The Mathematical Modeling of Main Operation Mode of AIC-144 Multipurpose Isochronous Cyclotron

I.V. Amirkhanov[1], G.A. Karamysheva[1], I.N. Kiyan[1], J. Sulikowski[2]

e-mail: kin@nusun.jinr.ru, [1]Joint Institute for Nuclear Research, Dubna, Russia

[2]Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland

Introduction

The AIC-144 multipurpose isochronous cyclotron is located at the Institute of Nuclear Physics, Polish Academy of Sciences (INP, PAS) in Krakow and intended both for carrying out proton radiotherapy of eye melanoma (in the main operation mode) and for producing radioisotopes to be used in nuclear spectroscopy researches. The created technique makes it possible to model new operation modes of the AIC-144 cyclotron and switch to them without stopping and dismantling the accelerator for carrying out additional magnetic measurements. This technique comprises a set of algorithmically connected methods for calculation of currents in the main coil, twenty trim coils, and two pairs of harmonic coils of the AIC-144 cyclotron [1, 2].

The new technique was developed at the Dzhelepov Laboratory of Nuclear Problems, Joint Institute for Nuclear Researches (LNP, JINR) and the Laboratory of Information Technologies, Joint Institute for Nuclear Researches (LIT, JINR) in 2004-2012 within the Topical Plan for JINR Research (Theme No 03-2-1102-2010/2015 "JINR Phasotron improvement and design of cyclotrons for fundamental and applied researches") and the international protocols on cooperation between JINR and INP, PAS (Protocols No 3970-2-10/12 and 4268-2-13/15 on implementation of the projects "Revamping and preparation of the AIC-144 cyclotron for operation in the medical purposes (proton radiotherapy)" and "Revamping and operation of the AIC-144 cyclotron for proton radiotherapy of eye melanoma") with the financial support of the Russian Foundation for Basic Research (Projects No 10-01-00467-a and 13-01-00595-a).

Work Description

1. A set of interconnected methods combined into a new technique for mathematical modeling of the AIC-144 cyclotron operation modes was designed: (1) a new method for preparing maps of initial magnetic fields, (2) the first ever method for calculating the current in the main coil, (3) a new method for calculating the currents in twenty trim coils, (4) an advanced method for monitoring the accuracy of calculation of the isochronous magnetic field, (5) the first ever method for calculating the currents in two pairs of harmonic coils. The created technique makes it possible to model new operation modes of the AIC-144 cyclotron and switch to them without stopping and dismantling the accelerator for carrying out additional magnetic measurements.

2. The Cyclotron Operator HELP Program Complex 2004-2012 based on the created mathematical models and algorithms was developed in the C++ language. The computing kernel of the program complex is made in the form of the Gauss-DLL Dynamic-Link Library [3], which includes a set of matrix-vector operations and the solution of the SLAE with real coefficients.

3. In June 2009 the created technique was used on the AIC-144 cyclotron for the modeling of the main operation mode intended for accelerating and extracting a proton beam with the parameters necessary for proton radiotherapy of eye melanoma: the kinetic energy of proton extraction $E_k \sim 60\ MeV$ ($F_{rf} = 26,155\ MHz$); extracted beam current $I_{beam,ext} \geq 20\ nA$, and its stability $\sigma I_{beam,ext} \sim \pm 5\ \%$. As a result of the modeling, the AIC-144 cyclotron was successfully started up in the main operation mode on 04 June 2009.

4. The extracted proton beam without any corrections of the specified mode installed on the AIC-144 cyclotron was used:

a) For tuning of medical devices and equipment, which has been carried out for almost two years since of the installation of the specified mode.

b) For successful proton radiotherapy of eye melanoma in the first group of patients, which has been carried out for the first time in Poland in February-April 2011.

During 2011 and in the first half of 2012 the first 15 patients were successfully treated for eye melanoma [4].

5. In July 2012 in order to increase the kinetic energy of proton extraction this technique was used on the AIC-144 cyclotron for the modeling of another variant of the main operation mode: the kinetic energy of proton extraction $E_k \sim 60,5\ MeV$ ($F_{rf} = 26,26\ MHz$); extracted beam current $I_{beam,ext} \geq 20\ nA$, and its stability $\sigma I_{beam,ext} \sim \pm 5\ \%$. As a result of the modeling, the AIC-144 cyclotron was successfully restarted in the main operation mode on 17 July 2012.

6. In October 2012 the beam of extracted protons was used by LNP, JINR specialists for experiment-

calculated adjustment of the central region of the formed magnetic field. The adjustment, which involved relative positioning of the ion source, electrostatic deflector and magnetic channels increased the proton beam extraction factor by $k \approx 1,9$ *times* ($K_{ext} \approx 33$ %) [5].

