THE LOS ALAMOS FLUX COMPRESSION PROGRAM FROM ITS ORIGIN**

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1. Introduction

A short history of explosive flux compression as we know it was given in our first open publication in this field.¹ As noted there, the technique seems to have been first applied as a means of determining the motion of metals. This work, dealing partly with classified matters, was summarized in a 1944 report written by Joseph L. Fowler.² An analysis of the data given in this report, which was not cast in a form readily displaying the magnetic field values, showed that fields were compressed from a few gauss to a few hundred gauss. The first attempts to use explosives to make large magnetic fields were started in the early 1950's, acting on suggestions by Frank J. Willig and Edward Teller. Work was carried out for several years by W. B. Garn with some assistance by S. R. Arnold who worked with Garn as a summer student.

Fields as high as 200,000 gauss were achieved and reported by them³ before the program was abandoned.

The senior author first became exposed to this work in his capacity as a summer staff member working with Willig's group. This group was also engaged in other programs during this period, one of which was that of producing high speed jets of various materials by the use of high explosives. More will be said of this program in section 2. This author also had occasion to become somewhat familiar with the Los Alamos Sherwood program, which was then classified. The thought gradually evolved of combining the techniques of producing deuterium jets explosively followed by explosive magnetic flux compression of the deuterium plasma with the aim of producing large neutron bursts. This concept*

* Before starting the program this author had the benefit of several valuable discussions with E. E. Salmi of Los Alamos and J. M. Walsh, now with General Atomic.

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ultimately lead to the present flux compression program at Los Alamos.

The present program began in late 1957, with the first objective of starting the flux compression program again, hopefully, to produce magnetic fields in the megagauss range. If this could be achieved, some additional studies on the deuterium jet problem were to be undertaken, and then the two techniques were to be combined, as noted above.

By the end of 1958, we thought that the basic principles of implosion flux compression were sufficiently established that fields in the megagauss range could be produced fairly reliably. Our very high fields, in the 10 or more megagauss range, which required the use of coils inside the liner, are now the subject of some controversy and will be discussed later. Implosion systems of this type were never intended for plasma applications. Further developments were left for the future if the lower fields attainable with external coil pairs gave encouraging results, although a short article in the 1960 edition of "Atomic Energy Research in the Life and Physical Sciences"⁴ might give the impression that these fields were to be used with the plasma experiment.

Some preliminary experiments were started on the explosively produced deuterium jet problem, but already we had begun to worry about the volume taken up by the glass tubes into which the jets were discharged. Our primary concern at that time was that the non-conducting imploding glass robbed valuable flux compression volume. This led us ultimately into several programs. A considerable amount of time was lost in trying to make slotted liners vacuum tight, with the idea of using the slotted liner, itself, as the region where the deuterium jets finally interacted. Although this objective was partially met, it was never considered satisfactory. In turn, the thought of using resistive, unslotted liners occurred about this time, but was not pursued actively until some time later.

The recent Sherwood successes at this time, particularly the rapid development of the fast theta pinches, had led us to think

increasingly along the lines of using this method to produce the initial plasma. In addition, components necessary for the fast capacitor banks required began to become available to us through our Sherwood groups. These included low inductance, high voltage capacitors, ignitrons and low inductance, high voltage cable. This latter item was one of considerable importance, in that it was clear, fairly early, that many cables would have to be run in parallel to keep the source inductance down. We also decided that a 20 kV bank was about optimal, in that the cable problem would become prohibitive for substantially higher voltages, and further that slot insulation would be difficult. (It might be mentioned here that with the availability of new products such as Mylar, this latter difficulty has been alleviated, although problems involving creep may still arise.) At this point, it is well to acknowledge our Sherwood people, who have always maintained a keen interest in our work and have been most generous in offering technical advice and equipment when available.

