STABILIZATION METHODS OF THE RCNP CYCLOTRON

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Abstract

Stable operation of a cyclotron is the basis for acceleration of high quality beams. A high stability of an accelerator is needed not only for narrow energy spread beams but also high time resolution beams or high power beams. Persistent ultra-precise proton beams with dE/E $\fallingdotseq 1.5\times10^{-4}$ have been successfully accelerated up to 392 MeV. For stable operation of the cyclotron, among others stability of magnetic fields is essential. To stabilise magnetic fields, the temperature of the cooling water for coils is controlled and the temperature change of the magnet cores is able to be kept less than 0.01deg,/day and the magnetic field drift is suppressed less than 10^{-6}/day.

1 INTRODUCTION

The RCNP cyclotron complex consists of a six sector ring cyclotron (K=400) and an injector AVF cyclotron (K=140). The cyclotron complex has been operated to serve various kinds of beams for the nuclear physics experiments and high-quality stable beams in narrow momentum spread have been strongly required. In order to accelerate beams stably, high stability of the magnetic fields and the rf acceleration fields is needed.

Since the first beam, various efforts for improving the beam quality have been done. Three variable frequency single gap acceleration cavities and a single gap flat-topping cavity are used to accelerate high quality beams.[1] Extremely high stability is required for relative phase between the acceleration and flat-topping voltage. Typical phase excursion of the cavity voltage is less than 0.1deg./100hrs. Voltage variations are less than 0.01 and 0.05% for the acceleration voltage and the flat-topping voltage, respectively. With respect to the magnetic fields, the current stability of the main coils for the injector cyclotron and the ring cyclotron are better than 4×10^{-6}, and those of the trim coils are better than 1×10^{-5}.

Despite the stable operation of the electric devices, a long-term stable operation was still a remaining problem. In summer, 1996 it was found a correlation between temperature of the iron cores of the magnets and the magnetic field. Suppressing temperature changes of the iron core with adjusting the temperature of the cooling water for the magnets, the stability of the magnetic field is significantly improved. Finally ultra-precise beams have been accelerated successfully for a long time.

2 THERMAL EFFECTS ON MAGNETIC FIELDS

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

$$B \fallingdotseq U\mu_0/g \quad (1)$$

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 depends only a magnet gap. More than 90% of magnetomotive force is spent to generate magnetic field at the magnet gap, thermal effect on magnetization of iron core is negligible.

The action of magnetic field upon beams ions depends not only flux density but also a size of a magnet pole. The size is also influenced by thermal expansion as well as the magnet gap. This effect is important to a sector magnet. This implies that a feedback control to keep a field strength based on a measurement of a magnetic field by a NMR method does not function effectively. But in case of compact cyclotron, of which most beam orbits are within a magnet pole, the field correction by a NMR monitor is effective under small and uniform variation of magnetic fields.[2],[3]

A correlation between temperature and magnetic field is complicated. An un-uniformed temperature variation brings complicated deformation of an iron core. In case of temperature change of the cooling water for the ring trim coil, temperature change of +1℃ causes change in gradient of field drift of −1.6x10-5/day. Under such small temperature change, thermal deformation is uniform. On the other hand, large temperature change generates complicated deformation of pole-tip and position dependent field variation is observed. Little data of temperature distributions and degree of freedom to control temperature, it is practically impossible to control field drift by adjusting temperature of an iron core. Only practical way is keeping of same distribution of iron core temperature.

3 CAUSES OF TEMPERATURE CHANGE

There are various factors in temperature change of cyclotron magnet core.

The trim coils made of ceramic coated copper plates are fixed on the pole surface of sector magnets directly through 0.125 mm polyimid film without heat insulators. According to good thermal contacts, the thermal time constant of about 6 hours is observed.

Heat conductivity between main coils and iron cores are relatively small, but temperature control of cooling water for the main coils is important. As power consumption of main coils varies with a change of accelerated particles, temperature changes of the coils are large without temperature control of the cooling water. The thermal time constant of about 100 hours creates long-term drift of the magnetic field. The cyclotron complex is required to accelerate high quality stable beams lastingly for more than a week. The time constant is harmful characteristic for stable operation of the cyclotrons.

The sectors No.1, No.2 and No.3 contain magnetic channels in the gaps. The temperature rises of the channels are large and thermal effects are not negligible. To reduce thermal effects, a water cooling system for the magnetic channels was made. The water temperature is controlled 20±0.2.

Every temperatures of cooling water for main coils, trim coils and magnetic channels are independently settled.

