HIGHLY STABILIZED OPERATION OF THE RCNP CYCLOTRON

T. SAITO, K. HATANAKA, T. ITAHASHI, K. SATO, A. SHIMIZU,
K. TAMURA, T. YAMAZAKI, S. ANO, M. KIBAYASHI and H. TAMURA

Research Center for Nuclear Physics, Osaka University
Mihogaoka 10-1, Ibaraki-shi, Osaka 567-0047, JAPAN

In order to accelerate high quality beams stably in a long term with cyclotron, high stability of the magnetic field and the rf accelerating voltage is needed. It was found that the field strength of sector magnets of the RCNP Ring Cyclotron varies with time depending on temperature of the iron core. A correlation between temperature of the cooling water of the trim coils and field drift was found. To suppress temperature changes of the iron core with adjusting temperature of the cooling water of the trim coils, the stability of the magnetic field is significantly improved. Together with highly stabilized RF system, we provided high quality proton beam over 152 hours without readjustment of parameters of the accelerator. The temperature change of the magnet was estimated to be less than 0.01 ℃ /day.

1 Introduction

The RCNP ring Cyclotron has been operated to serve various kinds of high quality beams for the nuclear physics experiments. In order to achieve a stable operation of the cyclotron cascade system, various improvements and developments have been carried out. A variable frequency flat-topping system is used for high beam energy resolution and single turn extraction. Upgrading of the rf accelerating system of the Ring Cyclotron has advanced resulting in small amplitude variation of the accelerating voltage and flat-topping voltage less than 0.01% and 0.05%, respectively. A typical phase excursion of the cavity voltage is less than 0.1 degree/100hrs.[1] The current stability of the main coils for the injector cyclotron and the Ring Cyclotron are better than 4×10^{-6}. The current stability of the trim coils are better than 1×10^{-5}.

Despite the fact that all the components work well, the beam extracted from the Ring Cyclotron has not been stable in a long term. In summer, 1996, it was found that the field strength of sector magnets is affected by the temperature of cooling water for trim coils. The field variation to the temperature change is fast. A new procedure to control the temperature of cooling water for trim coils has led to a long-term stability of the magnetic field within 2×10^{-6} over a week

2 Thermal Effects on Magnetic Field

An importance of a control of temperature of magnet has been pointed out.[2],[3],[4] The NAC Separated-sector Cyclotron at south Africa realize quick change of acceleration energy and stable operation improving the stability of the magnetic field by stabilizing the average temperature of the inlet and outlet cooling water for main coils.

In general, magnetic flux density B of an electromagnet is given by:

$$B \fallingdotseq U\mu_0/g$$

where U: magnetomotive force
μ_0 : permeability of vacuum
g : magnet gap

As long as considering only small thermal expansion of a magnet, flux density is depend only a magnet gap. Even though flux density is independent of cross section of a magnetic path, when considering thermal effect, effect of variation of actual size of pole is not negligible for a separated sector cyclotron. Bending force or bending angle is proportional to actual size of the magnet pole. Thermal effects on area of the magnetic field and flux density are both proportional to coefficient of thermal expansion for iron core of a magnet and temperature change. This implies that a feedback control to keep the field strength based on a measurement of the field strength by a NMR method does not function effectively. In case

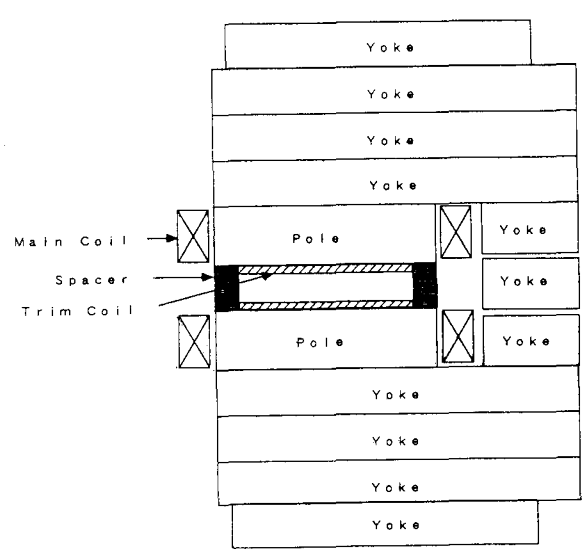

Figure 1: The schematic view of the sector magnet for the Ring cyclotron.

of compact cyclotron, the feedback control by a NMR method is effective under small and uniform variation of magnetic field.[5]

