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Four Decades in the Megagauss World

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Abstract: This paper contains a short history of the generation of megagauss magnetic fields obtained by explosive flux compression at Los Alamos over the last four decades, a brief description of the high field systems most commonly used for solid state research, and a survey of selected physics experiments performed using these systems as high magnetic field sources.

Keywords: megagauss fields, explosives, flux compression

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Introduction

As often happens ,the present Los Alamos program, in which explosively produced high magnetic fields are used in solid state studies, started out with a different purpose in mind, as noted in Reference [1]. In this reference, a very brief discussion is given of explosively produced very large magnetic fields [2]. As noted, the primary use of these fields was to use them to magnetically compress D-T plasmas with the aim of producing large bursts of neutrons. However, it was also noted that other experiments were contemplated, such as high field solid state studies.

It is probably safe to say that these publications inspired much of the later work in this area elsewhere. In any event, DT plasma compression was a major reason for the large efforts undertaken at Arzamas-16 in Russia and a smaller effort at the Euratom laboratory in Frascati, Italy. An exception was the facility developed at the Illinois Institute of Technology in Chicago that flourished for several years. Here, the motivation was to produce magnetic fields large enough that interesting quantum electrodynamic effects could occur when particles of high enough energy were passed through the fields.

There have been other explosive flux compression facilities developed here and there for various purposes. We have singled out the above three facilities because in each instance there was sufficient freedom in the facility operation that high-field solid state studies could also be carried out, but usually on a fairly limited basis.

During the forty some years that I've been involved in this activity it has been my good fortune to meet and often to work with some extraordinarily talented people. Among the giants in magnetism, we were fortunate in having the late Francis Bitter join us as a consultant for the last several years of his life. I also had a very pleasant visit with Peter

Kapitza in 1984. Although he was then 89 years old , he was still quite energetic and gave me an informative and interesting tour of his Institute, which he was still directing. There are many people from other places with whom we have worked, a number of whom are at this Symposium. However, one of the disadvantages of being in a field for so many years is that it is almost impossible to credit all of your colleague, but I deeply appreciate the opportunity to have workrd with them.

In a very real sense , I am writing on behalf of the many dedicated Los Alamos people who have worked and contributed to our extensive overall explosive flux compression program. Most have been associated with programs that use explosive flux compressors as pulsed power sources to drive various devices, the other broad area of application of these compressors. Those more directly involved in the high magnetic field generators and solid state applications, for whom I have taken the liberty of speaking, include W.B. Garn, J.C. King, D.J. Erickson, B.L. Freeman, D.G. Rickels, J.G. Goettee and the late Robert .S. Caird, to whom this paper is dedicated.

In the next two sections of this paper we describe two kinds of high field flux compression systems and conclude with a description of several high field physics experiments done over the years that have used these systems.

High Magnetic Field Systems

Two generic types of high field systems are sketched below, together with representative field-time histories. Figure 1 shows a cylindrical implosion system. A ring of high explosive contains a thin-walled cylinder, or liner, that surrounds an initial magnetic field, B_o,, at an initial radius, r_o, as shown in the top and left views. After symmetric detonation of the explosive, the liner is compressed, as shown in the right-hand view, where the liner is shown at a radius r and a magnetic field B. In the ideal situation (for a perfect conductor) flux is conserved and the magnetic field would increase as the inverse square of the radius. Thus, a ten-fold decrease in the radius would result in a hundred-fold increase in the magnetic field.. While there are no ideal liners, fields in the megagauss range have been measured with amplifications exceeding 200, while values of a hundred are commonplace.

