Simulation of operation modes of isochronous cyclotron by a new interative method

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Abstract. Operation mode simulation methods are based on selection of trim coil currents in the isochronous cyclotron for formation of the required magnetic field at a certain level of the main coil current. The traditional current selection method is based on finding a solution for all trim coils simultaneously. After setting the calculated operation mode, it is usually necessary to perform a control measurement of the magnetic field map and to repeat the calculation for a more accurate solution. The new current selection method is based on successively finding solutions for each particular trim coil. The trim coils are taken one by one in reverse order from the edge to the center of the isochronous cyclotron. The new operation mode simulation method is based on the new current selection method. The new method, as against the traditional one, includes iterative calculation of the kinetic energy at the extraction radius. A series of experiments on proton beam formation within the range of working acceleration radii at extraction energies from 32 to 59 MeV, which were carried out at the AIC144 multipurpose isochronous cyclotron (designed mainly for the eye melanoma treatment and production of radioisotopes) at the INP PAS (Kraków), showed that the new method makes unnecessary any control measurements of magnetic fields for getting the desired operation mode, which indicates a high accuracy of the calculation.

Key words: cyclotron • operation mode • mathematical model

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Received: 25 July 2006
Accepted: 20 November 2006

Introduction

The operation mode of a multipurpose isochronous cyclotron designed for acceleration of particles with different A/Z ratio comprises a set of currents in the main coil and trim coils and calculated value of the RF oscillator frequency and dee potential. The operation mode is simulated for a particular particle acceleration task and allows the desired magnetic field to be formed with a given accuracy within the range of working acceleration radii from the injection system to the ion beam extraction system. The initial data include the type of particles to be accelerated, the extraction radius, the kinetic energy of particles at the extraction radius, the harmonic number, the magnetic structure periodicity, the working point selection radius and the measured or simulated magnetic field maps (for the flutter accounting). The working point is the cross point of the isochronous magnetic field and the mean magnetic field from the main coil current. The isochronous magnetic field at the working point selection radius is used for the main coil current calculation. The operation mode

