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PROCEEDINGS

Development of a magnetic field monitoring system for the JAERI AVF cyclotron

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Abstract We have developed a probe of a nuclear magnetic resonance (NMR) magnetometer for measurement of a fluctuation of an AVF cyclotron field. The stability of the magnetic field of the JAERI AVF cyclotron, measured with the NMR probe, was within 1×10^{-5}. A field-measurement accuracy of the order of 1×10^{-6} was achieved using a set of field-compensation coils and optimizing the probe position to obtain enough homogeneity of the magnetic field around the probe for measuring the cyclotron field with a high gradient. To eliminate a major bottleneck in the field measurement inside the cyclotron, the probe was specially produced with the cable shielding against RF noises and proper materials applied.

Key words compensation coil • cyclotron • magnetic field • NMR • stability

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Introduction

In the K110 JAERI AVF cyclotron, unstable phenomena, such as a beam intensity decrease, were observed after starting up the cyclotron or changing an excitation level of the magnet. The magnetic field correction of $\Delta B/B = 1 \times 10^{-4}$ every tenth hours was needed over a few days. We found out that an increase in temperature of the iron body of the magnet induced the unstable phenomena. Stabilization of the iron body temperature was achieved by precise temperature control of the cooling water for thermal isolation plates installed between the iron body and a main coil [2]. As a result, the magnetic field has been stabilized in the order of 10^{-5}.

In the cyclotron, a collimation method was applied for microbeam production, but the minimum beam size was around several μm. To achieve a beam size of 1 μm in diameter, a focusing system has been constructed. Reduction of the energy spread of the beam, from $\Delta E/E = 1 \times 10^{-3}$ to 2×10^{-4}, is required for reducing chromatic aberration in lens focusing. We are, therefore, developing the flat-top acceleration system [1] for the energy spread reduction, and it was required to guarantee the tolerance of the magnetic field, $\Delta B/B < 2.0 \times 10^{-5}$.

In general, a magnetic field measurement with an accuracy of the order of 10^{-6} can be achieved by using a nuclear magnetic resonance (NMR) magnetometer, which is normally used in air and in the homogeneous magnetic field, such as the dipole magnets without field gradient. We have developed an NMR probe available inside the AVF cyclotron to overcome difficulties: the gradient field of the magnet, the harsh electromagnetic environment, etc.

Structure of the cyclotron

The JAERI AVF cyclotron has a 4 spiral sectors with an extraction radius of 923 mm. The acceleration electrodes consist of a couple of 86-degree dees; each dee is connected with a coaxial type resonant cavity. The magnet has an H-type iron body with the pole diameter of 2156 mm. The pole gap and the sector gap are 405 mm and 166 mm, respectively. The magnetic field is mainly produced by exciting a pair of main coils. Twelve pairs of circular trim coils wound concentrically on the sectors are used to form an isochronous field. A pair of ground plates covers the pole surface area including the trim coils and the sectors to maintain a high vacuum of the acceleration space. The vertical acceleration space is restricted to 40 mm by four pairs of dummy electrodes with a 50 mm height, while the gap of the ground plates is 140 mm.

Since the pole surface is covered with the ground plates, installation space for the NMR probe inside the cyclotron is restricted to the areas on the ground plates facing the acceleration space without the dees. The path of the cable from the probe to the air was carefully chosen to run in the restricted space inside the cyclotron.

Problems in application to the cyclotron

Besides spatial constraints, it is required to overcome the problems for a precise measurement of the magnetic field inside the cyclotron with the probe. The most important problem is that the NMR resonance signals of the probe get smaller and wider in the gradient field of the cyclotron; the accuracy of the measurement deteriorates and the signals disappear at worst. In the AVF cyclotron, the magnetic field increases radially to keep isochronism and varies azimuthally to increase axial focusing force. It is, therefore, required to reduce the field gradient at the sample point of the probe; as well as searching for the position of the easier field gradient, an additional magnetic field for compensating the field gradient locally is needed. The feasible position for the probe is restricted to the center of the sectors, which are favorable in terms of field homogeneity. The second problem is electromagnetic disturbance on the probe, especially on the signal transmission between the probe and the amplifier, since the path of the cable has to run near the dee to reach to the feedthrough on the chamber frame. An acceleration RF voltage of the dees, 60 kV in maximum, tends to distort the NMR signal, and, moreover, the insulation of the signal cable tends to be destroyed by RF heating. In the high magnetic field, 2.1 T in maximum on the sectors, large electromagnetic noises are induced on the signal cable even by a very slight vibration. The main source of the vibration is cryopumps mounted on the resonant cavities. The third problem is the use of the probe in vacuum with a pressure of 10^{-5}–10^{-6} Pa. Materials with low outgassing and high heat resistance have to be used to fabricate the probe and the cables. The fourth problem is radiation damage on components of the probe. From our experience, diodes, which are used for band selection of the NMR, are destroyed frequently; to refrain from using the diodes, the magnetic field measurement was restricted to the range from 1.6 to 2.1 T, which fulfills the beam condition for the microbeam production.

