Investigation of temperature dependence of magnetic field for stabilization of the JAERI AVF cyclotron beam

Susumu OKUMURA,Kazuo ARAKAWA, Mitsuhiro FUKUDA, Ikuo ISHIBORI, Yoshiteru NAKAMURA
Watalu YOKOTA, Takayuki NARA, Takashi AGEMATSU, Hiroyuki TAMURA
Akihiko MATSUMURA, Masami SANO*, Toshiki TACHIKAWA*
Japan Atomic Energy Research Institute (JAERI)
1233 Watanuki-machi, Takasaki, Gunma, 370-1292, Japan
*Sumitomo Heavy Industries, Ltd.
5-2, Soubiraki-cho, Niihama, Ehime 792-8588, Japan

Abstract

It has been found necessary to correct the magnetic field gradually to keep a beam current constant during long time operation of the JAERI AVF cyclotron. The unstable phenomenon of a cyclotron beam was induced by temperature change in the iron caused by thermal conduction from the main coil. We have observed a dependence of the magnetic field on temperature by measuring the magnetic field with an NMR probe and the temperature of a cyclotron magnet with platinum resistance thermometers.

1 Introduction

In the course of a normal week of operation, the JAERI AVF cyclotron is started up on Monday morning, and turned off on Friday evening. The parameters of the cyclotron are adjusted so that the beam current reaches its maximum value. After several hours, the beam current gradually decreases and the phase of the beam also changes. Fine tune of the magnetic field is required to keep the beam current constant. A typical example of a drift of the beam current for 195 MeV $^{36}Ar^{8+}$ is shown in Fig. 1.

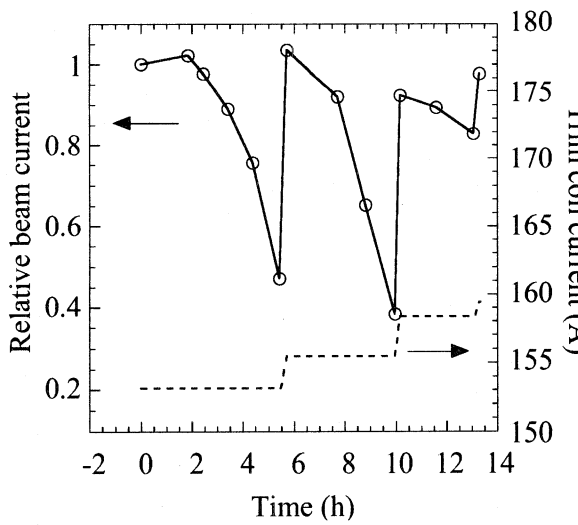

Fig. 1 Beam current drift for 195 MeV $^{36}Ar^{8+}$. The current returned to the initial value by increasing the current of the most outer trim coil as shown by a dashed line.

The correction of the magnetic field by adjusting the current of the most outer trim coil was required usually for high magnetic field of the cyclotron. The same unstable phenomena were reported by other facilities [1,2].

A magnetic field of the cyclotron is generated by a pair of main coils and twelve pairs of circular trim coils, which are cooled by water. The trim coils are wound concentrically and excited to form an isochronous magnetic field. Small corrections to the excitation level can be made using the most outer trim coil.

The main coils surround the pole tips and face the magnet yoke. Since the heat generated by the main coil is very large, theses coils likely cause the increase in temperature of the pole and the yoke. Therefore, we investigated the relation of the temperature and the magnetic field of the cyclotron.

2 Stability of a Power Supply for the Main Coils

The magnetic field is excited with a highly stable power supply with stability of better than 10^{-5}. The change in phase is given by $\Delta\sin\phi = 2\pi hN\Delta B/B$, where N is a turn number, h a harmonic number, $\Delta B/B$ the change of the magnetic field. The turn number for the third harmonic acceleration, h=3, is around 210 just before extraction, which is defined by a constant orbit method. In case of the magnetic field change of $\Delta B/B=10^{-5}$, the change in phase is estimated at 2.2 degrees RF. Thus the changes of the magnetic field in the order of 10^{-6} do not influence the acceleration of the beam.

3 Measurement of Magnetic Field and Temperature

The magnetic field was measured with an NMR probe at a distance of 800 mm from a centre of the cyclotron. The probe placed on a grounded plate in vacuum chamber, as shown in Fig. 2. The probe should be used in a uniform magnetic field to achieve precise and stable measurement; the variation of the field dB/B is less than $10^{-4}/cm^3$. Since the magnetic field of the cyclotron varies radially to form the isochronous field using the trim coils, we achieved the measurement by exciting only the main magnet to produce a uniform field distribution.

Figure 3 shows the change of the magnetic field at 820.5 A of the main coil current. Assuming that the change of the magnetic field is regarded as a relaxation phenomenon expressed by a function

