RCNP TECHNIQUES FOR PRODUCING ULTRA-PRECISE BEAMS

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Abstract

Ultra-precise beams with $\Delta E/E \approx 1.5 \times 10^{-4}$ have been successfully accelerated up to 392 MeV in the RCNP cyclotron complex. Stability of a magnetic field is essential. It is found that temperature stabilization of an iron core is significantly important, which is realized to control the temperature of the cooling water for coils. Now we can keep the constant magnetic field within the order of 10^{-6}.

1 INTRODUCTION

The Research Center for Nuclear Physics (RCNP) in Osaka University has a cyclotron complex, which consists of a large-sized ring cyclotron (K=400) and an 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 ultra-precise beams and in keeping them for a long time. For example, the ratio of the energy spread to the beam energy ($\Delta E/E$) is achieved as $\approx 1.5 \times 10^{-4}$ both for 392 MeV and for 300 MeV protons.

A new beam line which accomplish both lateral and angular dispersion matching with the Grand Raiden spectrometer in the RCNP[1] was designed and constructed in 2000[2]. In dispersive mode, the energy distribution of the beam itself can be principally cancelled out. In the commissioning experiments, energy resolutions of $\Delta E = 13.0 \pm 0.3$ keV and $\Delta E = 16.7 \pm 0.3$ keV in FWHM were achieved for 295 MeV and 392 MeV protons[2], respectively, i.e., $\Delta E/E \approx 4 \times 10^{-5}$.

Even in dispersive mode, an energy resolution of the beam itself is much important practically. The lateral size of the beam on a target point is approximately proportioned to the momentum spread of the beam itself, which means that a high-quality beam is experimentally expected. Requirement for beam stability is also much harder than that for achromatic transport mode. An ultra-precise and stable beam, therefore, is also needed in dispersive mode.

A single turn extraction from the Ring cyclotron is realized by a flat-topping Rf system and, therefore, the condition of obtaining ultra-precise beams is satisfied in principle. A long-term stable operation for such beams, however, is still a remaining problem. It was already found that the long-term stability of the magnetic field of the Ring cyclotron can give no adjustment operation of the cyclotron [3]. A method to stabilize the magnetic field of the AVF cyclotron was, however, not reported. It is necessary that Stabilization procedure of the magnetic field both of the Ring cyclotron and of the AVF cyclotron is settled with unified comprehension.

The RCNP cyclotron complex is continuously operated during a few month even for weekends. Beam energy is typically changed a few times per month. In this condition, an "effective equilibrium concept" of the temperature is powerful to realize the high stable magnetic field. It should be pointed out that a feedback control of coils should be minimized for long-term operation of an ultra-precise beam, because non-uniform deformation of magnet pole and return yoke due to thermal effect should be avoided in keeping the isochronism at any radii.

2 MAGNETIC FIELD MEASUREMENT FOR THE AVF CYCLOTRON

Though an NMR probe gives magnetic field with precision, it is difficult to use the NMR probe for an AVF cyclotron, because of lack of uniformity of the magnetic field. Recently, magnetic field measurement with an NMR probe for JULIC was reported[4].

Relative measurement is considered to be enough in order to observe trends of the magnetic field. A small type of an NMR probe attaching small field correction coils is suitable for this purpose. After careful testing, two NMR-probe systems were installed in the AVF cyclotron. The probes were inserted between the magnetic pole and the base plate of the trim coils in a valley with different radii of the cyclotron, that is, ≈ 50 cm and ≈ 70 cm, respectively. The base plate made of copper prevents penetration of Rf noise. Since correction coils were replaced far from the medium plane of the cyclotron, no significant influence on the particles was observed.

We have continually succeeded to measure the magnetic field of the AVF cyclotron with the resolution of 0.1 μT, which is precise enough to operate the cyclotron. Figure 1 shows the magnetic field of the AVF cyclotron for 392 MeV proton as a function of a relative time t. Magnetic field increased with a rate of $\Delta B/B \approx 1.2 \times 10^{-5}$ per day without any operation.

