Design Optimization of 10 MeV Cyclotron Magnet Using the Sequential Approximation Technique

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The systematic process of design optimization was proposed by using the sequential approximation technique for a 10 MeV cyclotron magnet, which is a Positron Emission Tomography (PET) cyclotron for producing radioactive isotopes. The aim of this optimization process is to reduce the size of magnet while producing radioisotopes efficiently with the minimization of beam loss. For optimization process, here, we adopted the Latin Hypercube Sampling (LHS) method, one of design of experiments (DOE), and generated sampling data. And based on these data, an approximation model was modeled by using the Kriging technique. To find out an optimal shape, an iterative searching technique was implemented incorporating with the approximation model and the Restricted Evolution Strategy (RES) and boundary shifting technique. The initial magnet model was obtained from the conventional routine procedure for cyclotron. To verify our proposed model, the final magnet model was tested with the beam simulation for checking the trajectory of ^{18}F with the level of 10 MeV at the extraction point.

***Index Terms*— Cyclotron, Magnetic field, Sequential Approximation Techniques, Kriging, Restricted Evolution Strategy.**

I. Introduction

RECENTLY, cyclotrons have been developed with a lot of designs according to the increasing demand of low-energy machine for radioisotopes production [1]-[2]. To design the cyclotrons in the conventional routine approach, it needs too much time because it is quite difficult to get the stable acceleration of particles inside magnet and to achieve the level of 10 MeV at the extraction point. Until now, however, the systematic and numerical optimization process has been rarely seen in the previous research articles. To meet the goal, therefore, this paper presented the designing 10 MeV cyclotron magnets for the purpose of radioisotope ^{18}F production.

In this paper, the systematic design process was developed for conventional cyclotron magnets and conducted a magnetic field optimization with an initial model obtained from the analytic approach. To get the optimal shape, we adopted the design of experiment with the Kriging technique employing the Restricted Evolution Strategy (RES) and boundary shifting technique. The optimization process was performed by changing the degrees of side of hill according to radius. After this process, the beam simulation was performed to check the verification. When the beam characteristics get satisfactory results, finally, a magnet design could be completed.

II. Initial Design with Conventional Approach

To design an initial magnet, first, the magnetic rigidity should be calculated considering the type of accelerated particle and maximum acceleration energy as follows:

$$B \cdot r = \frac{\sqrt{T^2 + 2TE_0}}{300Z} \tag{1}$$

where T is the maximum acceleration energy of particles, E_0 is the rest energy of proton, and Z is the mass number. After that, the design parameters such as size and magnetic field of initial magnet can be calculated by using the magnetic rigidity. In our initial design, the magnetic rigidity was 0.458 T·m. The design parameters of magnet were summarized in Table I. The initial magnet was built based on these parameters and was shown in Fig. 1.

TABLE I
MAIN PARAMETERS OF 10 MeV CYCLOTRON MAGNET

Parameters	Values
Maximum Energy	10 MeV
Accelerated particle	Negative hydrogen
Radio frequency	83.2 MHz
Dee voltage	40kV
Harmonic number	4
Pole radius	0.38 m

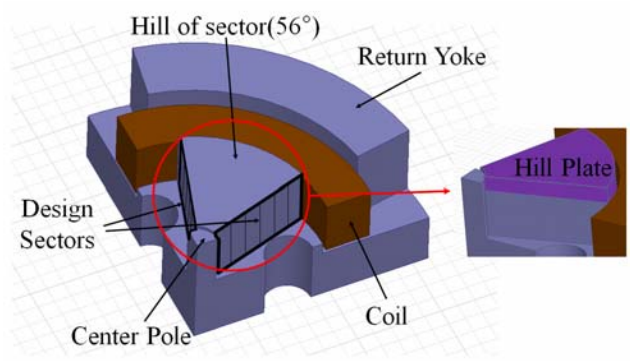

Fig 1. Initial design of magnet structure (1/8model)

III. Magnetic Field Optimization Using the Sequential Approximation Technique

The performance of cyclotron is so sensitive in magnetic field even with a small variation of electromagnet shape. We, therefore, need more reliable analysis with mesh controls in the Finite Element Method (FEM). Additionally, 3D-analysis with optimization procedure has time constraints for testing all shapes within the design variable range. To resolve these numerical difficulties, here, we adopted the sequential approximation technique incorporating with the Latin Hypercube Sampling (LHS), the Kriging meta model, the RES, and boundary shifting technique. Fig. 2 shows the procedure of the proposed optimization framework.