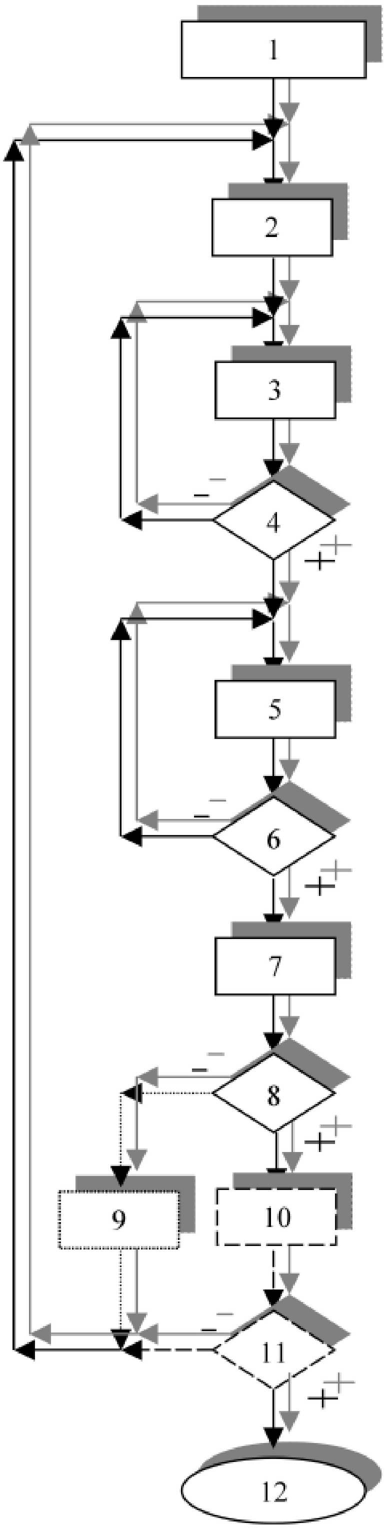

Fig. 1. Block diagram of the simulation of the isochronous cyclotron operation modes. 1 – Input of initial data: the type of particles to be accelerated, the extraction radius, the kinetic energy of particles at the extraction radius, the harmonic number, the magnetic structure periodicity, the working point selection radius and the measured or simulated magnetic field maps (for the flutter accounting); 2 – calculation of the particle circulation frequency as a function of the kinetic energy at the given extraction radius; 3 – calculation of the main coil current for the isochronous magnetic field at the working point selection radius; 4 – accuracy evaluation criterion for the calculation of the main coil current $|\Delta I_{mc}| < \varepsilon_I$; 5 – in the traditional method: simultaneous calculation of a set of employed trim coil currents at the calculated level of the main coil current. In the new method: successive calculation of current in each employed trim coil at the calculated level of the main coil current; 6 – in the traditional method: criterion for evaluation of the isochronous magnetic field shift value depending upon the influence of the contributions from the trim coils on the flutter $|\Delta B_{is}| < \varepsilon_{\Delta B}$ (optional). In the new method: criterion for evaluation of the maximum phase motion value depending upon the error of the mean magnetic field: $|\Delta\varphi| < \varepsilon_{\Delta\varphi}$; 7 – calculation of the kinetic energy at the given extraction radius; 8 – accuracy evaluation criterion for calculation of the kinetic energy at the given extraction radius $|\Delta E| < \varepsilon_E$; 9 – correction of the kinetic energy at the given extraction radius; 10 – setting of the calculated trim coil currents with subsequent measurement of the magnetic field; 11 – criterion for evaluation of the maximum phase motion value depending upon the error of mean magnetic field: $|\Delta\varphi| < \varepsilon_{\Delta\varphi}$; 12 – calculation of the RF oscillator frequency and formation of the isochronous cyclotron operation mode.

calculation is carried out using a set of measured or simulated magnetic field maps. The pointers to corresponding files are stored in the isochronous cyclotron database. Simulation of the operation mode is based on selection of trim coil currents at the calculated level of the main coil current. The traditional current selection method is based on finding a solution for all trim coils simultaneously. The new current selection method is based on successively finding solutions for each particular trim coil. The trim coils are taken one by one in reverse order from the edge to the center of the isochronous cyclotron.

Operation mode simulation algorithm

Figure 1 shows a general block diagram of the simulation algorithm for the operation mode of an isochronous cyclotron. Marked in dash lines is that part of the algorithm which is used only with the traditional method and marked in point lines is that part of the algorithm which is used only with the new method of selecting trim coil currents at the calculated level of the main coil current.

In the traditional method, after setting the simulated operation mode, it is usually necessary to perform a control measurement of the magnetic field map and to repeat the calculation for receiving corrections to the previous solution. A series of experiments on proton beam formation within the range of working acceleration radii at extraction energies from 32 to 59 MeV, which were carried out at the AIC144 isochronous cyclotron at the INP PAS (Kraków), showed that the new method makes unnecessary any control measurements of magnetic fields for getting the desired operation mode, which indicates a high accuracy of the calculation.

Mathematical models

In the traditional as well as in the new trim coil current selection method all calculations are carried out at the calculated level of the main coil current determined on the basis of the working point selection.

Using the traditional trim coil current selection method, one first takes the difference between the isochronous magnetic field and the mean magnetic field from the main coil current

$$(1)\qquad \Delta\overline{B}_{bs,i} = \Delta\overline{B}_{is,i}, \quad (i = 0 \sim n, I_{mc})$$

where: i is the index of the radius value; $\overline{B}_{is,i}$ is the isochronous magnetic field at the i-th radius; $\overline{B}_{bs,i}$ is the averaged by azimuth mean magnetic field from the main coil current at the i-th radius; I_{mc} is the main coil current. The radius values are taken from 0 to maximum value according to the range and step of the magnetic field map measurements.

To compensate for the above difference, one takes, with some residual, a sum of the mean magnetic fields of the contributions from the trim coils:

$$(2)\qquad \Delta\overline{B}_i = \sum_{j=0}^{m} \frac{\Delta\overline{B}_{i,j}}{\Delta I_j} \cdot I_j, \ (i = 0 \sim n, I_{mc})$$

where: $\Delta\overline{B}_{i,j}$ is the mean magnetic field of the contribution from the j-th trim coil at the i-th radius; ΔI_j is the change of the j-th trim coil current for $\Delta\overline{B}_{i,j}$; I_j is the current of the j-th trim coil. The dependence of the trim coil contribution upon its current at the calculated level of the main coil current is assumed to be directly proportional for all values of the trim coil current.