The energy spread was intermittently measured by the users. When the energy resolution became significantly bad, the main coil current of the AVF cyclotron was adjusted. Energy resolutions before adjustment of the

magnetic field and after adjustment are also shown in Fig. 1. For example, at $t = 24$, the energy resolution before and after adjustment are 180 keV and 83 keV, respectively. The energy resolution was roughly represented when the magnetic field was represented. For $t > 50$ hours, the suitable magnetic field strength decreased by about 5 μT,

the reason of which may be that non-uniform deformation of the magnet pole and the return yoke happened. It should be noted that the frequency to change the coil current is only about 5 times per day.
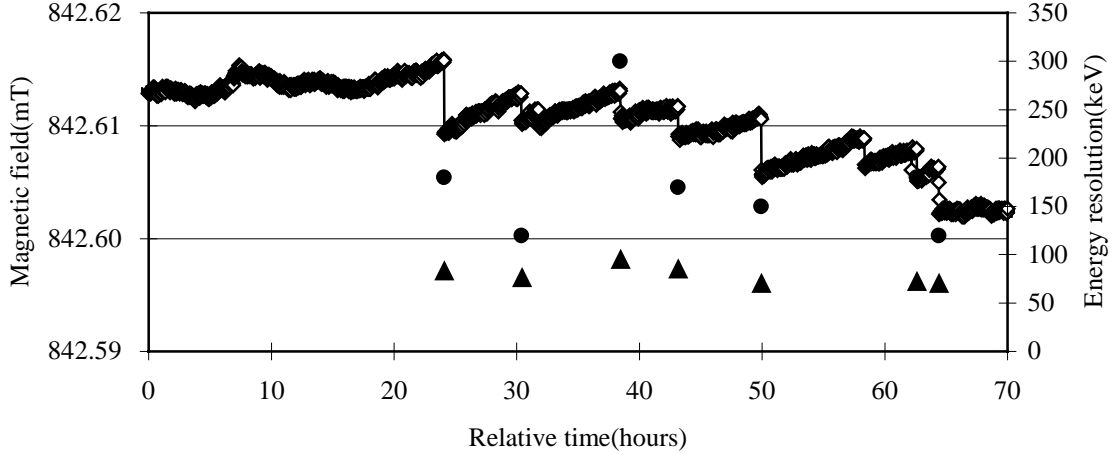

Figure 1:Magnetic field of the AVF cyclotron (open diamond). Energy resolution before adjustment (solid circle) and after adjustment (solid triangle) of the main coil are also shown.

From fig. 1, it is found that the magnetic field of the AVF cyclotron needs to be controlled on the order of 10^{-6}. Using the main-coil power supply, we need to control the current by a few mA in comparison with the total main coil current, ≈ 574 A, in this case.

3 THERMAL EFFECTS FOR MAGNETIC SYSTEM

3.1 Simple Model

As shown in Fig. 1, the energy spread of the beam strongly correlated with the magnetic field strength. For long-term stable operation of an ultra-precise beam, a drift of the magnetic field should be avoided. As the current stability of the main coils for the AVF cyclotron and the Ring cyclotron is good enough (better than 4x 10^{-6}), the stability of the temperature of the iron core may be a problem. An importance of a control of temperature of magnet has been pointed out[3]-[7].

A very simple model for heat transfer of a cyclotron is shown in fig. 2. Three systems, i.e., coils, an iron core and outer circumstance nearby the coils and the iron core, are considered with their temperature as 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

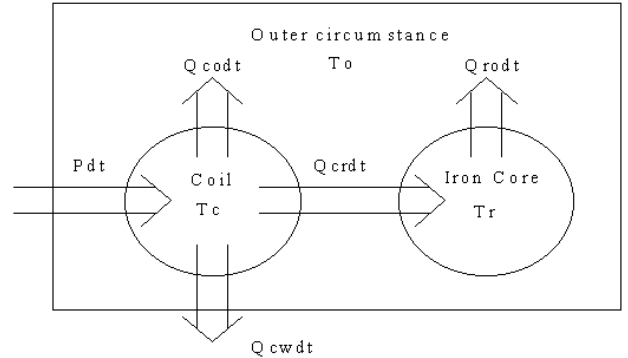P is the electric power from the power supply of coils per unit time.

Figure.2: 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 C_c and C_r are thermal capacity of the coils and the iron core, respectively.

It is very important that "dynamical" equilibrium condition of these systems is realized as soon as possible. After the dynamical equilibrium condition is satisfied, only we need to do is $Pdt - Q_{cw}dt$ keeps constant in case of beam energy change. Even when $Pdt = 0$, cooling

water may give heat and the dynamical equilibrium condition can be continued in principle. Standing by this criterion, to control spatial heat transfer inside an iron core seems to be the secondary effect to obtain an ultra precise beam with long-term stability.

