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# OPTIMIZATION OF RAPID MAGNETIC FIELD CONTROL OF THE CYCIAE-230 CYCLOTRON BEAMLINE MAGNETS

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*Abstract*

The magnetic field precise and rapid control of the beamline magnets is essential to the Energy Selection System (ESS) for the proton therapy facility. During the scanning of proton beam for therapy, the field of each beamline magnet should be precisely controlled within the set time, layer upon layer. The position of beam spot to the nozzle should undoubtedly be stable and unchanged during the process. In practice, however, due to the wide energy range of proton therapy (70 ~ 230 MeV), the dynamic response of the beamline magnets usually shows nonlinear performances at a different energy, e.g., the magnetic field may cause a significant overshoot for some specific beam energy if one ignores the nonlinear effect. More challenge is that the magnetic field drops too slowly between the energy steps, which compromises the overall performance of rapid intensity modulated scanning therapy. A dynamic PID parameter optimization method is reported in this paper to address this issue. According to the transfer function of each magnet, the entire energy range is divided into several steps. Then, the experiments are carried out to find the most suitable PID parameters for each energy step. Finally, the "beam energy − excitation current − PID parameters" lookup table (LUT) is generated and stored in the beamline control system BCS for automation. During the treatment, using the LUT allows the energy setting for beamline magnets to be adjusted automatically with the most appropriate PID parameter, guaranteeing the overall performance of rapid scanning therapy. The experimental results show the overall response time of all the beamline magnets reduced from several hundred milliseconds to less than 65 ms, which meets the design requirement of less than 80 ms.

## INTRODUCTION

CIAE is developing a proton therapy facility base on a superconducting cyclotron. The beamline is one of the important components of the therapy facility, which guarantees the proton track can be fixed from the cyclotron to the nozzle [1, 2]. When adjusting the treatment layer, the dynamic response of beamline magnets should be as fast as possible, reasons as follows: Firstly, it can reduce the treatment interval time between different layers and improve the efficiency of the therapy. Secondly, it minimizes the damage to the patient's healthy tissue. Thirdly, a long energy switching process will undoubtedly increase the cyclotron operation time when treating a patient. The total time loss added up by every treatment layer will be considerable. So, it will lead to a significant increase in total energy consumption. At present, the total energy selection time of proton therapy centers worldwide is mostly on the order of several hundred milliseconds scale. For example, the time for IBA in Belgium is 500 ms and the time for PSI in Swiss and Varian in America can be 150 ms. The energy selection time of the HUST-PTF proton therapy system at Huazhong University of Science and Technology is 144 ms, and its magnetic field dynamic response time is 105 ms [3].

The total energy selection time of CYCIAE-230 developed by CIAE is less than 80 ms. To guarantee the faster speed of magnetic field response, this paper presents a dynamic PID parameter optimization method.

## MAGNET POWER SUPPLY CONTROL

The discrete PID algorithm is used for the magnet power supply. Figure 1 shows the control block diagram. The control loop adopts a double closed-loop control structure of output current outer loop and load voltage inner loop. The output current feedback value is obtained by DCCT. The load voltage control loop can solve the voltage disturbance in the main circuit of the power supply more quickly, and increase the stability of the system. In contrast, if there is only a single current control loop, the voltage disturbance needs to be reflected as output current fluctuation, then compensated. This process has hysteresis, and voltage disturbance cannot be eliminated essentially either.

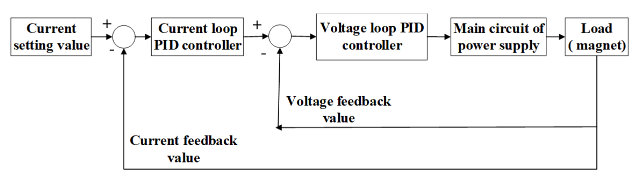


Figure 1: Control block diagram of magnet power supply.

## OPTIMIZATION OF RAPID MAGNETIC FIELD CONTROL

### *Two Main Difficulty of Accelerating the Dynamic Response of Magnetic Field*

The energy range of proton therapy is wide, which is 70 ~ 230 MeV. This leads to one set of PID parameters not being adapted to all the energy steps. The reasons are mainly divided into two aspects: the nonlinear variation of the magnetic field and the influence of hysteresis.

