HIGHLY ACCURATE 3D MODELING OF THE C-80 ISOCHRONOUS CYCLOTRON MAGNETIC STRUCTURE

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Abstract

Very complicated magnetic structure with extremely high spiral angle and set of 17 correction shim types in each of 8 sectors is used in the H-minus ion isochronous cyclotron C-80. The 3D Novosibirsk code MERMAID was applied to optimize geometry of the sectors and shims in the hill and value region. A precision finite-element model allows take into account the iron non-linear effects and the detailed magnet geometry. MERMAID makes use about 20.5 millions nodes and provides magnetic field calculation accuracy in 10-20 Gs. The integral magnetic field parameters (isochronism, transversal motion frequency, H-minus ion electromagnetic dissociation) have been optimized by using the trajectory analyses. Program provides the significant reduction the time and efforts for the determination the necessary shims set in comparison with trial-and-error method.

INTRODUCTION

The isochronous cyclotron C-80 constructed at PNPI is planned to use as well for fundamental researches in nuclear physics, the solid state physics and biology, as for applied program - production of medicine isotopes for, therapy of an eye melanoma and surface forms of a cancer. As a first approximation the magnetic system of cyclotron C-80 was designed a few years ago on the basis of 2D calculations by using the POISSON program and measurements on two small models [1, 2]. The final version of C-80 magnetic structure optimized by 3D calculations with the MERMAID program was used for measurements and the field correction on the full scale magnet is presented in this report.

MAIN CALCULATION DIFFICALTIES

One of the central problems for every isochronous cyclotron is forming the radial and azimuthally magnetic field distribution. Another problem is connected with acceleration of H^- ions. To reduce the H^- dissociation losses in C-80 is used magnetic structure with very high spiral angle [3]. It is also necessary to mention the essential mathematical nonlinearity of the problem. It is to note that in isochronous cyclotron C-80 the magnetic structure is used three types of the steels. The main magnet yoke is constructed from a set of two types of the steels: steel 3 – $\mu_3(B)$ and steel 10 – $\mu_1(B)$. Poles are constructed from steel 10 – $\mu_1(B)$. Sectors, 17 correction shim types in each of 8 sectors and valleys shims are constructed from other steel 10 – $\mu_2(B)$. In the following figure it is visible that these curves μ(B) very strongly differ in a working range of magnetic fields of a cyclotron: 11000-18000 Gs. It is obvious that this creates additional computing difficulties and problems at creation of 3D model.

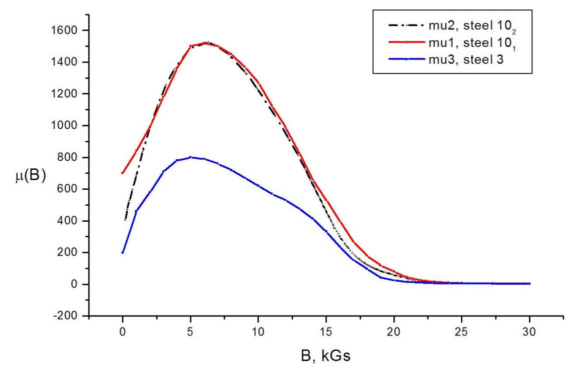

Figure 1: Permeability curves μ(B) in C-80.

PROCEDURE OF A MAGNETIC FIELD FORMATION

Procedure of the necessary magnetic field formation and selection of magnetic structure parameters for C-80 according to the program MERMAID [4] was made step by step method.

As the first step, the key parameters of magnetic system C-80 [5] were fixed. It was supposed that the geometry and height of sectors equals to 90 mm and during the further optimization is not changed. For obtaining the required isochronisms the heights of the correction sector shims have been varied. The initial heights of these shims were selected equal to 20 mm. Besides, in the course of optimization special the constrained condition was used. The amplitude of 4-th harmonic do not exceeded ~3000 Gs and the hill B_{max}≤17000 Gs near the extraction radius. Under this conditions H^- dissociation are below ≤5 % [3]. For this purpose it was introduced into the magnetic system additional valley shims. Thus formation of a demanded isochronous field is carried out only by changing iron geometry without use of corrector coils.

