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A method of the magnetic field formation in cyclotron DC-72

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Abstract A method of the magnetic field formation in the cyclotron DC-72 model (scale 1:5) is described. The cyclotron is planned to be built in Slovakia. The stages in the shimming of the cyclotron sectors and an automatic system designed for magnetic measurements are described. The data on the magnetic field measurements in the median plane of the cyclotron are presented. A brief description of a computer simulation model and an algorithm of fitting the required sector profiles is presented, as well as the data on the computer simulation of magnetic field distributions. The data on the magnetic field measurements and those on the computer simulations are compared and analyzed. Possible reasons of differences between the measured and simulated data are discussed. The results of the above mentioned computer simulations will be used for building a large facility – the cyclotron DC-72.

Key words cyclotron • magnetic field measurements • magnetic field simulations

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Introduction

The isochronous cyclotron DC-72 [5] will be installed at the Centre of Nuclear Physics and Medicine of the Slovak Institute of Metrology, Bratislava, Slovakia. The cyclotron is dedicated to research in nuclear medicine and oncology. DC-72 is applicable for neutron therapy, neutron dosimetry and standardization, metrology of radioisotopes and ionizing radiation. The facility will be used for applied research in surface processing and ion implantation on various materials as well as for fundamental investigations in nuclear physics.

Methods of magnetic field forming

One of the key goals in the design of complex electromagnetic devices is to provide required magnetic field, especially in case of precise field distribution in the active area. An isochronous cyclotron requires enhanced quality of a formed magnetic field (accuracy of forming averaged isochronous field is up to 10^{-4}).

There are two basic methods of field forming, which supplement each other. The first method is to simulate field map using POISSON [4], TOSCA [6], KOMPOT [2] or similar programs. Prior to simulation, a *B–H* curve is measured on samples of ferromagnetic materials used in the constructions. The measured data are used to calculate magnetic fields. The second method implies direct magnetic measurements (if feasible) with the use of Hall probes or NMR-magnetometers. A field in the 1:5 scaled DC-72 prototype was formed using a combination of a mathematical synthesis of sector shapes and field mapping and measurement in the median plane. The measured and simulated data were used for a subsequent shimming of sectors.

Requirements to field distribution. Forming technique

Figure 1 presents an operating diagram for the DC-72. The cyclotron is designed to accelerate ions with A/Z from 1 (H^-) to 7.167 ($^{129}Xe^{18+}$) up to a final energy of 72.0 MeV/A and 2.7 MeV/A, respectively. This makes it necessary to provide isochronous fields inside the limits 0.9–1.5 T at the 0.08 T field difference between the cyclotron center and the extraction radius for H^- ions and zero difference for heavy ions.

The field forming in DC-72 was started from specifying requirements to an isochronous field in a nominal operating point. Azimuthal field variations measured on the 1:5 prototype was used to calculate the isochronous field for ions H^- (A/Z = 1.0, E_k = 72 MeV) at an average field of 1.122 T on the extraction radius of 118 cm. The calculated data were applied to estimate the isochronous field difference between the extraction radius and the cyclotron center. This difference was found to be 0.072 T. Then, an iterative procedure was used to choose an ion satisfying a halved field difference of 0.036 T at the unchanged field on the extraction radius. As a result, the ion with A/Z = 1.36 and resonant frequency of rotation f = 12.262 MHz

