ULTRA STABLE MAGNETIC FIELD OF THE RCNP CYCLOTRON FOR HIGH RESOLUTION BEAM OPERATION

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Abstract

Ultra-precise beams have been successfully accelerated up to 392 MeV/u in the RCNP cyclotron complex. It is found that stability of a magnetic field is essential. The temperature of an iron core have been stabilized by controlling the temperature of the cooling water for coils. Now we can keep the constant magnetic field within the order of 10^{-6} and ultra-precise beams are kept for a long time without any tuning of cyclotron parameters.

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). The RCNP cyclotron complex is continuously operated during a few months even for weekends. Accelerated particles and/or their energies are typically changed a several times per month for several kinds of nuclear physics experiments.

One of the strong requirements for beams is high-quality beam in momentum spread. 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 150 keV for 420 MeV and 450 MeV 3-herium beams, and 108 keV for 400 MeV 4-herium beam, respectively. Especially, it should be noted that the ratio of the energy spread to the beam energy ($\Delta E/E$) is about 1.5x10-4 for proton beams[1].

In past a few years, we have obtained such "ultra-precise" beams, i.e., $\Delta E/E$ is less than $4\text{x}10^{-4}$, in almost every machine time. In other words, reproducibility of beams themselves is quite good, even though cyclotron parameters need to be slightly changed among independent beam times. It should be noted that to keep a ultra-precise beam as long as possible is also important to use. As described below, long-term stability of such beams, however, was still a remaining problem.

We considered that temperature control of the iron core is essential and improved a cooling system of the injector cyclotron in the RCNP. Recently, we have succeeded to obtain an ultra-precise beam for a long time without any tunings of cyclotron parameters, which supports our simple model and criterion for the temperature.

2 FORMER RESULTS

There are a large number of parameters in the RCNP cyclotron complex. In these parameters, it has been found to be very important to stabilize the magnetic field for good operation of a cyclotron. Figure 1 shows a former record[2] a magnetic field of the AVF cyclotron for 392 MeV proton beam and the observed energy resolution ($\Delta E/E$) , which was intermittently measured by the users, as a function of a relative time t. The magnetic field is shown as a ratio of a difference from the average field to the average field ($\Delta B / B_{av}$).

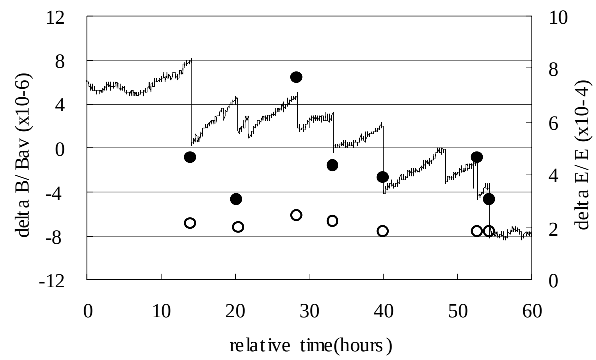

Fig.1 Magnetic Field of the AVF cyclotron (line). Energy resolution before adjustment(solid circle) and after adjustment (open circle) of the main coil are also shown.

At t=14, after adjusting some cyclotron parameters including the main coil current of the AVF cyclotron, we obtained a good beam of which energy spread good enough for experiments and started the experiments. After that we found that the magnetic field of the AVF cyclotron increased. Decreasing the main coil current of the AVF cyclotron to reproduce the magnetic field, the energy spread was represented for t < 33. However, for t > 40, the suitable magnetic field strength observed for ultra-precise beam slightly decreased. It should be noted that the energy resolution after adjustments retains about 2 x 10^{-4}.

In this machine time, in order to continue to obtain ultra-precise beam, occasional measurements on energy spread of the beam and decreasing the main coil current were necessary. It is noted that, without any adjustment of the main coil, the magnetic field may increase with a rate of $\Delta B / B_{av}$ is about 1.2 x 10^{-5} per day. Even though such adjustments were carried out only a few times per day, a more stable beam was suitable. Especially, since some nuclear reactions have very small cross sections, some users strongly require ultra-precise beam for a long time, e.g., 24 hours or more.

