ULTRA HIGH STABILIZATION OF THE MAGNETIC FIELD OF THE RCNP AVF CYCLOTRON

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Abstract

High-quality beams have been successfully accelerated in the RCNP cyclotron complex. For such beams, it is found that stability of a magnetic field of a cyclotron is essential. Now we can keep the constant magnetic field within the order of 10^{-6} and high-quality beams are kept for a long time without any tuning of cyclotron parameters. In this contribution, the stabilization of the magnetic field of the RCNP AVF cyclotron by temperature control was reported.

1. INTRODUCTION

The RCNP cyclotron complex consists of a large-sized ring cyclotron (K=400) and an injector AVF cyclotron (K=140). Beams are used mainly for nuclear physics research and high-quality beams in momentum spread have been strongly required. Recently, we have succeeded in producing such high-quality beams. For example, energy spreads were achieved as 55 *keV* and 62 *keV* for 300 *MeV* and 392 *MeV* proton beams, 89 *keV* and 110 *keV* for 420 *MeV* and 450 *MeV* 3-herium beams, and 125 *keV* and 108 *keV* for 210 *MeV* and 400 *MeV* 4-herium beam, respectively.

For high-quality beams, severe controls of the magnetic and electric fields to ion beam should be needed. Therefore, one needs to install good probes. In order to measure magnetic fields, two NMR probes with correcting coils were installed in the AVF cyclotron[1][2]. These probes were inserted between the magnetic pole and the base plate for the trim coils with different radii of the cyclotron, that is, ~50 cm and ~70 cm, respectively. Now the magnetic field can be measured with the resolution of 10 *nT*, i.e., $\Delta B/B$ can be measured on the order of 10^{-8}.

It was found that stability of the magnetic fields B of the injector AVF cyclotron is much important. For example, for 392 *MeV* proton beam, when the AVF magnetic field increased with a rate of $\Delta B/B \sim 4\mathrm{x}10^{-6}$, the energy spread $\Delta E/E$ was observed to increase roughly twice[2]. At that time, $\Delta B/B$ increased with a rate of ~ $1.2\mathrm{x}10^{-5}$ per day without any operation. Clearly, a severe control of the magnetic fields of the AVF cyclotron is a key to obtain high-quality beams. At least, $\Delta B/B$ needs to be controlled within the order of 10^{-6}.

2. STABLIZATION OF A MAGNETIC FIELD

A magnetic field of a cyclotron B is not only a function of coil current, but also a function of form of iron core and magnetic permeability. For example, the magnetic field is very roughly estimated by $B = NI / (L / \mu + l / \mu_0)$, where N is a turn number of the coils, I is coil current, L is length of the magnetic circuit, l is air gap length, μ is magnetic permeability of an iron core and μ_0 is magnetic permeability of the air(or vacuum), respectively.

For a cyclotron operation, current feedback to a magnetic field is usually adopted. In our opinions, however, current feedback is not the most suitable method to correct a magnetic field of a cyclotron in order to obtain high-quality beams at all times.

Generally speaking, stability of a power supply is quite good for a cyclotron. For the RCNP AVF cyclotron, the current stability of the main coil is better than $4 \mathrm{~x~} 10^{-6}$. The origin of the drift of the magnetic fields does not come from current instability in most cases, and therefore, comes from drifts of other parameters, such as L, l and μ for the above simple model. When these parameters drift, non-uniform deformation of magnetic fields may happen and one can not reproduce the magnetic fields by current feedback.

Both form of iron core, such as L and l, and magnetic permeability, μ, have hidden parameters, i.e., temperature T. The coefficient of linear expansion for iron and the temperature coefficients of the magnetic permeability are roughly on the order of 10^{-5} and 10^{-4}, respectively. Therefore, generally speaking, both parameters can cause drifts of the magnetic fields.

For the RCNP AVF cyclotron, main origin of the drift of the magnetic fields was found to come from deformation of the iron pole and the return yoke[3]. In order to realize that $\Delta B/B$ stays within the order of 10^{-6}, the temperatures of the iron pole and return yoke were found to be controlled within 0.01 degree[3].

3. A SIMPLE MODEL

In order to realize the temperature of the iron core keep constant, heat transfer of a cyclotron should be considered.