For more simplified explanation, both T_c and T_o are assumed to be constant on every set of accelerated particles. In this case, only eq.(2) determines the temperature of the iron core, T_r. Within this assumption, changing T_c like a step function is allowed to discuss. Also Neuton's empirical raw was assumed, i.e.,

$$Q_{cr} = Q_{cr}(T_r) = k_{cr}(T_c - T_r) \quad (3)$$
$$Q_{ro} = Q_{ro}(T_r) = k_{ro}(T_r - T_o) \quad (4)$$

where k_{cp} and k_{po} are constants. Then we get

$$T_r = (T_{rf} - T_{ri})(1 - \exp(-t/\tau)) + T_{ri} , \quad (5)$$

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

$$\tau = \frac{C_r}{k_{cr} + k_{ro}} \quad (6)$$

$$T_{rf} = \frac{k_{cr}T_c + k_{ro}T_o}{k_{cr} + k_{ro}} . \quad (7)$$

Ring cyclotron

In the Ring cyclotron, surface temperature of the main coil, i.e. T_c, was directly measured with the cooling-water temperature. Now we try to keep constant of T_c with controlling the temperature of the entrance side of the cooling water.
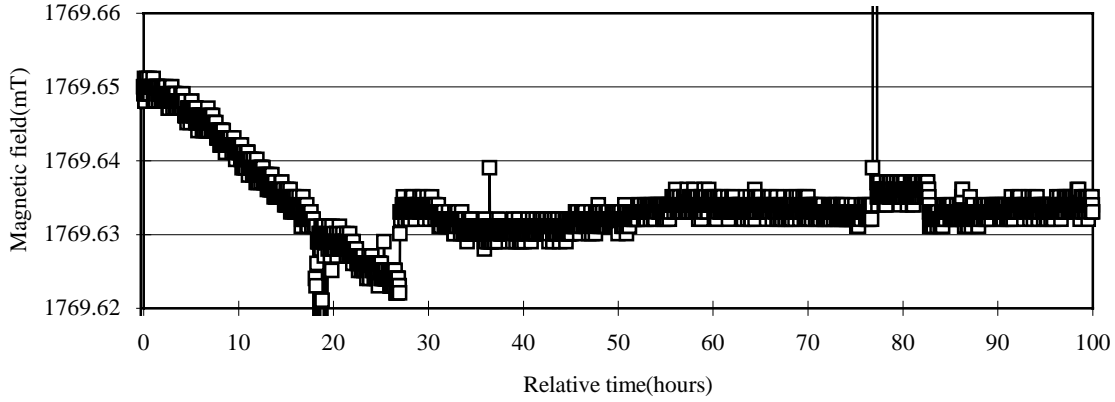

Figure 3: Magnetic field of the Ring cyclotron.

A minimized feedback control is useful for the Ring cyclotron. Figure 2 shows magnetic field monitored with the NMR probes as a function of a relative time t. For $t <$ 27 hours, the magnetic field decreased by -1.4×10^{-5}/day. At t = 27, the temperature of the trim coil was decreased by 0.1 degree. In case of the RCNP Ring cyclotron, we have a proper and uniform thermal contact between pole tips and trim coils[3] and, therefore, .within the model, k_{cr} is rather large. Then the magnetic field kept constant within $\pm 3 \times 10^{-6}$ over 3 days without any adjustment. By carefully adjusting the cooling-water temperature, stability of the magnetic field better than 1×10^{-6} over a weak is achieved.

Within the model, changing the temperature of the cooling water causes changing T_c, and changing T_{rf} through eq. (7). Though the time constant τ does not depend on T_c (see eq. (6)), the difference between T_{rf} and the temperature at the present time becomes small when the temperature of the trim coils is changed. This is the reason why the magnetic field can be kept constant.

Time constant τ does not seem to be a suitable parameter to estimate the effective time t_{eff}, needed for stabilization of the magnetic field from the present time. Assuming approximate equilibrium condition is satisfied even when $T = T_{rf} - \Delta T$, t_{eff} can be estimated as

$$t_{eff} = \tau \ln \frac{T_{rf} - T_{now}}{\Delta T} , \quad (8)$$

where T_{now} is the present temperature.

3.3 AVF cyclotron

Since the AVF cyclotron has no apparatuses of which thermal contact to the iron core is good enough, the dynamical equilibrium condition is strongly required. Recently, a cooling system of the AVF cyclotron was improved. A main point is that the cooling water of the main coil and the water of the trim coils are separated in order to control the water temperature easily.