As shown in fig.1, the energy spread of the beam strongly correlated with the magnetic field strength of the AVF cyclotron. Therefore, it is expected that no drift of the magnetic field may become long-term stable operation of an ultra-precise beam.

A magnetic field in a cyclotron is not only a function of coil current, but also a function of form (length, width and so on) of iron core and magnetic permeability. As the current stability of the main coil for the AVF cyclotron is good enough(better than 4 x 10^{-6}), the form of iron core and/or magnetic permeability should change, which have a hidden parameter, temperature *T*.

3 A SIMPLE MODEL

Figure 2 shows a very simple model for heat transfer of a cyclotron. 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.

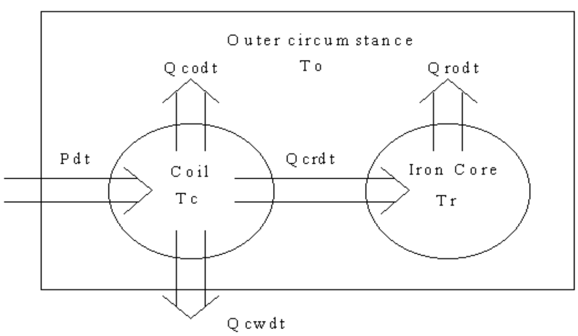

Fig. 2: A simple model for heat transfer

In this model,

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

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

For simplicity, we put strong restrictions, that is, both T_c and T_o keep constant. Neuton's empirical raw was also assumed to Q_{cr} and Q_{ro}, i.e.,

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

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

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

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

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

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

4 RESULTS

From the former result shown in fig.1, it seems that a drift of the magnetic field should be within the order of 10^{-6}. Since the temperature coefficients of the magnetic permeability and coefficient of linear expansion for iron are roughly on the order of 10^{-4} and 10^{-5}, respectively, the temperature of the iron core should be controlled on the order of 0.01 degree.

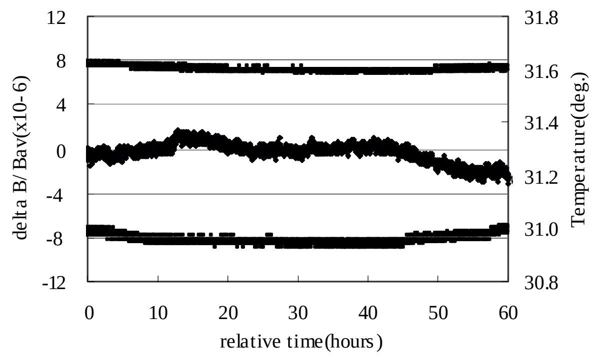

Fig 3. Magnetic field of the AVF cyclotron(center), temperature of the pole surface(upper) and temperature of the return-yoke surface(lower). The return yoke temperature has an offset of 2.3 degree.

It is again noted that, in order to realize the ex. (5), the below simple conditions should be satisfied,

$$\Delta To = 0 \quad (8)$$
$$\Delta Tc = 0 \quad (9).$$

We improved a cooling system of the AVF cyclotron and achieved exs. (8) and (9) in some machine times. Figure 3 shows the magnetic field of the AVF cyclotron for 300 MeV proton with the temperature of the pole surface and the return-yoke surface as a function of a relative time *t*. The return-yoke temperature has an offset of 2.3 degree.

Both temperatures stayed within ±0.06 degree over 60 hours. The magnetic field kept the level within $\pm 2.5 \times 10^{-6}$ 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.

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. As a reference, the former results already shown in fig.1 are also shown.

