PROGRAM COMPLEX FOR CYCLOTRON BEAM DYNAMIC SIMULATIONS

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Abstract

The program complex in MATLAB intended for particle dynamic simulations is described. Programming in an easy-to-use environment permits creation of models in a short space of time. Advanced graphical tools of MATLAB give good visualization features to created models. The beam dynamic modelling results by the example of two different cyclotron designs are presented.

PROGRAM COMPLEX

It is necessary to perform large quantity of computer simulations for design and development of cyclotrons. There is a need to carry out 3D electric and magnetic field calculations and then beam dynamic simulations in calculated fields taking into account various multiparticle effects, for example space charge effects, ion losses due to charge exchange with the residual gas or H$^-$ dissociation losses in electromagnetic field. For this purpose MATLAB is useful because numerous Toolboxes of this system can provide researcher with all necessary subprograms of integrating of differential equations of motion, finite elements codes for 3D electric and magnetic field calculations and codes for statistical analysis. To perform all necessary for cyclotron design calculations one need to solve systems of differential equations of particle motion written in Cartesian coordinate system (to simulate particle motion in transport lines) and in cylindrical coordinate system (to simulate particle motion inside cyclotron). It is essential to use time as independent variable if you want to consider space charge effects. But if you may neglect space charge effect it is more convenient to use azimuth angle as independent variable (in cylindrical coordinate system) This is why subprograms of three types of differential equation systems were written and used in our simulations depending on kind of cyclotron system under consideration.

First of all we'll say a few words about cyclotrons by the example of which we'll demonstrate wide possibilities of programmes written in MATLAB. The fist one is cyclotron CYTRACK dedicated to irradiate by heavy ions the polyethylene foils, which are used for the membrane production. CYTRACK started working in Dubna in August 2002. The second one is the project of Cyclotron Injector CI-5 into JINR Phasotron.

CYTRACK DYNAMIC SIMULATIONS

CYTRACK is an isochronous cyclotron with E-shape electromagnet, four pairs of sector shims for axial focusing, axial injection, radio-frequency accelerating system and electrostatic deflectors for extracting ions from the accelerator [1].

The main characteristics of CYTRACK are given in Table 1.

Table 1:

Accelerated particle		$^{40}Ar^{8+}$
Ion source type		ECR
Type of injection		axial
Injection energy	(MeV/nucleon)	0.003
Final energy	(MeV/nucleon)	2.4
Injection radius	(mm)	53
Extraction radius	(mm)	730
Mean magnetic field	(T)	1.48
Voltage amplitude	(kV)	40÷50
Frequency	(MHz)	18.258
Harmonic number		4

Numeric simulations are carried out for 1000 particles. For ion dynamic simulations in CYTRACK cyclotron code KRYC is developed which takes into account space charge effects and ion beam losses due to charge exchange with the residual gas. Calculated 3D electric accelerating field map and measured magnetic field maps [2] are used for simulations.

Initial transversal emittances are equal to 140 π×мм×мрад, initial phase extension - 20° RF. Ion beam dynamic simulations are made for ion motion modelling through injection line, spiral inflector, accelerating area, extraction system and high energy beam transport. Here we'll demonstrate some results of ion dynamic simulations.

Fig. 1 demonstrates beam bunch creation along z-axis after sinusoidal double drift buncher (z = 0 corresponds to the beginning of the first accelerating gap). The axial buncher is driven by a single frequency and it is designed to operate at the same frequency of the cyclotron. Voltage amplitude on the buncher was 100 B, providing focus location from the buncher – 120 cm. The operation tests have showed an increasing of the extracted beam current of a factor 3÷3.5 when the buncher is switched on. These values of bunching efficiencies are in good agreements with buncher modelling results and evaluated longitudinal acceptance of the central region which is of about 35° RF.

Fig. 2 shows beam energy variation vs distance from buncher. One can see small energy spread narrowing induced by space charge. The paths of argon ions in the

cyclotron including extraction system (computer modelling with accelerating voltage amplitude equal to 40 kV) are presented in Fig. 3.
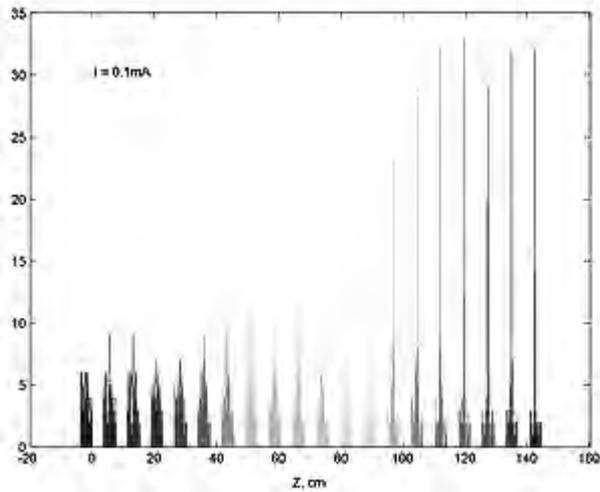