The energized rf cavities are also heat sources and some effects are observed. The effects are negligible. Thermal contacts between cavities and iron cores are small. In usual operation, the temperature rise of the cavities is small and almost constant. The temperature of cooling water for the cavities is controlled within ±0.1℃.

Thermal effect of room temperature is small as long as room temperature is kept constant within ±1℃ or so. Temperature change of 1℃ causes temperature drift of about 0.1℃/week to iron cores. This drift is tolerable. The stability of room temperature for the AVF cyclotron is not well. Some counter-plan may be needed.

4 TEMPERATURE CONTROL OF THE MAIN COILS

The coils of the main magnets are consisted of pancake made of hollow conductor. The structural reason of the pancake, there is a thermal contact between going and returning waterway of cooling water. Owing to the thermal contact, temperature of the midpoint of the conductor is higher than the outlet of cooling water. The midpoint is closest to the iron core, the temperature of the midpoint should be kept constant. By simple analysis shows the temperature distribution along waterway is given by:

$$y=(t_{out}-t_{in})\{-qx^2/2+(q+1/2)x\}+t_{in} \quad (2)$$

where t_{in}: temperature at inlet
t_{out}: temperature at outlet
q: heat conductivity

In the ring cyclotron surface temperature of the main coil near the magnet pole is directly measured together with the cooling water temperatures. Figure 1 shows temperature distribution calculated using observed data.

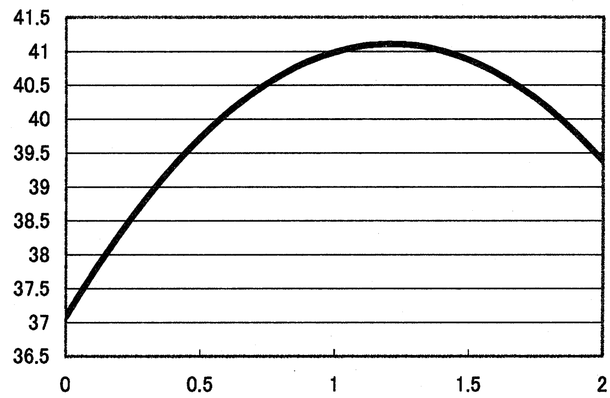

Figure 1. Typical temperature distribution of hollow conductor of a pancake along waterway.

The temperature at inlet and outlet are 37.1℃ and 39.4℃, respectively. 0 corresponds to the inlet of cooling water and 2 corresponds to the outlet. Maximum temperature near midpoint is 41.1℃. The data are observed at acceleration of 300MeV proton beams (coil current 425A). Maximum temperature difference between inlet and outlet is 5.4℃ at acceleration of 400MeV alpha particles (coil current 628A). To maintain a constant temperature at midpoint, dynamic range of 8℃ is needed for the cooling system according to various acceleration condition (coil current 253-628A). To keep constant temperature at midpoint of coils at a shift of acceleration particle, the temperature change of iron core minimized and rapid start-up of magnetic field is realized.

5 START UP PROPERTY OF MAGNETIC FIELD

Figure 2 shows trend data of temperature of ring sector magnet after 2 months interruption for maintenance. The magnets are warmed up with high temperature cooling water before excitation of the magnet for a week. Heat generated by a water pump itself can heat up cooling water up to 40℃. It needs about 90 hours to arrive at stable situation of temperature and magnetic field. Drift of the magnetic field was less than 10^{-5}/day. The temperatures of cooling water of main and trim coils were adjusted on occasion to stabilize magnet temperature.

Figure 3 shows the magnetic field deviation of the ring cyclotron after cycling for change acceleration particle. Keeping constant iron temperature with proper setting of cooling water temperature, field drift converged less than 10^{-6} within 100 minutes after start of cycling. Proper cycling procedure is also needed for rapid convergence of eddy current effects.

