ULTRA HIGH STABILIZATION OF THE MAGNETIC FIELD OF THE RCNP CYCLOTRON

S. Ninomiya, T. Saito, H. Tamura, K. Sato, RCNP, Osaka Univ. Osaka, Japan

Abstract

Ultra-precise beam have been accelerated in the Research Center for Nuclear Physics (RCNP) in Osaka University. In order to obtain such beams, stabilization of the magnetic field is essential. Thermal effects on magnetic field were quantitatively obtained. To control the temperature of cooling water and air temperature of the cyclotron rooms gives a long-term stable operation for ultra-presice beams without any adjustments of the cyclotron parameters.

INTRODUCTION

The RCNP has a cyclotron complex, which consists of a large-sized ring cyclotron (K=400) as a main accelerator and an AVF cyclotron (K=140) as an injector. Beams are mainly used for nuclear physics research and high-quality beams in momentum spread have been strongly required.

Recently, we have succeeded in producing ultra-precise beams. For example, the ratio of the energy spread to the beam energy ($\Delta E/E$) is achieved as < $2\text{x}10^{-4}$ for light ions with different energies.

In order to obtain such ultra-precise beams for a long time, stabilization of the magnetic field both for the AVF and the ring cyclotron has been found to be essential[1]-[2]. Especially, the beam quality strongly depends on the magnetic field of the injector cyclotron. At that time, checking measurements of the beam quality and frequent corrections of the magnetic field were necessary about four times per day[1]. Even though the magnetic field was reproduced to the initial value, observed $\Delta E/E$ was not perfectly reproduced. Similar thermal effects have been reported by other facilities[3]-[5].

In this report, thermal effects on the magnetic field of the AVF cyclotron are quantitatively given. A result on a long-term temperature control is also shown. Finally we show the result on a high-stable long-term operation without any tunings of the cyclotron parameters.

THERMAL EFFECTS ON MAGNETIC FIELD

A thermal effect on magnetic field was roughly obtained from one-dimensional analysis, when temperature drift is small enough. The magnetic field of a cyclotron, B, is roughly estimated by

$$B=\frac{NI}{\dfrac{g(T)}{\mu_0}+\dfrac{L_h(T)+\{L_v(T)+2L_p(T)\}}{\mu(T)}} \qquad (1),$$

and

$$g(T)=L_v(T)-2L_p(T) \qquad (2),$$

where N is a turn number of the coils, I is coil current, L_h is length of horizontal yoke, L_v is length of vertical yoke, L_p is length of pole, g is air gap length, μ is magnetic permeability of an iron core and μ_0 is magnetic permeability of the air(or vacuum), respectively. L_h, L_v, L_p (also g) and μ are functions of a temperature T. Recently, coil current I is well stabilized on the order of 10^{-6}. Therefore, temperature effects should dominate drift of magnetic field.

For the RCNP AVF cyclotron, as the first term of the denomination in eq. (2) is much larger than the second term, we obtained,

$$\frac{\Delta B}{B_0}\approx-\frac{\Delta g}{g_0}=\frac{-\sigma\left(L_{v0}\Delta T_y-2L_{p0}\Delta T_p\right)}{g_0} \qquad (3),$$

where T_y and T_p are temperatures of yoke and pole, and σ is coefficient of linear expansion of iron, respectively.

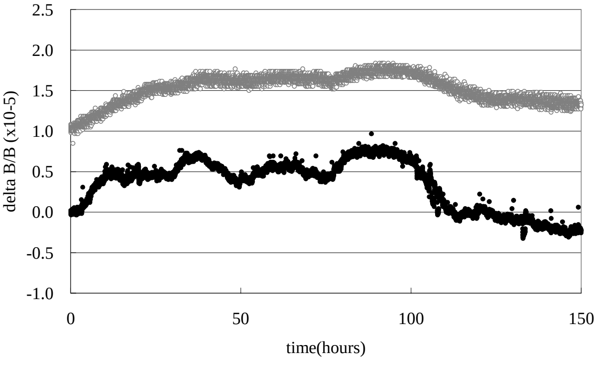

Figure 1: measured (lower) and calculated (upper) $\Delta B/B$. Calculated values were shifted by 1E-5.

The magnetic field of the AVF cyclotron have been measured by two NMR probes with correction coils[1]. The temperatures of the pole and yoke have been also measured. Figure 1 shows $\Delta B/B$ obtained and calculated from eq. (3). During this period, the coil current was not changed. The temperatures of the yoke and the pole were within ± 0.1 and ± 0.15 degree, respectively. The value of coefficient of linear expansion of iron is adopted as 1.17E-5. Calculated value was shifted by 1E-5. Calculations agreed well with measurements in terms of both trends and absolute values. Therefore, main origin of the drift of the magnetic fields comes from deformation of the iron pole and the return yoke.

