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Inductances of a Superconducting Magnet for Cyclotron K120

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***Abstract*-- The design of a superconducting magnet system producing very high magnetic field is underway at Korea Basic Science Institute (KBSI) to accelerate three kinds of carbon irons (C+2, C+4, C+6) to 120 MeV. A quarter-scaled prototype will be manufactured in order to confirm the feasibility of our design. Magnet Inductances in the system have a great influence on the current ramping rates and contribute to the stored energy, which are usually considered to be unfavorable in magnet operation. The modeling and simulation scheme of a prototype superconducting magnet for the cyclotron K120 is described in this paper. The inductances are calculated by a numerical method with and without iron yokes, respectively. These calculation results will be used as engineering design details such as a current ramping rate and a quench protection design.**

1. INTRODUCTION

A 120 MeV cyclotron will be built in the Korea Institute of Radiological and Medical Science (KIRAMS), which will provide high energy proton beam for various applications, especially in material science. The design of a cyclotron superconducting magnet system is underway at the Korea Basic Science Institute (KBSI) [1]. In order to confirm the feasibility of the design, a quarter-scaled prototype will be manufactured and tested. A structure of the prototype superconducting cyclotron K120 is illustrated in Fig.1.

The superconducting magnet of K120 cyclotron will produce more than 3 T magnetic fields to accelerate variable ions. A current ramping rate and a quench protection system should be particularly considered since both magnet size and stored energy are large. Inductances of the magnet system have a great influence on current ramping rates and contribute to the stored energy, which are usually considered to be unfavorable in a large high field magnet operation [2].

In this paper, an effective modeling and simulation scheme of the K120 cyclotron superconducting magnet is discussed. The inductances are calculated by a finite element analysis (FEA) method with and without iron yokes, respectively. The calculation results will benefit to an engineering design of the magnet system.

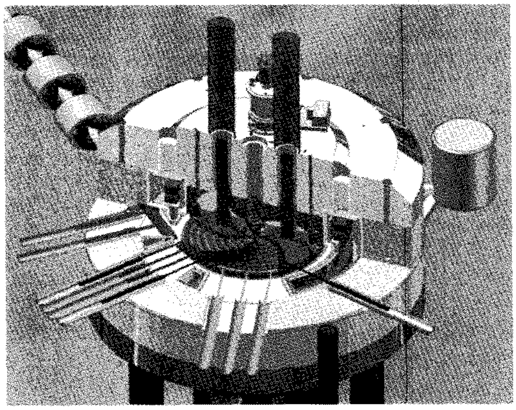

Fig. 1. Prototype superconducting cyclotron K120.

2. DESIGN OF SUPERCONDUCTING MAGNET COILS

The prototype superconducting cyclotron magnet mainly consists of a cryostat assembly and a coil assembly. The cryostat comprises cooling circuits system, cold mass supports system, heat shields and thermal intercepts, current leads, cryocoolers and a helium re-condenser, vacuum chambers, temperature, and pressure instrumentations. A volume of subcooled liquid helium directly cools down the coils.

Fig.2 shows a 1/4th cross-section view of the axi-symmetric superconducting coils and yokes. The coil assembly is composed of coil windings and their cases. There are two pairs of main coils which are coaxially arranged to form the magnet. The coils carry the currents in the same direction which can provide a maximum central magnetic field more than 3 T. The yoke irons are composed of four pieces. The positions of the yokes are very important to generate precise and accurate field. Table Ⅰ presents the specification of magnet coils. The standard NbTi conductor will be used for the coils. The coil A and B have the same inner radius (R_{in} = 400 mm) and outer radius (R_{out} = 460 mm), but the height of coil A and coil B in the axial direction is 30 mm and 42.5 mm, respectively. The layers and turns for coils are also listed in Table Ⅰ.

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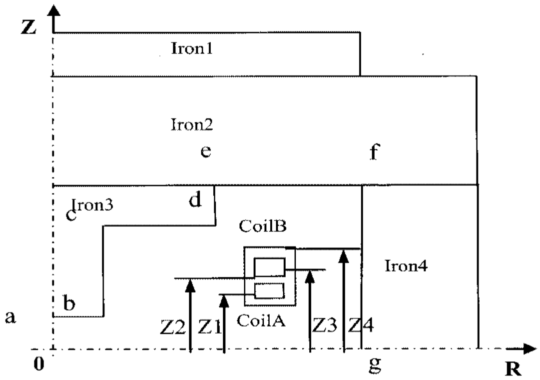

Fig. 2. Cross section of superconducting coils and yokes.