When using the point least-squares method, one constructs the following functional to minimize the sum of squares of residues over all i-th radii:

$$(3)\qquad S(I_0, I_1, ..., I_m) = \sum_{i=0}^{n} \left(\Delta\overline{B}_i - \Delta\overline{B}_{bs,i}\right)^2, \quad (I_{mc})$$

where: $I_0, I_1, \ldots, I_m$ are the trim coil currents.

The least-squares method yields the following inhomogeneous system of linear algebraic equations:

$$(4)\qquad \sum_{j=0}^{m}\left[\left(\sum_{i=0}^{n}\left(\frac{\Delta\overline{B}_{i,j}}{\Delta I_j}\cdot\frac{\Delta\overline{B}_{i,k}}{\Delta I_k}\right)\right)\cdot I_j\right] = \sum_{i=0}^{n}\left[\Delta\overline{B}_{bs,i}\cdot\frac{\Delta\overline{B}_{i,k}}{\Delta I_k}\right],$$
$$(k = 0 \sim m, I_{mc})$$

where: i is the index of the radius value; j is the index of the trim coil, and k is the index of the algebraic equation in the system.

A solution of the inhomogeneous system of algebraic equations can be found by the direct Gaussian method and represented as

$$(5)\qquad I_j, \quad (j = 0 \sim m, I_{mc})$$

where I_j are the trim coil currents at the calculated level of the main coil current.

In the new trim coil current selection method, the difference between the mean magnetic field, depending upon the set of currents in all coils of the isochronous cyclotron and the isochronous magnetic field, is taken for each trim coil:

$$(6)\qquad \Delta\overline{B}_{mn,i}(I_l) = \overline{B}_{mn,i}(I_l) - \overline{B}_{is,i}, \quad (i = 0 \sim n, l = 0 \sim s, I_{mc})$$

where: i is the index of the radius value; l is the index of the trim coil current value; $\overline{B}_{mn,i}(I_l)$ is the mean magnetic field at the i-th radius depending upon the l-th current value in the trim coil under consideration when main field and contributions from the considered earlier trim coils are taken into account; $\overline{B}_{is,i}$ is the isochronous magnetic field at the i-th radius; I_{mc} is the main coil current. The aforementioned difference is taken as many times as it is prescribed according to the required step in the current in the trim coil under consideration and the range of its permissible values.

Then, one constructs a discrete function of the current in the trim coil under consideration at the calculated level of the main coil current for the radius-averaged square of the deviation of the mean magnetic field from the isochronous magnetic field:

$$(7)\qquad F_l(I_l) = \frac{\sum_{i=0}^{n}\left(\Delta\overline{B}_{mn,i}(I_l)\right)^2}{n+1}, \quad (l = 0 \sim s, I_{mc})$$

where n is the maximum index value for the last radius value.

The necessary interpolation of the values of the discrete function is carried out by the cubic-splines method. Then, an optimum value of the current of the trim coil under consideration at the calculated level of the main coil current is found with the required accuracy by the Newton method:

$$(8)\qquad I_{\text{opt}}, \quad (I_{mc})$$

Isochronous magnetic field is successively calculated according to the procedure described in [1], using the software described in kind of the separate module in [2] (see references therein). Optimum currents in each particular trim coil are successively calculated one by one in reverse order from the edge to the center of the isochronous cyclotron. The minimum and maximum main coil current values, the minimum and maximum trim coil current values and the low limit and upper limit values of the isochronization range are used as boundary conditions.

The main difference between two mathematical models is conditioned by the methods of finding the solution. The traditional trim coil current selection method implies finding the solution from the main field by one step. The new trim coil current selection method implies finding the solution from the main field step by step.

Results

On 16 December 2004, 20 June 2005 and 15 December 2005, experiments on proton beam formation within the range of working acceleration radii for the calculated middle, high and low kinetic energies of the particles respectively were carried out at the AIC144 multipurpose isochronous cyclotron of the INP PAS (Kraków). All the ion beams were successfully accelerated without empirical trimming of the trim coil currents and without empirical trimming of the RF oscillator frequency within the range of the working acceleration radii. Table 1 shows the results of the calculations.

