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智能化回旋加速器主磁铁 CAE 系统的研制及应用

INTELLIGENT CAE SYSTEM OF CYCLONE TYPE CYCLOTRON MAIN MAGNET AND ITS APPLICATIONS

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摘　要

回旋加速器的主磁铁是加速器建造中最重要的部件，它代表了回旋加速器的特性。虽然有许多解磁场计算问题的程序，但结果却大不相同，取决于用户的水平和经验。为了帮助磁铁设计者们获得可接受的结果，开发了一个智能化的 CYCLONE 型回旋加速器主磁铁设计、分析与指导加工的 CAE（计算机辅助工程）。由于程序中安装了专家知识库，即使设计者是一位初学者，也可得到合理的设计结果。

INTELLIGENT CAE SYSTEM OF CYCLONE TYPE CYCLOTRON MAIN MAGNET AND ITS APPLICATIONS

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ABSTRACT

The main magnet that represents the feature of the cyclotron is the most important part in a cyclotron construction. Though there are many codes devoted to solve magnetic field computation problems, the results from them depend on the user's skill and experience very much. To help cyclotron magnet designer get acceptable result an intelligent CAE system for CYCLONE type cyclotron magnet design and machining has been developed. A reasonable good results in the design could be got even the designer is a beginner because the help from an expert knowledge library installed in the program.

INTRODUCTION

There are many magnetic field computation software packages in the world today to help people in magnet design. The results from the codes depend on the user's skill and experience very much. Sometimes the results are completely wrong even the input data are right according to the usre's manual of the codes. Reason for that is the user lacks of the knowledge of the magnet engineering conception. The case can be found in cyclotron magnet design too. To help cyclotron magnet designer get acceptable results a CAE system for CYCLONE type cyclotron main magnet was developed. The intelligent CAE system—CYCCAE allocates and works on VAX-11/780 and PC 386. Computation and analysis of the magnetic field were based on the codes which had been used in many practical applications. To make the field isochronous, a CAM program provides a date file designed compatible with numerical control manufacture center to machine the sector shimming bar. The iteration procedure may be necessary when the phase shift is too large to be accepted. Two examples were given to show how CYCCAE works.

1 SCHEME OF CYCCAE

The scheme of CYCCAE shown in Fig. 1 consists of three parts: intelligent CAD, beam dynamics analysis programs and CAM. Because 3D field computation and analysis requires large RAM, VAX/VMS was chosen as the working environment for CYCCAE. In order to make the program work on PC, CYCCAE had to be divided into many independent modules written in FORTRAN except an assembly connected to the graphic interface. Because DOS manages 640 KB RAM only, the program runs as a series of executable files rewritten by MS FORTRAN$_{5.1}$ (Graphic interface is rewritten by MS assembler$_{5.0}$). Executable file connections are based on data communication. The files are called by a management code written in DOS command. A multi-level menu makes user choose the executable files easily. The main management menu page is shown in Fig. 2.

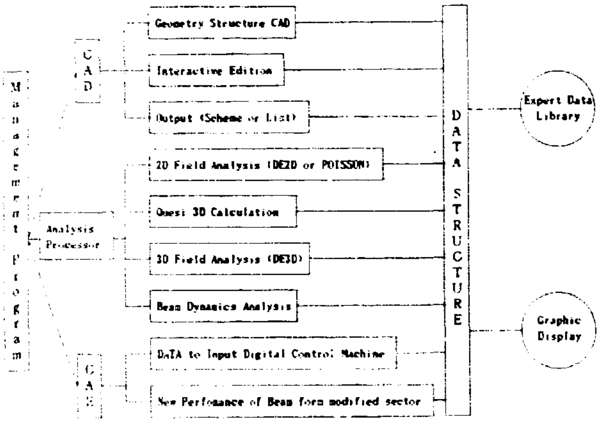

Fig. 1 The Scheme of CYCCAE

CYCCAE	Version 1.00 3/15/91
1. Contents	——Files on CYCCAE system
2. DEIE	——2D FEM & 3D IEM field computation
3. OS shell	——Operation system shell
4. GRAPH	——Graphical support software
5. CYCCAD	——CAD for cyclotron magnet system
6. DE2D/POISSON	——2D field computation
7. DE3D	——3D magnetic field computation
8. VACUUM/FOURRIER	
• VACUUM	——Vacuum correction
• FOURRIER	——Fourrier analysis
9. ORBIT/DYNAMICS	
• ORBIT	——Calculate the orbit in magnetostatic field, use for extraction & injection computation
DYNAMICS	——Frequences of betatronic oscillations, phase shift, equilibrium orbit
0. POLE	——Pole CAM
Select a number to continue:	(ESC to Exit)