At the second stage 3D model of the magnetic system C-80 was developed and was constructed. It carefully describes geometry of magnet yoke, sectors (4 pairs), sector shims (17 correcting shims on each sector), and valley shims, the coils current, external boundaries. It also considers nonlinear magnetic properties used electro technical steels μ (B).

Due to high spiral angle sectors we were forced to use in calculations 1/2 magnets with the vertical

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symmetry boundary conditions. The external boundary of calculated area was chosen rather far to exceed the influence on the magnetic field in working area and to correct calculation of the fringing field. The fringing field is necessary for the correct calculation of extraction beam optics. Thus, for the description of magnetic structure of C-80 in the MERMAID program it was required ~20.5 million direct prisms that allowed reaching necessary accuracy of calculation of a magnetic field $\sim 10^{-3}$—10^{-4}.

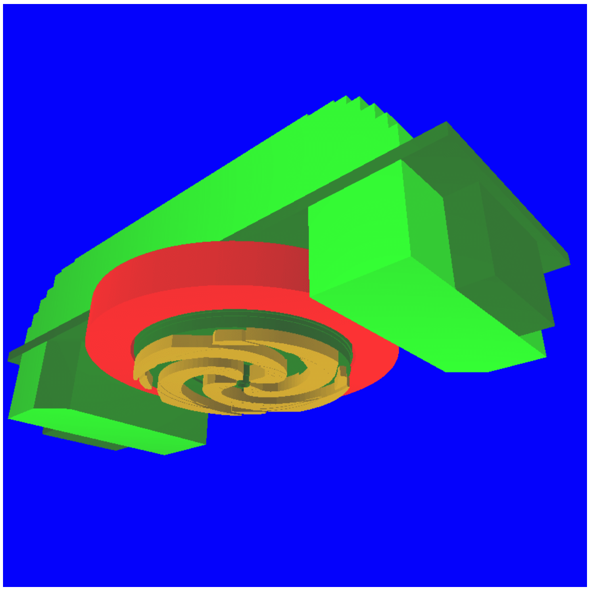

Figure 2: MERMAID model C-80.

ALGORITHM OF OPTIMIZATION

The developed computing model was used for receiving necessary spatial distribution of a magnetic field and for its subsequent analysis.

Thus procedure of the analysis of the received data across the field was divided into two complementary stages.

At the first stage the average on an azimuth magnetic field C-80 was calculated, and for obtaining other characteristics of cyclotron analytical formulas from work [6], in particular, for an isochronous field and frequencies of betathrone frequencies were used. Then various geometrical changes were made to the developed model for the purpose of receiving the minimum difference between the calculated average field and an isochronous field with control of other required characteristics of a cyclotron, and the following iteration was carried out if necessary. Such approach is rather simple, evident and fast, but it doesn't possess sufficient accuracy for an isochronous cyclotron.

Therefore periodically through some successful iterations of the first stage was made transition to the second stage where according to the calculated map of a field the full trajectory analysis of particles in the course of acceleration was carried out, and also isochronous dependence [7] was specified. I.e., at the second stage the corresponding nonlinear equations of movement were solved numerically and static equilibrium orbits in an initial magnetic field were calculated. Frequencies of betathrone oscillations were determined by these decisions, and the cycle time of an accelerated particle on each radius was calculated. Being guided by these data, there was on special procedure a new isochronous field. Then finally for this stage frequencies of betathrone oscillations in this isochronous field were defined and losses in it ions accelerated the H-minus on electro dissociation were calculated.

Then again, if it was necessary, after the analysis of results of the second stage, was made transition to the first stage where further specification of geometry of varied objects was made, leaning any more on an analytical isochronous field and frequencies of betathrone oscillations, and on an isochronous field and frequencies of the second stage. Procedure repeated until then while the discrepancy between an average and an isochronous field didn't become ~10-20 Gs. Such value just also corresponds to accuracy of calculation of an average field.