TABLE I
SPECIFICATION OF MAGNET COILS.

	coil A		coil B	
coil inner radius(mm)	400		400	
coil outer radius(mm)	460		460	
coil position along Z	z1	125	z3	175
direction from center(mm)	z2	155	z4	217.5
coil winding (layer × turn)	75 × 24		75 × 34	
coil winding (no. of turns)	1,800		2,550	
operating current (A)	Max 180		Max 180	

3. CALCULATION AND ANALYSES

3.1. Coils inductances without iron yokes

Finite element analysis can give us detailed inductances calculation for the solenoid coils. The computer program for the inductances, magnetic field and magnetic force has been developed in the KBSI based on secondary development in ANSYS. The three dimensional ANSYS dummy element type SOURC36 was used, which is only to represent the shape and location of current sources, to create the coils but not modeled as an integral part of the geometry. Fig. 3 shows the calculation model and mesh. In order to create mesh (mesh is not created in coils), three dimensional finite element SOLID96 is used, which is designed for magnetic field modeling zone for 0.6 m in radius and 3.0 m in axial direction. To save the calculation time, 1/36 magnetic field zone was modeled. We impose the flux parallel boundary condition at ends of the air zone.

The currents are used to calculate a source magnetic field intensity using a numerical integration technique involving the Biot-Savart law. We can invoke macro LMATRIX for inductance and macro FMAGSUM for magnetic force calculation. The magnetic field distribution is showed in Fig.4. The magnetic flux density at the center (R, Z) = (0, 0) can reach 1.8 T and the maximum flux density around the coils is about 4.6 T without iron yokes. Table II gives the comparative results of self inductances and mutual inductances by ANSYS FEA and by some approximate expressions calculation [4]. Coil A' and coil B' are a mirror image of coil A and B. Comparing with the two calculation methods, it provides consistent results. The total inductance is more or less 65 H, so the maximum total stored energy is 1.05 MJ by the following equation

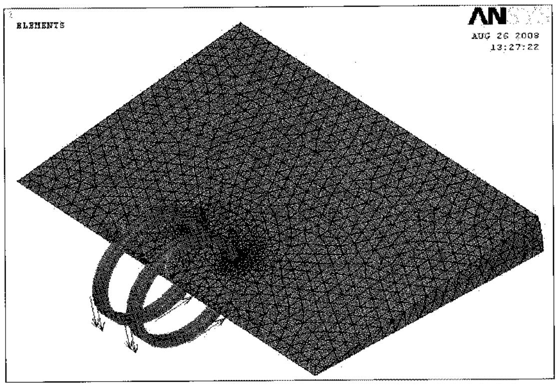

Fig. 3. Model and mesh for inductances calculation.

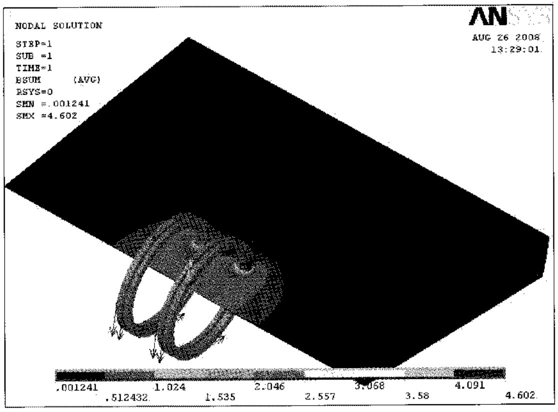

Fig. 4. Magnetic field distribution for the coils without yokes.

TABLE II
COMPARATIVE RESULTS OF INDUCTANCES BY ANSYS AND SOME APPROXIMATE EXPRESSIONS.

		coilB	coilA	coilA'	coilB'
approximate expressions	coilB	10.59	5.41	1.42	1.57
	coilA		5.50	1.29	1.42
	coilA'			5.50	5.41
	coilB'				10.59
ANSYS	coilB	10.56	5.32	1.32	1.52
	coilA		5.43	1.26	1.32
	coilA'			5.42	5.31
	coilB'				10.55