Fig. 2 The main management menu page

2 INTELLIGENT CAD

2.1 Intelligent CAD

A designer of the cyclotron magnet should possess good background of cyclotron knowledge such as theory, engineering and technology experiences. It is not easy to get a reasonable results for a beginner even he knows how to use the magnetic field software packages. For this reason a library of the expert knowledge was developed to advise beginers to chose the magnet parameters when some parameters such as type of the accelerated ion, final energy, etc. are given. For example, to accelerate minus hydrogen particle to 30 MeV, the following table will be shown on screen for user's reference once the program starts out to run:

Table 1 Design parameters for main magnet

Particle Parameters			
Energy	Rest Mass	Acc. Mode	Charge Number
E =30 MeV	M_0 =938.27 MeV	MD=4	q = −1
Magnetic Parameters			
Field in Hill	Field in Valley	Height of Ring	Sector Angle
B_H =1.7 T	B_V =0.12 T	H_{43} =0.15 m	α =54°
Coil and Gap			
Height/ Width	Conductor/Coil	Current Density	Gap
PHW=1.5	ETA=0.67	AJ=1 A/mm²	H_1 =0.03 m

The parameters on the table can be changed by moving the cursor to a corresponding position or kept the default values. The extraction radius of the accelerated ion should be:

$$R_{ex} = \frac{M_0 \gamma \beta c}{q < B >}$$

From the relation of R_{ex} , E , and H_1 , the library of expert knowledge will provide the radius of sector R_1 and H_{54}, R_{21}, R_{43}, H_2, B_3 =0.85 B_H , and $R_5 = \sqrt{\frac{S_1}{0.9\pi} + R_3^2}$, R_4, etc. will be found by using magnetic circuit analysis. The basic dimensions of main magnet will be determined in one or two minutes on PC.

Two examples: 30 MeV and 10 MeV proton cyclotron were done by CYCCAE.

The basic parameters are very close to existed CYCLONE 30 and CYCLONE 10/5 developed by IBA, but the power needed is slightly reduced.

2. 2 Interactive I/O

Once the dimensions of the magnet are known, CYCCAE would go on into the interactive graphics system for further analysis or save the data, or print a hard copy, etc.

3 ANALYSIS PROGRAM

3. 1 Magnetic Field Analysis

A group of data files are ready for further analysis in more detail after CAD. The most important task is the field computation to make sure whether the magnet can provide the request field including the magnitude and distribution. A group of output data files of the CAD are designed compatible with input data of field computation softwares. Though the input data files seem large and troublesome, what CYCCAE user does is to choose a number from the menu and strike the key, for example 6 or 7, the main menu tells the computer what to do next. The functions of each module are listed in Refs [1~3]. The computed fields of a cyclotron CYCLONE 30 against the measured fields are given in Fig. 3.

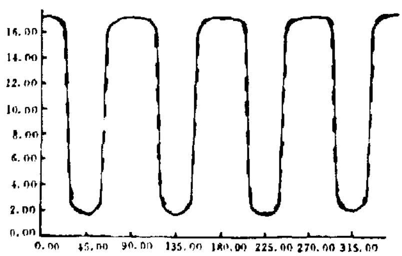

Fig. 3 The computed and measured fields of a cyclotron CYCLONE 30

Though the field on the symmetry plane both in the valley and on the hill can be found appoximately by 2D field computation, only 3D software can compute the real three dimensional field and check whether the design is acceptable or not. To keep the results with enough precision VAX has to be used for the problem with more elements and nodes. Data pre-processor and post-processor of 3D field analysis are on PC.

Besides the real three dimensional field analysis, another approximate method called integral algorithm is used for estimation of the magnet basic structure. The method is established by integral of magnetization of the iron elements which can be found based on the fields of the symmetry planes both in the valley and on the hill obtained by using 2D codes. The field at any point can be computed by integral of all sources: conductor currents and magnetized iron elements[4]. In this way, the codes can work on PC because smaller RAM is needed. Of course, it takes CPU time.

So far all informations of magnetic fields both in azimuthal and radial are given and ready for beam bynamics analysis.

3.2 Beam Dynamics Analysis

Magnetic fields computed and measured in atmosphere conditions have to be corrected on account of the particles accelerated in vacuum. The correction formula is:

$$B_{new} = a_1 B_{old} + a_0$$

Where a_0, a_1 are variable with radius R.

Fourier analysis was taken for the field before the orbits being computed. The Fourier coefficients a_n, $b_n (n = 1, 40)$ and the average field in radial order are shown in Fig. 4.

3.3 Central and extraction region

There in no electric field in the extraction region. In the central region, the field in the injector electrostatic deflector can be replaced by using an equivalent magnetic field. The orbit is computed by the module based on the charged particle motion equation in magnetostatic field[5]. The computation results of orbit are shown in Fig. 5.

3.4 Phase Shift, Equilibrium Orbit and β Oscillation

There is difference between the actual and the ideal isochronous field anyway, so the phase shift is produced. The revolution time t of the charge particle is calculated by integral of motion. The phase shift can be found by comparing t with R. F. period T. The module PHASE in program DYNAMICS does this calculation. The phase shift is shown in Fig. 6.