Thus the self-consistent task on optimization of magnetic structure C-80 was realized. Each time such task for decrease of number of parameters was executed with the fixed minimum gap. Thus the current of the main coils and geometry of sector tips and valley shims varied so that to receive necessary parameters of magnetic system. In total in the course of optimization the following set of gaps was considered: 146, 156, 170, 176 and 164 mm.

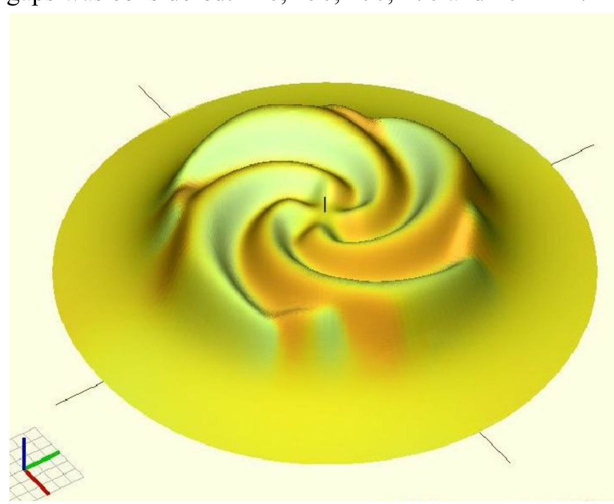

Figure 3: 3D MERMAID magnetic field for C-80.

MAIN RESULTS OF CALCULATIONS

The final version of magnetic structure of isochronous cyclotron C-80 has a minimum gap, equal 164 mm. Briefly we will enumerate the main modifications of the initial magnetic system [1,2] executed on a basis 3D simulation.

Direct sectors were continued from radius of 27 cm to radius of 40 cm, but with two turns on the fixed angles, keeping previous sector length along azimuth. It led to blocking of uncontrollable penetration of a magnetic spiral angle to the area near the central region. Thereby

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growth of amplitude of the main harmonic was provided that led to stable motion of particles in this area.

The central region was changed in the spatial C-80 model so that to consider real geometry of system for axial injection. Besides, by means of a magnetic plug necessary fall of a magnetic field in the central region was created.

Angular expansion of sectors was made for reduction of quantity valley shims and for ensuring vertical stability of movement of accelerated ions near extraction radius on ~20 mm from radius of 70 cm to the final radius equal 102.5 cm.

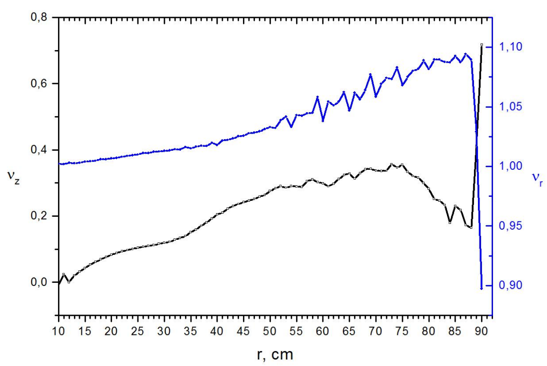

Figure 4: Vertical and horizontal frequencies in C-80.

The accepted changes of magnetic structure led as well to decrease in losses the H-minus of ions on dissociation in the course of acceleration to 2.2-2.5 %.

Finally, as a result of all-round 3D modeling the following optimum magnetic structure for cyclotron C-80 was received:

Figure 5: View of the pole tip C-80.

CONCLUSION

The careful analysis 3D data on the magnetic field, executed on the procedure which has been in detail described in [7], showed that practically all problems by constructed isochronous cyclotron C-80 to be overcome. Frequencies of betathrone fluctuations are represented rather well almost in all working area of the cyclotron. However, most likely, more careful specification of isochronous dependence of a field is required, relying on experimental measurements. Final distribution of the magnetic field was measured experimentally with 2-6 Gs precision. They are supposed to be executed after mounting of sectors in cyclotron C-80.

Then simulation 3D fields were used in trajectory calculations for the construction of extraction system of the cyclotron and the beam transport lines. Thus it is possible to confirm that the last option of magnetic structure of isochronous cyclotron C-80 meets all design requirements.

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