It has been already found that the magnetic field of the AVF cyclotron needs to be controlled on the order of 10^{-6} in order to obtain ultra-precise beam[1]. When $\Delta T_p = \Delta T_y$, we get $\Delta B/B_0 = -\sigma \Delta T_p$ from eq. 3. Thus, $\Delta T_p(\Delta T_y)$ should keep on the order of 0.1 degree. However, since less than 10^{-5} of $\Delta B/B_0$ is enough for normal requirement of beam, $\Delta T_p(\Delta T_y)$ should be kept within 0.5 degree.

We would like to emphasize that a feedback control of the coil current is not an adequate method, because effects of non-uniform deformation of magnet pole and return yoke can not adjust by coil current.

LONG-TERM TEMPERATURE CONTROL

The RCNP cyclotron complex is continuously operated during a few months even for weekends, which is a merit to control temperatures. Once the cyclotron system reaches to equilibrium, we can keep the condition in principle. Beam energy is, however, typically changed a few times per month. Namely, coil currents are changed in large ranges.

A simple model for heat transfer has been already reported[1]. The points of our opinions are that 1) one should keep the temperature of the circumstance nearby a cyclotron, and that 2) heat transfer from coils to the iron core should also be kept constant by controlling temperature of the cooling water, even when coil current is changed.

Temperature of the iron core T_r represents as

$$T_r = (T_{rf} - T_{ri})(1 - \exp(-t/\tau)) + T_{ri}\,, \qquad (4),$$

where T_{ri} and T_{rf} are initial and final temperature of the iron core and τ is time constant, respectively[1]. Measuring time constant of the AVF cyclotron, we got τ is about 40-60 hours. Such large time constant is effectively suppressed, when T_{ri} is almost equal to T_{rf}. For practical operation, we have some permissible ranges of the temperature, ΔT. Namely, the drift of the magnetic field does not affect to beam quality and intensity with $T_r = T_{\rm rf} \pm \Delta T$. Thus, an "effective" time constant τ_{eff} can be estimated from eq. (4) as

$$\tau_{eff} = \tau \ln \left| \frac{T_{rf} - T_{ri}}{\Delta T} \right| \qquad (5).$$

Obviously, the constant ΔT depends on required beam quality. Our final goal is $\tau_{eff} = 0$ at any time, which can be realized by constant $T_{\rm rf}$ at any energy and ion accelerated.

Recently, a water-cooling system was improved for the RCNP AVF cyclotron. In order to control the water temperature for the main coil independently, an additional water pump and a heat exchanger were installed. A new buffer tank for chilling water was also installed to avoid its sudden temperature change due to turned on/off of the high power electric chilling unit. Two three-way water valves were newly installed nearby a cooling tower in order to cancel out influence on outer disturbance. By these improvements, water temperatures both for the main coil and the trim coils can be controlled with 0.1 degree independently of outer circumstance. An air conditioning system for the AVF cyclotron room was also improved. Two air-conditioners were installed and power of the air conditioning system became stronger by about 20 %.

For the RCNP AVF cyclotron, the main coil seems to be a main origin of heat transfer to the iron core. Thus, main-coil temperature should be kept constant. Unfortunately, a surface temperature of the main coil, T_c, can not be directly measured. So weighted average between the entrance side(T_{in}) and the exit side(T_{out}) of the cooling water for the main coil is assumed to be an index. i.e., $T_c = (T_{in} + 2T_{out})/3$ and is automatically controlled to keep 38 degree centigrade.

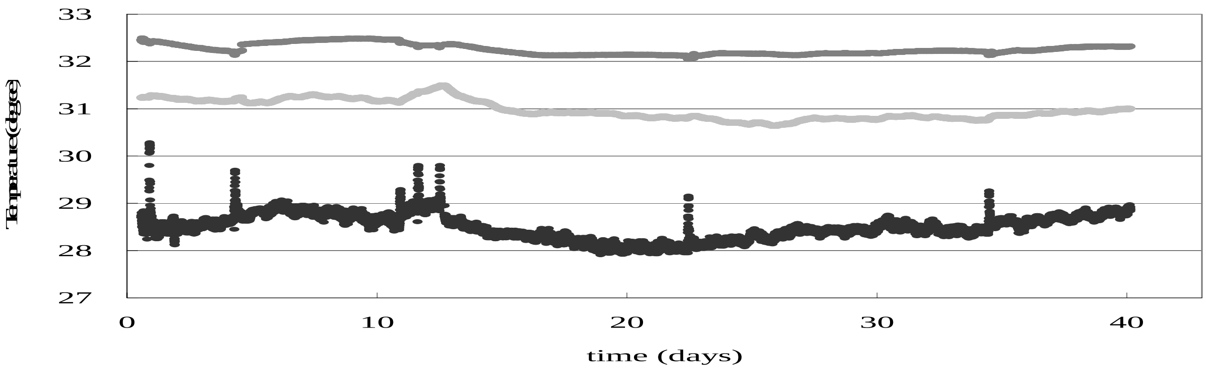

Figure 2: Temperatures of the AVF room(lower), of the iron yoke(middle)and of the iron pole(upper).

