# THERMAL EFFECTS IN STABILITY OF CYCLOTRONS

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*Abstract*

In order to accelerate high-quality beams stably in a long term with cyclotrons, a high stability of both the magnetic field and the rf accelerating voltage is needed. Recent extensive observations and measurements on performance of the RCNP Ring Cyclotron show that various kinds of thermal effects on magnets dominate the instability of the cyclotron through thermal deformation of sector magnets.

It was fortunate to find the fact that the change of temperature of cooling water for trim coils affects the field strength very fast. This fast response of several hours has led to a new tuning procedure for stabilizing the temperature of the sector magnets to keep the field strength constant.

The long-term stability of the beam is significantly improved and the high quality of the beam was realized in a long term more than 150 hours without any tuning of cyclotron parameters. During this operation, the field change was within $2 \times 10^{-6}$ and the temperature change of the magnets is estimated to be less than $0.01°C$/day.

This highly-stable long-term operation allows further studies of thermal effects due to various kinds of heat sources of magnet coils, rf power, and room temperature.

## 1 INTRODUCTION

The RCNP cyclotron cascade consists of the AVF cyclotron as an injector accelerator and the Ring Cyclotron as a main accelerator. The Ring Cyclotron is designed to use the flat-topping rf voltage in order to produce a high-quality beam and to extract the beam with a single-turn mode.

In order to achieve a stable operation of the cyclotron cascade, various improvements and developments have been carried out. 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. Upgrading of the dc power supplies of both cyclotrons has advanced resulting in small variation of current within a relative amount of 2 ppm/24hrs.

Despite the fact that all the components work well, the beam extracted from the Ring Cyclotron has not been stable in a long term. Extensive observation shows that the magnetic field of sector magnets of the Ring Cyclotron varies with time beyond the performance of the rf accelerating voltage and the power supplies.

A study has been started to find unknown causes of unstable performance of the cyclotrons. In summer, 1996, it was found that the field strength of sector magnets of the Ring Cyclotron varies with time depending on temperature of the iron core. This finding is based on the measurement of the field variation associationg with the temperature change of cooling water for trim coils of the Ring Cyclotron. Another finding is a fast response of the field variation to the temperature change.

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 $2 \times 10^{-6}$ over a week.

## 2 FIELD VARIATION OF CYCLOTRONS FOR COOLING WATER TEMPERATURE

Variations of magnetic fields of both cycltorons were measured when the temperature of cooling water for some coils was changed.

In the case of the Ring Cyclotron, a response of the field variation to temperature change of cooling water for trim coils is fast as shown in Fig. 1. The fields were measured by NMR probes at four different radial positions of near injection, a middle , an extraction, and an outer of the extraction. The fields vary as soon as the temperature of the cooling water is changed and reaches a peak within several hours.

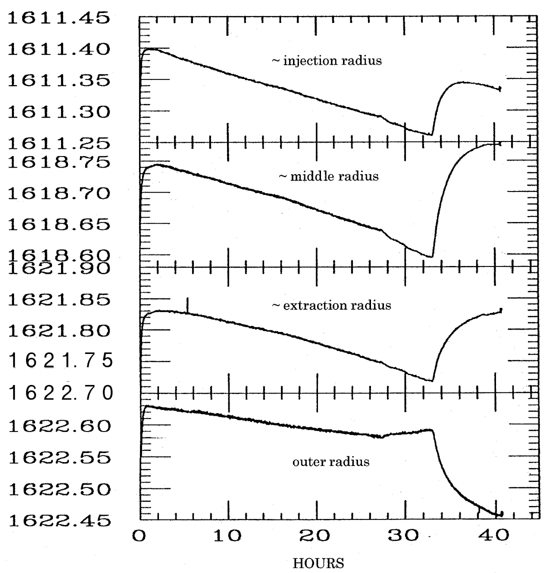


Figure 1: Field variation with time after temperature change of cooling water for trim coils of the Ring Cyclotron. Four data correspond to the fields at four radial positions. From upper to lower, positions are at near an injection, a middle, an extraction, and an outer of the extraction.

The reason why the response is so fast is because 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 tight heat insulator.

On the other hand, the observation shown in Fig. 1 features that the field variations depend on positions and have the opposite sign at the outer radius in contrast with that at other radius. This may imply that a thermal deformation occurs in a complicated manner to give a spatial distribution.

