IMPERFECTION INVESTIGATION FOR THE MAIN MAGNET CONSTRUCTION FOR COMPACT CYCLOTRON*

Tianjue Zhang#, Junqing Zhong, Jianjun Yang, Yinlong Lv, Sumin Wei, Chuan Wang, Hongjuan Yao, CIAE, Beijing, 102413, China

Abstract

The tolerance of the magnetic field is as tight as 1.2 Gauss for isochronous field and 2 Gauss for first harmonics inCYCIAE-100. Due to the absence of coil adjusting in this machine, a measure that helps to achieve a more compact structure, the imperfection hence becomes a much more critical factor in our consideration. The effects by the various kinds of imperfection are investigated numerically and the imperfection fields are predicted for beam dynamics simulation, serving as a basic guidance in the magnet construction for CYCIAE-100. Some of the important results will be reported in this paper, including the deformation of the main magnet, inner imperfection induced by the casting procedure, fabrication and assembling tolerance, and thermal deformation.

INTRODUCTION

As a driving accelerator for BRIF[1], CYCIAE-100 adopts a compact structure with 4 straight sectors. The H- ions produced by the multi-cusp ion source are accelerated, and the high intensity proton beams are extracted through dual stripping. The extracted beam is 200 μA featured with an energy of 75-100 MeV, which is continuously adjustable. The magnet is comprised by top/bottom yokes, four return yokes, eight sectors and sixteen shimming bars. The lower part of magnet is shown in Fig. 1. The core parts, such as the sectors, take use of forged pure iron, and the top/bottom yokes and return yokes adopt casting piece. To get a precise prediction of effect on magnetic field induced by the imperfection factors during the heat treatment, fabrication and operation, and to effectively reduce the design and construction risks of the key part as the main magnet, those imperfection factors are simulated and studied through finite element method analysis. In this paper, the effect of imperfection factors on magnetic field will be depicted.

THE IMPERFECTION OF MATERIAL

It is inevitable in the process of casting and forging that the inclusion and contraction cavity will stay inside of the magnet as well as the impurities. The defects will impose influence to the magnetic field distribution. Therefore, it is necessary to study this influence caused by the defect, and set up technical requirement for the defect of the forging and casting pieces.

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tjzhang@ciae.ac.cn

Internal Imperfection

The inclusion and contraction cavity will stay inside the magnet in the process of casting and forging, and positions of those imperfections can not be predicted. Therefore, it is necessary to study the influence to the magnetic field caused by the defect at different location and of different size, and set up technical requirement for the internal defect of the forging and casting pieces. The inclusion and contraction cavity are considered as ellipsoidal bubbles. The main magnet is divided into three divisions in the simulation, and the separate division is shown in Fig. 2. The permitted defect in zones of the magnet is shown in Table 1.

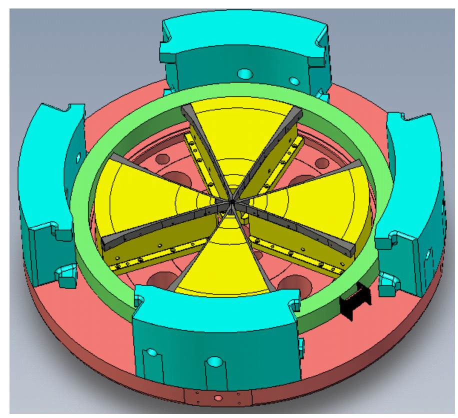

Figure 1: Lower part of the main magnet.

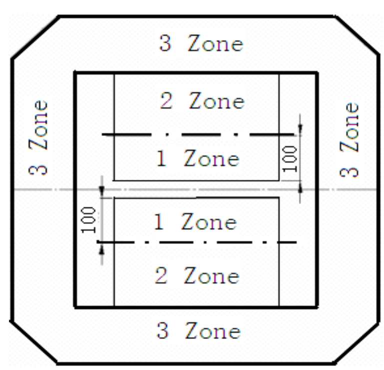

Figure 2: Three zones for ultra-sonic detection.

Table 1: Tolerant Defect of Each Zone in the Magnet

Division	Equivalent diameter	In an area of 200 mm x 200 mm, less than 5 Equivalent diameter
1 Zone	Φ3 mm	Φ2 mm
2 Zone	Φ6 mm	Φ4 mm
3 Zone	Φ8 mm	Φ6 mm

Unhomogeneous Magnetic Property

The chemical composition and heat treatment of sectors and yokes are important factors to impose the magnetic property, While sectors and the top/bottom yoke are under casting and heat treatment, evident discrepancy of the chemical component and crystallization state will show up, The discrepancy will result in the imperfection field at the medial plane such as the 1st harmonic. While conducting the simulation, we assume that the magnetic property of one pair of the sectors is different by 1% from the other three pairs of sectors. During the simulating calculation, the top/bottom and return yokes apply the property of ANSI1008 steel at room temperature. The numerical simulation result shows that the amplitude of the 1st harmonic increases along with the radius, but the largest amplitude for the 1st harmonic is no more than 8 Gausses. According to the basic result from numerical simulation, the deviation for the magnetic permeability between sectors should be within 1.5%.