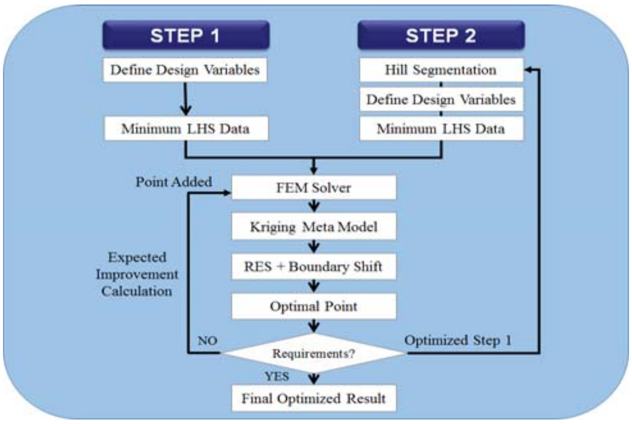

Fig 2. Procedure of proposed optimization technique

The systematic optimization procedure for cyclotron is as follows: 1) The initial sample data is set within design sectors as shown in Fig. 1 by using the LHS method; 2) With the FEM, we investigated correlation between design variables and objective function; 3) The Kriging meta model is composed based on analyzed data; 4) The optimal solution will be found using the RES[3]. To get a better solution, here, we employed a boundary shifting technique; 5) The convergence is checked; 6) When it is not converged, an optimal solution point is added and the Kriging model is reconstructed with the updated sampling set. Procedure 4-6 is repeated until the condition the process is satisfied.

In cyclotron, RF system and beam phase at the dee gap should be coincided in order that beam can stably obtain accelerated energy. And we call the difference between two phases, the phase shift. The phase shift is steadily accumulated according to increasing turn number of beam. If the accumulative value exceed the specific value, beam is deviated from accelerated region of RF system and is decelerated. Therefore, the integrated phase shift, Φ, should be existed within the specific value as follows [4]:

$$\Phi \le \pm \frac{\theta_{dee}}{2} \qquad (2)$$

where θ_{dee} is degree of RF system. In this study, RF system is 30 degree and the integrated phase shift should be satisfied with the condition within ±15 degree. This criterion is very difficult in the conventional design approach.

IV. Results and Discussion

Fig. 3 shows the optimized procedures obtained from step 1. The geometry to satisfy the magnetic field was acquired through total of three iterative optimization process. The optimized procedures from step 2 is shown in Fig. 4. After 17th iterative optimization process, an optimum model was obtained within the integrated phase shift condition. And then, we tested the beam trajectory to get the beam energy level of 10 MeV through beam simulation using the optimized Cyclone. As a result, the beam trajectory was stably accelerated until the 10 MeV.

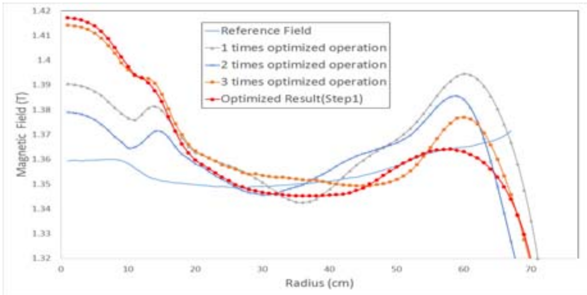

Fig 3. Optimized process and result of average magnetic fields according to increasing radius in step 1

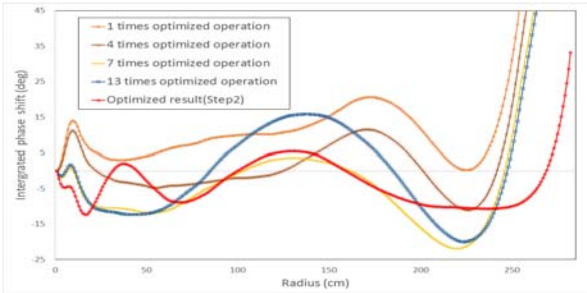

Fig 4. Optimized process and result of integrated phase shift according to increasing radius in step 2

V. CONCLUSION

The design optimization of cyclotron magnet was conducted using the sequential approximation technique and boundary shifting technique. To get a better result, we employed the boundary shifting technique for searching more optimal solution. The systematic design process was developed to increase the time efficiency and it is expected to lower the initial technology entry barrier in the design of cyclotron magnet.

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