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A Cylindrical Explosive Flux-Compression System*

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ABSTRACT

A simple device for producing megagauss magnetic fields consists of a hollow resistive metal cylinder with a ring of explosive around it. An initial axial field is produced within the cylinder by a pair of coils situated on either side of the explosive. The basic techniques and some results have been described in earlier publications. Further developments of these techniques and more recent results are presented in this paper. An extensive series of shots using stainless steel cylinders with a 1.6 mm wall shows that field compression ratios in the range of 120-150 are attainable reliably within a 2.5 mm diameter. Fields as high as 5.4 MG have been measured starting with initial fields of 28 kG. A 300 kJ capacitor bank allows still higher initial fields with correspondingly greater final fields. Fields in excess of 6 MG have been measured with stainless steel liners. Coil construction problems will be discussed.

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A CYLINDRICAL EXPLOSIVE FLUX-COMPRESSION SYSTEM

Introduction

Explosively-driven flux compression systems have been used since 1959 to produce multimegagauss magnetic fields. The principles and techniques employed by the Los Alamos group are described in previous publications. (1, 2, 3) Of the many ways of compressing magnetic flux with explosives, the cylindrical system described in reference 3 has proved to be the most reliable in achieving fields substantially over one megagauss.

The initial axial magnetic field is provided by coils situated on either side of the explosive. This pair of coils, connected in series, is energized by a capacitor bank. The explosive charge most frequently used is a ring of Composition B, 23.5 cm o. d., 10.8 cm i. d., and 7.62 cm long. There are 25 detonators equally spaced around the periphery of the charge in the midplane. Both the explosive and detonators are subject to rigorous quality control by our explosives fabrication groups.

A hollow metal cylinder, or liner, is positioned inside the explosive ring. This liner is 10.8 cm o. d. and 10.2 cm long. It is continuous and seamless in order to minimize any hydrodynamic disturbances. For the reasons discussed in reference 3, almost all our recent high field work has been done with coil pairs and continuous liners. An 18-8 stainless steel (type 347) is the liner material generally employed. A schematic drawing of a shot assembly is shown in Fig. 1.

It should be noted that the capacitor bank and coils must have a long enough period to induce a sizable fraction of the magnetic field within the rather conductive liner.

Experiments with the Low Energy System

Most of our experiments have involved a capacitor bank of 435 μF charged to 16 kV in conjunction with a 16 μH coil pair. This system, with a 1.59 mm wall stainless steel liner is the one employed in all the shots to be discussed in this section. The initial field is from 26 to 28 kG.

A series of seven carefully controlled shots was fired in order to test the reproducibility of high field production and the effect of small variations in liner mass. The high field probes consisted of a single loop of wire with an effective area of about 0.05 cm^2 . The probes were covered by glass tubing 0.55 cm in o. d. Thus, the theoretical area compression available should have been about 360. The initial field was measured by a probe of 6 cm^2 area situated inside the liner volume. The liner was evacuated for all shots. The shot films were read with a digitized microscope comparator. The data, together with calibration readings, were placed directly on punched cards. A 7094 computer then fitted the data to the calibration grid by a least-squares procedure⁽⁴⁾ and performed the subsequent calculations necessary to derive field and compression curves.

Figure 2 shows a plot of the field compression ratio, σ , against time from first detectable liner motion for the first three shots in the

series. α is the ratio of the measured field during implosion to the initial field. The other shots are not plotted in order to reduce confusion; however, the curves fall reasonably close to their proper positions with respect to the first three. The results indicate that liner mass differences of the order of a few percent are detectable in the compression curves.

It is of some interest to note that the peak fields ranged from 2.2 to 4.7 MG and the α 's ranged from 79 to 169. All are well below what might be expected on the basis of probe and liner diameters alone. The rather wide variation would seem to indicate that a perturbation of the liner destroyed the probe prematurely. Six of the seven shots produced peak fields of about 3 MG or higher.

A more recent shot, using a probe with a jacket only 2.5 mm in diameter gave a peak field of 5.4 MG. The α was about 190. Thus, it seems that a compression ratio of about 200 is the maximum attainable for this particular explosive-liner configuration; and a compression greater than 100 is reasonably certain.