We assume 1/4 of the top/bottom yoke is Q235 (Chinese steel standard) in simulation calculation, and the remaining 3/4 of the yoke is ANSI1008 steel. The magnetic property of Q235 and ANSI1008 is shown in Table 2. The maximum amplitude of the 1st harmonic at the medial plane is ~4 Gauss in large radius.

Table 2: Magnetic Property of Q235 and DT4

H(A/m)	500	1000	2500	5000	10000	20000
Q235(T)	1.18	1.39	1.53	1.67	1.78	1.87
1008(T)	1.50	1.55	1.63	1.72	1.84	2.12

As the dimension of top/bottom yoke cast is large, its magnetic property is not guaranteed by manufacturers. Therefore, the key point is to control the compositions of C, P, S, Si and their uniformity, and the process of heat treatment for cast will be focused. The chemical composition for the top/bottom yokes and return yokes is shown in Table 3. The carbon segregation at the sampling points for the same circle and same height should be within 0.02%-0.04%. There are two ways to get a large ferritic grain from a large austenitic grain [2]: 1) A slow cooling after the austenitiation, particularly during the ferritic transformation. The smaller the cooling rate is, the lower coercivity is and the larger the induction is at low field. 2) After air cooling, annealing just below the AC1 temperature improves the magnetic properties. After casting of top/bottom yokes, the cast will be annealed to get the large ferrite crystal, the heat treatment technics is shown in Fig. 3.

Table 3: Chemical Composition of the Yokes

C	Si	P	S	Cr	Cu
≤0.11	≤0.37	≤0.035	≤0.035	≤0.10	≤0.25

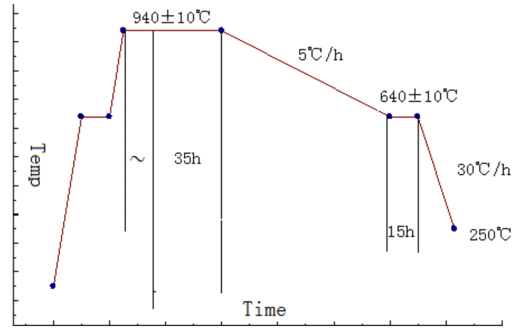

Figure 3: Draft of heat treatment technics.

DEFORMATION OF THE MAGNET

While the cyclotron is in operation, the magnet will be deformed by the electromagnetic force, gravity and atmosphere pressure. The magnetic filed distribution is analyzed through numerical method, and thus we get the result that the electromagnetic force between the sectors is 420t in total. The upper part of the magnet weighs 170t, and the vacuum pressure on the top/bottom yokes is 120t. We optimize the structure of top/bottom yokes to reduce the deformation by FEM code because the magnetic field in median plane will be affected by the deformation. The deformation for the even height and uneven height structures of top/bottom yokes has been considered in simulation, and the result of deformation is shown in Fig. 4. When the top/bottom yoke of even height is chosen, the deformation will be reduced for 89 μm in 25 cm radius to even height structure while the total weight of the top/bottom yokes remains unchanged. The structure for the top/bottom yokes of uneven height is shown in Fig. 5.

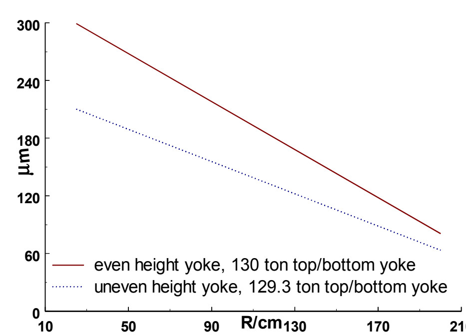

Figure 4: The result of deformation for different structure.

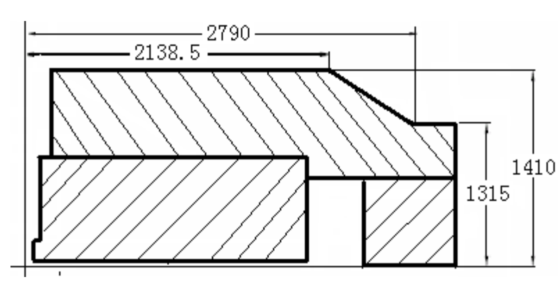

Figure 5: The structure of the uneven height yokes.

