New pulsed-magnets for 100 T, long-pulse and diffraction measurements

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Abstract. Development of non-destructive pulsed magnet aiming at 100 T-generation beyond 80 T-field is our mission. For that purpose, we have been developing a new coil system, so-called “dual coil system” and succeeded in generation of 85 T. This magnet will open the non-destructive 100 T-field in the near future. New type of magnet with longer pulse duration also has been developed. This magnet has a gap between the inner coil and the outer one where liquid nitrogen can flow. Therefore, the magnet can be cooled down by liquid nitrogen rapidly. The repetition time has been reduced to 15 minutes for 60 T-field with the duration of about 30 msec. By means of this rapid-cooling technique, a magnet for X-ray diffraction measurement has been made. This magnet consists of split coils with a split gap of 5 mm and a duration time of about 30 msec. This magnet allows us to carry out X-ray diffraction measurement under pulsed high field. The maximum field of the magnet is found to be 38 T, which is limited by utilized energy of the capacitor bank.

1. Introduction

The High Magnetic Field Laboratory of ISSP has been reorganized in 2006. New mission arisen is to make a long pulse field by use of the largest DC generator and make a 100 T-field by combining a short pulse magnet driven by the capacitor bank with the long pulse one energized by the DC generator. The DC generator had been used for the experiments of nuclear fusion and will be moved to Kashiwa in 2007. The generator can store energy of 210 MJ and its output is 51.3 MW. High field generation with this generator is scheduled to fully operate in 2010. Before the full operation, we have to develop something to meet the necessity for long pulse- and 100 T-field. 100 T-field is considered to obtain by dual coil method as expected in many places in the world. It, however, takes a long time to make an outer coil fit to the generator. Then, we have started the new project in advance from a research for the inner coil based on techniques developed at Osaka University in the past decade. In the next section, we will summarize developed 80 T-class coils, and test-experiment for dual coil method by using one of the 80 T-class coils will be mentioned in section 3.

New laboratory has another mission to open user-friendly magnets for researchers. In contrast to the mission, only destructive short pulse magnets characterized former ISSP, but needs for longer pulse fields always have existed because accumulation of signal become better and eddy current induced on metallic materials can be suppressed. New ISSP has started to develop new user magnets as the answer to the users’ needs. Larger 80 T-class coils shown in the next section brought a longer pulse 60 T-fields
with time duration of about 30-40 msec., which is fairly long and high. Though the long-pulse magnet so far has an advantage mentioned above, it has been disadvantage that the repetition rate was limited because the repetition time for 60 T-shots was raised up to about one hour or more. We will show the improvement on the cooling technique for the long pulse magnet in section 4. At the last section, another type of magnet will be shown briefly. That magnet consists of split-pair coils and is suitable for diffraction measurements, especially combined with synchrotron X-ray radiation. As it is very important to make the duration time longer for the X-ray diffraction measurement, the rapid cooling technique is also used. Recent results about this magnet will be shown.

2. 80 T-class mono coils

Our efforts to generate higher field by use of mono coil have resulted in two types of 80 T-class magnets. Both magnets adopt 2x3 mm² Cu-24wt%Ag wire wrapped with Kapton™ tape as a coil material and are reinforced by maraging steel. Tensile strength of the Cu-Ag wire is distributed in the range between 800 and 960 MPa with a small difference in resistivity and brittleness. First 80 T field was obtained in 1996 by the ‘small 80 T-magnet” as presented in RHMF 2000 [1]. This magnet has been used for the user 70 T-magnet and also used as the outer coil for the test of dual coil method described later. One of typical examples [2] for 70 T-measurements is shown in figure 1. Magnetization curve up to 70 T indicates the end of plateau at 65 T, which implies the field-induced spin gap is collapsed and the magnetization increases again.