The extraction radius is the mean radius of the closed equilibrium orbit. The extraction radius value is used for calculation of the rotation frequency and the kinetic energy of the particles. Conditions for the optimal phase motion within the range of the working

Table 1. Isochronous cyclotron operation modes

Item	Mode 1 (15.12.2005)	Mode 2 (16.12.2004/I)	Mode 3 (16.12.2004/II)	Mode 4 (20.06.2005)
Type of particles	protons	protons	protons	protons
Working point selection radius (cm)	60.5	61.5	62	57
Isochronization range (cm)	8 ~ 61.5	8 ~ 61.5	8 ~ 62	13.5 ~ 57
Extraction radius (cm)	61.5	61.5	62	62
Extraction energy (MeV)	32.852	45.459	46.239	59.018
RF oscillator frequency (MHz)	20	23.31	23.31	26.15
Dee voltage (KV)	65	50	50	65
Main coil current (calculated) (A)	169.742	276.640	277.940	573.040
Main coil current (A)	169.800	276.250	277.840	573.880
Trim coil current N01 (A)	+30.0	+141.2	+211.0	+2.8
Trim coil current N02 (A)	0.0	–51.9	–78.3	0.0
Trim coil current N03 (A)	–98.5	+34.7	+40.2	+95.0
Trim coil current N04 (A)	–37.2	–54.3	–57.4	–5.6
Trim coil current N05 (A)	0.0	+ 166.2	+171.1	+93.6
Trim coil current N06 (A)	+11.2	–46.0	–51.2	+82.0
Trim coil current N07 (A)	+30.1	+157.0	+161.2	+75.5
Trim coil current N08 (A)	+25.9	+38.2	+36.2	–3.5
Trim coil current N09 (A)	+4.4	+35.7	+37.2	–98.9
Trim coil current N10 (A)	–12.5	–21.4	–23.3	–149.2
Trim coil current N11 (A)	–17.8	–8.1	–7.5	–213.9
Trim coil current N12 (A)	+9.7	+21.0	+18.8	–232.6
Trim coil current N13 (A)	+55.8	+39.6	+36.4	–138.9
Trim coil current N14 (A)	+78.1	+162.6	+166.8	–101.0
Trim coil current N15 (A)	+67.3	–52.7	–59.0	–338.7
Trim coil current N16 (A)	+113.9	+61.8	+59.0	–389.8
Trim coil current N17 (A)	+196.6	+47.4	+38.1	–54.1
Trim coil current N18 (A)	+164.6	+10.8	+27.7	–192.9
Trim coil current N19 (A)	+188.5	+97.8	+55.4	–165.0
Trim coil current N20 (A)	–21.9	+184.7	+170.2	–55.0

acceleration radii are achieved according to the following ratio: the working point selection radius value ≤ the upper limit value of the isochronization range ≤ the extraction radius value. The best result can be achieved when the working point selection radius value is equal to the extraction radius value. The phase motion can be corrected by changing the bump parameters or by changing the edge magnetic field gradient value. The phase motion correction is used for optimal ion beam extraction through the electrostatic deflector.

Figures 2a and 2b show the calculated phase motion and the experimental proton beam current value in mode 1.

The significant phase losses of the ion beam current in the operation mode 1 are due to the repair of the magnetic system of the isochronous cyclotron before the experiment. The experiment showed the necessity for new measurements of the main magnetic field maps used in calculations. The following measurements confirmed the validity of this conclusion.

Figures 3a and 3b show the calculated phase motion and the experimental proton beam current value in mode 2.

Figures 4a and 4b show the calculated phase motion and the experimental proton beam current value in mode 3.

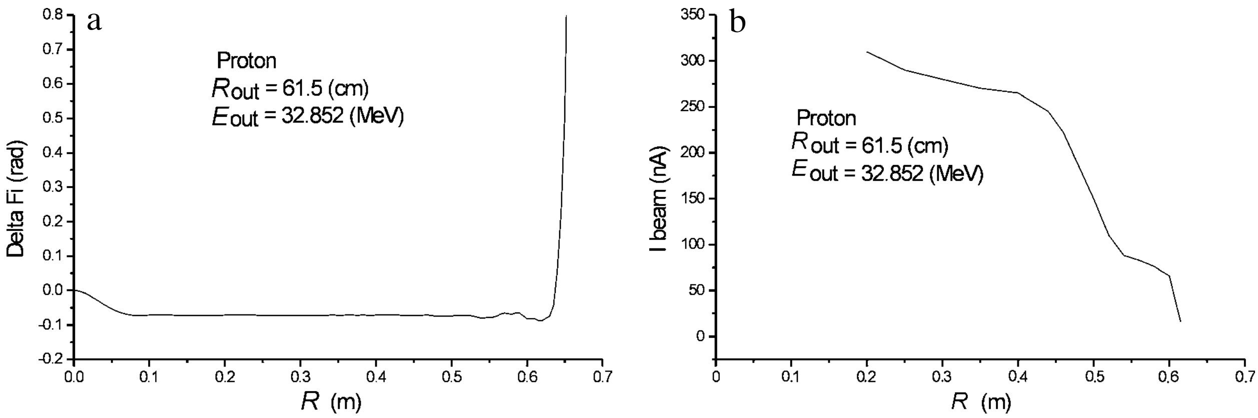

Fig. 2. Phase motion (a) and beam current (b) in mode 1.