Capacitor banks are the usual energy source used to supply the system's initial magnetic flux. The fields are generated by coils placed in such a way as to give maximum coupling with a minimum of interference with the liner compression. Naturally, larger initial energy sources allow more freedom in coil placement and for more initial flux. The best possible coupling is to put the coil directly undre the liner or explosive. This was done for the systems described in [2]. However, when such irregular objects are placed under explosives, serious perturbations usually result, frequently destroying the field measuring probe before peak field occurs, as was often the case here. Still, the system workrd often enough to establish the principle. Pavlovskii et al [3] developed an ingenious system where the coil was also under the explosive. Here, however, they established how much radial compression could be tolerated before serious perturbations developed.. At this radius, they inserted another smaller liner that became conducting only after it was hit by the original inward moving liner-thus essentially postponing the onset of serious perturbations. By adding still another smaller liner (called cascades) they have reached fields as large as 1600 T in similar systems. Figure 2 shows magnetic field-time traces obtained with these systems at Los Alamos, using two different explosives. These devices are called MC-1 generators by the Pavlovskii group. Figure 3 shows a "strip" generator. The explosive is so placed that it drives the the initial flux, in the triangular cavity, into the cylindrical load coil, of much smaller area. Under otherwise similar conditions the size of the magnetic field obtained depends upon the load coil diameter. The field-time plot for a coil of 12.6 mm diameter is shown on Fig. 4. Although the peak fields generated are mush smaller than the implosion produced fields, the systems have a number of advantages. The load coil volumes are very large for megagauss fields and the region of field uniformity is large.since the lengths are also relatively large (typically,76 mm). Also of importance in many experiments is the existence of a field peak and its subsequent decay, thus allowing measurements to be made in both increasing and decreasing magnetic fields, an option not normally available in implosion produced fields. An even greater advantage the strip systems have, particularly when they are used for experiments that require electrical diagnostics such as four-ternimal resistance measurements, is their much smaller values of dB/dt. The voltage induced around an effective area A perpendicular to the magnetic field is AdB/dt Since it is impossible to completely eliminate stray areas normal to the field in systems containing electrical leads, there will always be stray pickup signals , or electrical noise, in competition with the true experimental signals sought. A rough inspection of the curve of Fig. 2 shows that dB/dt signals can be as large as 10^{9} T/s. This value produces voltages of a kV /mm^2 of incompensated area normal to the field! A corresponding inspection of Fig. 4, shows values of dB/dt nearly two orders of magnitude smaller, an enormous advantage in many cases.

The electrical noise problem does not arise when the diagnostics are optical, such as in light absorption or Faraday rotation experiments, which accounts for the fact that far more work has been done in megagauss fields with optical rather than electrical diagnostics. For those experiments that have required electrical diagnostics much of the labor has been dircted towards the control of the electrical noise, as shown in the remarkable results obtained in some the Dirac Series experiments described elsewhere at this Symposium.

Addition of a second stage of explosive flux compression can produce substantially higher fields than the strip system shown in Fig. 3. in similar volumes. Occasional reference to such systems is made later, a description of which may be found in Ref.[4].

Experiments

As noted earlier, most explosive flux compression work has been for dedicated uses, in particular the design and application of various kinds of power supplies. Consequently, the exploration of material properties in explosively produced megagauss fields has been limited. Surveys or references to much of the Los Alamos work of this kind may be found in [4-6] Ref [6] contains a summary of most of our work on the high-temperature superconductor, YBCO, up to 1993. The major findings cited there , for samples with the c-axes parallel to the magnetic field, included identification of several dHvA frequencies and, somewhat later, a determination of the low- temperature critical field as lying between 130-140 T. Strip generators, both single and two stages, were used throughout. Some tests were made where the c-axes were mounted perpendicular to the magnetic field. Only at temperatures near the zero-field critical temperature were the attainable magnetic fields sufficiently large to reach critical values. Extrapolation of these data suggested the low temperature critical field to be at least 600 T, which would require implosion systems to produce.

At the end of [6] it was noted that a joint Los Alamos-Russian high magnetic field shot series was soon to take place. This series did indeed take place in November-December, 1993. Ultra-high field shots (up to 1100 T) employed the Russian MC-1 generator (with Los Alamos explosives) while the intermediate field shots (100-200 T) employed one and two stage Los Alamos strip generators. This series was historic in several ways. First, it brought together scientists from two major nuclear weapon centers, formerly in opposition, that worked together as an effective team; secondly, it was the first time that Russian scientists worked in a secure area at Los Alamos; and finally, as discussed below, the success of the series led to the formation of the "Dirac" Shot Series which has become international in scope as described elsewhere at this Symposium.

