Cryogen-Free 3T-MRI System for Human Brain Research using Bi-2223 High-Temperature Superconducting Tapes

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Introduction

The demand for the exhaustible natural resource helium is increasing rapidly, with 20% of global production used as the cryogen in superconducting MRI magnets. High-temperature superconducting (HTS) materials show great potential for realizing helium-less magnets. This is the first report for a cryogen-free 3T-MRI scanner for human brain research using Bi-2223 tapes operating at a temperature of 20K.

Cryogen-free MRI

In this project, not only the magnet but also the gradient coils, RF coils, spectrometer and system software have now been developed/produced. Adjustment and imaging experiments will be carried out at 1.5T first and then at 3T.

Bi-2223 HTS tapes (DI-BSCCO Type HT, Sumitomo Electric Industries, Ltd., Japan) (Fig.1) were used for the magnet. In general, HTS material is ceramic and brittle, making winding impossible. However, Bi-2223 tape, a flattened HTS multifilamentary-core covered with Ag and AG-alloy, is flexible and can be bent to enable coil winding. At the conditions of 20K and 3T, its critical currents are around 600/300 A (parallel/perpendicular to the tape surface), which provide a considerable margin for error above the necessary electric current required (184 A) to generate a magnetic field of 3T. The critical temperature at 184 A and 3T is approximately 30K.

Figure 2 shows the design of the magnet [1]. The scanner is built for human brain research and the magnet bore is vertical (Fig.3). The magnet consists of five main coils chilled with only GM cryocooler and thermal conduction. Because this project is the first trial, no self-shielding was incorporated and the five-gauss line is 6.5 m from the magnet center. The inductance of all coils is 137.5 H, the maximum axial/hoop stresses are 4.7/137 MPa and the stored energy is 2.3 MJ, at 3T.

In total, 44.6 km of tape was wound and fixed by painting stycast (2850FT, National Starch & Chemical Co., USA) to form the five main coils. The maximum piece-length of a single tape was about 400 m and more than 130 tapes were joined. For the joints, soldering was used because, in contrast to NbTi wires generally used for MRI magnets, there is no technique to join tapes that maintains superconductivity. These soldered joints have a small resistance so that a super-stable power supply (Model 854, Danfysik, Denmark) is needed to maintain constant electric current. The magnetic field stability depends on the stability of the power supply which is better than 0.3 ppm. Magnetic field homogeneity of the unshimmed magnet was 893 ppm at 1.5T in the targeted FOV region; a 25x25x20 cm spheroid. After the fourth passive-shimming trial, this was improved to 15 ppm. Since this system has another passive-shim layer on the outer surface of gradient coil, additional passive-shimming will be performed after mounting the gradient coil.

The gradient coil wire paths were designed for maximum gradient strength, less than 5% gradient field error and zero net torque whilst optimising the maximum current density, slew rate, power dissipation, and eddy currents via active screening [2]. Copper elements for the x/y-gradient and shim coils were produced by chemical etching and bent with a numerically-controlled bending machine. After assembling the elements and cooling pipes on a fibreglass/resin composite bobbin they were cast with epoxy resin (Fig.4). The gradient coil efficiencies were 0.06/0.06/0.15 mT/m/A for the x/y/z gradients, respectively. To isolate the magnet from gradient coil vibration, the coil was fixed not to the magnet but to an aluminium frame surrounding the magnet (Fig.3).

An FPGA (programable IC chip) based spectrometer with gradient coil control functions was developed based on the "*OPENCORE NMR*" technology [3,4] (fig. 5). For transmitter/receiver RF coil, a birdcage type coil was produced. The system software consists of two consoles: the "*sequence console*" (fig.6) and the "*image console*". The former is for developing sequences with a graphical user interface to specify imaging parameters, send the command codes to the spectrometer to run a sequence and reconstruct the received raw data. The latter is to store images in a DICOM database, display images and position slices for the next sequence. The two consoles are separate software but they communicate with each other for transferring information and data.

Discussion

Although a magnet using HTS tapes might be expected to have problems with magnetic field stability (because it must be power supply driven) and homogeneity (because of the special winding), both of them were not problematic in this case. The stability of less than 0.3 ppm is still large if the change happens during TE but the huge inductance of the magnet is expected to work as a low-pass filter and suppress such a rapid change. After installation of the spectrometer and the RF coil, that is, a high-sensitive magnetic field sensor, we will measure this subtle field change. At the conference, we expect to have SE/GE images taken with this scanner.

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Fig.1 Cross-section of the Bi-2223 tape.

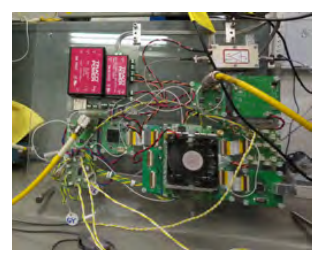
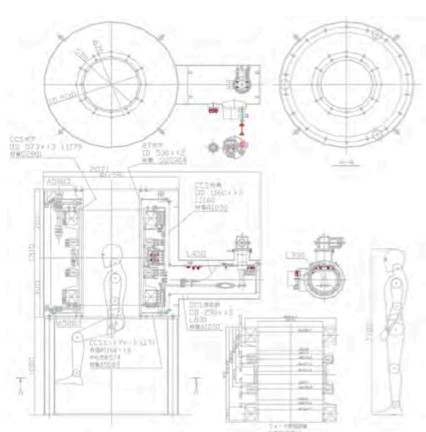


Fig.3 Magnet and aluminium frame for mounting the gradient coil. Fig.5 Spectrometer.



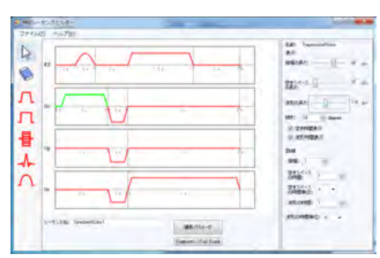


Fig.2 Design of the magnet Fig.4 Produced gradient coil. Fig.6 Sequence console.