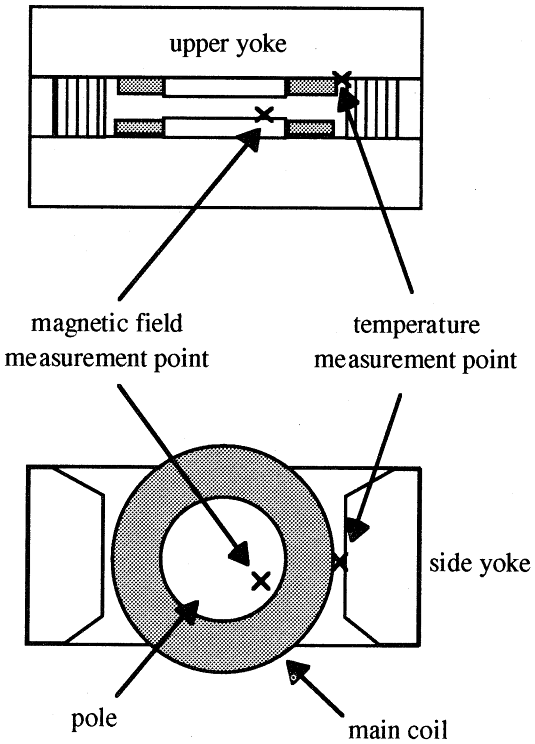

Fig. 2 Measurement points of the magnetic field and the temperature of the yoke, shown in Fig. 3.

$$\Delta B = \Delta B_{\max}\left(1 - \exp\left(-\frac{t}{\tau}\right)\right) + \Delta B_{offset} \qquad (1)$$

where τ is the time constant, t time, ΔB_{max} the maximum change of the magnetic field, ΔB_{offset} an offset for the magnetic field change. The time constant of the magnetic field change, τ_B, is estimated at 35 hours.

Temperatures of the iron were measured at 50 different points on the surface of the pole and the yoke using platinum resistance thermometer elements and copper-constantan thermocouples.

Change in temperature at the point on a symmetrical axis of an upper yoke close to the main coil, indicated in Fig. 2, is shown in Fig. 3. The time constant of temperature change, τ_T, was estimated at 40 hours, which approximated to the τ_B. Therefore, the change of the magnetic field was linked to temperature change of the iron of the magnet yoke.

4 Dependence of Magnetic Field on Temperature

In this measurement, the magnetic field decreased with the temperature increase of the iron of the magnet. The main coil heated the iron, since the residual heat that could not be removed by cooling water flowing inside a hollow conductor of the main coil, was transmitted to the yoke. This temperature drift of the iron causes a change of the magnet performance.

According to a rough approximation using a magnetic circuit, the strength of the magnetic field in an acceleration area is expressed by $B = \mu_0 \times NI/d$, where μ_0 is magnetic permeability in vacuum, N a turn number of the main coil conductor, I a main coil current, d a distance between pole tips. The strength of the magnetic field is inversely proportional to the distance between the pole tips. The increase in temperature of the side yoke results in thermal expansion of iron itself. A linear expansion coefficient for iron is $\lambda = 1.2 \times 10^{-5}/℃$.

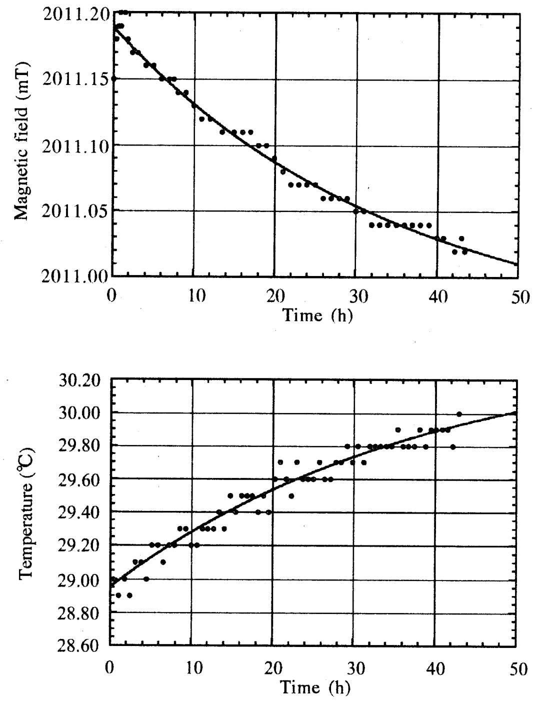

Fig. 3 A drift of the magnetic field measured with an NMR probe at a point 800 mm from a centre of the cyclotron (the upper figure) and a drift of the temperature at a point on a symmetrical axis of an upper yoke close to the main coil (the lower figure).

A rate of the magnetic field change as a function of temperature, (dB/B)/dT, can be obtained by differentiating the relaxation functions of ΔB and ΔT, that is dB/dt and dT/dt, and by calculating a ratio of (dB/dt)/B to dT/dt. The (dB/B)dT was estimated at around $9 \times 10^{-5}/℃$, which was larger than the linear expansion coefficient for iron. Change of the physical properties of iron and/or expansion of the pole tips might be considered for a full understanding of the observed beam current drift (Fig.1).

5 Model Calculations

Model calculations of the present situations have been performed. In the model, it was assumed that the thermal conductivity from the coils to the upper and lower yoke plates was high. As a result, the obtained temperatures were higher than the measured temperatures. New calculations will be performed using a more realistic temperature insulation at these locations.

6 Conclusion

We observed that the instability of the cyclotron beam resulted from the change of the magnetic field originating from the temperature increase of the magnet yoke. The change in temperature was caused by the heat mostly conducted from the main coil.

In order to reduce the change of the magnetic field, it is required to keep the temperature of the magnet constant at different excitation levels. A heat insulator will be installed between the main coil and the magnet yoke. Even the air-conditioning of the cyclotron vault might help to stabilize the magnet temperature constant.

References

[1] L. P. Roobol, S. Brandenburg, and H. W. Schreuder, Cyclotrons and their Applications 98, Caen, France (1998) 211-214.

[2] T. Saito et al., The 11th Sympo. on Accel. Sci. and Tech., Harima, Japan (1997) 71-73.