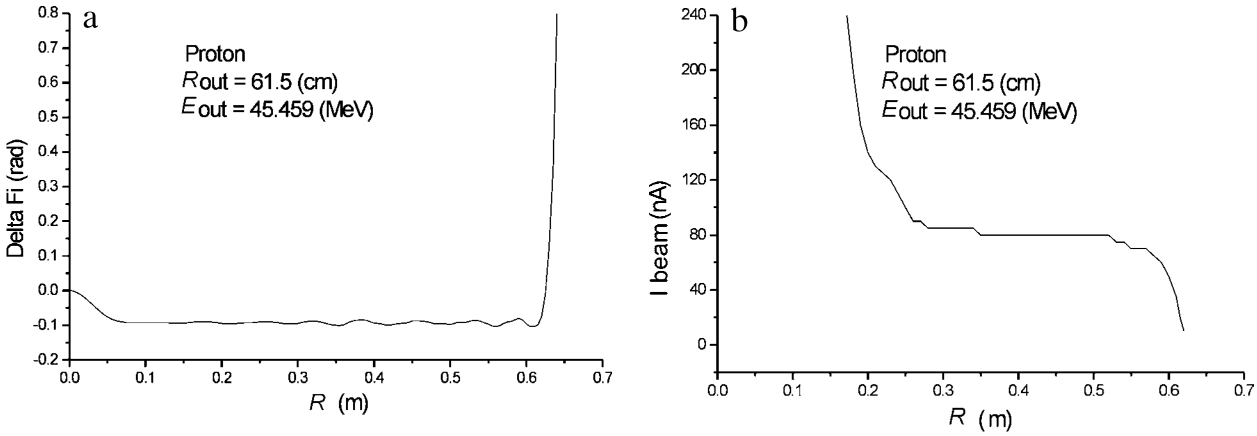

Fig. 3. Phase motion (a) and beam current (b) in mode 2.

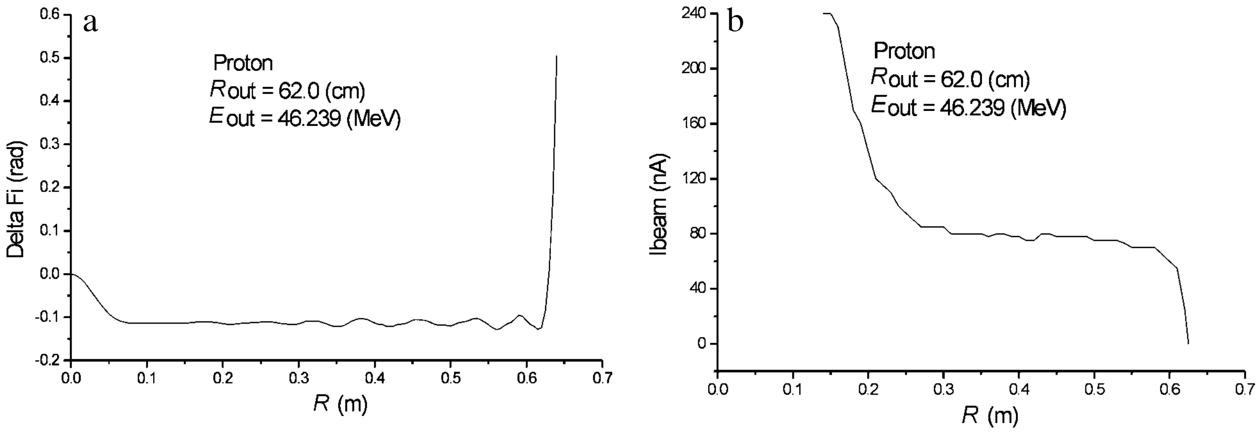

Fig. 4. Phase motion (a) and beam current (b) in mode 3.

