2. Generation of Megagauss Magnetic Fields and Their Application to Solid State Physics

NOBORU MIURA

"Nature does not favour high magnetic fields." This is the well-known dictum given by Professor S. Chikazumi who had been working on the generation of high magnetic fields for many years. The statement symbolizes well the difficulties involved in the generation of megagauss fields. Indeed, when we want to generate magnetic fields higher than some threshold value, all the physical laws are such that they seem to prevent it. There are so many difficult technical problems in the generation of ultra-high magnetic fields. However, once we overcome these difficulties and succeed in achieving convenient means for the generation of high fields, it will open up various new possibilities for application. For solid state physics, in particular, a magnetic field is one of the most important physical parameters that determine the existing form of matter. Therefore, it is a very powerful means for solid state physics to investigate phenomena which take place in solids when the applied magnetic field becomes extremely high.

Usually, when we investigate the magnetic properties of solids we apply magnetic fields to solids, measuring their susceptibility or magnetization. In such cases, the applied magnetic field is moderate, and we usually assume that it is a small perturbation which does not significantly modify the energy states in the solid. We obtain information about the energy states by simply observing the response to the perturbation given by the applied field. On the other hand, when the applied field becomes extremely high, the properties of the substance may undergo a large change. For instance, various magnetic field-induced phase transitions or non-linearities are brought about by ultra-high magnetic fields. In extremely high magnetic fields, electronic states are greatly influenced since they have spins and move around in crystals. The spin Zeeman energy or the cyclotron motion energy becomes enormous, and can exceed various characteristic energies in the solid. Therefore, when the applied field exceeds some threshold value, properties of solids which have been hidden in the background may show up. This is the most attractive aspect of the use of megagauss fields.

What are the technical difficulties in generating ultra-high magnetic fields? Magnetic fields are usually generated by supplying a current to coils. If we put in an iron core in the coil, higher fields are obtained due to the magnetization of the iron core. Iron cored electro-magnets are still conveniently utilized for laboratory experiments. In fields above 3 T, however, the use of iron cores is no longer useful because of the saturation of the iron magnetization, so that air-core
solenoid coils are employed. As the field is proportional to the current in the solenoid, a large current is needed to generate high fields. One of the difficulties of high magnetic field generation is the large power consumption in the coil, namely the necessity of a large power supply and the large Joule heat produced by the large current, which gives rise to a temperature rise in the coil.

Superconducting magnets can generate high fields without the accompanying Joule heating. However, in superconducting materials there exists an upper critical field $H_{c2}$ above which the superconductivity breaks down. At present, the highest field available by means of superconducting magnets is limited to about 20 T. Recently discovered high $T_c$ superconductors possess a high $H_{c2}$ which may enable higher field generation in the future, but it will take a few more years to develop these materials for their practical use. In several large facilities in the world, high magnetic fields are produced by using water cooled solenoid coils made from normal conductors (usually copper) [2.1]. However, for such facilities, a large power supply of the order of 10 MW and cooling water of the order of 400 ton/hour are needed. Hybrid magnets combining a superconducting magnet on the outside and a water cooled normal magnet mounted inside can generate a field above 30 T. Some facilities in the world now have new projects to produce a field of up to 40 T by employing hybrid magnets [2.1].

Much higher fields than steady fields can be readily generated in a pulsed form for a short duration. A large current can be more readily supplied to a solenoid from the point of view of power supply and Joule heating if the duration is short. The pulsed current can be obtained from a condenser bank. However, the current is limited by the electromagnetic force between the current and the field. Figure 2.1 shows a series of high speed photographs representing what will happen if we supply an excessive current to a pulsed magnet. The electromagnetic force is called Maxwell stress and is proportional to the square of the field. The direction of the force is radially outward and attractive between each winding. Figure 2.2 shows the Maxwell stress as a function of magnetic field. The stress increases rapidly with increasing field. At 100 T, it reaches 400 kg/mm$^2$ and exceeds the material strength from which the coil is constructed. As a result, the magnet is inevitably destroyed in such high magnetic fields. This problem of the destruction of the magnet is the second big problem for the production of high magnetic fields, and it is for this reason that especially developed techniques are required for producing ultra-high magnetic fields in the megagauss range ($> 1$ MG, or $> 100$ T).

2.1 Various Techniques for Generating Ultra-high Magnetic Fields

Figure 2.3 shows the maximum available field generated by various methods. As mentioned in the previous section, high magnetic fields above the range of the steady field can be generated as pulsed fields, whose duration is shorter as the field is increased.