Further details of our efforts to produce initial plasmas by means of theta pinches are given in another paper.¹¹ We also began discussions with our explosives group with the idea of developing a cylindrical lens. A good reliable system was produced some months later.*

2. Jet Experiments

Our attempt to make fast deuterium jets explosively was patterned after the technique outlined by Koski et al.⁵ Fig. 1 shows a diagram of the assembly used. Jet velocities were observed in two ways -- by means of a sweeping image camera and by means of small pickup loops, nested between magnetic field producing coils. Fig. 2 shows a

* The system finally evolved is, basically, a plane wave lens, rotated about an axis, the axis corresponding to the central cylinder axis. Thus detonation is required only about a single circle. D. M. Mosher assumed the major design responsibility for this lens.

typical sweep picture and Fig. 3 shows electrical pickup signals generated in the pickup loops as the ionized jet passes through the loops. Velocity measurements by these methods were consistent and invariably somewhat lower than the 100 mm/ μ sec expected from reference 5.

Various other experiments were performed. It was shown that the jets could be channeled somewhat by magnetic fields, that two jets could be made to collide in space to within a couple of centimeters even though the jet tubes were each about a meter long.

Sweeping image spectrograms taken of the jet failed to show any deuterium lines and instead generally revealed a number of aluminum lines which were followed closely by an unresolved continuum as shown in Fig. 4. The continuum was thought to arise from material removed from the glass confining tube. An increase in the tube diameter confirmed this speculation by showing an increasing time lapse between the initial appearance of the aluminum lines and the continuum. The appearance of the aluminum lines corresponded very closely with predictions made from the jet velocity determinations. It was finally concluded that any deuterium present was probably cold, and did not lead the massive, aluminum contaminated jets sufficiently to be useful in a magnetic compression experiment.

3. Motion of Materials

Our first attempts to produce the initial deuterium plasma utilized a fast theta pinch operating on the third quarter cycle mode. This required a much simpler system than that needed to heat the plasma on the first quarter cycle, which was employed later, in that only a weak preionization of the cold deuterium gas, followed by the fast main compression field was required.

After an expenditure of considerable time, we concluded that the thin-walled, slotted, implosion coils used suffered too great an electrical distortion in three quarters of a cycle to be usable. On the other hand, electrical probing followed by implosion tests showed that the coils held up quite well through the first quarter period.

This highlights a difficulty that arises continually in flux compression systems where an insulated slot must be closed. Frequently, the flux trapping materials must be thin to give good implosion characteristics and to achieve large implosion velocities. The problem of distorting metal parts from purely electrical forces prior to the implosion then arises.

The following qualitative analysis has served us well as a design guide. On Fig. 5 is plotted the relative motion of two parallel plates under the action of a sinusoidal current flowing through them. The curve applies to other systems such as the motion of the coils in a coil pair arrangement, provided that the inductance of the system doesn't change appreciably. The displacement scale may be shown to be proportional to $C^2 V_o^2 / \text{Mass}$. From this figure, it is quite understandable that a slotted coil might not be distorted appreciably through the first quarter of a period but become badly distorted by the third quarter period.

In many of our systems, we are frequently near the danger point of electrical destruction of slotted liners, breaking up of a ring charge by coil pairs moving together, and from other similar causes. In one such system, by accepting only 90% of the maximum field, coil-pair motion is reduced to less than a third of that occurring at peak field. This small sacrifice in initial magnetic field allows a workable system.

The scaling of motion with $C^2 V_o^2$ also shows the desirability of faster rise times. Factoring out the energy term, $1/2 CV_o^2$, the motion achieved at a given state in the discharge is still proportional to the bank capacitance. Thus, for the same energy input (and consequently the same maximum field in a given system) there are systems that are quite usable at the field peak achieved with a 435 μF bank, but unacceptable when a 1450 μF bank is used.

As has probably happened to most workers in this field, shots have been lost by premature firing of a condenser bank. (Another unfortunate consequence of such a catastrophe is the presence of undetonated explosive fragments lying around the firing table.) We have finally developed a device, called a "mousetrap", which protects most of our

loads (those with inductances greater than a tenth or so of a microhenry) from such destruction. Figure 6 shows the mousetrap coupled to a condenser bank header. Basically, it is a spring-loaded, low inductance short connected accross the condenser bank header. The firing button actuates a relay that releases a closing latch. The jaws of the mousetrap fly up, under spring action, thus removing the low inductance short. The upper plate of the mousetrap ultimately closes a relay which fires the shot. The total time elapsed in this operation, during which the shot is not protected, is of the order of a tenth of a second. So far, we have not been unfortunate enough to have a premature breakdown in this time interval. On the other hand, a number of shots have been saved, any of which has more than repaid the effort required to build and install the mousetrap.