Figure 1 shows schematic view of the sector magnet for the RCMP Ring Cyclotron. The trim coils made of ceramic coated copper plates are fixed on the pole surface of sector magnets directly through 0.125 mm kapton film without a heat insulator. The gap of the sector magnets is fixed at both ends of the magnet pole by spacers which is made of non-magnetic material of SUS316L. Therefore, magnet gaps at spacers are determined by a height of spacers. Thermal effect on spacers may be major factor of drift of the magnetic field. Heat conductivity between main coils and iron cores are relatively small. Temperature rise of the cooing water of main coils and trim coils at normal operation are designed to be less than 5 ℃ and 2℃ respectively. These are the reason for strong correlation and fast response of the field variation to the temperature change. Figure 2 shows the effect of

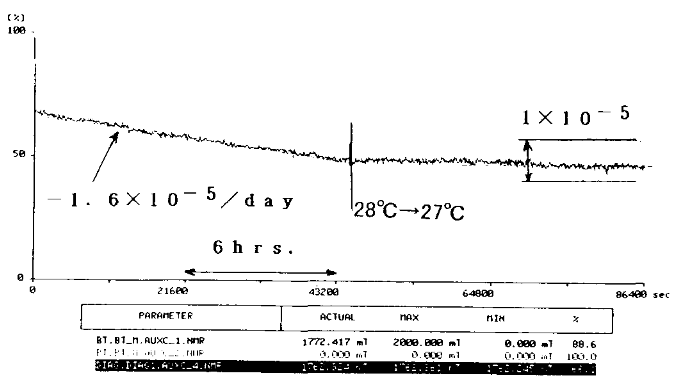

Figure 2: The trend data of the magnetic field.
Effect of the temperature change of cooling water for the trim coils is shown.

temperature change of the cooling water for the trim coils to the magnetic field at position of an outer of extraction radius. Temperature change of +1℃ causes change in gradient of field drift of -1.6×10^{-5}/day. Under such small temperature variation, temperature of pole tips and spacers varies uniformly and gradually and deformation of the spacers cause field drift. On the other hand, large temperature change causes a complicated deformation on the core of the magnet and generates position dependent field variations. When temperature of cooling water for the rim coil is varied more than 10℃, position dependent field variation is observed clearly. In another case, after long shut down of the cyclotron, the magnetic field starts to drop with a rate of about -10^{-5}/day from start up of the Ring Cyclotron and after a week the field stability become better than 10^{-6}/day. The weight of the iron core of one sector magnet is 370 tons. A simplified model calculation of heat conduction of a iron block shows that if there were initially a temperature difference of 5℃, it needs more than 100hours to reach thermal equilibrium within 0.1℃. So the origin of the long term field drift is considered to be effect of a change in temperature of the magnet core. In anyway these field variations are difficult to compensate. So ti is important to avoid large temperature change of magnets. Field drift caused by small temperature change is effectively compensated by adjusting temperature of the cooling water for trim coils.

Methods to suppress a variation of magnetic field is depends on structure of the magnets. Unlike to the NAC Separated Sector Cyclotron, in case of the RCNP Ring Cyclotron there is a proper and uniform thermal contact between the pole tips and the trim coils. Control of temperature of the cooling water for the trim coils is effective to stabilize magnetic field of the Ring cyclotron. In case of NAC Separated Sector Cyclotron the main coils are in good thermal contact with iron core. The temperature of the iron core is well stabilized by the temperature of the cooling water.

Thermal effect of room temperature was observed but such an effect is small in the Ring Cyclotron even considering a temperature distribution of the vault. Effects of temperature change of cooling water for the main coils is also small. This implies that heating of iron core of the Ring Cyclotron is dominated by trim coils. At ordinary operation, room temperature is kept about 26℃ throughout the year. Except for a large change in temperature, absolute value of the room temperature or temperature of cooling water for the trim coils is not so important.

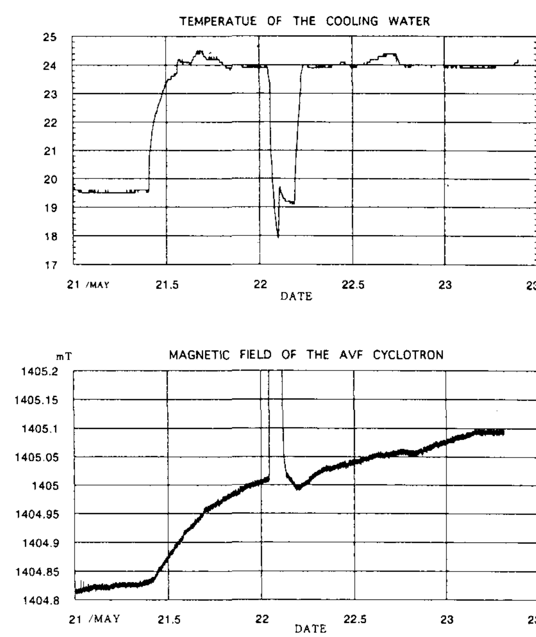

Figure 3: Field variation with time after temperature change of cooling water for the main and the trim coils of the AVF cyclotron.
Upper : Temperature change of cooling water.
Lower : Field variation.

