TEMPERATURE CONTROL OF A CYCLOTRON MAGNET FOR STABILIZATION OF THE JAERI AVF CYCLOTRON BEAM

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Abstract

Frequent corrections of the magnetic field of the JAERI AVF cyclotron were required for keeping a beam current constant during long time operation. We observed correlation between the magnetic field and the temperature of the cyclotron magnet yoke by measuring the magnetic field with an NMR probe and the temperature with platinum resistance thermometers. As a result, this instability of a cyclotron beam was induced by temperature-change of the magnet yoke caused mainly by thermal conduction from the main coil. To restrain the thermal conduction to the yoke, we have inserted temperature-controlled copper plates between the yoke and the main coil. In addition, a temperature control system for the cooling water of the trim coils has been installed, which is independent of the total cooling system for controlling the pole tip temperature. An optimum condition of the temperature control systems for stabilizing the magnetic field has been investigated.

1 INTRODUCTION

The JAERI AVF cyclotron provides various kinds of beams mainly for research on materials science and biotechnology with frequent change of ion species and energy. The cyclotron is operated from Monday to Friday and is usually turned on/off several times in a week for satisfying the requirements of the experimenters.

Unstable phenomena of the cyclotron beam, decrease of the intensity and drift of the phase, were observed at a high excitation level of the cyclotron magnet, more than 500A of the main coil. The operators had to adjust the current of the most outer trim coil frequently to recover the beam intensity, while the cause of the phenomena was not clear. In summer 1995, using several thermocouples, we found increase of the temperature of the cyclotron magnet yoke and correlation between the amount of correction of the magnetic field and the increase of the temperature[1]. Similar unstable phenomena were reported by other facilities[2,3].

2 UNSTABLE PHENOMENA

2.1 Beam Intensity Decrease

An example of the beam intensity decrease is shown in Fig. 1. In this case of 195 MeV $^{36}Ar^{8+}$, the current of the main coil is 820.5 A and the cyclotron was started up in Monday morning, for the first time after stopping on Friday.

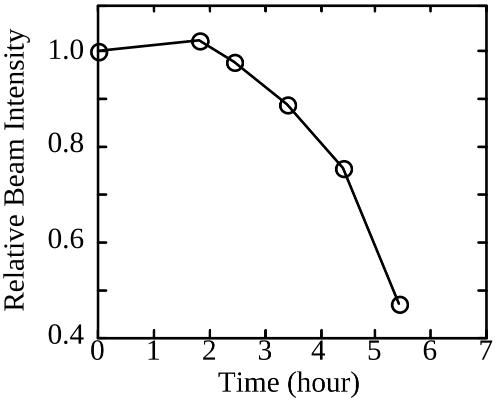

Figure 1: Beam intensity decrease.

2.2 Magnetic Field Drift

The drift of the magnetic field was estimated from the amount of the adjusted current of the most outer trim coil. The time constant of the drift of the magnetic field, assuming as a exponential relaxation, is about 40 hours, nearly equal to the one of the drift of the yoke temperature. It suggests that the changes of the magnetic field and the temperature of the yoke are correlated with each other.

2.3 Cause of the Drift

Since the stability of the power supply was confirmed to be in the order of 10^{-6}, it is supposed that the drift of the magnetic field is caused by the thermal effects on the magnet[2]. Heat is produced mainly by the main coil and the twelve trim coils, which face the yoke and the pole. The cooling water temperature for these coils is 30°C at

CP600, *Cyclotrons and Their Applications 2001, Sixteenth International Conference*, edited by F. Marti

the inlet for easy control and low operating cost. The coil temperature depends on the current of the coil; the maximum temperature is nearly 60°C in the case of the main coil. The temperature of the iron, around 25°C in Monday morning, raises gradually after the cooling water and the coils are started up.

3 MEASUREMENT

3.1 Temperature

Temperatures of the iron were measured on the surface of the yoke and the pole using platinum resistance thermometer elements. These elements were connected to a control unit, which can process multi-inputs (40 inputs/unit) with 0.01°C resolution.

3.2 Magnetic Field

The magnetic field in the acceleration region was measured with an NMR probe at a distance of about 800 mm from the center of the cyclotron. The probe, mounted on the grounded plate, was about 6 cm lower from the median plane. Since the probe should be used in a uniform magnetic field ($dB/B < 10^{-4}$) for precise and stable measurement, the optimum position was searched on the plate over a sector by moving the probe.

A correction coil, which compensates a radial gradient of the magnetic field, was mounted on the probe. The coil helps to increase the uniformity of the local magnetic field by adjusting the current of the coil.

3.3 Correlation between Temperature and Magnetic Field

It was found that the drifts of the temperatures on the iron and the magnetic field were very similar and could be expressed by relaxation functions. The time constants of the temperatures range from 20 to 80 hours depending on the distances from the main coil; most of them has a range from 30 to 50 hours. The time constant of the magnetic field, about 40 hours, is considered to be nearly equal to the ones of the temperatures.

4 THERMAL ANALYSIS

4.1 Thermal Model

A thermal model was used to understand heat transfer mechanisms in the cyclotron, since it is difficult to get actual temperature distributions on the magnet for its complicated structure and large volume. The key parameters are thermal conductivities between the coils and the iron because the surfaces of the coils are not so flat that air gap areas, which work as thermal insulator layers, are existed. In this model, we assumed that each contact face between the coils and the iron has an average thermal conductivity.

4.2 Analysis by Code “NASTLAN”

The thermal analysis code “NASTLAN” using the finite-element method was used for three-dimensional thermal analysis. By optimizing the average thermal conductivities, a calculated temperature distribution on the magnet agreed well with the measured data. Using the optimized average thermal conductivities, measures were examined to prevent the iron from heating.