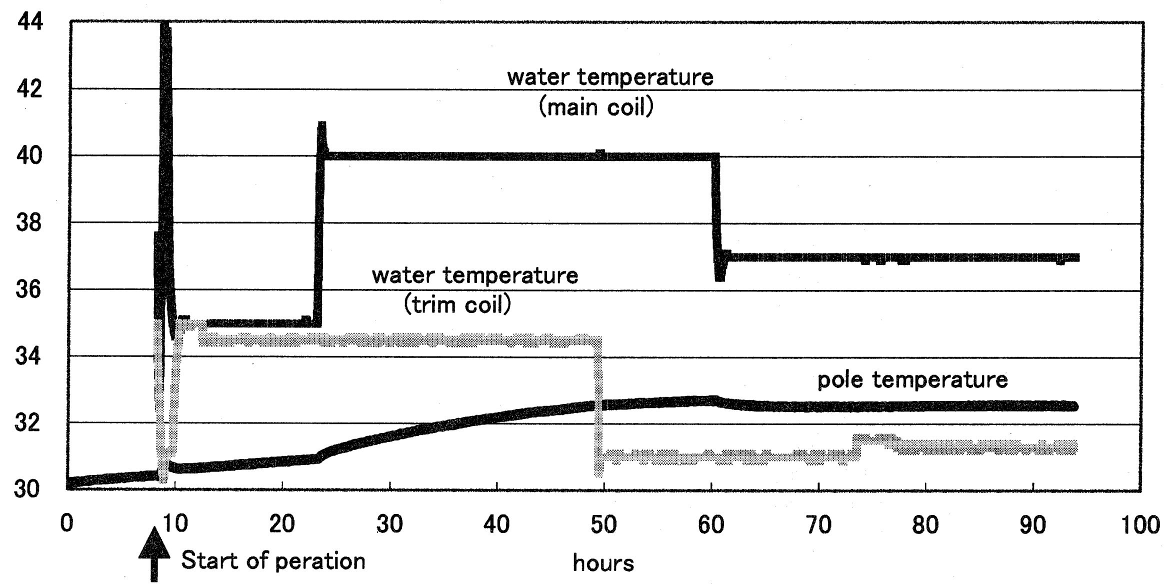

Figure 2. Temperature of the ring sector magnet. Start up trend after 2 months interruption for maintenance.

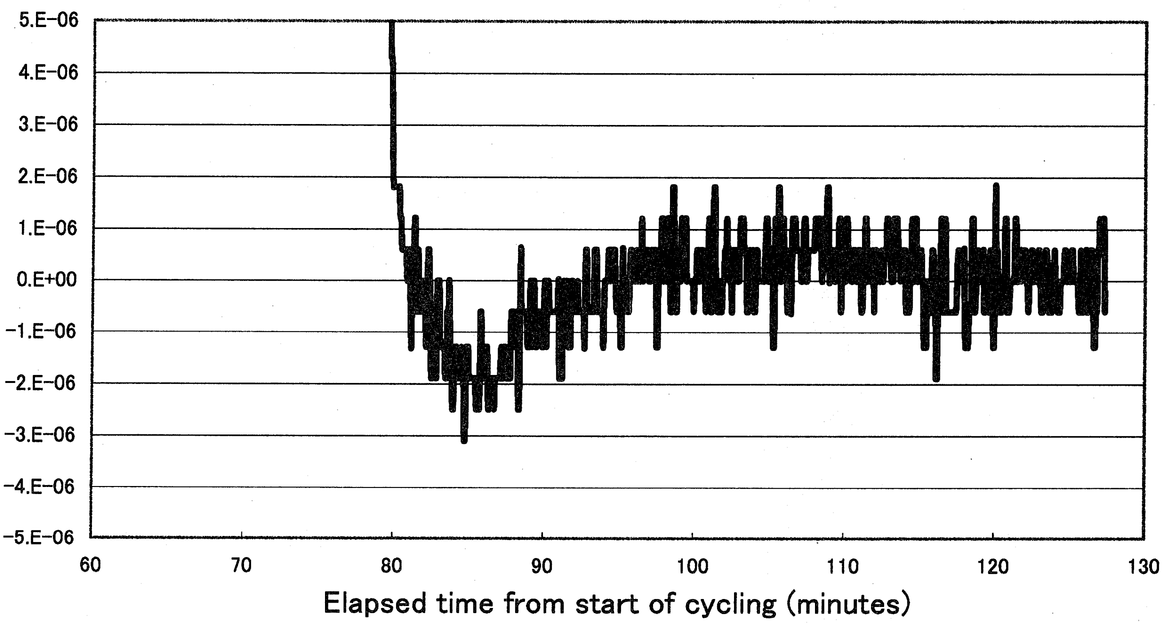

Figure 3 Magnetic field deviation of the ring cyclotron after cycling.

6 COLNCLUSIONS

Stable operation of the cyclotron is essential to accelerate an ultra-precise beams in a long term.

With proper setting of cooling water temperature, stability and start up property of magnetic field is significantly improved. Control of thermal deformation of large structure such as magnets of an accelerator is practically impossible. The key technic is to keep or to reach quickly stationary state of thermal equilibrium.

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