Generation of a pulsed ultra-high magnetic field with a small-size bellows type explosive driven flux compression device

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We have utilized the power of high explosives to generate ultra-high magnetic fields. We have developed 30cm-size bellows-type explosive driven flux compression device for application to material synthesis and investigation of material properties. In this device, the initial fields were supplied with external coils so that the amount of explosives could be reduced to about 250g. Strong external coils were developed in order to generate an initial field higher than 10T. We have succeeded to compress a field up to 110.7T through improvement of the shape of a bellows coil. These improved coils enlarge the meeting area of driver plates and reduce the current density in the plates. Sample holders inserted in the load coils were recovered without serious damages.

1. Introduction

Magnetic fields were a powerful tool in various fields including not only scientific research but also practical application. In order to improve these utility, extensive and continuous efforts to produce higher magnetic fields have been made. Recent development of superconducting magnets makes it possible to generate steady fields of 21.1T[1]. With hybrid magnets in which water-cooled magnets are installed in superconducting magnets, steady fields of about 34.2T are available[2]. As far as a non-destructive pulsed magnet is concerned, fields up to about 71.8T have been available recently[3]. However, it is extremely difficult to generate still higher fields without destruction of the magnet by each pulse because the Maxwell stress during the field generation exceeds the strength of the existing coil materials for fields over about 80T. This is why fields higher than 80T or 100T are called "ultra-high magnetic fields".

In order to produce ultra-high magnetic fields, it is required to discard the conventional idea of producing magnetic fields non-destructively. Namely, such a high field should be confined either by external implosion or inertial force. The magnetic flux compression technique[4] is based on the former idea, and the single turn coil technique[5] is based on the latter. To compress a magnetic field, it is necessary to shrink the metalic coil area faster than the magnetic flux escapes from the coil as explained in the next section. High explosives are suitable power sources for the acceleration of the coil material becauce the high explosives generate a power of 10^{12} watts in their explosion.

Compared to the other methods, the magnetic flux compression with bellows type explosive driven devices[7] has several merits despite that it may be difficult to produce several hundred tesla through it. One of the merits is that the increasing rate of a field at the start time is much slower and duration time of a field is longer than with the single-turn coil system. This is favorable for transport measurements under ultra-high magnetic fields because electrical noise caused by induced voltage can be reduced. Another merit is that recovery of samples set in the center of the load coil is not so difficult as in the cylindrical type compression method because parts of field generation and flux compression with explosives are separated.

In conventional bellows-type devices, initial fields are generated through supplying initial currents into

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the bellows coil. If one increases the initial current in order to get a higher initial field in this method, a heavier and stronger bellows coil and, consequently, more explosives are required. In addition, a fast capacitor bank should be used to feed the low-inductance bellows coil efficiently.

Caird et al. developed compact bellows-type devices in which initial fields are generated with external coils[6]. Matching between the external initial field coil and usual capacitor bank is improved in this device. Furthermore, the amount of explosives can be reduced because bellows coils can be composed of light materials such as thin copper sheets. These merits seem favorable for the application of ultra-high magnetic fields to study materials properties and chemical reactions. Further improvement of the compact device will be possible through development of stronger external coils and examination of the bellows coil shape. In this paper, the development of compact bellows-type devices and the possibility of recovery experiments will be disscused.

2. Fundamentals of flux compression

The flux compression technique takes advantage of the physical phenomenon that a magnetic field can not penetrate deeper into a material than the skin depth. This phenomenon is due to electric currents induced in a coil material by the movement of magnetic flux. The magnetic fields generated by the induced currents are superposed with the original fields so as that the original fields is prevented from changing. The expression for the skin depth (δ) is given as $\delta=(2/\sigma\mu\omega)^{1/2}$, where σ, μ and ω are electric conductivity, magnetic permeability and angular frequency of the field, respectively. To give an example, the skin depth of copper where $\sigma\sim58\times10^{6}\Omega^{-1}\cdot m^{-1}$ and $\mu\sim4\pi\times10^{-7}$ $\Omega\cdot s\cdot m^{-1}$ is 0.095mm for $\omega=2\pi\times3\times10^{5}s^{-1}$(500kHz). If we shrink a metalic coil with the thickness of order of 1mm in a short time of order of 10^{0-2} μs, a magnetic field inside the coil is increased because most of the magnetic flux can not escape outside the coil.