In the AVF cyclotron, as direct measurement of the temperature of the coil surface is difficult, the average

temperature between the entrance side and the exit side of the cooling water is assumed to be an index of T_c and is automatically controlled to keep constant(35 degree).

Magnetic field of the AVF cyclotron and temperature of the pole surface and the return-yoke surface is shown in Fig. 4. At $t = 0$, all cyclotron parameters were changed from the sets of 176.7 MeV $^{11}B^{4+}$ beam to those of 64.6 MeV proton beam. Especially, main coil current was changed from 947A to 575A. Temperature both of the pole and the yoke surface stayed within 0.1 degree during this period. As machine time for users started at $t \approx -500$, the effective equilibrium condition was well achieved within a window here, even the particle energy was changed 3 times before $t = 0$. In other words, it was realized that $Pdt - Qcwdt$ in eq. (1) was kept almost constant in every sets of accelerated particles.
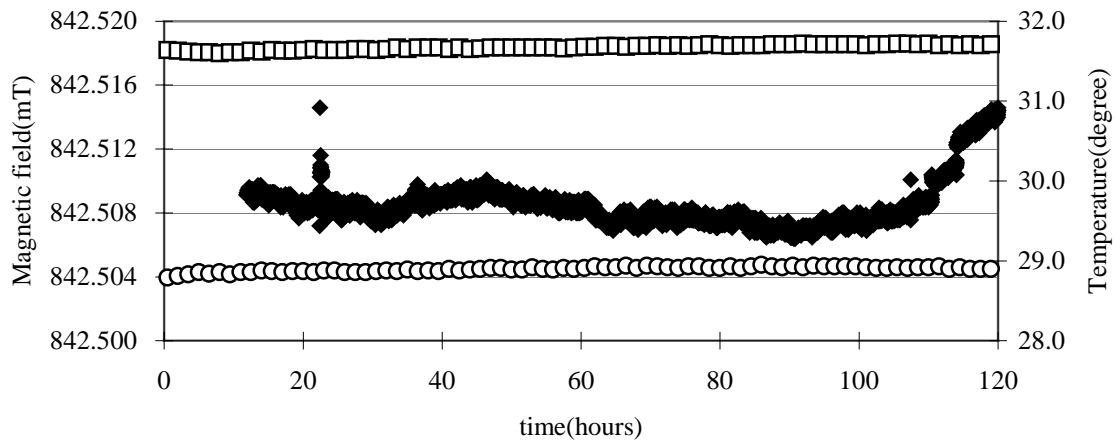

Figure 4:Magnetic field of the AVF cyclotron measured by an NMR probe (solid diamond) and temperature of the iron core; surface of the pole (open square) and return yoke (open circle).

For $12 < t < 110$, the magnetic field kept the level within $\pm 2 \times 10^{-6}$ without sudden hopping at $t = 23$. The field drifted for $t > 110$ hours, which may be caused by changing the temperature of the other cooling system. Possibly the position of the NMR probe moved a little bit.

Even the energy spread of the beam was not measured at that time, we are convinced that an ultra-precise beam should be obtained without any significant adjustments of the cyclotron parameters in this case (compare fig. 1).

In order to adjust the magnetic field in very detail, it is not so suitable that changing the main coil current by a few mA, i.e., 10^{-6} order of the total current. Therefore, a one-turn coil called fine tuning coil (FT coil) was installed to the AVF cyclotron. Typical current is ≈ 10 A. Current control of a few tens mA leads to control the magnetic field on the order of 10^{-7}.
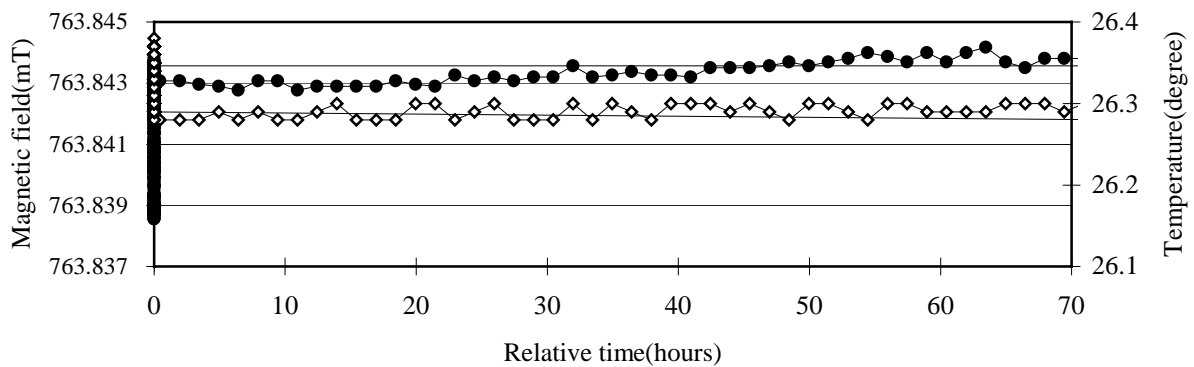

Figure 5:AVF magnetic field (solid circle) and temperature of return yoke(open diamond).