A number of shots have been fired with this "standard" assembly to investigate Faraday and Zeeman effects. In addition to paving the way for future interesting physics experiments, these tests serve to confirm the probe measurements up to the point where the assembly is destroyed. Both types of measurement necessitate a diameter greater than that of the probes described earlier. Therefore, the peak fields

to be expected are correspondingly lower.

The optical configuration for the Faraday effect consisted of a low pressure mercury source, a polarizer, a fused quartz sample, a second polarizer, an interference filter, and a fast photomultiplier. All components except the quartz were situated out of the magnetic field region. Shots were fired with the polarizers initially both parallel and crossed. Also, both the mercury green and blue lines were used.

The results were consistent with the probe measurements up to a maximum field of 2.2 MG, with some indication that the Verdet constant for the blue line decreases slightly. The data are not sufficiently accurate, however, to settle this latter point.

The Zeeman effect was observed with a streak spectrograph having a dispersion of $25.3 \text{ \AA}^{\circ}/\text{mm}$ at the film plane. Two types of light source, positioned at the liner midplane, have been used. One is a rather large low-pressure mercury tube. The splitting of the Na D lines (present as a contaminant from glass) and the HgII $3984 \text{ \AA}^{\circ}$ line implies a peak field of 1.5 MG. This result is consistent with the source diameter. The second type of source is an exploding wire. A smaller diameter assembly is feasible with this technique. Measurements on the Na D lines and an In I $4102 \text{ \AA}^{\circ}$ line give a peak field of 2.5 MG. A more complete description of these experiments is contained in two recent papers. (5, 6)

The High Energy System and Future Experiments

We now have available a capacitor bank of 1450 μF rated at 20 kV. In the near future, this capacity will be doubled. Our present efforts are devoted to applying this high energy bank to flux compression systems. The purpose is twofold. First, it would be very desirable to be able to employ megagauss fields in a larger volume than has been available up to now. A number of interesting experiments would become feasible in this case. Second, we could explore the possible limitations on high field production. There have been a number of papers recently concerning the influence of liner resistivity on magnetic flux compression. (7, 8, 9) Unfortunately, there is insufficient data on the resistivity of the liner materials to permit definite predictions from the theoretical calculations. The experiments, to date, have been inadequate to distinguish between the effects of liner perturbations and flux diffusion. It is hoped that a careful study using higher initial fields and differing liner materials and explosives would shed some light on this question. At least, one might discover whether the present limitations are in peak field or compression ratio.

A rather inefficient trial system has been fired using coils made of 4 turns of 4/0 welding cable. An initial field of 40 kG was obtained inside a stainless steel liner with a 1.6 mm wall. The 1450 μF bank was charged to 16 kV. The one evacuated shot gave a peak field of 6.1 MG.

Our latest work has centered on 1 mH coils (2 mH in series)

consisting of 80 turns of No. 6 wire heavily reinforced with glass fibre tape and epoxy. The period, with the present 1450 μ F, is about 10 msec. When the second half of the bank is in operation, we expect to obtain about 80 kG in a 1.6 mm copper liner, and 100 kG in any stainless steel liner up to 6.4 mm wall. These extrapolations assume a 7.6 cm separation between the coil faces.

The difficulties with the high energy system have been many. For example, there are 16 ignitrons (32 for the eventual bank) to perform the switching. Although they are pretested and cooled, there is a disconcertingly high probability of a prefire during charging. For this reason, we have placed a mechanical shorting switch ⁽¹⁰⁾ in the circuit to absorb the bank energy in the event of a breakdown. The shot is fired by the opening of the switch, thus reducing the vulnerable time to a minimum.

A consequence of the long rise time of the field is that the coils have plenty of time to move. ⁽¹⁰⁾ The present design seems sufficient to prevent destruction by radial forces during the 2.5 msec quarter period. However, Fastax pictures show that the charge would be pulverized within 2 msec unless the coil faces were at least 6 mm back from the charge. The axial forces drawing the coils together are very troublesome. In addition, there is adequate time for vibration and gross motion to disturb the experimental assembly unless the supports are mechanically decoupled from the coils. We are trying a number of expedients to circumvent these problems.

Figure 1. Cross-sectional view of a typical shot assembly.

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Figure 2. Field compression versus time from first liner motion for three shots. α is the ratio of the measured field to the initial field for the particular assembly. Only the later portion of the curves are shown.