Second success of generating 80 T was obtained in 2000 by the “large 80 T-magnet” shown in figure 1. This magnet has a bore of 10 mm and 18 layers with inner reinforcement. Its inductance is about 7 mH, and then the pulse duration become longer as shown in figure 2. Figure 2 also shows its maximum field of 82.7 T with a small failure inside the coil. After the magnet test, coils have been taken apart to pieces and deformation of second and third reinforcing pipe could have been seen. It should be pointed out that the first coil was not damaged at all, which suggests a possibility to push up the maximum field of this magnet. Whole profile without any failure can be obtained in generating only 80.8 T-field. On generating the maximum field, 1.2 MJ (charging voltage; 18kV, capacitance; 7.5 mF) was used. After the shot, coil-temperature had risen in excess of room temperature. Then, it can be deduced that to avoid damage due to the Joule heating, capacitor bank with higher charging voltage and lower capacitance should be used for the field beyond 80 T by the
mono-coil. This large magnet brought another benefit to the people who had not been satisfied with the short pulse magnet. It was a natural way to construct user-long pulse magnet by removing the first inner coil from the "large 80 T-magnet". That user-magnet has a sufficient space of 18 mm-bore and long durability supplying 60 T-field. This magnet, however, has a weak point that users have to wait for a long time to cool the magnet down to 77 K. Recent improvement on cooling the long pulse magnet will be shown in section 4.

3. From mono to dual

Alternative way to avoid the excess of Joule heating is driving multiple coils in parallel, which seems to be equivalent to using the high-voltage-capacitor bank. Dual coil method, moreover, is regarded as the most realistic way to obtain 100 T-field. There have been many laboratories in the world developing the dual coil system [3-8]. Historically speaking, Yamagishi and Date had examined dual coil method for the first time in Osaka University in 1988 and they succeeded in 80 T-generation [7] but the dual coil method had not been used for any measurement. High field laboratory of Amsterdam planned to build dual coil system in the quasi-static manner [8] but it could not be realized. Only Toulouse has succeeded in generation of two-pulse fields for some measurements up to now [3] and other laboratories aiming at generation of 80-100 T in Europe have plan for construction of the dual coil system. Los Alamos in United States has the same idea [4] for a long time because they have a large AC generator, which is a great advantage for dual coil system. For our case, we have started construction of dual coil system, based on the idea of Date’s method for making multilayer coils. The idea [9] is as follows. The outer coil can be regarded as a single coil and generate the highest field up to the limit of the mono-coil. The inner coil can produce an additional field to the outer field if its current density is small enough to avoid any destruction of the coil, then the dual coil can be expected to produce higher field than that of the mono coil. For the first test of dual coil, we have made the inner coil from Maraging steel as shown in figure 3. Outer diameter is 10 mm for the limited bore of the outer coil. The bore of the inner coil is set to 4 mm to keep the outer to inner diameter ratio to be 2.5. The coil was made in the same manner as the Date magnet [10]. We used 300 kJ bank with a capacitance of 6 mF for the outer coil and 250 kJ bank with a capacitance

Figure 3. Pulse shape of the large 80 T-magnet. A small failure can be seen at 7 ms on generating 82.7 T-field. A gray curve just beneath a black one is a whole profile on generating 80.8 T.

Figure 4. Cut-view of the first dual coil in ISSP. The small 80 T-magnet is used as an outer coil and an inner one is made from Maraging steel.
of 5 mF for the inner coil. Putting this coil into the small 80 T-magnet, pulsed field has been obtained as indicated in figure 4. The inset of figure 4 shows the inner coil was destroyed on the way to reach the peak field. At the peak-like point, 85 T-field is obtained by this system where destruction of the inner coil occurs simultaneously. This shot was planned to generate 90 T-field expecting 75 T and 15 T for the outer and the inner coil, respectively. From this result, the single inner coil will add 12 T to the outer field. Second test is now under planning to establish the 85 T-generation in the same manner as the first test but it would be better to change the material of the first coil into the conductive one because the Joule-heating of the Maraging coil is too serious to increase the magnet current. Making the single inner coil more conductive and multi layer will bring a success of generating 100 T-field.

In the near future, DC generator will energize large outer coil, which enable us to make larger inner coil and a reasonable sample space. We will have real experimental condition to use a 100 T-field after installation of the DC generator.