$$E = \frac{1}{2} L I^2 \qquad (1)$$

3.2. Coils inductances with iron yokes

The yokes have the shape of a cylinder which is enclosed by an endcap on either side. The iron yokes return the flux of the superconducting coils. Iron J23-50 magnetization is used for this calculation [3]. Fig.5 shows magnetic induction (B) as a function of magnetic strength (H). Fig.6 shows the self inductances vs. current for the magnet coil A and coil B. Inductances of the magnet employing iron yoke are function of iron saturation. From Fig.6, the inductance of coil B is almost two times larger than the inductance of coil A after iron yokes saturation, because the coil B has more coil windings. Self inductances slightly change with current for magnet coils with iron yokes. Mutual inductances vs current for magnet coils with iron yokes is showed in Fig.7. The mutual inductance between coil A and coil B is the largest and the mutual inductance of coil A and coil A' is the smallest one. This certifies that the mutual inductances rises with the coil turns number and reduces with the gap between two coils. From the Fig.6 and Fig.7, the total inductance is about 70 H when the operating current is 180 A, i.e. the iron yoke is saturated. So from equation (1), the coils stored energy is 1.14 MJ with iron yokes. Fig.8 gives the magnetic field distribution around the coils with iron yokes (region o-a-b-c-d-e-f-g in Fig.2). From this figure, the maximum magnetic flux density is about 4.9 T. And in the central of zone (coordinate origin o point), the field is already 3.2 T. The field in the center rises more rapidly than those around the coils. That means the iron3 mainly acts as increasing carbon ions acceleration zones field, but other yokes act to return field flux and make field flux leaks as small as possible.

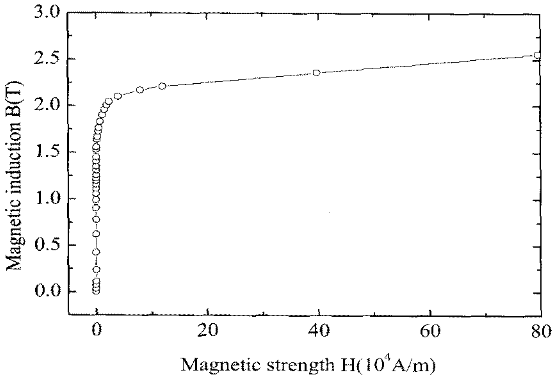

Fig. 5. Magnetic induction (B) as a function of magnetic strength (H).

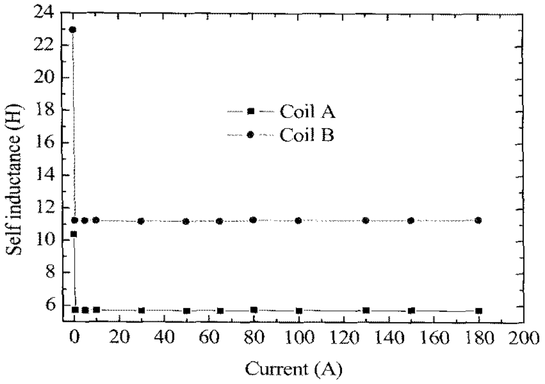

Fig. 6. Self inductances vs. current for magnet coils with iron yokes.

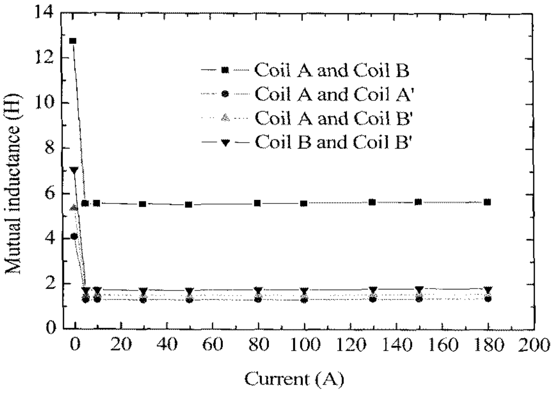

Fig. 7. Mutual inductances vs. current for magnet coils with iron yokes.

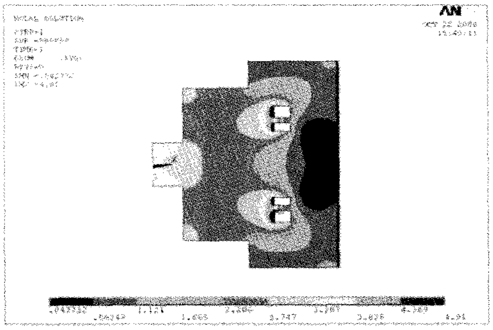

Fig. 8. Magnetic field distribution around the coils with iron yokes.

4. CONCLUSION

The effective modeling and computer program for the inductances, magnetic field and magnetic force has been developed in this paper. The inductances are calculated by ANSYS without iron yokes, which get consistent results with some approximate expressions. The total inductance is about 65 H and the total stored energy is about 1.05 MJ without iron yokes. The self inductance and mutual inductance vs. current are also calculated with iron yokes, respectively. The corresponding total inductance is 70 H and stored energy is 1.14 MJ with iron yokes saturation. These calculation results will benefit to the detail magnet ramping and quench protection designs.

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