X-ray and neutron transparent pulse magnets

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Abstract. A new type of pulse magnet, x-ray and neutron transparent pulse magnet, is suggested for use in high-field diffraction experiments. The magnet is made of aluminum-based material, so we expect that the scattered beam penetrates the magnet body and hence the total number of reflection points available substantially increases. This feature possibly allows full determination of the lattice and magnetic structure in strong magnetic fields. To realize this idea, we constructed a prototype transparent magnet consisting of aluminum wire and duralumin reinforcement. With a portable capacitor bank, the maximum field of 25 T was successfully generated in a 1.6 mm bore, even though the aluminum wire is less strong and less conducting than copper wire. Since the total energy is small ($E_{\text{bank}} \sim 100$ J), high repetition rate, which is necessary for sufficient signal-to-noise ratio, is realized. Technical details, coil performance, and future prospects will be described.

1. Introduction
Recently, there are growing demands for the microscopic understanding of exotic phenomena in high magnetic fields. High-field x-ray and neutron diffraction experiments are regarded as one of such experimental tools. They give direct evidence for the lattice and magnetic structure, and so play decisive roles in studies of magnetism. Indeed, high-field diffraction experiments are now undertaken at intense x-ray and neutron beam facilities.

In these high-field experiments, the incident beam is first introduced into a specimen, and then scattered beams are detected outside the magnet. Therefore, there is a severe experimental constraint that scattered beams are almost screened by the magnet itself. For this reason, split-pair coil magnets are usually used in high-field diffraction experiments at the expense of the maximum field. Even for this case, however, most of reflection points are still screened by the magnet, and full determination of the crystallographic and magnetic structure in high magnetic fields is impossible. In addition, geometrical alignment between the magnet and sample orientation has to be checked carefully prior to experiments.

To overcome this fundamental but critical difficulty, we propose a new type of magnet, x-ray and neutron transparent magnet, in this work. This magnet is a miniature pulse magnet made of aluminum wire, and so is expected to be transparent to intense x-ray and neutron beams. In this work, we constructed a prototype transparent magnet as the first step, and tested the coil performance. In the following, we will show the basic design, test results, and future prospects.
2. Basic concept

As mentioned above, the total reflection points available are limited by the magnet geometry in high-field diffraction experiments. However, if magnets are transparent to x-ray or neutron beams, scattered beams penetrate the magnet and any reflection points could be detected in principle even outside the magnet. This is the basic idea of transparent magnet, and will have a strong impact on high-field diffraction experiments if realized. For example, full determination of the lattice and magnetic structure in strong magnetic fields would be possible. In addition, field-induced satellite peaks, whose positions cannot be predicted in zero magnetic field, could be pursued. Indeed, this feature is of potential importance for studies on field-induced structural transition accompanying magnetic transition or field-induced charge density wave. Furthermore, sample alignment prior to experiments would become rather easier.

The basic idea to realize a transparent magnet is rather simple: the magnet has to be made of materials highly transparent to x-ray and neutron beams and also has to be small enough for scattered beams to penetrate the magnet body. Then, it is found that the element satisfying this requirement is only aluminum (Al). It is known that Al is highly transparent to x-ray and neutron beams. In addition, Al possesses high conductivity of $0.3 \times 10^6 \, \text{S cm}^{-1}$ at room temperature, which is 60% of the conductivity of copper (Cu), and is easily processed into thin wire. These features are suitable for coil winding.

Another important point is the coil dimensions. Even if Al is more transparent than other elements, there is still substantial absorption. Therefore, the magnet size has to be comparable or smaller than the characteristic decay length, which strongly depends on the element and beam energy, and also differs between x-ray and neutron. Generally, this decay length is shorter for x-ray beam than for neutron beam because x-ray interacts more strongly with materials. The practical coil size has to be determined, taking account of the signal-to-noise ratio. Namely, large sample volume ($\sim 1 \, \text{cm}^3$) is necessary in neutron diffraction experiments, contrary to the x-ray case ($\sim 1 \, \text{mm}^3$). This fact suggests that a larger magnet size is preferred for neutron diffraction experiments.

For more concreteness, we make rough estimation of coil dimensions for x-ray experiments. The x-ray intensity decays obeying $I = I_0 \exp(-\mu x)$, where $\mu$ is the linear absorption coefficient. Since this factor decreases with increasing x-ray energy, we expect that higher energy x-ray is more transparent. Indeed, the length where the incident beam intensity decays by 1/10 is 0.17 and 7.6 mm at $E=8$ and 30 keV for Al, respectively. The former corresponds to the characteristic x-ray energy for the Cu Kα line, which is widely used in laboratory-scale equipments. Therefore, the use of synchrotron radiation facilities, where relatively high energy x-ray beam is available, is suitable for our purpose. Even for this case, however, magnet size should be less than 10 mm or so, otherwise the scattered beams are substantially decayed. If we compare Cu with Al, this decay length of Cu becomes more than thirty times shorter. Therefore, it is impossible to construct a transparent Cu magnet with realistic dimensions.