**The Influence of Nonlinear Magnetic Field Variation** The SRIM software was used to approximate the energy required for the beam to hit the body at various thicknesses. As the interval between each treatment layer is 2 mm in this project, the proton range interval is set as 2 mm in the calculation. Figure 2 shows the calculation results. It can be seen that the relationship between energy and range is not linear. To increase the same range, the energy variation

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(dE) is 1.89 MeV for 70 MeV and 0.81 MeV for 230 MeV. The difference can be 2.33 times.

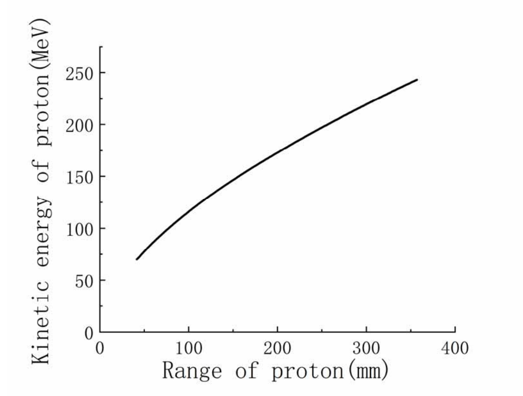


Figure 2: Proton range versus energy diagram.

According to the magnetic stiffness formula, the required field and excitation current of the bending magnet at each energy is calculated. The magnetic stiffness formula is as follows.

$$B = \frac{\sqrt{E^2 - E_r^2}}{300\rho} \tag{1}$$

where B is the magnetic induction intensity of the bending field, and the unit is T; ρ is the radius of curvature of the beam bending orbit; E is the proton's total energy and $E_r$ = 938 MeV is the rest energy of the proton. By bringing in the energy data obtained by SRIM, the required magnetic induction intensity at each energy can be obtained. Derivation of Eq. (1) gives:

$$\frac{dB}{dE} = \frac{1}{300\rho}\sqrt{1 + \frac{E_r^2}{E^2 - E_r^2}} \tag{2}$$

where one can see that the smaller the energy is, the greater the magnetic field variation (dB) will be.

Table 1 shows the dE, dB, and the excitation current variation (dI) of the 60° deflection magnet. It can be seen that dB for 70 MeV extraction is 121.03 G while it is 30.99 G for 230 MeV. The difference can be 3.5 times.

Table 1: Comparison of dE, dB, and dI in different energy steps of 60° bending magnet

| **Energy segments** | **dE** | **dB** | **dI** |
|---|---|---|---|
| ~ 230 MeV | 0.81 MeV | 30.99 G | 1.2319 A |
| ~ 145 MeV | 1.12 MeV | 50.93 G | 1.8627 A |
| ~ 70 MeV | 1.89 MeV | 121.03 G | 4.2335 A |

In PID control, the steady-state error is controlled by the integral link, therefore the greater the dB, the stronger the integral effect. In the low energy segments, e.g., 70 MeV, due to a large amount of magnetic field change, the integration effect is very powerful, so it is very easy to cause an overshoot in response. In contrast, smaller dB makes a weaker integral effect, which results in a slow descent response when the beam energy is around 230 MeV. Figure 3 shows the different responses for 70 MeV and 230 MeV with the same PID parameters. Both of them take more than 80 ms.