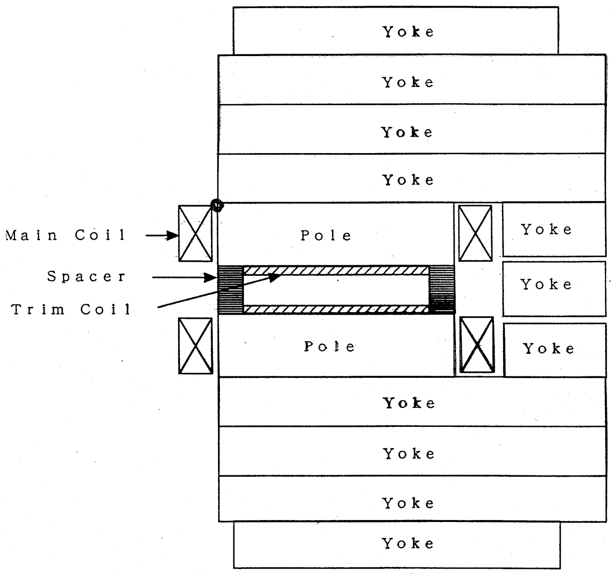


Figure 2: Schematic cross section of the sector magnet of the Ring Cyclotron.

It is noted as shown in Fig. 2 that the magnet 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 possibly determined by a height of spacers. Thermal effect on spacers should be taken account of the field variation as described later.

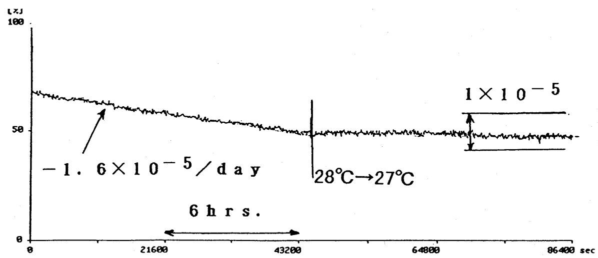


Figure 3: Upgraded stability of the field strength based on an adjustment of temperature of cooling water for trim coils.

The fast response, however, can allow a new procedure to keep the field strength constant as shown in Fig. 3. The temperature of cooling water for the trim coils is changed by operators manually with some idling time after the magnet coils are energized [1].

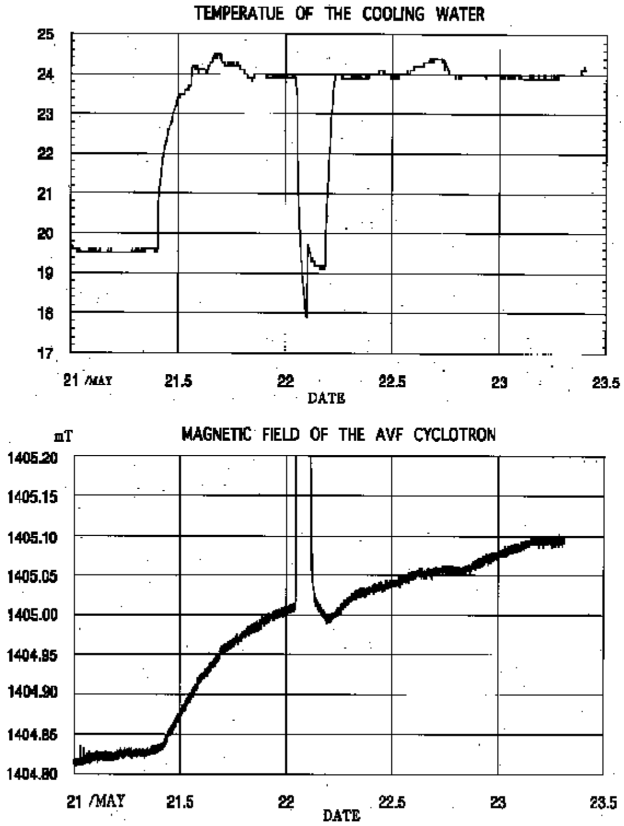


Figure 4: Field variation with time after temperature change of cooling water for main and trim coils of the AVF cyclotron. Upper: Temperature change of cooling water. Lower: Field variation.

In the case of the AVF cyclotron, a response of the field variation to temperature change of cooing water for main coils and tim coils is slow as shown in Fig. 4. The field measured by an NMR probe did not reach a peak even 2 days after the temperature change. 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 RING CYCLOTRON MAGNETIC FIELD

Remarkable achievements were obtained several times since summer, 1996. As shown in Fig. 5, a small variation of the magnetic field within 2 ppm for 3 days in January, 1997 during a machine time for experiments of 392 MeV protons. As shown in Fig. 6, a highly-stable long-term operation without any tuning of cyclotron parameters for 7 days in July, 1997 during a machine time for experiements of 300 MeV protons. In both machine times, unique nuclear physics experiments have been carried out successfully.