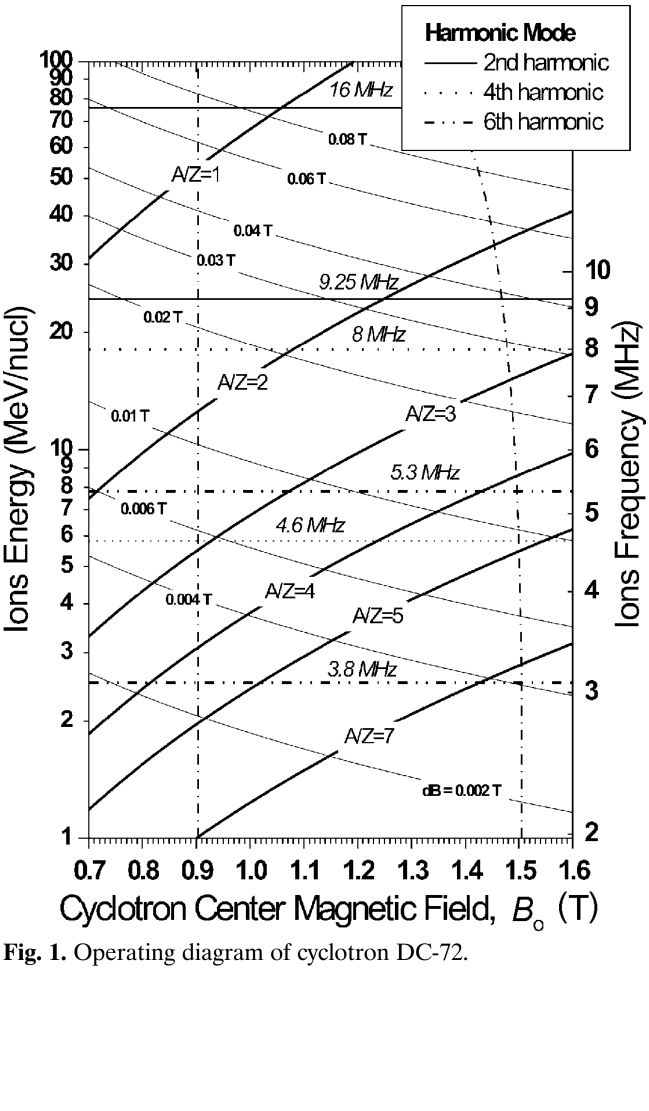

Fig. 1. Operating diagram of cyclotron DC-72.

(nominal operating point) was selected. The desired isochronous field in the operating point was then formed by varying a sector shim thickness. This field was taken as a basis to create isochronous fields for different types of ions using previously obtained estimates of correction coil responses. Quality of resulting isochronous fields was assessed from the computation of an ion phase drift.

Analysis of shimming methods

There are three basic methods of sector shimming to ensure desired field distribution in a cyclotron: axial shimming from a gap side, axial shimming from a pole side, and azimuthal shimming. In the DC-72 prototype, the azimuthal shimming was applied in the central plug region. The sector end was shaped in order to provide a required magnetic length of an ion path. During the sector shaping, a study was carried out to select the most effective shimming method to fit the operating diagram shown in Fig. 1.

10 pairs of correction coils were used to adjust the average field distribution in the active area and provide isochronous acceleration of ions. Effective acceleration of the wide range of ions requires extremely accurate field distribution (forming accuracy of 2×10^{-4}, that corresponds to 2 G at the average field level of 10.000 G). Behavior of the growth function $dB = f(B_o)$ of an averaged radial field is the major design criterion for the magnet system. dB is determined as a difference $B_{rout} - B_o$, where B_{rout} is the average field on the extraction radius, B_o is the field in the center of the cyclotron. Reasoning from the experimental data, the axial shimming from the gap was chosen as a basic shimming technique. The azimuthal shimming will be used for the final trimming of magnetic field distribution including here 1st harmonic of field inperfections. The results of the analysis have been presented in details at the EPAC'2002 [7]. The shimming algorithm is described in [3].

Program complex KOMPOT and synthesis algorithm for sector shaping

Numerical simulation for the DC-72 prototype was made using the KOMPOT package [1, 5]. KOMPOT is a finite-element program package developed for 3D simulation of stationary fields (magnetic, electric, thermal, electric current distributions) in devices with intricate configurations. It has been used for 20 years in practical applications. KOMPOT-M is the most advanced subsystem of the package intended for solving magnetostatic problems. KOMPOT-M provides field simulation for magnet systems with known geometrical and electrical parameters with outputs in the form of a spatial field map and a detailed distribution of ponderomotive force density. In addition, KOMPOT-M enables synthesis of magnetic systems to ensure appropriate distributions of 3D fields. The subsystem is also capable of reconstructing a 3D field inside any volume using boundary magnetic measurements in existing machines.