Magnetic flux is compressed as follows in a bellows–type device. The device is composed with bellows plates, explosives and a load coil (Fig. 1 (a)). In the first stage, the initial field is supplied into the space between the driver plates by some means. Then the explosives on the bellows plates are initiated at the opposite end to the load coil side. As the detonation front propagates towards the load coil, the part of the plate behind the detonation front is aceralated toward the other plate. Thus, the area surrounded by the driver plates is reduced. If the reduction rate is so large that the skin depth is smaller than the thichness of the plates, the initial flux is gathered in the load coil except for losses due to joule heating and imcomplete electrical contact between the plates at the meeting point (Fig. 1 (b)).

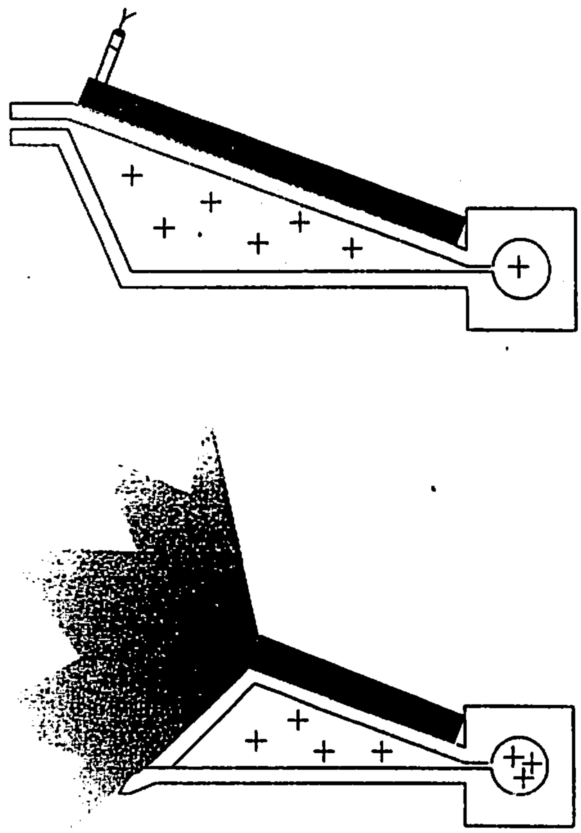

Fig. 1 Process of the explosive-driven flux compression in a bellows-type device. (a) An initial field (represented by '+') is supplied in the bellows coil. (b) A magnetic field is compressed in the load coil during the explosion.

3. Preparation of the bellows-type flux compression device

A schematic view of the bellows-type flux compression device is shown in Fig. 2. The device consists of a primary field coil and a bellows-type flux compressor with a single turn load coil. Components of the flux compressor are similar to those of minigenerators reported by Caird et al. [6] The flux compressors were fashioned from 0.5mm thick copper plates. The load coil and driver plates on which the explosive sheets were put were made in one body. Three types of compressor which had different widths for the load coil

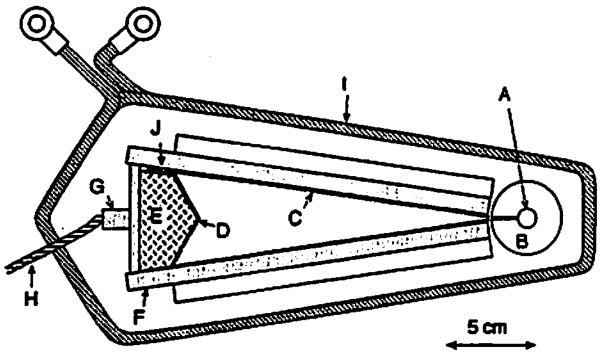

Fig. 2 A schematic view of the bellows-type flux compression device. A:load coil, B:collar, C:driver plate, D:base plate, E:base block, F:explosive sheet, G:booster, H:detonation cord, I:external coil, J:gap.