We close this section with a brief discussion of the results obtained in the 1993 series, an extensive discussion of which is given in [7]

The program objectives were first, of primary importance, the adaptation of Los Alamos eeplosives and detonation systems and the capacitor bank used to supply the initial flux, to Russian built hardware. Secondly, we hoped to measure the low-temperature critical magnetic field of YBCO, already established as lying beyond the present strip generator fields readily available at Los Alamos.. We were successful in both of thses objectives and, additionally did an add-on experiment that helped unravel some long-known , high-field optical peculiarities in CdS.

• Los Alamos Adaptations. Los Alamos composition B explosive (60% RDX,40% TNT) is slightly more energetic than the Russian explosive used for these generators (50% RDX, 50% TNT). The Russian detonation system voltage for these systems is several tens of kilovolts, while the Los Alamos systems use about 2500 volts. These differences were of some concern, as were some of the differwences in the capacitor banks at the two firing sites. As demonstrated by the results shown on Fig. 2, however, all our concerns were groundless. Not only did the system work well, but we obtained very good results using an even more powerful explosive, PBX 9501 [8], which we now use as the standard explosive for the MC-1 generators fired at Los Alamos.

• YBCO Critical Field.. A brief description of the experiments and a B vs T phase diagram are given in [9]. The phase diagram combines earlier lower field data with the very high fild data abtained here. The low temperature critical field is given as 340+40 T. The primary diagnostic employed was a 4 mm microwave interferometer. Earlier work [10] with an 8 mm interferometer led to somewhat anamolous results, attributed, in part, to non-uniform samples. In the present experiments, the samples, with c axes perpendicular to the field, were placed between plastic wave guides, in foam cryostats located in the high field region. Metallic waveguides, to and from the interferometer, were connected to the plastic guides only at distances of 30 cm or more. Analysis of the transmitted and reflected signals allowed calculation of the real and omaginary parts of the sample conductivity. Vanishing of the imaginary component was assumed to end the superconducting state. The values of magnetic field B, where this occured for a given temperature experiment, then made up the phase diagram [11

• CdS Nonlinearities] High field optical nonlinearities were observed in CdS many years ago [12]. Among these were increases in the Verdet constants with magnetic field, particularly at the shorter wave-lengths as they approached the absorption edge (somewhat less than 500 nm at 6^0 K) It was also observed that the absorption edge , itself, changed at high magnetic fields, permitting transmission of light with wavelengths about 6 nm shorter at a field of about 200 T. A Faraday rotation experiment was added to this shot series using 543 nm light, a wavelength long enough that a non-linear effect was difficult to observe in the earlier 200 T experiments. Here, transmission was observed to 500 T, and non-linear rotation became very pronounced at the higher fields. Using thios data, the earlier data abd some results obtained later in Russia (to 750 T), Druzhinin et al [13] were able to develop a theoretical model that accounted for the non-linear Faraday rotation, as well as the shift in the absorption edge.

Dedication

This paper is dedicated to the memory of Robert S. (Bob) Caird, a long-time friend and colleague, who died on March 27, 1997. Bob was one of the pioneers in the field of explosive magnetic flux compression. His work touched many areas related to the field and , among other things, included substantial contributions to field, current and voltage measurement diagnostics; design, modelling and application of various flux compressors for use in specific applications; and development of computer codes to treat various problems associated with the field. Bob was a true gentleman in every sense of the word, possessing a keen sense of humor and maintaining the highest ethical standards. He will be missed by his friends and colleagues as a scientist and as a person, but will be remembered with pleasure.