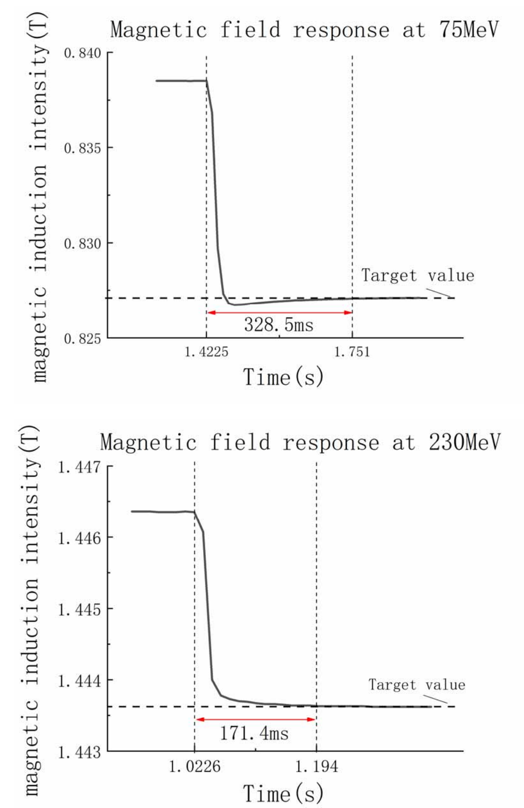


Figure 3: Under the same PID parameters, the responses at 70 MeV (top) and at 230 MeV (bottom) are apparently different.

**The Influence of Hysteresis on Magnetic Field Response** Hysteresis refers to the hysteresis loop relationship between magnetic induction intensity (B) and magnetic field intensity (H) when the magnetic state of ferromagnetic materials changes. The stronger the magnetic field, the more obvious the hysteresis effect. The formula of magnetic field intensity (H) and excitation current (I) is as follows:

$$I = \oint \vec{H} \cdot \vec{dl} = 2\pi r H \tag{3}$$

There is a linear relationship between H and I, so in the process of energy reduction, when the magnetic field is stronger, e.g., at 230 MeV, the hysteresis of B relative to I is more obvious. Figure 4 shows a comparison of responses with or without hysteresis. The error caused by hysteresis also needs to be eliminated by the integral link of PID control. Therefore, a larger integration factor is needed in higher energy segments.

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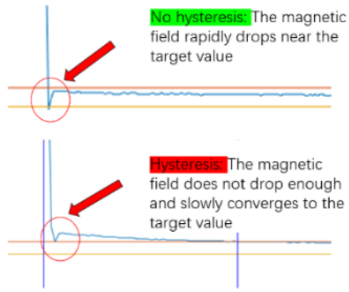


Figure 4: Comparison of response with/without hysteresis.

In summary, the field dynamic response usually shows nonlinear performances at different energy steps due to the two main difficulties. Therefore, facing a load of such characteristics, an optimal control method with dynamic PID parameters is proposed in this paper to speed up the magnetic field dynamic response.

### *Optimal Control Method for Dynamic PID Parameters*

Firstly, a large number of magnetic field response data in different beam energies are obtained through vast experiments. Based on this, the energy range of 70 ~ 230 MeV can be divided into several segments. Each energy segment uses one set of PID parameters appropriate for the segment. This guarantees that the magnetic field at each energy converges quickly to the target value.

Secondly, the magnetic field dynamic response at 230 MeV is prioritized to regulate. At this time, since the field variation is small and the hysteresis is obvious, it is advisable to use a larger scale factor ($K_P$) and integration factor ($K_I$) to make the field value converge to the target value quickly. This group of PID parameters is suitable for the high-energy segment.

Thirdly, experiments with lower energy are gradually performed until a significant overshoot of the dynamic process occurs. This means that this set of parameters is no longer appropriate for this beam energy segment, and is definitely not suited for beam energies smaller than this. The PID parameters need to be set again to obtain a better dynamic response for this segment. Then, record this set of parameters and their appropriate energy segment. Repeat the above process until the parameterization of the entire energy range is completed.

Finally, a "beam energy – excitation current – PID parameter" LUT can be made based on the above results and stored in the BCS controller.

For the three kinds of bending magnets in CYCIAE-230, the first set of PID parameters with a larger integration factor ($K_I$) is used in the beam energy range of 230 ~ 145 MeV. Using the second set of PID parameters in the range of 145 ~ 110 MeV, the $K_I$ is reduced. And the third set of PID parameters matches the range of 110 ~ 70 MeV, the $K_I$ is further reduced to prevent overshoot, while the scaling factor ($K_P$) is appropriately increased.

The "beam energy – excitation current – PID parameter" LUT is made and stored in the controller of BCS, which is automatically called during the dynamic process of energy reduction, as illustrated in Fig. 5. The left side indicates the stepdown of the magnetic field with the beam energy during the treatment process, layer upon layer; the right side indicates the automatic modification of suitable PID parameters for different energy segments.

