Increase of energy transfer efficiency in the electromagnetic flux compression technique generating ultra-high magnetic field

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Abstract. Magnetic fields of over 100 T can be generated only through the use of a destructive pulsed magnet. Electro-magnetic flux compression (EMFC) is an efficient method to generate such ultra-high magnetic fields. The EMFC system at Institute for Solid State Physics holds the world record for the highest magnetic field produced in-doors. This system has been used for various sorts of measurements applied to matters under ultrahigh magnetic fields. Recently, we successfully improved the coil system to generate a higher field using less energy injection and more simplified preparation processes. The new system increased the electro-magnetic energy transfer efficiency to at least twice that of the previously employed system. Our new primary coil using a copper current guide has the advantage of shallower high-frequency current skin depth and less contact impedance than previous ones. Therefore the discharge current spark is completely avoided. The improved skin depth resulted in a symmetric implosion of the liner coil with less influence of the feed gap. A high degree of cylindrical liner symmetry was observed during implosion. A fast liner speed of 2.4 km/s was achieved, and 350 T could be generated by 1 MJ and 470 T by 2 MJ.

1. Introduction

A magnetic field of over 100 Tesla can be attained only through the use of a destructive pulsed magnet. Three types of methods are capable of generating such an ultrahigh magnetic field: the single turn coil method[1], the explosive-driven flux compression method[2], and electro-magnetic flux compression (EMFC) method[3-5]. Although an ultrahigh magnetic field can be generated leaving the inner sample space intact through the use of the single turn coil method, the maximum field is limited to about 300 T for a reasonable bore radius. The explosive-driven flux compression method or electro-magnetic flux compression method can generate much higher fields than the single turn coil method in spite of the complete destruction of the substances in the sample space after the field generation. Explosive-driven flux compression method can generate the highest magnetic field of the three types mentioned. However, measurements regarding solid-state physics are limited because the necessary use of up to 200 kilograms of explosives results in the total destruction of all equipment placed within a few meters of the magnet. The electro-magnetic flux compression method is more suitable for measurements of solid-state physics than explosive-driven flux compression method because the destruction is limited to a relatively small space, and can be placed in an indoor environment.

The EMFC was originally developed by E. Cnare [3]. The EMFC system at Institute for Solid State Physics (ISSP) has been developed since the early 1970s. This system is now acknowledged as
generating the world’s highest magnetic field (622 T) using an indoor system [5] and has been used in various measurements of the solid state physics of ultra-high magnetic fields. Recently, a group at Loughborough University developed the EMFC system by using a fast capacitor bank which had previously been used in the single turn coil method. They reported successfully generating over 300 T [6]. The EMFC system consists of a primary coil and a liner ring (a liner). We have recently improved the primary coil system allowing it to generate a higher field using less energy injection and involving a more simplified coil preparation processes. Steel has been adopted as a material for the primary coils for some time at the ISSP. Two technical problems are inherent in the old type of primary coil. One is a structural problem. The old coil consists of three separate parts (a coil part and upper and lower electrodes). A small gap near the junction is unavoidable because of the inadequate geometrical contact due to the coil structure (Figure 1 (a)). This gap can cause an undesirable electric discharging during the primary current injection. We have found that such a discharge is an important factor in reducing the energy transfer efficiency and in the emission of electro-magnetic noise. Another is the problem of the material itself. The old coil is made of steel which has high electrical resistance and accordingly renders a deep high-frequency current skin depth. A high electrical resistance reduces the efficiency of the electro-magnetic energy transfer. The deep skin depth serves to increase the effective feed-gap, which is unfavorable for the symmetrical liner implosion.

To solve these problems, we changed the structure and the material of the primary coil.

![Figure 1. (a) photograph and diagram of the old primary coil and (b) those of the new primary coil. A photograph of each coil is shown at the top. The structure of each coil is illustrated at the bottom.](image)

2. Experimental procedure
The new coil system has a bent copper sheet inside a steel coil (Fig.1 (b)). In the new coil system, the copper sheet bears the main primary current flow. The shape of copper sheet is specially designed to improve the electric contact with the electrode of the current collector plate from the capacitor bank. Copper has 1/9th the resistance and 1/3 shallower skin depth than does steel. The role of the steel coil in the present coil system differs from that in the conventional type coils. The steel coil in the new type is designed to provide sufficient mass to avoid the deformation of the copper sheet during the acceleration of the liner.