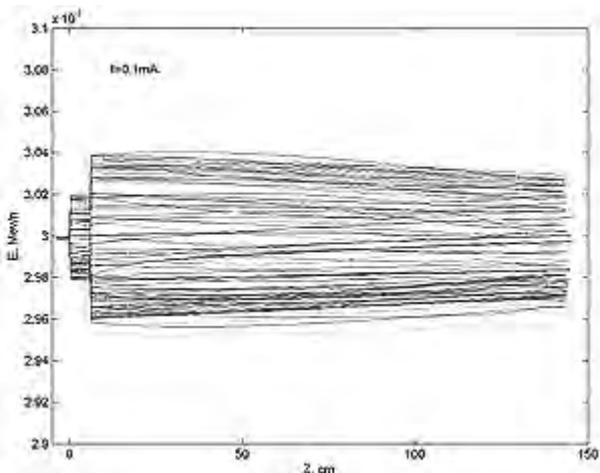Figure 1: Sinusoidal buncher (taking into account space charge effects).

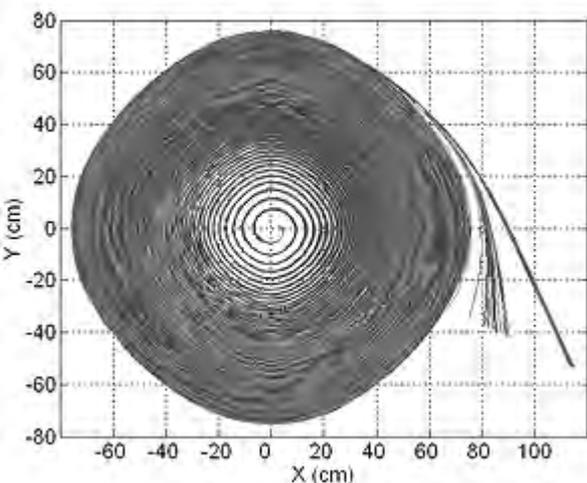Figure 2: Beam energy vs distance from buncher (taking into account space charge effects).

Figure 3: The paths of argon ions.

Thus computer model of CYTRACK cyclotron for beam dynamic simulations through all accelerator systems in MATLAB is developed.

CI-5 DYNAMIC SIMULATIONS

Separated sector cyclotron injector CI-5 has been studied in the framework of the external injection into Phasotron project. The main parameters for calculation are given in Table 2.

Table 2:

Accelerated particle		H^-
Injection energy	(MeV)	0.5
Final energy	(MeV)	5
Injection radius	(cm)	27.4
Mean magnetic field	(T)	0.43
Voltage amplitude	(kV)	160÷240
Frequency	(MHz)	54.372
Harmonic number		8

Numeric simulations are carried out by integration of differential equations in cylindrical coordinate system direct Coulomb particle-to-particle method is used to take into account space-charge effects. For this purpose in MATLAB new code KASCADS is developed. Calculated electric accelerating field map and magnetic field maps are used for simulation.

Fig. 4 shows voltage amplitude increase along radii received from analytic estimation (red hatch) and numeric 3D high frequency calculation of the cavity (blue firm line). Program for analytical estimation of cavity voltage distribution is written in MATLAB. One can see good enough coincidence of both results.
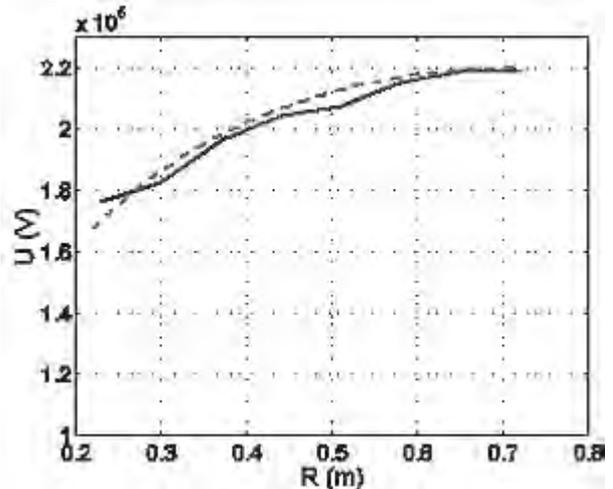

Figure 4: Voltage amplitude vs radii.