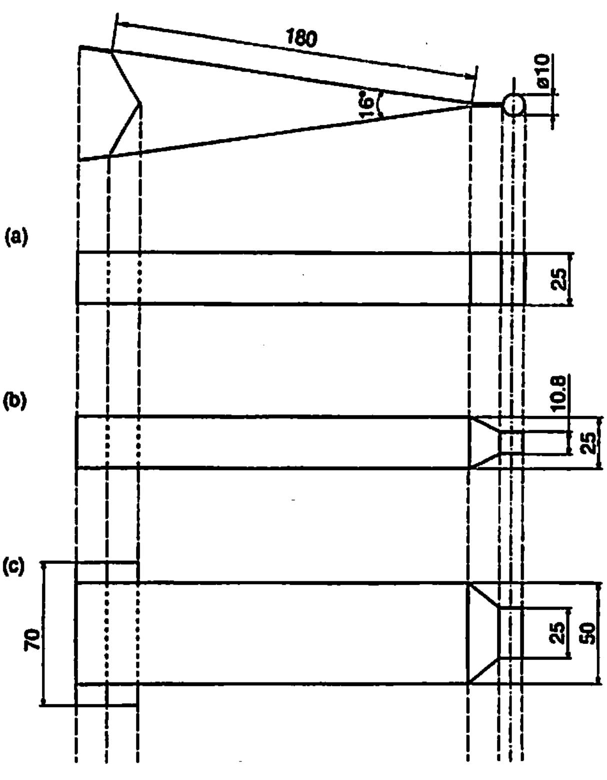

Fig. 3 Shape of the bellow coils employed in this work. The thickness of the copper plate was always 0.5mm.

and driver plates were prepared as shown in Fig. 3. Type (a) had the load coil and driver plate of the same 25mm width, type (b) 10.8mm and 25mm, and type (c) 25 mm and 50mm, respectively. The inner diameter of the load coil was 10mm in all types.

The coil was supported by a brass collar with an outer diameter and a width of 40mm and 25mm, respectively, in order to prevent the Maxwell force from deforming it during the flux compression process.

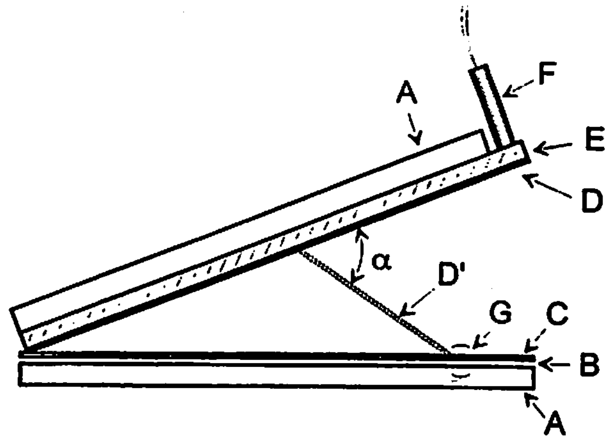

Fig. 4 A schematic view of a device for the flight angle measurement. A:Acrylic acid resin plate, B:argon gap, C:steel shim, D:driver plate, E:explosive sheet, F:detonator. The broken line (D') illustrates how the driver plate (D) would be deformed some time after the initiation. The angle α is the flight angle and argon gas in the gap (B) around the area 'G' emits a flush light.

The inner diameter of the collar was 11mm in type (a) and (c), and 12mm in type (b). The length of the driver plate was 180mm.