Synthesis of the DC-72 prototype magnet system was performed in two phases. The first phase comprised computation of the influence of variable parameters on a radial distribution of the azimuthally averaged field in the median plane. Influence functions of the variable parameters were obtained as a difference between the initial and disturbed field distributions. In simulating a disturbed field, one of the parameters was varied slightly to mark out the linear component of its influence function without losing accuracy. The second phase was devoted to adjustment of the parameters with the aim of providing a field distribution best fitted (in terms of mean-square error) to the required performance. Since the influence functions are actually non-linear, the simulated field with a new set of parameters will differ from the expected distribution. This necessitates an iterative procedure until simulated field matches the expected field distribution. The required field in the DC-72 prototype was generated in 4 iterations. The DC-72 prototype simulations required 17 variable parameters: one is the main coil current, 14 parameters describe the sector shape, and two parameters describe the central plug shape. Such approach provided good agreement between the simulated and required field: 7 G in the central area and 1.5 G below the sector up to 236 mm in the radial direction at the level of 1.1 T.

Accuracy of simulation is governed by a set of factors, both calculational and technological. The decisive factor is a fineness of a calculation mesh. However, a large number of mesh nodes requires extensive computational efforts. The calculation mesh applied to the DC-72 prototype simulation gives a ~10 G error. $\mu(H)$ curves used in the model also involves errors associated with uncertainty of magnetic measurements and adequacy of the properties of samples and materials of the magnet system. Another influential factor is manufacture and assembly errors of the magnet system.

Comparison of simulated and measured fields

Figures 2 and 3 present simulated fields in the median plane of the DC-72 prototype magnet system. Figure 4 illustrates a comparison between the synthesized and the actual shapes of the sector. Figure 5 shows the required isochronous field, simulated field for the synthesized shapes of the sector and the central plug, and measured field for the actual magnet system. A mismatch between the simulated and measured field at both levels of magnet excitation is associated with some disagreement between the synthesized configuration and the performed design. Specifically, the simulated sector surface was formed by a smooth curve, but the real sector is terraced to approximate the curvature. As obvious from Figs. 2 and 3, the measured field also shows a stepwise distribution. Also, in reality, the sector is located slightly closer to the median plane than its simulated position. This leads to a higher concentration of magnetic flux below the sector and slight field drop at the sector ends. Besides, the measurements were made on the cyclotron prototype with a flat central plug, while the synthesized configuration implies a cone-shaped plug.

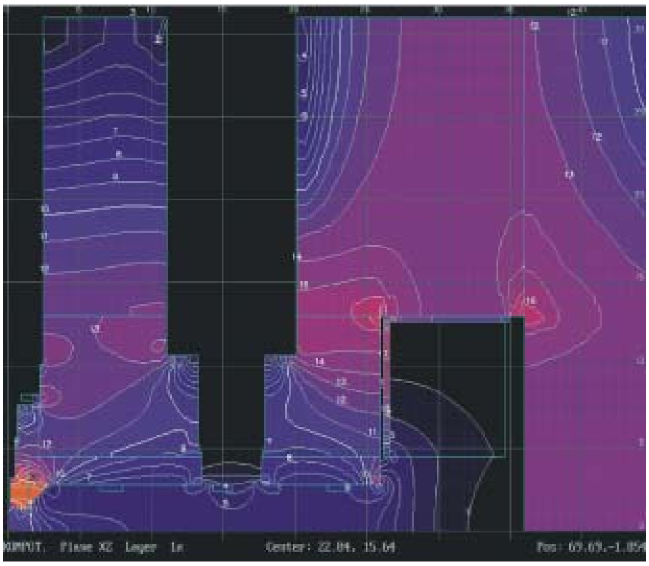

Fig. 3. Simulated fields in the vertical cross section in the "valley".