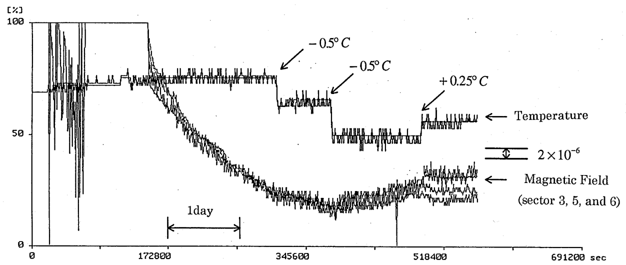


Figure 5: Field variations before and after temperature change of cooling water for trim coils of the Ring Cyclotron for stabilizing the field strength.

## 4 FURTHER STUDY OF THERMAL EFFECT

A magnet gap of sector magnets of the Ring Cyclotron is fixed by spacers as described before. If the height of the spacers varies due to thermal effect, the field strength will vary. A possible heating of the spacers is considered to come from both the rf accelerating cavities and a leakage rf power from the rf cavities.

The energized rf cavities are surely one of heat sources for affecting the iron-core temperature. This heating, however, is considered to have a fast response and become an equilibrium state in a short term because the rf power loss associating with the constant rf accelerating voltage is nearly constant.

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. When positions of two tuners are set at different positions but keeping the resonant frequency constant, the heating power due to rf power should be constant but an rf leakage power should be increased.

Due to this operation of the rf cavity, the magnetic field strength varied surely. 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.

Thermal effect of room temperature was observed but such an effect is small in the Ring Cyclotron. This implies that heating of iron core of the Ring Cyclotron is dominated by trim coils.

## 5 DISCUSSION

As known from Fig. 1, thermal effect on field variation is not uniform because of a spatial distribution. Moreover, bending force or bending angle is proportional to actual size of the magnet. Thermal effect on area of the magnetic field should be also considered. This implies that a feedback control to keep the field strength based on a measurement of the field strength by a NMR probe at a certain radius does not function effectively because it is impossible to control the spatial distribution of the magnetic field, and compensate bending force of the magnet.

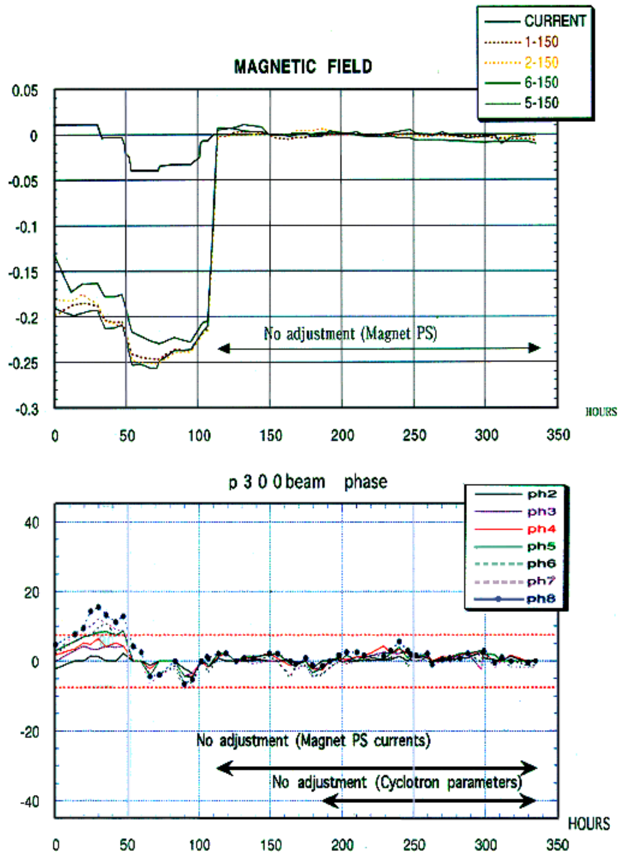


Figure 6: Highly-stable long-term operation without any tuning of all accelerator parameters of the Ring Cyclotron.

It is thus unavoidable to suppress the temperature change of magnets at least within $1^\circ C$. After this control of the temperature, a more precise control of the temperature is needed.

In order to achieve such precise control, a strcutural feature of the Ring Cyclotron is considered to be effective. A magnet gap is fixed by spacers and trim coils are fixed on the surface of magnet poles directly without a tight heat insulator. In this configuration, a precise control of the temperature can be achieved due to a fast response.


## 6 ACKNOWLDEGEMENTS

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## 7 REFERENCES


[1] T. Saito et al.:'Recent performance of the RCNP cyclotron', Proc. of the XVI RCNP Osaka Int' l Symp. on Multi-GeV High-Performance Accelerators and Related Technology, Osaka, 12-14 March 1997, pp.208-209.