The angle between the driver plates was 16°. We made a insulation gap between the driver plate and a base plate on a plastic support block so that the initial field could penetrate into the compressor. The explosive sheets on the driver plates were made of Pentaerythritol tetranitrate (PETN) bonded by silicon rubber in the weight ratio of 7 : 3. The explosive sheet was fired in the center of the backside of the base block through detonation cords and a booster. The explosives were initiated so as to close the gap between the driver plate and the base plate nearly at the peak of the initial field. A thickness of the explosive sheet was 9 mm, which was determined in the procedure described below.

3.1 Determination of a thickness of the explosive sheet

In order to determine a thickness of the explosive sheet and the angle between the driver plates, we conducted measurements of flight angle (α) of the 0.5mm thick copper plate accelerated by the explosive sheets of various thicknesses (t). We prepared devices for the measurement as shown in Fig. 4. We made a gap filled with argon gas between a steel shim and an acrylic acid resin plate. The driver plate and the

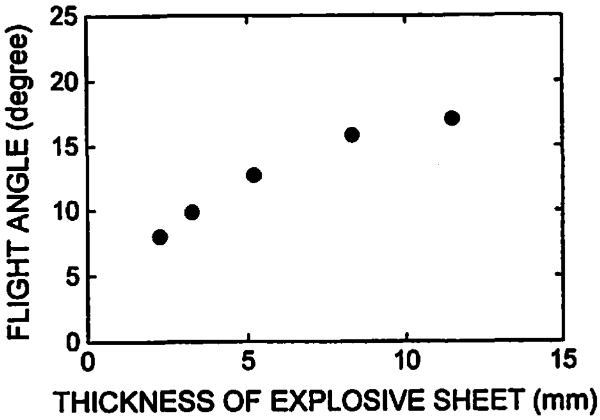

Fig. 5(a) The flight angle of a driver plate vs. the square root of the explosive sheets thickness (t). The driver plate was a 0.5 mm thick copper plate. The explosive sheets were made of PETN bonded by silicon rubber in the weight ratio of 7 : 3.

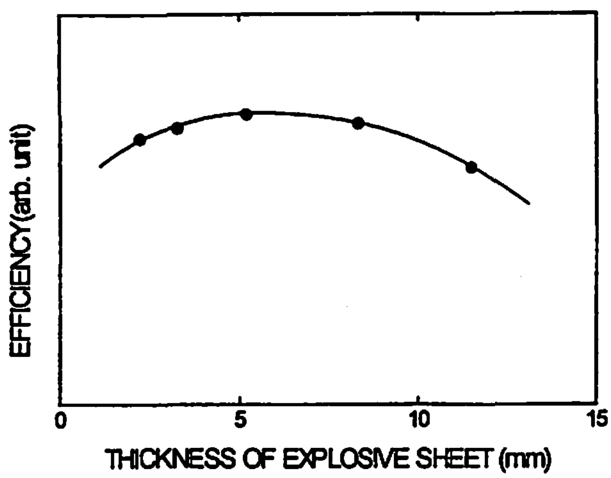

Fig. 5(b) The explosive sheet thickness dependence of the efficiency of the driver plate acceleration by the explosive sheet. A solid line is only aids to the eye.

explosive sheet were placed over the shim. The angle between the shim and the driver plate was adjusted by each measurement. The explosive sheet was initiated on the lifted side. The argon gas in the gap emitted a flush light when the driver plate reached the shim and the argon gas was compressed by shock wave. We calculated the flight angle of the driver plate from the trace of the flush light observed with a high speed streak camera. The flight angle was found to increase with the thickness of the explosive sheet increased, as shown in Fig. 5(a).

The efficiency (ε) of the acceleration of the driver plate by the explosive sheet would be estimated as the ratio of the kinetic energy of the driver plate to the explosive energy of the explosive sheet.[8] The former would be proportional to the square of the flight velocity and, therefore, to $\sin^2(\alpha/2)$. The latter would be proportional to t. After all, ε would be proportional to $\sin^2(\alpha/2)/t$. In Fig. 5(b), ε in arbitrary unit versus t is shown. In the region where t is larger than 9 mm, we found that ε tends to decrease. Though the larger flight angle is more favorable for the flux compression, use of too much explosives may ruin the handiness of the devices and destroy materials inserted in the load coil. Therefore, a 9 mm thick explosive sheet was employed with a flight angle of 16° for the maximum performance with this thickness coil.