5 TEMPERATURE CONTROL SYSTEM

From the results of this calculation, we determined to adopt the following methods:

- Insertion of temperature-controlled plates between the main coil and the yoke with thermal insulation plates inserted between the plates and the main coil to keep the yoke temperature constant, as shown in Fig. 2.
- Control of the cooling water of the trim coils independent of the total cooling system to keep the temperature of the surface of the sector constant.

Using these methods, it is expected that temperature increase in most of the iron can be reduced from 5°C to less than 0.5°C in 50 hours after starting up.

A temperature control system[4], based on the methods, has been installed in March 2000. The temperature-controlled copper plates 8 mm thick with hollow conductors were inserted by shifting the upper/lower main coils toward the median plane. A new additional cooling unit controls three water loops independently of the total cooling system; one is for the temperature-controlled copper plates and the others are for the trim coils. Since the trim coil #11 induces heat generation more than 50% of the sum of the trim coils, the trim coil water loops are divided into two loops: for the trim coil #11 and the rest of eleven trim coils. In each loop, average temperatures of the inlet and the outlet water can be controlled with an

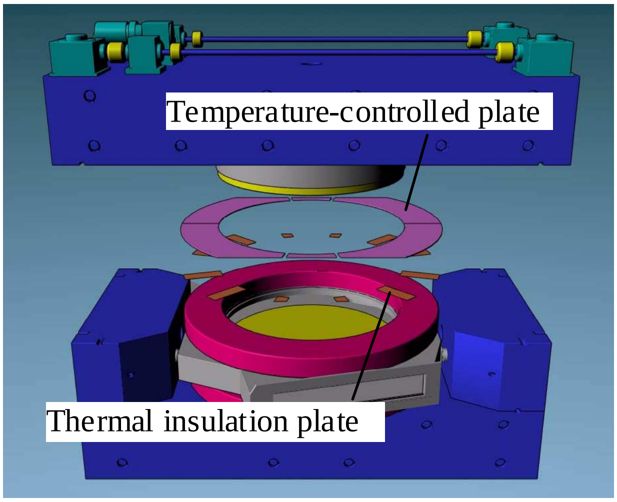

Figure 2: Temperature-controlled plates and thermal insulation plates.

accuracy of ± 0.5°C.

6 BEAM STABILIZATION TEST

6.1 First Test

The first beam stabilization test was carried out by controlling the temperatures of the cooling water of the three loops to the initial temperature of the iron, 24°C in this case. The temperatures of the iron increase in the range of 2 to 3°C in 50 hours, which were a half of the ones in the case without the temperature control system. The time, in which the beam intensity decreases to a half of the initial one, was extended from 5 to 20 hours, and the beam intensity decreased to 10 % of the initial one after 40 hours from starting up.

6.2 Second Test

From the result of the first test, it appears that the initial temperature of the iron is too low to keep constant because of residual heat conduction from the water of the total cooling system keeping the temperature at 30°C and from the bore of the main coil facing the pole side through an air gap of 7 mm. We examined the following way.

- Warming the iron in the weekend. The temperature of the iron is maintained to be around 26°C by operating the temperature control system.
- Lower temperature of the copper plates. According to the amount of the heat generation mainly in the main coil, the temperature of the copper plates is adjusted to compensate the residual thermal effect.

The changes of the temperatures of the iron were reduced within 1°C / 50 hours. Figure 3 shows the beam intensity fluctuations. The beam intensity was stabilized within 10% decreasing. The magnetic field was also stabilized, as shown in Fig. 4, though the measurement with the NMR probe had larger influence of noises than the former ones.

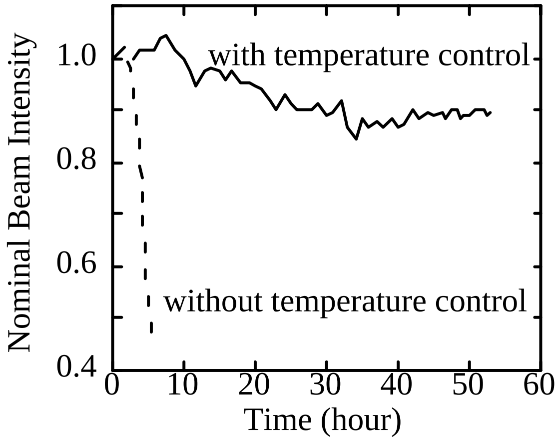

Figure 3: Beam intensity fluctuations.

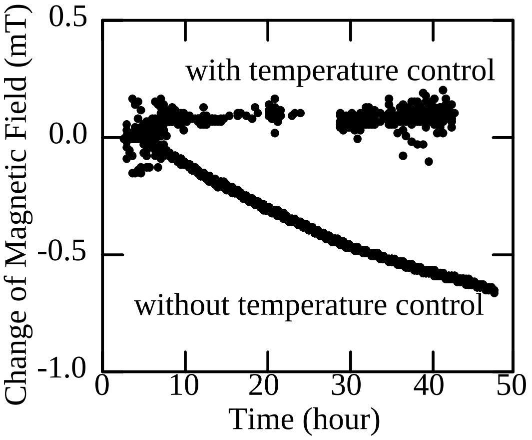

Figure 4: Magnetic field fluctuations.

7 CONCLUSION

A 195 MeV $^{36}\mathrm{Ar}^{8+}$ beam was stabilized using the temperature control system. To meet various beam conditions, more careful optimization of the operation is needed. Monitoring the magnetic field is one of the most useful tools for stabilization, while it is very difficult to use an NMR probe in the acceleration space because of poor uniformity of the magnetic field and noisy environment. Monitoring the beam phase seems to be proper to get information of total change of the magnetic field.

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