Not only the phase shift of ion influences the particle accelerated to the final energy, but also the β oscillation is an important factor too. They represent the stability of transverse motion. According to the transmission matrix $(m_{ij})_{2\times2}$ of motion, the frequency of β oscillation v is $v = \frac{\sigma \times N}{2\pi}$. Where σ is defined by $\cos\sigma = \frac{1}{2}(m_{11} + m_{22})$, and N is the number of magnetic field periods. The frenquency of radial oscillation v_r is shown in Fig. 7. It is calculated by the module FREN in program DYNAMICS.

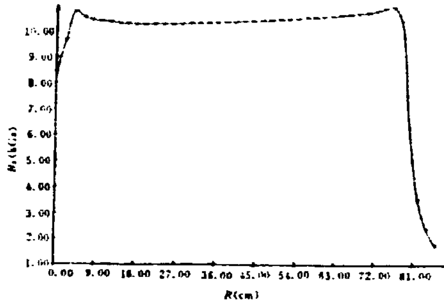

Fig. 4 The average field in radial order

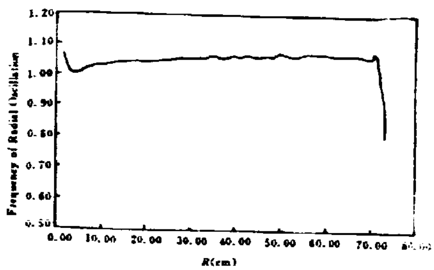

Fig. 7 The frenquency of radial oscillation ν_r

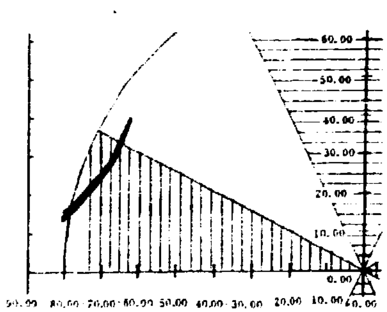

Fig. 5 The computation results of orbit

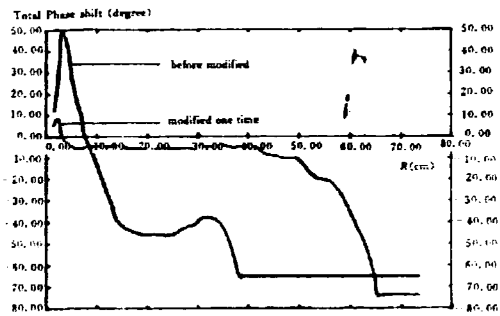

Fig. 6 The phase shift

4 CAM FOR MAIN MAGNET

After the iteration of intelligent CAD, magnetic field and beam dynamics analysis, CYCCAE gives the basic dimensions of the magnet. The magnet can be divided into many parts ; top yokes, return yokes and rings. The mechanical drawings are made and the machining can be started except the sector edge. The isochronous field will be obtained by shimming the sector edge mainly. Therefore, the sectors remain the same in the machining iteration. What needs to be modified is the sector edge shimming bar. The CAM program was developed for machining the shimming bar. The curved face of the bar is so complicated that it can be expressed by a group of data (r_i, l_i) only. Based on the (r_i, l_i) and the double-circular spline approximation output data files from CAM program are designed compatible with numerical control manufacture center. After machining and installation, the measured results of magnetic field is used again for further iteration to mod ify the shimming bar and improve the field. The measured data have the same structure as computed. The phase shift (r_i, p_i) is automatically given by the module PHASE according to the measured field, once the user has chosen the function of beam dynamics computation in the main menu. Then the CAM program calculates the correction (r_i, c_i) by the following formulas:

$$b_i = 13 + r_i \times (10 - 13)/(R - 0) \qquad a_i = f_i \times p_i \times B_i/b_i$$

$$c_i = r_i \times a_i \qquad t_i = t_i + c_i$$

$$Bi_i = B_i \times (1 + p_i)$$

where f_i is a factor of correction. Bi_i is the field provided by the new bar. The data will be recalled by module PHASE to check the new phase shift. Iteration does not stop until the field is acceptable.

5 WORK ENVIRONMENT

Hardware configuration

The computer hardware is VAX-11/780, VT-125 terminal or IBM PC: CPU-80386, RAM-2MB, 80387 coprocessor, VGA or EGA graphic adaphic. Plotter can be DMP-52 or DXY-1100. Printer is chose HP laserjet Ⅱ or Brother M2024.

Software Environment

Operation systems are VMS 4.5 on VAX or MS-DOS 3.3 & XENIX 2.3.2 on PC. Three dimensional graphics system is GRAPH developed by FORTRAN and ReGIS (MS assembler 5.0 on PC). It abides by graphic standard CODE.

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