The paths of H^- ions in the cyclotron (computer modelling for beam intensities I = 0 mA and I = 30 mA) are presented in Fig. 5, Fig. 6. Axial trajectories of H^- ions are shown in Fig. 7, Fig. 8 (also for two values of intensities).
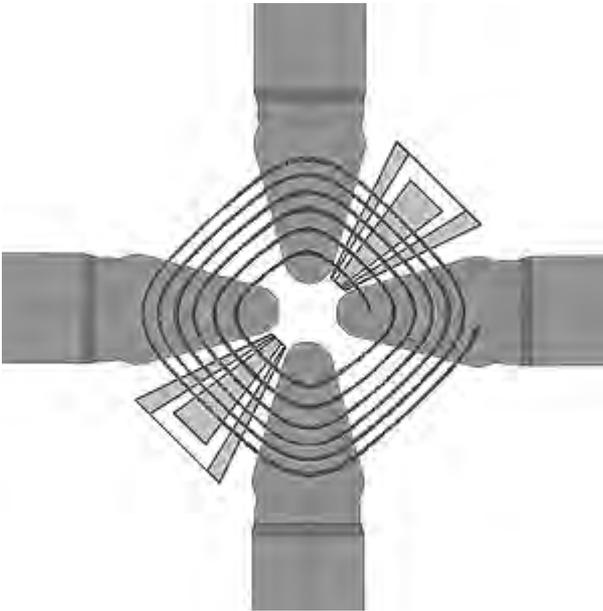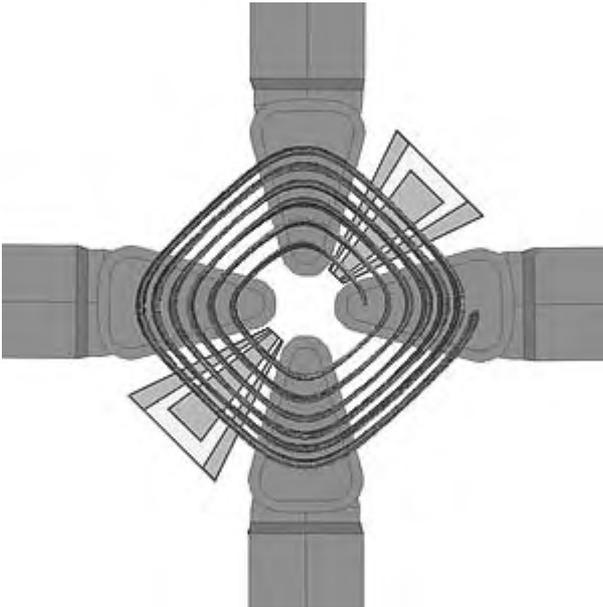
Figure 5: The paths of H⁻ ions in CI-5 (I = 0 mA).

Figure 6: The paths of H⁻ ions in CI-5 (I = 30 mA).

Computer modelling of the particle motion confirms that it is possible to achieve separated orbits in a 5 MeV, 30 mA separated sector cyclotron (accelerating voltage varies depending on radius from 160 kV in the centre to 240 kV in the extraction region). The aperture of the accelerator must be greater than 3 cm. Figures presented demonstrate extensive facilities of MATLAB for displaying numerical results.

CONCLUSION

Programming with MATLAB opens wide possibilities of the development of the complex program, able to perform complete block of calculations required for the design of the accelerators.
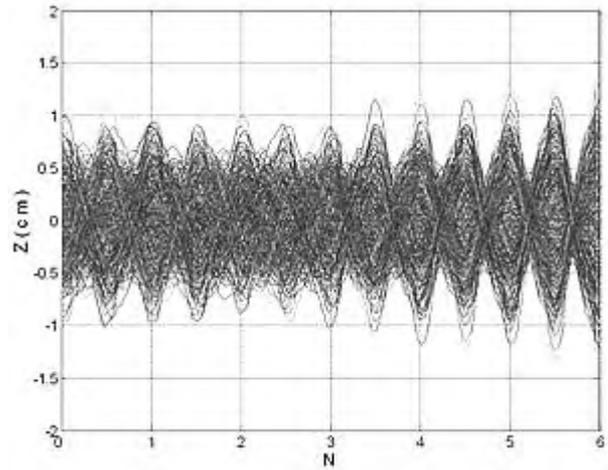

Figure 7: Axial trajectories of H⁻ ions (I = 0 mA).
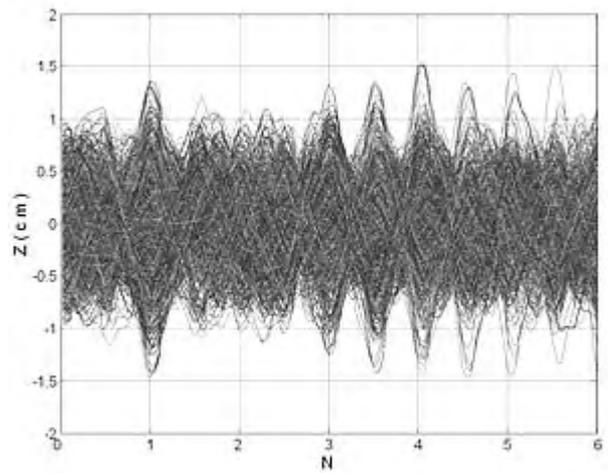

Figure 8: Axial trajectories of H⁻ ions (I = 30 mA).

REFERENCE

[1]. Yu. G. Alenitsky et al., Design and manufacture of complex ALFA for track membranes production, submitted to Atomnaya energia.
[2]. Yu. G. Alenitsky et al., Magnetic system of the heavy ions cyclotron for track membranes production, Nukleonika, Suppl. 2/03, 2003, p. 342.