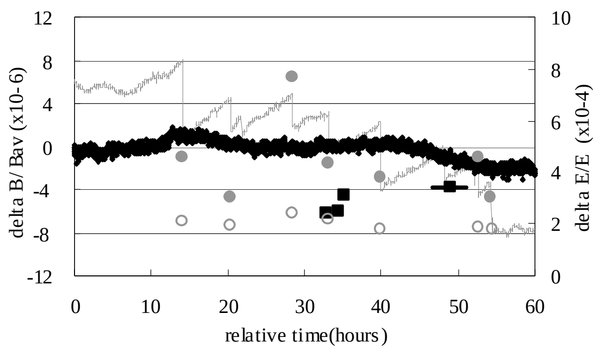

Fig. 4:Energy resolution (square) and Magnetic Field of the AVF cyclotron (diamond) for 300 MeV proton beam. The former results for 392 MeV proton beam are also shown.

The energy resolution at t=33 was observed as about $3x10^{-4}$. As t increased, the energy resolution became slightly worse. However, comparing the former energy resolution for 392 MeV proton, time dependence was very small. During t=47-51, 102 keV of the energy spread was observed without any checking measurements. Totally, the energy resolution retained within $4x10^{-4}$ during about one-day beam time without any adjustments of the cyclotron parameters.

We would like to emphasize that a feedback control of the coil current is not an adequate method for magnetic field of a cyclotron. Generally we consider that a main reason why the magnetic field moves in a cyclotron is to change the temperature of an iron core. A feedback control of the coil current may not cancel out the thermal effect on the total iron core. For example, effects of non-uniform deformation of magnet pole and return yoke, which causes discrepancy from isochronism at any radii, can not adjust by main coil current.

Measuring time constant τ of the AVF cyclotron in the RCNP, we got the order of τ is about a few tens of hours. Therefore, if the temperature changes very much, it can not come back to the adequate temperature soon. It is important that T_{ri} (and T_r) keep constant near T_{rf} to avoid the effect of such long time constant.

5 FURTHER PERSPECTIVE

Unfortunately, Conditions (8) and (9) was not actualized all time. Figure 5 shows temperatures of the AVF cyclotron room as a function of the date, which represented to T_o in eq.(8). In 2001, the temperature was roughly constant before the start of June. After that the room temperature increased by 2-3 degrees, because of lack of the ability of the air conditioning system for the AVF cyclotron room.

In the spring of 2002, we improved the air conditioning system, power of which became stronger by about 10 %. The room temperature in 2002 is also shown in fig. 5. Though we could keep the temperature constant before the mid-July, it increased by 1.5 degree in summer. In other words, eq. (8) was not satisfied especially in summer.

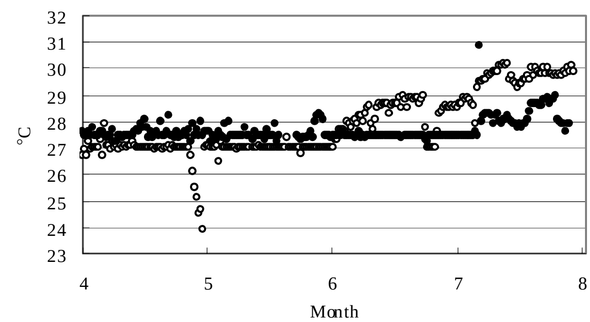

Fig.5 Temperature of the AVF cyclotron room in 2001 (open circle) and 2002 (solid circle).

Electric power for the main coil changes as the accelerated particles and/or their energies changes. Therefore the temperature of the cooling water needs to be controlled to satisfy the condition in eq. (9). However, we have not obtained sufficiently results and techniques, and, therefore, the temperature of the coil, T_c, slightly changed in every beam time. Since the differences of T_c for successive beam times depended on the difference of the main coil currents, we got negligible changing of T_c sometimes. At that time, a ultra-precise beam for a long time has been easily obtained.

In conclusion, for a long-term operation of the ultra-precise beam, the whole temperature distribution of the cyclotron needs to be kept at all times to keep the magnetic field within the order of 10^{-6} for the AVF cyclotron in the RCNP. In near future, improvement methods in keeping the temperature well for an each existing cyclotron will be studied, which may lead to a criterion to design a new cyclotron.

6 REFERENCES

[1] H. Saito *et. al.*, In this workshop
[2] S. Ninomiya *et. al.*, Proc. of the 16th Conf. on Cycl. and their App., East Lansing, USA, p.110, 2001.