7. In the first half of 2013 the license for the medical treatment of patients in the planned regime on the AIC-144 cyclotron was received, and proton radiotherapy of eye melanoma has been continued.

The Fig. 1 shows the photo of the AIC-144 multipurpose isochronous cyclotron.

Fig. 1: The AIC-144 multipurpose isochronous cyclotron.

The Fig. 2 shows the photo of the extracted proton beam profile at the exit from the AIC-144 cyclotron in the experiment of 17 July 2012.

Fig. 2: The photo of the extracted proton beam profile at the exit from the AIC-144 cyclotron in the experiment of 17 July 2012.

Mathematical Models

The most difficult and important task is correction of the main magnetic field generated by the main winding of the AIC-144 cyclotron. To this end, the calculation of currents in twenty trim coils of the AIC-144 cyclotron I_j, $j = 1, 2 \ldots z$ $(z = 20)$ is performed for the calculated level of current in the main coil $I_{main,work}$. The created mathematical model [6] is based on the least-squares method. It is a nonlinear functional that includes the penalty function intended for the directed component-by-component input of the solution vector (the vector of normalized values of optimized currents in the trim coils) into the range of admissible values. The nonlinear functional is minimized by equating to zero the partial derivatives with respect to each of the free components of the solution vector. A number of transformations results in a non uniform system of nonlinear algebraic equations, which is solved iteratively. At each step of the iterative cycle a non uniform system of linear algebraic equations is formed, which is solved by the Gaussian method with matrix pivoting.

The solution stability is provided by the stack mode exclusion from the calculation of a number of involved trim coils. (The current in the trim coil to be excluded from the calculation is set in 0 A). Each next trim coil is excluded on the basis of a new criterion: the minimum of the dependence of the product of the functional minimum and the SLAE conditionality number on the number of the trim coil to be excluded.

$$f = s \cdot cond(A), \qquad cond(A) = \|A\| \cdot \|A^{-1}\|$$

$$\|A\| = \max_{1 \le j \le k} \sum_{i=1}^{k} |a_{ij}|, \qquad \|X\| = \sum_{j=1}^{k} |X_j|$$

where s is the functional minimum; $\|A\|$ is the factor matrix norm; $\|X\|$ is the solution vector norm. ($\|A\|$ is being in subordination to $\|X\|$). Each iteration is based on the consecutive exclusion / inclusion into the calculation of all involved trim coils. The exclusion of each next trim coil is carried out with allowance for the maximum of admissible values of the functional minimum. The total number of the excluded trim coils is found from the minimum of the dependence of the calculated minimal values on the quantity of the excluded trim coils.

The improved method for monitoring the accuracy of the isochronous magnetic field calculation is based on the comparison of calculated relative error of the mean magnetic field (the relative difference between mean and isochronous magnetic fields) with calculated relative error of the rotation frequency of charged particles (the relative difference between the rotation frequency and the isochronous rotation frequency of charged particles). The rotation frequency of charged particles is calculated by numerical solution of equations of motion which is presented in the approach of closed equilibrium orbits. The equations of motion, initial conditions, and results of calculations for the main operation mode of the AIC-144 cyclotron are presented in [7]. For the better estimation of modeled operation modes it is necessary to consider the contributions from two pairs of harmonic coils and from magnetic channels of the AIC-144 cyclotron to the resulting magnetic field.

Conclusion

The main results of this work were reported at several Russian and international conferences and published in seven papers in four scientific peer-reviewed journals [1, 2]. The Cyclotron Operator HELP Program Complex 2004-2012 software is placed on the server of the AIC-144 cyclotron. The GaussDLL Dynamic-Link Library [3] is included in the JINRLIB program library accommodated on the JINR web-site.

The INP PAS Directorate took a decision based on the successful results of eye melanoma irradiation in the first 15 patients: To use the AIC-144 cyclotron for the planned medical treatment of patients beginning on 1 January 2013. The obtained results are confirmed by the letters:

a) From the INP PAS Directorate to the LIT JINR Directorate, No BD/47/2011 of 27 April 2011, about successful results of eye melanoma irradiation in the first group of patients.

b) From the INP PAS Directorate to the JINR Directorate, No ND/244/2012 of 12 October 2012, about using the AIC-144 cyclotron for the medical treatment of patients in the planned regime (registered in the JINR database, No 325-M of 26 October 2012).

In the first half of 2013 the license for the medical treatment of patients in the planned regime on the AIC-144 cyclotron was received, and proton radiotherapy of eye melanoma has been continued.

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