Field stability is also required for the injector AVF cyclotron. The structure of the magnet is different from that of the sector magnet. Heat transfer from the main coil or the trim coils is little and effect of temperature change appears slowly. A response of the field variation to temperature change of cooling water for the main coils and the trim coils is shown in Figure 3. Effect of the room temperature is also observed. It needs long time to reach a thermal equilibrium state of the iron core. It is thus difficult to stabilize the field strength of the AVF cyclotron by the same procedure as that of the Ring Cyclotron.

3 Long-term stability of the Ring Cyclotron magnetic field

By adjusting the temperature of the cooling water for the trim coils, the stability of the magnetic field batter than 1×10^{-6}/week is achieved. Together with the highly stabilized rf system, high quality beams are accelerated stably for long time. As shown in Figure 4 a highly-stable long term operation without any tuning of cyclotron parameters for 7days in July, 1997 during beam time for experiments of 300MeV protons. During this operation, the field change was within 2×10^{-6}/day and the temperature change of the magnets is estimated to be less than 0.01 ℃ /day. In the beam time, unique nuclear physics

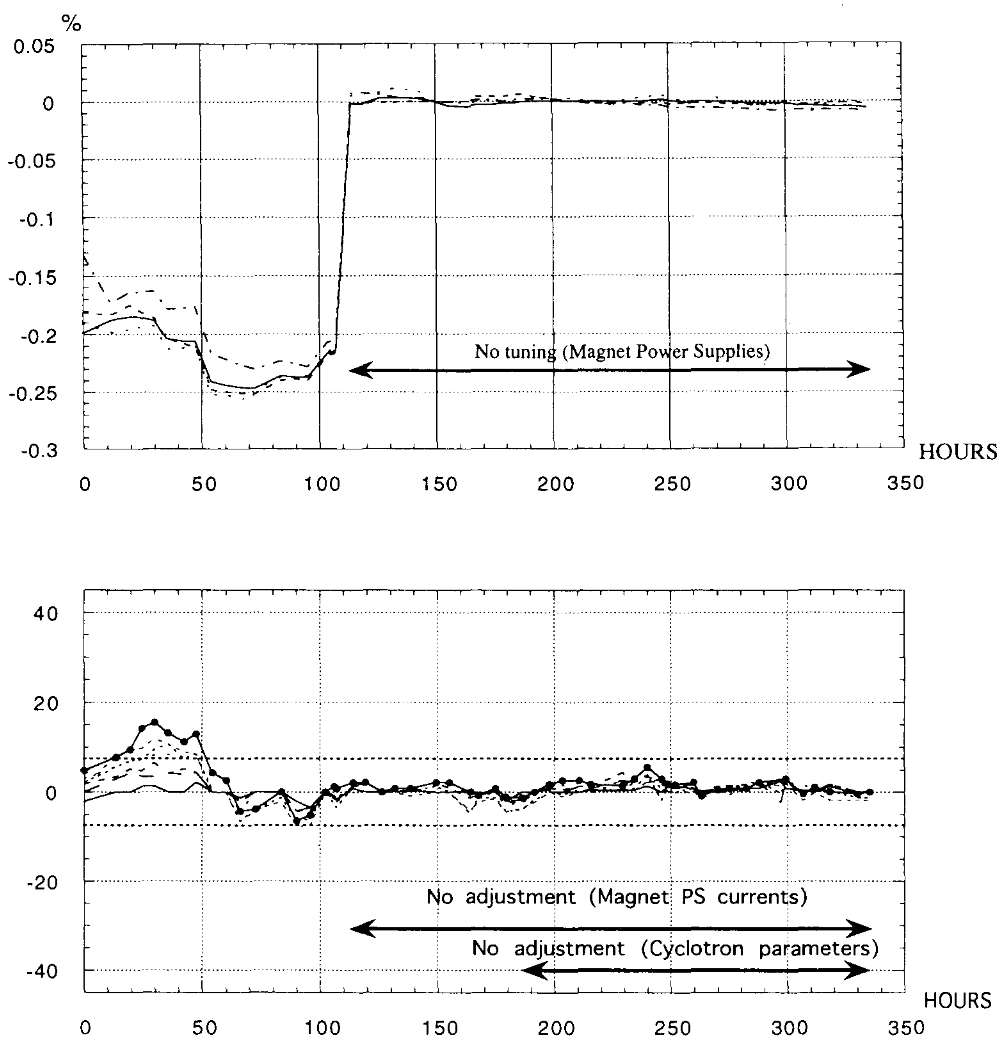

Figure 4: Highly-stable long-term operation without any tuning of all accelerator parameters of the Ring Cyclotron.
Upper: Magnetic field monitored with NMR at an outer of the extraction for sector No. 1, 2, 5 and 6. Field jump at 110 hours is corresponds to readjustment of the outer most trim coil current. Values are normalized at 150 hours. Lower: Beam phase observed at radius 2.20, 2.48, 2.76, 3.03, 3.31, 3.58, 3.85 and 4.1m.

experiment has been carried out successfully.

