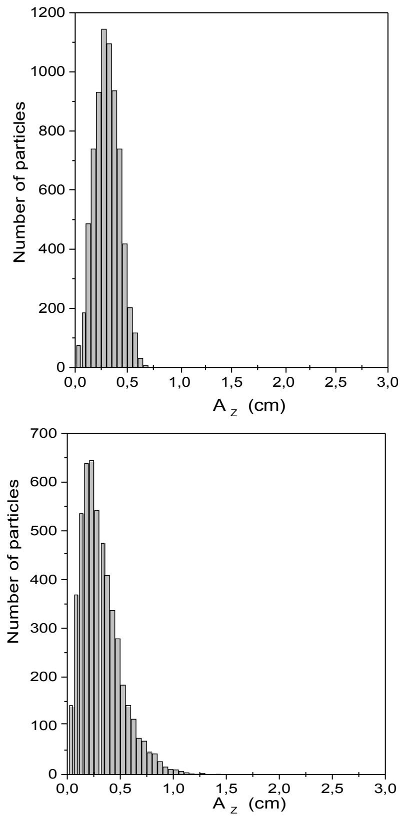

Fig.5. Particle distribution on amplitudes of axial oscillations after 2812 turns. Above – without SCE, below – with SCE

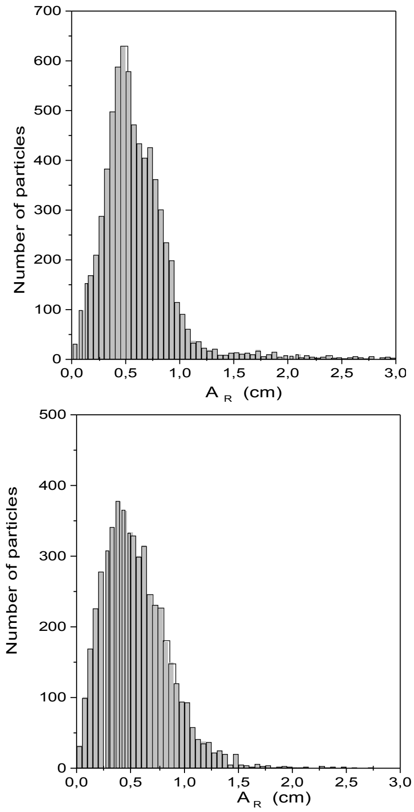

Fig.6. Particle distribution on amplitudes of radial oscillations after 2812 turns. Above – without SCE, below – with SCE

The capture efficiency is found to be 70% without SCE (only phase losses were observed) and 48% with SCE (31 and 21% of particles comprised axial and phase losses, respectively). Decreasing of the capture efficiency is occurred mainly due to the axial losses. The beam axial size at the end of simulation (2812 turns) is equal to 1.4 cm without SCE and 2.6 cm with SCE. There is no observed the radial betatron amplitude growth with SCE. Due to SCE the separatrix (see Fig.4) is filled up more homogeneously.

4. CONCLUSIONS

As follows from the performed simulation, the Phasotron intensity will be increased up to 37 μA (instead of planned 50 μA) for the injected beam current of 6.6 mA with energy 5 MeV.

We are going to extend our simulation at least up to 10000 turns and to study the influence of the RF-time program on the decreasing the phase losses.

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ВНЕШНЯЯ ИНЖЕКЦИЯ В ФАЗОТРОН ОИЯИ. ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ДИНАМИКИ ПУЧКА С УЧЁТОМ ПРОСТРАНСТВЕННОГО ЗАРЯДА

Л.М. Онищенко, Е.В. Самсонов

Разработана 3-х-мерная программа для расчёта динамики пучка в фазотроне с учётом 3-х-мерного распределения пространственного заряда. В результате численного моделирования с помощью этой программы в фазотроне в течение 2000 первых оборотов установлено, что из-за аксиальных потерь под действием пространственного заряда коэффициент захвата уменьшается на 17%. При этом амплитуда аксиальных колебаний частиц, захваченных в ускорение, удваивается.

ЗОВНІШНЯ ІНЖЕКЦІЯ У ФАЗОТРОН ОІЯД. ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ ДИНАМІКИ ПУЧКА З УРАХУВАННЯМ ПРОСТОРОВОГО ЗАРЯДУ

Л.М. Онищенко, Є.В. Самсонов

Розроблена 3-х-вимірна програма для розрахунку динаміки пучка у фазотроні з урахуванням 3-х-вимірного розподіли просторового заряду. У результаті чисельного моделювання за допомогою цієї програми у фазотроні протягом 2000 перших обертів установлено, що через аксіальні втрати під дією просторового заряду коефіцієнт захоплення зменшується на 17%. При цьому амплітуда аксіальних коливань часток, захоплених у прискорення, подвоюється.