4. Rapid cooling magnet

As mentioned above, to cool down the long pulse magnet rapidly, we have made an empty gap between the inner 8 layers and the outer 9 layers so that liquid nitrogen could flow. Marshall et al. [11] in Los Alamos firstly developed such a cooling method. They made long pulse magnet cooled down rapidly by liquid nitrogen flow, which stimulates this work. The gap-size dependence of the cooling time is shown in figure 5. Cooling effect can be seen even for 0.5 mm gap and for the gap wider than 2 mm the effect seems to be almost equal. The inset of figure 5 indicates there is small difference for the gap wider than 2 mm. From the results, it become clear that the cooling time is very sensitive to the gap and even tiny gap decreases the cooling time drastically. Though it is not easy to determine the gap length, we set the gap of the rapid cooling long pulse magnet to be 5 mm because the gap of 5 mm is enough to cool down the magnet rapidly. Comparison of the cooling time after 60 T shot between the magnets with and without gap is shown in figure 6. It is found that the cooling time reduces to 20 minutes that is three times faster than that without the gap. The inset of figure 6 shows the cooling curve for the rapid cooling magnet traces the curve for the slow cooling magnet perfectly when we
multiply the x-axis by 3.00.
The rapid cooling magnet, however, has a difficult point. It is not easy to keep the center of two coils at the same position and hold both coils tightly. Recently, we have made newly designed Maraging steel pipe that reinforces the inner 9 layers coil and has many ditches on the surface for liquid nitrogen flow as shown in figure 7. The ditch is straight and has a cross-section of 5x5 mm². There are 24 ditches on the surface and this is so-called fin-structure. This structure has made the magnet cool faster than the rapid cooling magnet as shown in figure 6 and the cooling time is about five times shorter than the slow-cooling magnet. In the inset of figure 6, a good agreement can be seen between two cooling curves for fin-type magnet and the slow cooling magnet when we multiply the curve for fin-type by 4.75.

One may have a question why the fin-type can cool the magnet faster than the empty gap. A plausible explanation for the question is that Zylon™ reinforces the inner coil for the magnet with empty gap so that the heat conductivity should be less than the Maraging steel reinforcement, and then the cooling rate of the empty gap magnet becomes worse. The long pulse magnet assembled the inner coil with the fin-structure is shown in figure 8.

Figure 7. Cooling process of various type of the long pulse magnet. Open circle, triangle and square stands for no-gap, empty-gap and fin-structure, respectively. Multiplying x-axis of triangle and square by 3.00 and 4.75, respectively, unifies three different curves as show in the inset.

Figure 8. (a) The inner coil of long pulse magnet reinforced by Maraging steel with fin-structure. (b) Long pulse magnet assembled with the inner coil described in (a).

5. Split pair coil magnet for diffraction measurements
Another development of new magnet has been dedicated to combine the pulsed magnet with synchrotron X-ray diffraction measurements. In this area, Matsuda et al. [12] have done the pioneering work. They made very tiny coil with a split gap and have done diffraction measurement up to 16 T. Our magnet is larger than theirs and split-pair based magnet with a split-gap of 5 mm. The first generation of
the split pair magnet consists of only 10 layers coils with 18 mm bore. This magnet driven by the capacitor bank of 250 kJ, 5 mF installed at SPring-8, Harima can generate the field up to 40 T. The maximum field of 40 T was satisfactorily good as the first step [13] but the pulse duration of 5 msec was too short to detect signals in good quality. As an X-ray diffraction image is stored for 1 msec around the peak field for the pulse-duration of 5 msec, the amount of data accumulation is not enough to detect a weak signal. Recently, the capacitor bank has been increased to 500 kJ, 10 mF. To make use of this merit, the second generation of the magnet has been developed. The new magnet consists of 18 layers coils as shown in figure 9 and has longer pulse duration of about 30 msec. The maximum field is limited to 38 T on discharging whole energy in the capacitor bank. Rapid cooling technique is also used for this magnet. There are many holes to flow liquid nitrogen between inner 8-layers coil and outer 10-layers. This structure allows us to generate the maximum field every 15 minutes. The next target is to make the efficiency better to increase the maximum field.

6. Summary
We have succeeded in generation of pulsed fields non-destructively in excess of 80 T. The 80 T-magnet with small inductance of 0.7 mH has been used for 70 T-class measurements with short pulse-duration. Large 80 T-magnet with the inductance of 7 mH is the most stable magnet ever constructed and has possibility to increase the maximum field. Dual coil method has been examined by combining the small 80 T-magnet as an outer coil and a small Maraging coil as an inner one. The inner coil was destroyed at the field of 85 T. The next step is to establish generating technique of the 85 T and to increase the maximum field by developing multilayered inner coil. Rapid-cooling technique has shortened time drastically to wait for cooling the long pulse magnets down to 77 K. Split pair coil magnet has been developed successfully. The magnet can generate 40 T-fields and allow us to carry out X-ray diffraction measurements under pulsed high fields.

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