Development of a NMR probe

We have developed a new NMR probe to monitor the stability of the magnetic field in the cyclotron with an accuracy of the order of 10^{-6}. The NMR signal picked up from the probe inside the cyclotron is transmitted to the amplifier for detection and amplification. The circuit of the probe was assembled on the copper plate, and electronic parts were fixed with epoxy resin. The sample size and the field gradient in the sample greatly affect the NMR signal. By repeated trials, the dimension of the solid proton sample for the probe was fixed at 1.5 mm in diameter and 4 mm in length.

To obtain a homogeneous field in the sample, we applied two pairs of field-compensation coils, which sandwich the head of the probe. By exciting the pairs of coils oppositely, the coil field has a gradient of around 10 G/cm with a current of 200 mA for compensation of the field gradient with the coil field falling to zero at the sample. Therefore, compensation of the field gradient in one direction can be realized. Since the main direction of the field gradient does not always correspond to the radial direction because of the complex field distribution of the cyclotron, the compensating direction was optimized by using a mechanism for rotating the pairs of coils with the rotary axis fixed at the center of the sample. A unit of the coils was made from polyimide-coated copper wire 0.3 mm in diameter with 60 turns in the shape of a square 40 mm on a side with the inside of a square of 17 mm. The wire was bonded with epoxy resin (Torr Seal). The thickness of the unit of the coils was suppressed to 1 mm to keep the rotating mechanism within the probe height of 15 mm.

The cable of the probe was designed to minimize the size and to reinforce the characteristics against high vacuum, heat, and radiation by using a polyimide insulator instead of a conventional multiconductor cable with a vinyl insulator. The cable was doubly shielded with meshes overall, and run through a copper pipe of 6 mm in diameter for shield reinforcement in the part facing the dee. To prevent vibrations of the signal lines in the pipe, the lines were bundled tightly and resin was filled into the copper pipe.

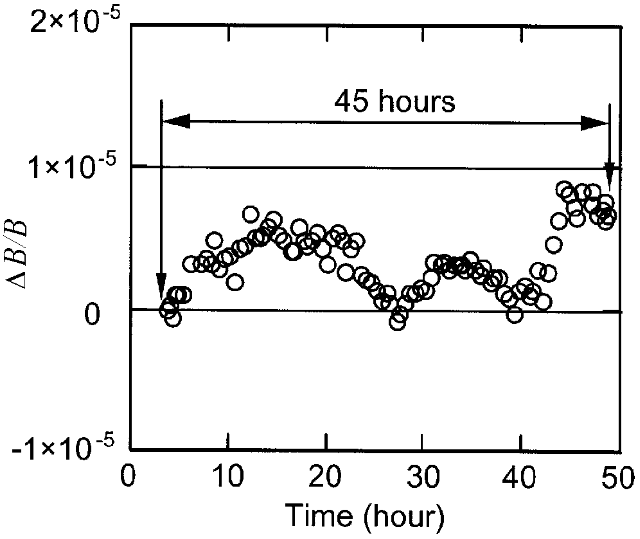

Fig. 1. Fluctuation of the magnetic field measured with the developed NMR probe during operation with a 195 MeV ^{36}Ar^{8+} beam.

Measurement of the magnetic field in the cyclotron

We have measured the magnetic field with the probe during operation with a 195 MeV ^{36}Ar^{8+} beam. The measured magnetic field B was 2.043 T and the stability $\Delta B/B$ was within 1×10^{-5} in 45 hours, as shown in Fig. 1. It fulfills the condition of the magnetic field tolerance for the microbeam production.

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