4 Further study of thermal effect

The sector No.1, No.2 and No.3 contain magnetic channels in the gap. The temperature rise of the channels is large and also thermal effect of the channels is not negligible. A new water cooling system for the magnetic channels was made in summer, 1997. To reduce temperature rise of the magnetic channels, the head pressure of output water is increased up to 7kgw/cm^2 and water temperature is controlled 20 ± 0.2℃. The Dynamic range of the temperature control system for the trim coils is narrow. With this system it is difficult to maintain highly stabilized magnetic field at high temperature and high humidity climate season. The cooling system will be improved in summer, 1998.

The energized rf cavities are one of heat sources and some effect is observed. This heating, however, is considered to have a fast response and become an equilibrium state in a short time because the rf power loss associating with the constant rf accelerating voltage is nearly constant, and thermal contact between the magnet cores and the rf resonators is small. The temperature of cooling water for the rf cavities is controlled within ±0.1 ℃ during operation. A magnet gap of the Ring Cyclotron is fixed by spacers. A possible heating of the spacers is considered to come from a leakage rf power from the rf cavities. Rf leakage occurs irregularly, and the leakage power is not constant, so the effect may be harmful. If the height of the spacers varied due to rf heating, the field strength will vary. In order to check the effect of rf leakage from the rf cavity, an rf power was forced to leak artificially towards a magnet gap. An rf cavity is of single-gap type with two tuners at upper and lower halves of the resonator to keep the resonant frequency constant. Owing to up-down asymmetry of the resonator an rf power leaks. When positions of two tuners are set at proper positions, an rf leakage power can be increased. Due to this operation of the rf cavity, the magnetic field strength varied. The NMR field monitor is sensitive to rf leakage. At present it is difficult to distinguish clearly thermal effect of rf leakage from rf noise effect. But an indication of thermal effect is observed. In order to suppress this heating process of the spacers, the spacers will be surrounded by thin copper sheets and the operation test similar to the former will be carried out soon.

5 Discussion

As described before, the thermal effect on field variation is not uniform except for small and uniform temperature change. It is thus unavoidable to suppress the temperature change of magnet at least within 1°C, if one needs field stability better than 2×10^{-5} variation. Considering a coefficient of thermal expansion of iron , this temperature difference corresponds to size variation of about 1.5×10^{-5}.

For stability of magnetic field, not only current stability of a power supply but also temperature stability of a magnet core is essential. Field error caused by thermal effect is impossible to compensate without stabilization of temperature because of its complicated position dependence and change in size of field region. To control temperature of a magnet core, the core needs to be connected to some controlled heat source and/or heat sink with low thermal resistance. If there were not such elements, magnetic field shows very long term drift and difficult to stabilize. The structure of the AVF cyclotron fit this case. In case of Ring cyclotron, a magnet gap is fixed by spacers and trim coils are fixed on the surface of magnet poles directly without a heat insulator. The trim coils have proper heat conductivity with magnet pole. The heat conductivity is not sufficient but useful to control temperature of the core of the magnet. For the RCNP Ring Cyclotron, high stability of magnetic field with drift less than 10^{-6}/day is needed on demand of nuclear physics experiment. In order to achieve such precise control, a structural feature of the RCNP Ring Cyclotron is considered to be effective. In this configuration, a precise control of the temperature can be achieved by controlling temperature of the trim coils.

References

[1] T. Saito, M. Uraki and I. Miura, Proc. of the 14th Conf. on Cycl. and their App., Cape Town, South Africa, 1995,pp169-172

[2] A.H. Botha et al., Proc. of the 12th Conf. on Cycl. and their App., Berlin, Germany, 1989,pp80-83

[3] P.M. Cronje, H.N. Jungwirth and W.A.G. Nei, Proc. of the 12th Conf. on Cycl. and their App., Berlin, Germany, 1989,pp467-470

[4] W. Brautigam, R. Brings, Proc. of the 14th Conf. on Cycl. and their App., Cape Town, South Africa, 1995,pp280-283

[5] W. Brautigam, R. Brings, ibid.