3.2 The external coil

In order to produce an ultra-high magnetic field, it is necessary to generate as high an initial field as possible. We have developed an external coil which can generate an initial field higher than 10T. For the coil wire material, we utilized a copper-welded steel wire which is coverd with polyimide and glass tapes. The diameter, copper ratio, and tensile strength of the wire were 6 mm, 60%, and 54.5 kg/mm², respectively. The coil was strengthened with epoxy resin. Because a potting frame for the resin was removed after its solidification, the coil could be made compact as shown in Fig. 2. This contributes to the improvement of the efficiency in supplying the flux compressor with an initial field. So far, a peak field of 11.7T has been generated with this coil.

4. Experiments and Results

Experiments of the flux compression devices were conducted in an explosive chamber. The external coil was charged with a capacitor bank whose maximum capacitance and voltage were 1500μF and 20kV, respectively. The firing time of detonators, fixed on the end of the detonation cord (Fig. 2, H), was adjusted with a delay pulse generator so that the insulation gap (Fig. 2, J) would close at the peak time of the initial magnetic field. The initial field and the field during the flux compression process were measured with a pickup coil inserted in the center of the load coil. The induced voltage in the pickup coil was integrated electrically and recorded in digital recorders. The trigger timing of the digital recorders, the capacitor bank and firing of the detonators was controlled with a delay pulse generator.

Table 1 Experimental conditions and results

#	Driver plate width, mm	Base plate width, mm	Base plate angle, °	Load coil length, mm	Initial field, T	Peak field, T	Compression time, μs
1	25.0	25.0	120	25.0	4.9	63.4	27.4
2	25.0	25.0	120	25.0	7.6	73.6	27.4
3	25.0	25.0	120	25.0	11.7	75.2	25.9
4	25.0	25.0	120	10.9	7.8	78.9	28.2
5	50.0	70.0	140	25.0	10.9	110.7	27.3

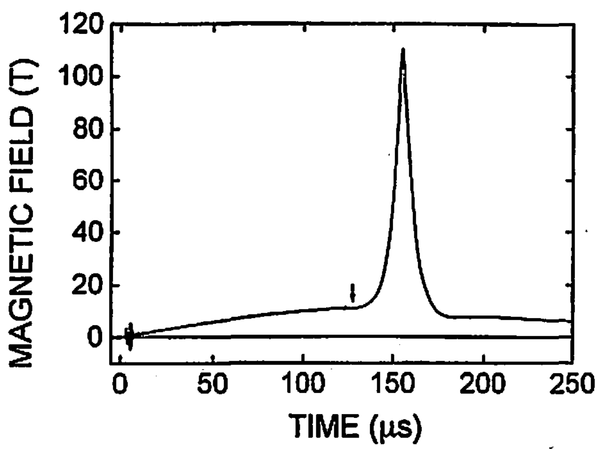

Fig. 6 Time variation of a magnetic field measured in the center of the load coil in experiment #5. The flux compression started at 127.9μs (indicated by the arrow) when the initial field was 10.9T and the field increased up to 110.7 T after 27.3μs.