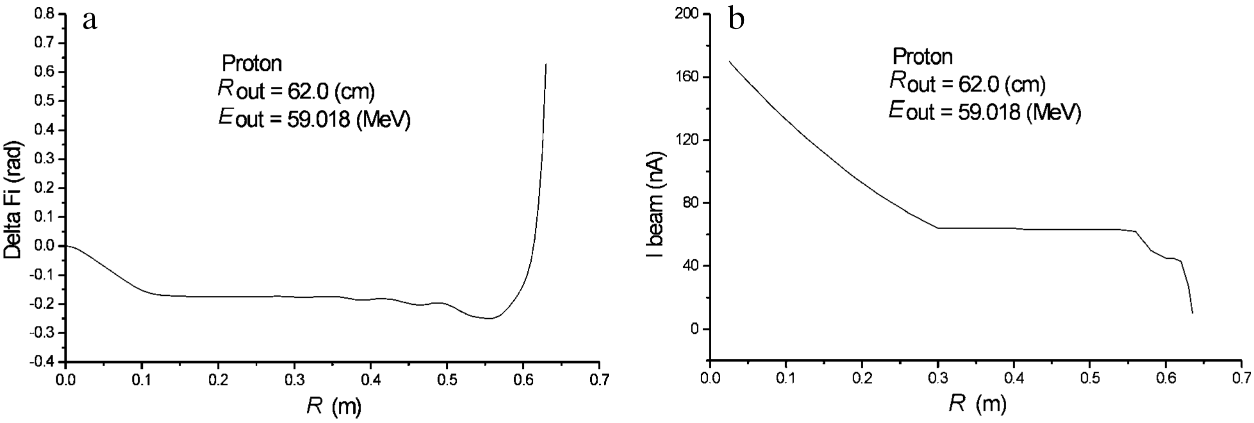

Fig. 5. Phase motion (a) and beam current (b) in mode 4.

Operation modes 2 and 3 were calculated for the same value of the RF oscillator frequency but for the two different values of the working point selection radii. Apart from that, two different isochronization ranges were set, which led to two different solutions.

Figures 5a and 5b show the calculated phase motion and the experimental proton beam current value in mode 4.

The working point selection radius value and the upper limit value of the isochonization range in operation mode 4 are significantly lower than in the previous operation modes. The selection of the radius value for determination of the working point is conditioned by the significant saturation of the main magnet iron at large values of the main coil current. The selection of the upper limit value of the isochronization range is conditioned by the small value of the vertical free oscillation frequency in front of the extraction radius.

An operation mode simulation program based on the new method of selecting trim coil currents at the calculated level of the main coil current was used for the calculations. This work was performed without taking into account the trim coil mutual influence, but the new approach provides such a possibility.

Conclusion

A series of experiments on proton beam formation within the range of working acceleration radii at kinetic energies of particles at the extraction radius from 32 to 59 MeV, which were carried out at the AIC144 multipurpose isochronous cyclotron at the INP PAS (Kraków), showed that the new method of operation mode simulation does not require control measurements of magnetic fields for getting the desired result. The new method, as against the traditional one, allows the time of bringing the ion beam to the final acceleration radius after setting the simulated isochronous cyclotron operation mode to be considerably reduced (to about 10 min), because the ion beam is accelerated without empirical trimming of trim coil currents and without empirical trimming of the RF oscillator frequency. The main coil current virtually does not differ from the calculated value and its insignificant adjustment arises only from temperature variation in the permeability of the main magnet iron. In addition, phase losses of the ion beam current within the range of working acceleration radii considerably are decreased because the mean magnetic field more closely approaches to the isochronous magnetic field. All the aforesaid indicates a high accuracy of the calculations by the new method, which leads to appreciable saving in the running time. This is especially important for the operation of a multipurpose facility which should be switched to a new, not yet calculated operation mode within a period of 2÷4 h between the task setting and the formation of ion beam at the final acceleration radius. Another advantage of the new method over the traditional one is simpler mathematical tools, which is in line with the main goal of mathematics to simplify the existing solution of the problem. On the other hand, the new method is far more complicated in realization than the traditional method because it implies processing large data arrays.

The program for simulation of operation modes of the isochronous cyclotron was developed in C++ using Visual C++ NET. The isochronous cyclotron database was developed in Transact-SQL for MS SQL Server 2000. The MS Windows Server 2003 operational system is used for running this software.

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