Acknowledgement

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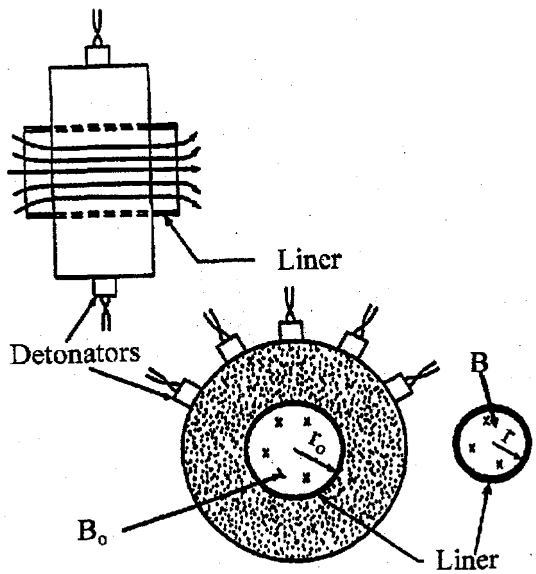
Figure captions

Fig. 1 Sketches of a cylindrical implosion system. The right view shows the system after detonation of the explosive shown in the two left views.

Fig. 2 Magnetic field-time traces obtained from MC-1 generators using two different explosives.

Fig. 3 Sketch of a strip generator showing a load co;i and metal conductors overlaid with sheet explosive. The conductor positions are shown by dashed lines when the detonation fronts have moved to D.

Fig. 4 Magnetic field-time plot obtained from a strip generator with a load coil diameter of 12.6 mm.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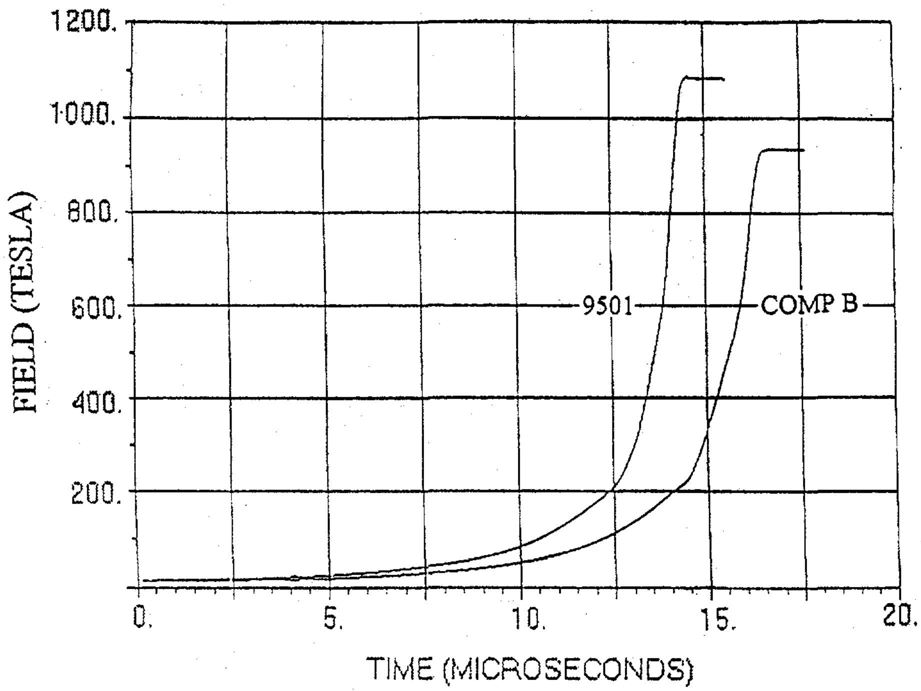
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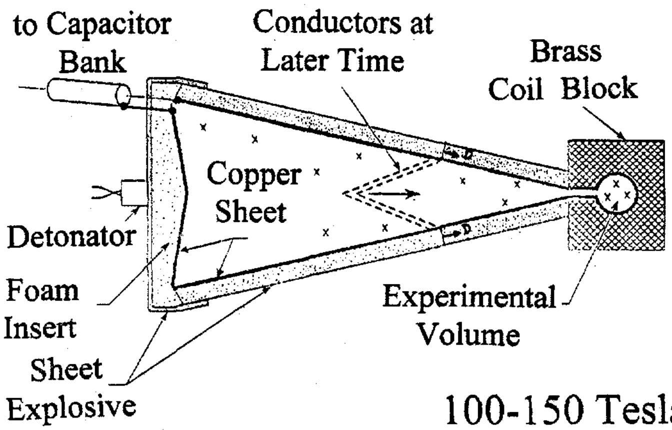

100-150 Tesla
Systems

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