We performed an EMFC experiment using the new primary coil. The dimensions of the copper coil (inner diameter/thickness/width) were 130 mm/2 mm/45 mm. The dimensions of the steel coil were 135 mm/25 mm/45 mm. The dimensions of liner were 116 mm/1.5 mm/50 mm. The liner was placed in a vacuum chamber. The pressure inside the chamber was about 10 Pa. The generated magnetic field was measured by using a pick up coil which is a wound thin copper wire. A high speed photograph was taken by an IMACON 468 high speed framing camera. The maximum energy of the main
capacitor bank at ISSP is 5 MJ (6.25 mF, 40 kV). That of the sub-capacitor bank is 1.5 MJ (30 mF, 10 kV).

3. Results and Discussion

Figure 2 shows a comparison of the magnetic field and the primary current between the new coil (a) and the old coil (b). The new coil system could generate up to 475 T by a 2.3 MJ energy injection (the maximum primary current 3.2 MA). This is a remarkable advance over the old system, in which 350 T was obtained with 4 MJ (the maximum primary current 4.2 MA). It is evident that the electromagnetic energy transfer efficiency has been improved a great deal by employing the new coil system.

![Figure 2](image-url)

**Figure 2.** The waveform of the magnetic field (blue line) and the primary current (red line). The results using the old coil are shown in (a) [6]. In this experiment, the energy of the main bank was 4 MJ (5 mF, 40 kV). The maximum field was 305 T. The results using the new coil are shown in (a). The energy of the main bank was 2.25 MJ (3.1 mF, 38 kV). The maximum field was 475 T.

The effect of the feed-gap of the new coil system was reduced as expected. Figure 3 shows a high speed photograph of the liner implosion, where the effect of the feed-gap was pronounced in the old coil (Fig 3 (a)), whereas the effect was much reduced in a new coil (Fig 3 (b)). The cylindrical symmetry of the liner implosion was comparable even with that adopting “the feed-gap compensator” (Fig 3 (c)), which has recently recorded the highest magnetic field of 622 T [6].

To generate the high field by flux compression, the most important factor is the velocity of the liner implosion. There is a definite correlation between the velocity of the liner implosion and the maximum field [6]. The velocity of the inner radius of the liner was estimated based on the high speed photographs shown in Fig 3(b). In the new coil, the estimated velocity was 2.4 km/s which was the fastest ever obtained at ISSP. The rising time of the field was also the shortest, which supports the fastest implosion of the liner.

The fastest velocity of liner is expected to produce the highest field. Unfortunately, in this experiment by using a newly designed coil, a pick-up coil for the field detection was destroyed by a luminous jet (see the photograph at 47.3 μs in Fig 3 (b)) before the field reached its maximum.
Figure 3. High speed photographs of liner implosion. The photograph (a) shows the liner implosion by using an old coil without a feed-gap compensator. The photograph (b) shows the liner implosion by using a new coil. The photograph (c) shows the liner implosion by using the old coil with a feed-gap compensator[6]. The numbers inside each photograph shows the time at which the photograph was taken.

4. Summary
We developed a new primary coil system using a bent copper sheet inside the steel coil. We performed an EMFC experiment involving the new coil system. This new coil showed two advantages. One was a remarkable improvement in the efficiency of the electro-magnetic energy transfer because of the much lower resistance of copper than steel. The other was that the liner implosion became remarkably symmetric because of the shallower skin depth of copper than that of steel. The symmetry of the liner implosion obtained by using the new coil without a feed-gap compensator was comparable with that obtained by using an old coil with a feed-gap compensator. We are convinced that the new system is promising for the generation of higher fields than those previously recorded using EMFC techniques.

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References
[1] Miura N, Matsuda Y H, Uchida K, Todo S, Mitamura H, Osada T and Ohmichi E 2001 Physica B 294-295 562
[2] Fowler C M, Garn W B and Caird R S 1960 J. Appl. Phys. 31 588
[3] Cnare E C 1966 J. Appl. Phys. 37 3812
[4] Herlach F, McBroom R, Erber T, Murray J and Gearhart R 1971 IEEE Trans. Nucl. Sci. NS-18 809
[5] Matsuda M H, Herlach F, Ikeda S and Miura N 2002 Rev. Sci. Inst. 73 4288
[6] Novac B M, Smith I R, Rankin D F and Hubbard M 2004 J. Phys. D: Appl. Phys. 37 3041