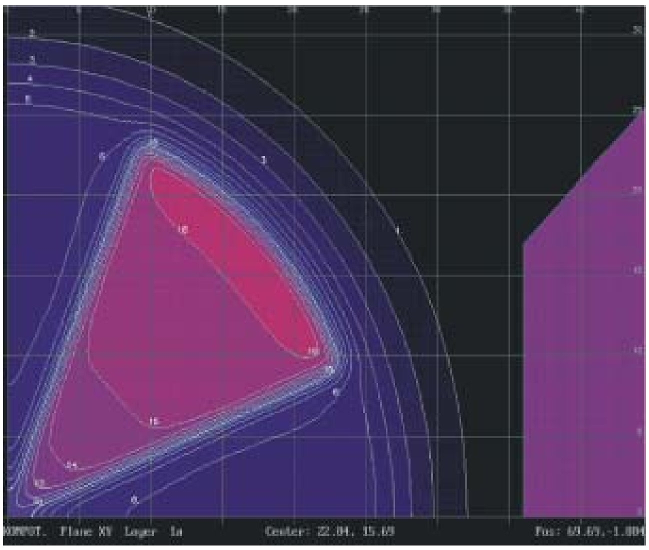

Fig. 2. Simulated fields in the median plane.

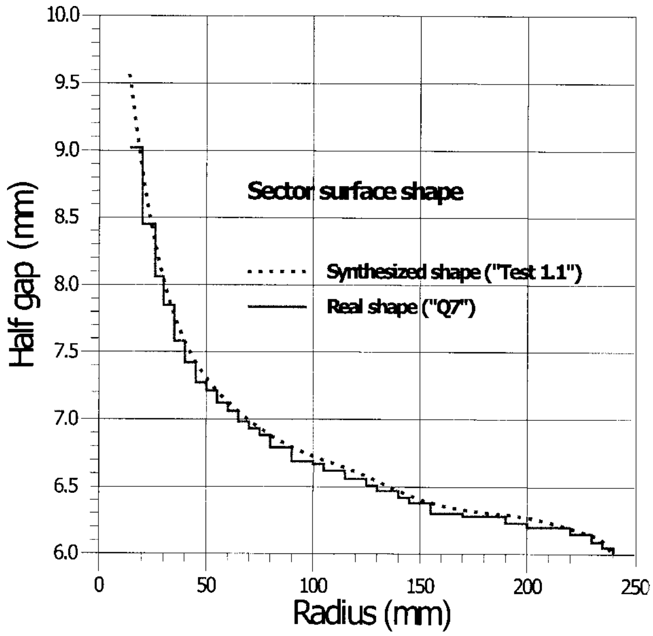

Fig. 4. Shape of a sector surface (distance between the sector and the median plane as a function of a radius): simulated and the actual sector shape.

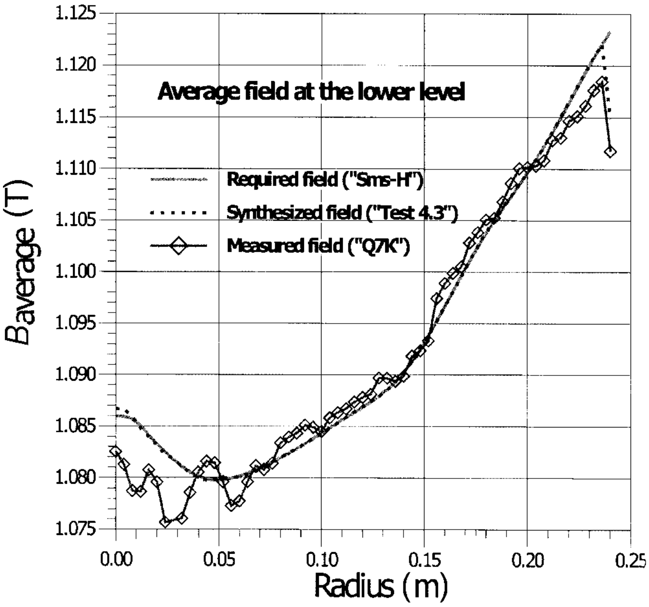

Fig. 5. Average field at the low level of magnet excitation: required, simulated and measured fields.

Conclusions

A comparison between the data of magnetic measurements and simulated results suggests that numerical simulation could replace completely the phase of the development of a physical model in the design of cyclotrons. This would reduce considerably the cost of preparation phase in the design of large electrophysical devices. The works on the DC-72 cyclotron in the FLNR JINR are in progress. The experience in synthesis of DC-72 sectors will be drawn on for improvement of the cyclotron U-400 in the FLNR JINR and design and fabrication of the cyclotron DC-60 for the Republic of Kazakhstan.

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