Here we roughly estimate the signal intensity for the x-ray case. It is noted here that Al is a normal metal, so the magnet has to be operated in the pulsed-field mode for high field generation. Therefore, the data acquisition time is limited during pulse field generation, and synchrotron radiation x-ray source such as SPring-8 has to be used for sufficient signal-to-noise ratio. Typically, Bragg spot intensity for such intense x-ray beam reaches $10^9 \, \text{cps}$. Then, scattered beam intensity decays by 1/10 when the beam penetrates the Al magnet with dimensions mentioned above. Since our magnet is operated in the pulsed mode, the intensity is further reduced due to the limited peak-field duration of $\sim 10 \, \mu$s. This roughly gives $10^3 \, \text{counts/shot}$, which is indeed in the detectable range. Although there are other factors to decrease the signal intensity in the actual system, we believe that high-field diffraction experiments using a transparent pulse magnet will be possible. The fact that pulsed-field x-ray [1, 2, 3] and neutron [4] diffraction experiments have been successfully performed supports our estimation.
3. Coil construction
A prototype Al magnet is constructed to test the high-field performance. Instead of pure Al wire, we used Cu-clad Al wire (15% Cu weight) in this work. This is simply because Cu-clad Al wire with polyester insulation layer was commercially available. Cu-clad Al wire shows similar properties to pure Al wires, and possesses 67% conductivity and 50% tensile strength of Cu wire. Therefore, it is expected that the performance of Al magnets is inevitably worse than that of Cu magnet.

A Cu-clad Al wire was wound around a polyimide tube to form a multilayer solenoid. The wire diameter was 0.36 mm including insulation layer. Reinforcement was made with a duralumin tube instead of a stainless tube, since duralumin is Al-based alloy possessing high tensile strength of \( \sim 360 \) MPa. This value is only slightly smaller than that of stainless steel (\( \sim 520 \) MPa). The length and bore size of the magnet were typically \( 2\ell=6-7 \) mm and \( 2r_1=1.6 \) mm, respectively. The outer diameter depended on the layer number, and was \( 2r_2=3.1 \) and 4.5 mm for magnets consisting of two and four layers, respectively. The coil resistance of a four-layer Al magnet was 176 m\( \Omega \) at room temperature, which decreased by a factor of seven at 77 K.

4. Pulsed field generation
Magnet test was performed at 77 and 4.2 K, using a desk-top capacitor bank [5]. The bank size was \( 0.32 \times 0.36 \times 0.30 \) m\(^3\), and the weight was 14.3 kg. The capacitance value and the maximum charging voltage were 2.1 mF and 300 V, respectively, which correspond to \( E_{\text{bank}} \sim 95 \) J. Current switching was made using a thyristor. Magnetic field was measured with a pickup coil consisting of a 50 \( \mu \)m single-turn copper wire. The pickup signals were recorded using a fast digitizer (Nicolet Pro 40), and integrated numerically to obtain the magnetic field value. A small shunt resistor (\( R=5 \) m\( \Omega \)) was connected in series to the circuit, so that the magnetic field (\( B \)) can be calibrated against the current (\( I \)) by monitoring the shunt voltage.

Shown in Fig. 1 is the pulsed field profile of a four-layer Al magnet. The test was carried out at 4.2 K where the magnet was directly immersed in liquid \(^4\)He. It is found that the maximum field increases with increasing the charging voltage, and reaches almost 25 T for 280 V discharge. The pulse duration was \( \sim 400 \) \( \mu \)s at low discharge voltages, but became longer at higher discharge
voltages. Asymmetric waveform observed for all curves is caused by Joule heating.

Shown in Fig. 2 is the maximum field vs. charging voltage for three types of magnets, Al-1, Al-2, and Al-3. The layer number and test temperature are shown in the figure. It is clear Al-2 generates higher fields than Al-1. This is accounted for by the difference in the initial coil temperature, and hence the coil resistance. Al-1 and Al-3 were broken at the discharge voltage of 240 and 220 V, respectively, probably due to overheating of the magnet.

We previously reported a coil performance of a Cu magnet with the same coil dimensions [5], in which 29.7 T was successfully generated at a similar discharge voltage. This fact indicates that the maximum field is reduced by 15% due to less conductivity of Al wire. Nevertheless, it is of interest that Al magnet can generate strong magnetic fields reaching 25 T, even if the tensile strength is about half of Cu wire. If we use thicker wire than the present one, the heating loss will be reduced and higher field can be generated. However, the larger coil volume causes stronger decay of scattered beams. Therefore, optimum dimensions may exist in the actual experimental configuration.

Magnet cooling time for the next shot determines the repetition rate. Though the cooling time strongly depended on the field value, it was at most one minute in the present test. This rapid cooling is due to a compact design of the magnet, and will help to average the signal intensity efficiently. In the present test, however, the magnet was immersed in liquid nitrogen or liquid $^4$He, and so it may take longer time when the magnet is set in vacuum.

5. Summary and future prospects

In this paper, we proposed a conceptually new type of magnet, an x-ray and neutron transparent magnet, for high field diffraction experiments. This Al-based magnet is small enough for intense x-ray and neutron beams to penetrate the magnet body, and so acquisition of reflection points is not limited by the magnet geometry. We constructed prototype Al magnets to test the coil performance, and have shown that they have a potential to generate strong fields greater than 25 T.

Toward practical use of a transparent magnet, coil parameters have to be optimized as the next step. This procedure is not straightforward, because a change of one parameter may affect a couple of magnet properties such as pulse duration, repetition rate, and scattered beam intensity. Numerical estimation of coil performance will be useful for this purpose. Durability, an important factor for signal averaging, also has to be tested, because some Al magnets were broken by overheating. Quantitative test of the signal intensity is desired in the future by combining a transparent magnet with intense x-ray or neutron beam. To this end, further technical development such as data acquisition system or cryogenics would be necessary to take full advantages of a transparent magnet.

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