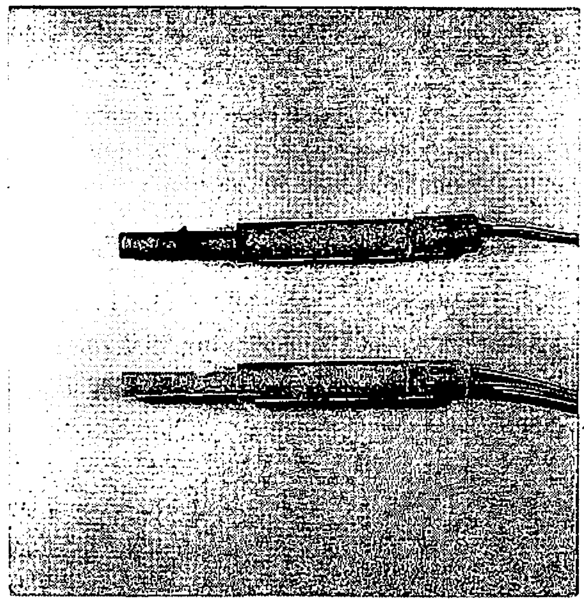

Fig. 7 Photograph of holders made of polycarbonate. The lower one has not used in the measurement. The upper one was used in Exp. #5. The holder was found not to be seriously damaged except for a few 2−4mm size holes.

The experimental conditions and results are listed in Table 1. The width of the explosive sheets was 25mm in the experiments #1−#4 and 44mm in experiment #5. For experiment #5, time variation of a magnetic field is shown in Fig. 6. The arrow in the figure indicates the time when flux compression started. In the bellows type (a), the maximum field increased with increasing the initial field up to 7.6T. Linearly expolarating the relation between the initial field and the peak field, we expected a peak field of at least 100T for experiment #3 where the initial field was 11.7T. However, the peak value was only 75.2T in this experiment. In addition, the time of the flux compression process is shorter in experiment #3 by about 1.5 μs than those in other experiments.

In the bellows type (b), we expected that the peak field would be increased with decreasing width of the load coil and increasing current density on the load coil. The initial field was 7.8T in experiment #4 which is almost same as in experiment #2. The width of the load coil was reduced by 57%; however, the peak field was increased by 7%.

In experiment #5, we used a type (c) bellows coil which had twice the width driver plates and a load coil of the same width as the type (a) bellows. A peak field of 110.7T was generated for an initial field of 10.9T.

In this experiment, the pickup coil holder inserted in the center of the load coil was made of polycarbonate tube whose outer diameter was 8mm and inner one 6mm. After the experiment, we were able to recover the holder as shown in Fig. 7. The holder was not damaged except for a few 2−4mm size holes.

5. Discussion

The initial fields measured at the center of the load

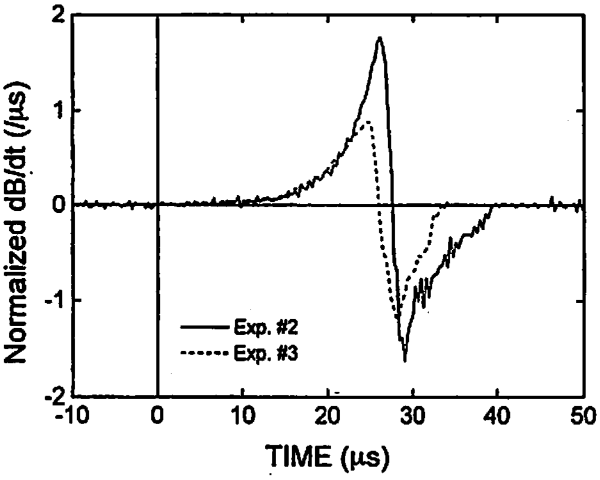

Fig. 8 Time derivatives of the magnetic fields normalized by the initial fields vs. time in experiments #2 and #3. In both curves, compression start time is set at zero.

coils were not proportional to the total initial flux because of differences in shape of the external coils. In order to compare these results to one another, we calculated average initial fields in the bellows coils numerically as 2.86T, 3.66T and 5.63T for the experiments #1, #2 and #3, respectively. In general, the maximum field is not propotional to the initial field because of the flux loss at the contact point of the driver plates and the Joule heating. The decrease of the efficiency found in the experiment #2 compared to that in #1 may be explained as a result of these losses. If we estimate the relation between the average initial field (B_{av}) and the maximum field (B_{max}) in the simple expression,

$$B_{max}=B_s\,(1-exp(B_{av}/B_N)) \qquad (1)$$

and adjust the parameters B_s and B_N to fit to the experiments #1 and #2, their values become 113T and 3.47T, respectively. According to eq. (1) with these constants, we could expect to generate 90.7T with an initial field of 11.7T. However, the maximum field was only 75.2T in experiment #3. This result means that serious factors other than mentioned above emerge in the case of generation of ultra-high magnetic fields with the type (a) bellows.