Figure 1 shows a very simple model for heat transfer. Let us consider three systems, i.e., coils, an iron core and outer circumstance nearby, where the temperatures of these systems are T_c, T_r and T_o, respectively. Q_{co}, Q_{ro} and Q_{cr} are heat transfer from the coils to the outer circumstance, from the iron core to the outer circumstance, and from the coils to the iron core per unit time, respectively. Q_{cw} is heat transfer from the coils to an imaginary heat sink through cooling water and P is the electric power from the power supply of coils per unit time. It should be noted that an iron core itself has no heat origin from electric power.

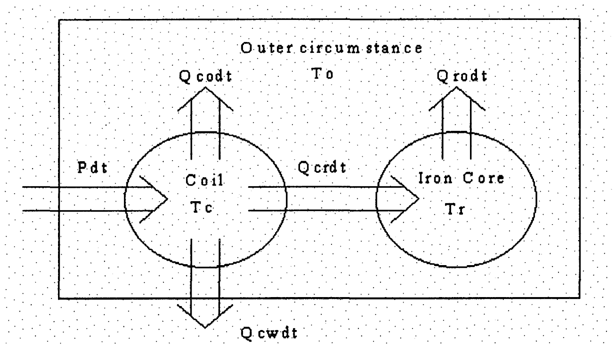

Fig. 1: A simple model for heat transfer

In this model,

$$C_c dT_c = Pdt - Q_{cw}dt - Q_{cr}dt - Q_{co}dt, \qquad (1)$$
$$C_r dT_r = Q_{cr}dt - Q_{ro}dt, \qquad (2)$$

where Cc and Cr are thermal capacity of the coils and the iron core, respectively.

For simplicity, we put strong restrictions, i.e.,

$$\Delta To = 0 \qquad (3)$$
$$\Delta Tc = 0 \qquad (4).$$

Newton's empirical raw was also assumed to Q_{cr} and Q_{ro}, i.e.,

$$Q_{cr} = Q_{cr}(T_r) = k_{cr}(T_c - T_r) \qquad (5)$$
$$Q_{ro} = Q_{ro}(T_r) = k_{ro}(T_r - T_o) \qquad (6)$$

where k_{cr} and k_{ro} are constant, respectively. Then we get

$$T_r = (T_{rf} - T_{ri})(1 - \exp(-t/\tau)) + T_{ri}, \qquad (7)$$

where T_{rf} and T_{ri} are initial and final temperature of the iron core, respectively, and

$$\tau = \frac{C_r}{k_{cr} + k_{ro}} \qquad (8)$$

$$T_{rf} = \frac{k_{cr}T_c + k_{ro}T_o}{k_{cr} + k_{ro}}. \qquad (9).$$

For the RCNP AVF cyclotron, time constant τ is estimated as ~ 40 hours[3]. Therefore, it is very difficult to control the temperature of the iron core rapidly.

The time constant, τ, itself is not a suitable parameter to estimate the effective time, t_{eff}, required from the initial temperature. Assuming that the temperature condition is empirically satisfied when $T_r = T_{rf} \pm \Delta T$, the effective time is estimated as

$$t_{eff} = \tau \ln \left| \frac{T_{rf} - T_{ri}}{\Delta T} \right| \qquad (10).$$

When T_{rf} - T_{ri} is 1 degree and ΔT is 0.05 degree, the effective time, t_{eff}, is estimated to ~ 120 hours.

4. IMPROVEMENT

The RCNP cyclotron complex is continuously operated during a few months even for weekends. Therefore, if the conditions in eqs (3) and (4) are always satisfied, the temperature of the iron core, T_r, stays constant after passing the effective time.

Recently, some improvements of the air and water cooling system for the RCNP AVF cyclotron have been carried out.

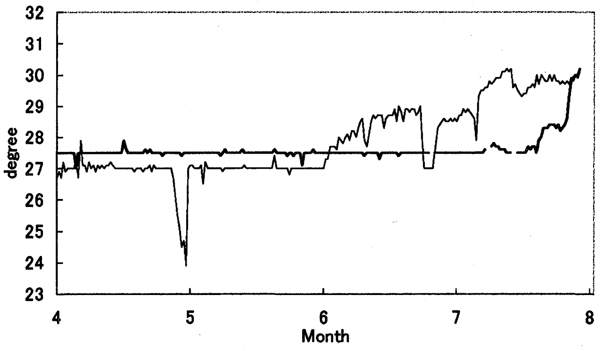

Fig. 2: Temperature of the AVF cyclotron room in 2001 (thin line) and 2003 (thick line).