3 FURTHER PERSPECTIVE

The effective equilibrium concept for the temperature control of the iron core is shown to be useful for operation in the RCNP. The important points are 1) $Pdt - Q_{cw}dt$ in eq. (1) and 2) T_o in eq. (4) should keep constant at all the time Effect of the T_o to the magnetic field and the return yoke temperature of the AVF cyclotron is shown in Fig. 5. For $t < 40$ hours, drifts of both magnetic field and the temperature are negligible. At $t = 40$, the magnetic field suddenly decreased and the temperature increased. In fact, at this point, the wind direction in the cyclotron room was suddenly changed for other technical requirements. It should be noted that the temperature of the return yoke increased only by 0.1 degree. Though the changing ratio of the magnetic field was less than 6×10^{-6}, the obtained beam was found to become slightly unstable. The effective equilibrium concept is also useful at the start time of a cyclotron operation. Even when a power supply is not switched on, you can use rather warm "cooling water" which gives heat to keep T_c constant and can keep a room temperature T_o constant, in principle. In the RCNP, however, these conditions can not be satisfied

For T_c, though heat generated a water pump itself is useful as an origin of the heat, its power is much less than that required. For T_o, the power of the air conditioner was found to be insufficient. Figure 6 shows the room temperature. This test was practiced in winter. At $t = 0$, the temperature setting of the conditioner was changed to the expected temperature, i.e., $T_o = 27$ degree. When the main coil fired at $t = 0$, the temperature reached to the expected value within a finite time. The time constant is estimated to be about 30 hours. Without coils, however, the temperature can not reach the expected value up to $t = 60$ hours.
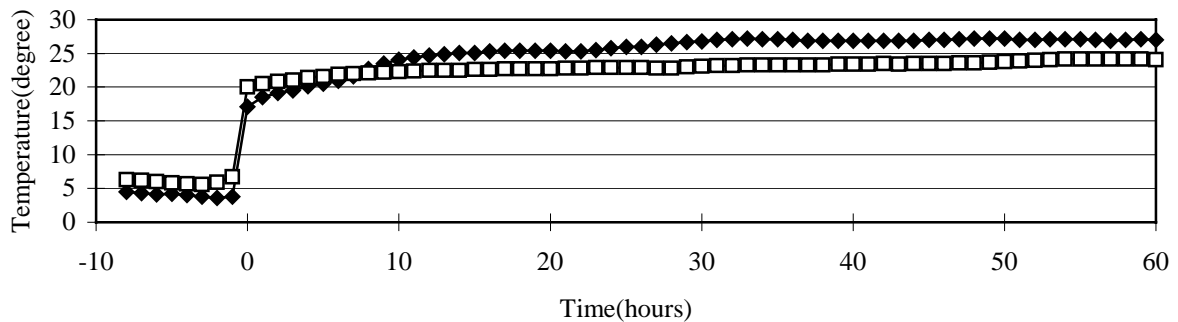

Figure 6: Room temperature of the AVF cyclotron with the main coils on(solid diamond) and off (open square).

Clearly, additional air conditioning system is needed for more precise operation of the AVF cyclotron. The cost, however, should be much expensive. We now plan to install cool plates well contacted to the return yoke to the AVF cyclotron. Within the simple model in Fig. 2, it is possible that $Q^{ro}dt$ keeps constant at any time by controlling the temperature of the plates.

4 CONCLUSIONS

It has been already reported that the temperature stabilization of the magnet would remove non-reproducibility of a cyclotron[7]. As is shown above, such stabilization is also needed to obtain an ultra-precise beam in a long-term stable operation.

Non-uniform deformation of the iron core due to thermal effect is not able to be cancelled out even by changing the coil current. In other words, the completely same magnetic field for a particle is only actualised by means that whole temperature distribution of the cyclotron is kept at all time.

In near future, improvement methods in keeping the temperature well for an existing cyclotron will be studied, which may lead to a criteria to design a new cyclotron.

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