Time derivatives of the magnetic fields normalized by the initial fields (dB_n/dt) vs. time are shown in figure 8 for experiments #2 and #3. For 22μsec from the start of flux-compression, the profile of dB_n/dt is almost the same in experiments #2 and #3. After that, the dB_n/dt suddenly became smaller in experiment #3 than in experiment #2. The compressed magnetic field peaks 1.5μsec earlier in experiment #3 than in experiment #2.

In experiment #3, the bellows coil was exposed to higher fields for longer time than experiment #2. This means that the bellows coil was affected by stronger Maxwell force and more intense Joule heating in experiment #3. Thus, the possibility that the low compressibility in experiment #3 was due to deformation of the driver plates in the part closest to the load coil by strong Maxwell force is suggested. It is necessary to reduce the current density in the driver plates while keeping that in the load coil high in order to avoid such deformation.

In experiment #4, the current density in the load coil was expected to increase up to 230% compared to that in experiment #2; though, that in the driver plates should be similar in both experiments. The Joule heating in the load coil may limit the current. In addition, the polyimid sheet inserted between the load coil and the brass collar for insulation might be broken during the flux compression, which was followed by the expansion of the load coil. If the diameter of the load coil expands from 10mm to 11mm, magnetic fields will be decreased by approximately 17%. The improvement of the efficiency may be achieved using a little longer load coil and a collar which has the same length with the coil and holds the coil without any insulation.

The successful generation of an ultra-high field up to 110.7T in experiment #5 would support the possibility that the driver plate may be deformed due to the strong Maxwell force generated by the high density current in experiment #3. There may be an additional effect that the increase of the contact area of the driver plates reduces the loss of magnetic flux through the contact area.

The pickup coil holder was recovered despite of the use of explosives. This is because there is no explosives around the load coil and because only a small amount of explosives were used with these small devices. Therefore, they turned out to be very favorable for the application to recovery experiments.

6. Conclusion

The compact external coil with copper welded steel wire and epoxy enforcement could generate an initial field up to 11.7T. As the initial field was increased, the efficiency of the flux compression decreased. Not only the flux loss due to Joule heating but also the deformation of the bellows coil due to Maxwell force during the flux compression was suggested to be a serious problem to be overcome in order to generate ultra-high magnetic fields. Enlargement of the width of the driver plates has turned out to be an effective method to reduce the Maxwell force. With the 30cm-size bellows-type explosive driven flux compression device thus improved, we could generate an ultra-high magnetic field up to 110.7T. Because we could recover the pickup coil holder without serious damage, the device turned out to be very favorable for the application to recovery experiments. These small-size flux compression devices may be regarded as an effective application of high explosives.

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Rference

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小型ベロー型爆薬駆動式磁束濃縮装置によるパルス超強磁場の発生

横井裕之*，角舘洋三*，薄葉　州*
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高性能爆薬のパワーを利用して超強磁場の発生を行い，物質合成や物性研究へ応用するために，30cmサイズのベロー型爆薬駆動式磁束濃縮装置の開発を行った。本装置においては，初期磁場を外部コイルから供給し，その結果，爆薬量を約250gに減らすことができた。10T以上の初期磁場を発生するために，強力な外部磁場コイルを開発した。さらに，飛翔板の閉合部面積と飛翔板での電流密度がそれぞれ拡大・減少するようにベロー型コイルの形状を改良することにより，磁場を110.7Tまで濃縮することに成功した。負荷コイル内に挿入した試料ホルダーは大きな損傷を受けることなく回収された。

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