Figure 2 shows the temperatures of the AVF cyclotron room(i.e., T_o in eq.(3).) at 2:00 and at 14:00 in every day as a function of the date. In 2001, the temperatures were well controlled to 27 degree before the beginning of the June, except the end period of the April. The reason why the temperatures decreased in this period is still unknown. Then the room temperatures increased from the beginning of the June. The room temperatures mainly depended on atmospheric temperatures and humidity outside. Finally, the temperatures got to 30 degrees.

The air conditioning systems for the AVF cyclotron room was reinforced by about 10 percent, by installing a new air conditioner to the old system. The new air conditioner has a long cooling-medium line(~60 *m*), for effective heat transfer from the radiation control area to outside. The old air conditioning system was also cleaned up to ensure arranged heat transfer.

The room temperature in 2003 is also shown in fig. 2, even though some data were missing. The target temperature was changed to 27.5 degree. The room temperatures were kept roughly constant until the beginning of the July. After that, the room temperature slightly increased. Large deviation at the end of the July came from a trouble of the new air conditioner.

In order to realize the condition in eq. (4), a water cooling system of the AVF cyclotron was improved. In order to control the water temperature for the main coil independently, an additional water pump and heat exchanger was installed. A three-way valve was also newly installed nearby the cooling tower in order to cancel out influence on outer disturbance. Finally, water temperatures both for the main coil and the trim coils can be controlled by the order of 0.1 degree.

5. RESULTS

Figure 3 shows the magnetic field of the AVF cyclotron for 300 *MeV* proton beam with the temperature of the pole surface and the return-yoke surface as a function of a relative time *t*. The return-yoke temperatures have offsets of 2.3 degree.

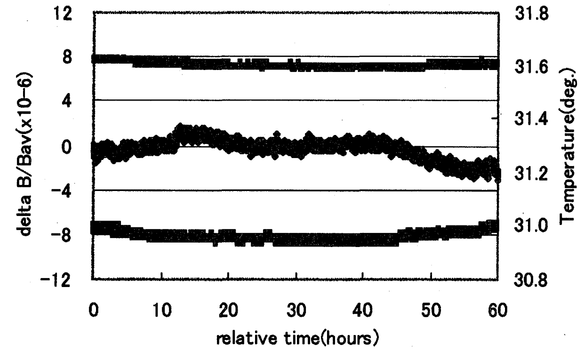

Fig. 3: Magnetic field of the AVF cyclotron(center), temperature of the pole surface(upper) and temperature of the return-yoke surface(lower). The return yoke temperature has an offset of 2.3 degree.

Both the temperatures stayed within ±0.06 degree over 60 hours. The magnetic field kept the level within $\pm 2.5\times10^{-6}$ during this period. In this period, any cyclotron parameters, including the main coil current, was not adjusted. Therefore, it is concluded that controlling temperature realizes a stable magnetic field, as expected.

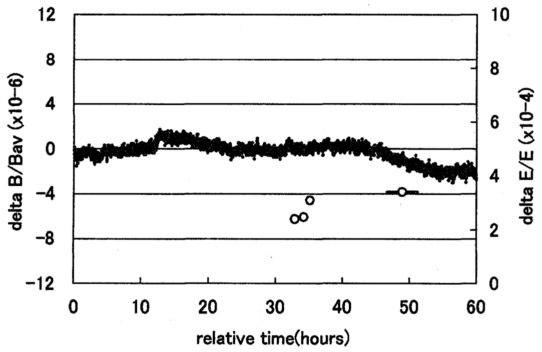

Fig. 4: Energy resolution (open circle) and magnetic field of the AVF cyclotron (diamond) for 300 *MeV* proton beam.

Figure 4 shows the observed energy resolution ($\Delta E/E$) at that time, as a function of a relative time *t*. The magnetic field is also shown in fig.4 again. The energy resolution at t=33 was observed as about 3×10^{-4}. As *t* increased, the energy resolution became slightly worse. The energy resolution, however, retained within 4×10^{-4} during about one-day beam time without any adjustments of the cyclotron parameters.

In conclusion, though the conditions in eqs (3) and (4) have not been always satisfied, remarkable improvement to obtain and to keep high-quality beams was achieved.

REFERENCES

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[3] T. Saito *et al.*, in these proceedings