TOLERANCE FOR FABRICATION AND ASSEMBLING

It is necessary to do the numerical analysis or analytical estimation for various factors that might cause harmful harmonic field error, for instance, angle error of the main magnet pole during its fabrication and error during its installation. According to the requirement of the isochronous field and imperfection harmonic field, the primary tolerance for the 100 MeV cyclotron is determined as follows.

- The 8 sectors are the same in size and angle, and the angle deviation between different sectors is less than 0.00286° (The arc length is less than 0.1 mm at 2000 mm of the outer radius). However, the angle of 47° for each sector can change ±0.1° uniformly.
- The symmetric planes are through the vertical axis of the machine and are mutually perpendicular. The range for angular errors is 90 ° ±0.00286 °.
- After the sectors are installed, the edges of upper and lower magnetic pole should be aligned very well, the error of slips should be within 0.1 mm while the radius is less than 1000 mm, and not over 0.15 mm when the radius is between 1000 mm and 2000 mm.
- The magnetic pole face is on the theoretically designed surface. The requirement for the profile tolerance is 0.1 mm.
- After installation, the gap between the upper and lower magnetic pole surfaces could be changed in parallel by ± 0.1 mm on the theoretically designed surface. The general profile tolerance of the surface should be less than 0.1 mm.
- The upper and lower parts of the main magnet can be opened after putting into operation for maintenance. It is required that when it returns to its normal position, the position accuracy should be ± 0.02 mm.
- The roughness for surfaces of the sectors, top/bottom yokes, central plugs, and shimming bars is 1.6 μm, and the roughness for other surfaces is 3.2 μm. The roughness for the vacuum surface between the top and bottom yokes is 0.8 μm; the roughness for the surface connected with the bottom side of the sectors is 1.6 μm, while for other surfaces, the roughness is 3.2 μm.
- The hill gap between the top/bottom yokes and magnetic poles should be less than 0.03 mm; the precision between the inner circle arch surface and the central plug outer circle surface is 0.05 mm (The hill gap is required to be uniformed for the whole cylinder); The hill gap between the sides of the pole and the shimming bar is less than 0.03 mm, and it is required to be capable of iterative positioning with a precision of 0.02 mm.
- The relative displacement error of the precision to return to the original position after several times of dismantle and installation of the top/bottom yoke and magnetic poles should be less than 0.05 mm. If this kind of dismantle and installation takes place after the mapping, the magnetic filed should be re-measured and shimmed.

THERMAL DEFORMATION OF MAGNET

The thermal deformation of magnet will be brought from the leakage of RF and the change of outside temperature. The leakage of RF will induce the expansion of sectors, and the room temperature will bring on the change of return yokes. The two factors will lead to the change of gap between top and bottom sectors, and this kind of change will be reflected on the change of magnetic field in median plane, when the cyclotron is being operated.

Assume that the temperature of the sectors rise 50°C due to the leakage of RF, the height of sectors will be increased by 0.4 mm, therefore the gap will be reduced by 0.8 mm. We assume the increase is uniform with radius in order to simplify the simulation, and the change of the magnetic field is shown in Fig. 6. This change of the field will be supplemented by trim coils installed in valley of magnet.

It has been assumed that the outside temperature will change ±5°C when the cyclotron is in operation, accordingly the height of return yokes will change about ±0.04 mm. Therefore the gap will be increase about 0.08 mm, and the magnetic field in median plane will be changed by less than 5 Gauss. The current of main-coils will be altered to adjust the field in order to get relative isochronous field.

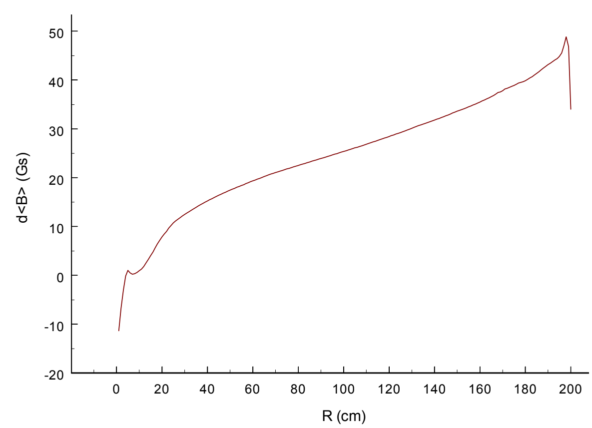

Figure 6: Change of the average magnetic field.

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[1] Tianjue Zhang, et al., Nuclear Instruments and Methods in Physics Research B 261 (2007) 25–30.
[2] J.P. Badeau, P. BocQuet, et al., " Control of the magnetic properties in very large steel pieces", EPAC-1994-2295.