Figure 2 shows the AVF room temperature(lower), the temperature of the yoke(middle) and that of the pole(upper) during 40 days. The return-yoke temperature has an offset of 2 degrees. Sudden increases and decreases of the room temperature were due to cycling procedures of the cyclotron. At these moments, we changed all of the coil currents. The room temperature was totally kept within ± 0.6 degree during this period except the moments of the cycling procedures.

Both the pole and the yoke temperatures seem to correlate to the room temperature. At the moments of the cycling procedures, these temperatures changed very little. During 40 days, the temperature of the yoke and pole were kept within ± 0.45 degree and ± 0.25 degree, respectively, i.e., $T_{\rm rf}$ at each energy and ion accelerated was controlled in this range. This is sufficient for normal requirement. It should be noted that during this period the main coil current of the AVF cyclotron ranged from 266A to 582A. Therefore, it was succeeded that heat transfer from the coils to the iron core was controlled independently of the main coil current.

LONG-TERM STABILIZATION OF THE MAGNETIC FIELD FOR ULTRA-PRECISE BEAM

Figure 3 shows the magnetic field of the AVF cyclotron for ultra-precise 300 MeV proton beam. The magnetic field was kept the level within $\pm 2.5\mathrm{x}10^{-6}$ during 60 hours. In this period, no cyclotron parameters, including the main coil current, was adjusted. The temperatures of the pole and yoke were simultaneously measured and were found to stay within ± 0.06 degree.

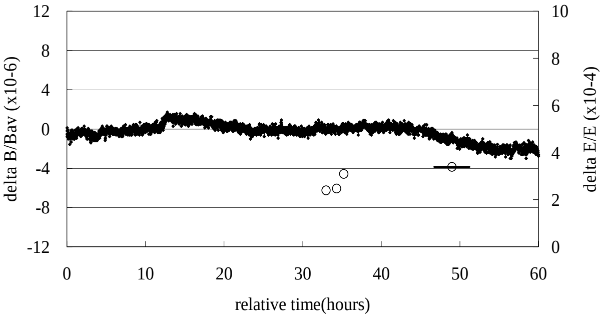

Figure 3: Energy resolution (open circle) and magnetic field of the AVF cyclotron (diamond) for 300 MeV proton beam. In this time period, no cyclotron parameters was adjusted.

Figure 3 also shows the observed energy spread ($\Delta E/E$) at that time. $\Delta E/E$ was observed as about $3\mathrm{x}10^{-4}$ at t=33. As t increased, the energy resolution became slightly worse. During t=47-51, 102 keV of the energy spread was observed without any checking measurements. Totally, the energy spread retained within $4\mathrm{x}10^{-4}$ during about one-day beam time without any adjustments of the cyclotron parameters.

For ultra-precise beam, ΔT in eq. (5) was found less than 0.06 degree and τ_{eff} was about 2τ, which is, however, not sufficient to obtain ultra-precise beam all the time. In order to control the magnetic field by little, a one-turn coil was installed to the AVF cyclotron[1]. Current control of a few tens mA leads to control the magnetic field on the order of 10^{-7}. Even though this one-turn coil is useful, the main part of the stabilization of the magnetic field should be taken by controlling temperature.

CONCLUSIONS

For a long-term operation of the ultra-precise beam, the whole temperature distribution of a cyclotron needs to be kept at all times to keep the magnetic field within the order of 10^{-6}. In the RCNP, the beam quality depends strongly on the stability of the magnetic field of the AVF cyclotron. Thermal effects on the magnetic field were quantitatively obtained and the cooling system was improved. Over 40 days, the room temperature and the iron-core temperature were kept the level within ± 0.6 degree and ± 0.45 degree, respectively. It was found that the magnetic field can be kept the level within $\pm 2.5\mathrm{x}10^{-6}$ when the iron-core temperature stayed within ± 0.06 degree. At that time, the observed energy resolution of the beam retained within $4\mathrm{x}10^{-4}$ without any adjustments of the cyclotron parameters.

REFERENCES

[1] S. Ninomiya *et al.*, Proc. of the 16th Conf. on Cycl. and their App., East Lancing, Michigan, p.94, 1998.
[2] T. Saito *et al.*, Proc. of the 15th Conf. on Cycl. and their App., Caen, France, p.609, 1998.
[3] S. Okuma *et al.*, Proc. of the 16th Conf. on Cycl. and their App., East Lancing, Michigan, p.330, 2001.
[4] W. Brautigam *et al*, Proc. of the 14th Conf. on Cycl. and their App., Cape Town, South Africa, p.280, 1995.
[5] L. P. Roobol *et al.*, Proc. of the 15th Conf. on Cycl. and their App., Caen, France, p.211, 1998