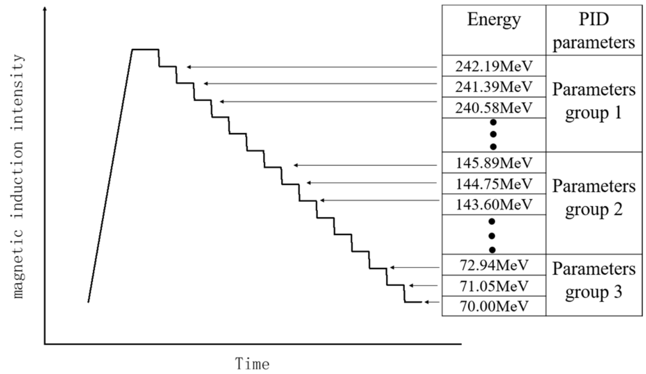


Figure 5: Logic schematic.

## TEST RESULTS

Tests were performed on the CYCIAE-230 proton therapy system beamline. Figure 6 illustrates the comparison of the magnetic field response before and after optimization, using a 60° magnet as an example. All the magnetic induction intensity values (B) have been normalized to fit in the same graph. After optimization, the dynamic responses of each energy segment are matched to the best PID parameters, so the responses could end within 80 ms, with the shortest time being only 32.5 ms. In Fig. 6, the red curve represents the response in the 230 ~ 145 MeV segment before optimization. It can be seen that it has a lower descending slope and takes 120.47 ms. In contrast, the black curve shows the optimized response in this segment, with the time reduced to 63.3 ms. The field drop rate increased to 1.9 times the original. The green curve represents the response in the 110 ~ 70 MeV segment before optimization, which shows the drop overshoot and response time up to 273.5 ms. In contrast, the blue curve indicates the optimized response of this energy segment. The time is reduced to 50.67 ms and the response speed is increased to 5.4 times the original.

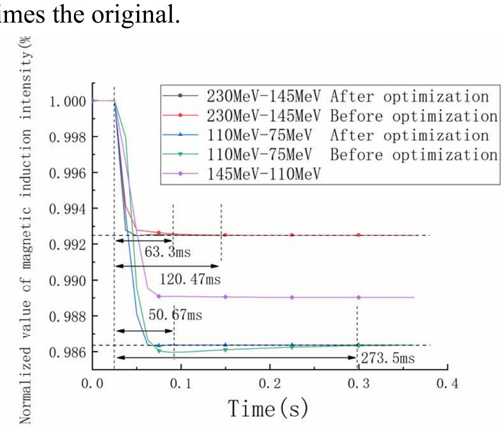


Figure 6: Comparison of field response before and after optimization.

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For other types of magnets, the energy range of 30° and 75° bending magnets is also divided into three segments. Figure 7 shows the normalized dynamic response data in different segments, represented by different colour curves. The response speed of the 30° bending magnet in the 110 ~ 70 MeV segment is the slowest one (purple triangle curve), and the time is 65 ms, within 80 ms.

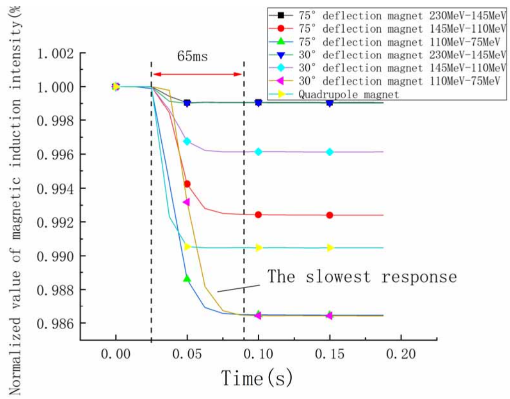


Figure 7: Comparison of other magnets in different energy segments.

## CONCLUSION

To achieve the field precise and rapid control of the beamline magnets within the set time, an optimal control method of dynamic PID parameters is proposed in this paper. Large quantities of experiments are carried out to find the most suitable PID parameters for every energy step and LUT is used to adjust parameters automatically. Test results show that the field response time has been shortened from hundreds of milliseconds to 65 ms, which meets the design requirements of less than 80 ms. This work has been applied to the ESS of CYCIAE-230 in CIAE and provides a new idea for solving the problem of slow field dynamic response of large magnets.

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