Some early plate-driving experiments were carried out with a source-inductance dominated condenser bank system, shown in Fig. 7. Framing camera pictures were taken of the projectile plate motion. Since the source inductance, L_0 , dominated the circuit, the currents were essentially sinusoidal. The results were in agreement with those predicted from Fig. 5 as modified by taking account of the appropriate damping factor. Terminal velocities of several tenths mm/ μ sec were obtained for thin dural plates.

Some time later, this work was extended using a very low source inductance circuit. The circuit inductance changed significantly with increasing plate separation, and the resulting differential equations (of plate motion and for the circuit) are non-linear. However, a terminal velocity formula can be derived readily, provided the motion required is small compared to the projectile plate dimensions and if it is assumed that the resistance of the circuit does not change. If M , L , W refer to the mass, length, and width of the projectile plate, E_0 and R to the initial energy of the condenser bank and resistance of the circuit, with $\mu = 4\pi \cdot 10^{-7}$, then the terminal velocity may be written as

$$v_T = -\frac{2RW}{\mu L} + \sqrt{\frac{2Eo}{M} + \left(\frac{2RW}{\mu L}\right)^2}$$

We found it possible to accelerate small dural strips in this manner to about 3 mm/ μ sec, in excellent agreement with the above formula. Attempts to push this value to 8 mm/ μ sec, with parameters adopted to the formula, resulted in vaporization of the plates.

4. Available Facilities

Some mention should be made of some of the facilities available to us.

The obvious advantage of having a large Sherwood organization in house, has been mentioned previously, as has our indebtedness to the Sherwood people. We are also fortunate in having available extensive machine shop facilities. We would here like to acknowledge, particularly, the help we have received from R. W. Livingston, our local branch shop foreman.

In one way or another, we have drawn upon the resources available in nearly every group of the laboratory's explosive (GMX) division. Without question, our greatest indebtedness is to group GMX-3. This group of 275 people is a modern explosive processing facility that is capable of casting, pressing, machining and assembling high explosives systems. Their conventional shop-type machine tools are supplemented with numerically controlled machines, so that there is an established capability for fabricating plane, cylindrical, spherical, and other shaped explosive systems, as desired, to tolerances of a very few thousandths of an inch. Quality control of the explosives is maintained by density and composition sampling techniques, by x-ray analysis of the components, and by standard inspection procedures.

Another facility that has been available to us upon occasion is the pulsed x-ray machine, Phermex, at GMX-11. A description of Phermex has been given by Venable.⁶ Figures 8 and 9 show flash x-ray pictures taken at a prescribed time for two different explosive systems. Figure 8

shows a relatively early stage in the implosion of a stainless steel liner driven by a cylindrical charge detonated by a row of detonators. The obvious detonator perturbations disappear in later stages of the implosion. Figure 9 shows a profile of a liner being imploded by a cylindrical lens.

Another technique that has been helpful to us is that of stereographic framing camera study of systems during implosion. Details of this technique have been given by Taylor and Hughes.⁷ Coordinates are put on the specimen under investigation (half of a cylinder, for example). The motion of the surface under implosion is determined by following the coordinates in stereo. A special computer code allows quick calculation and plotting of the surface motion from comparator readings taken off the film strip. With this technique, Taylor has shown the importance of accurate detonator spacing and the thickness of explosive wall to minimize detonator interactions.

5. The Current Program

A great variety of flux compression shot series has been fired over the years, with various objectives in mind. Forerunners of some earlier types have been presented in references 1 and 8. A number of other devices, including our so-called strip flux compression systems which will be described later, have been presented in various open lectures⁹ but not published. Several systems which display the versatility of flux compression techniques are presented in the excellent article by Herlach and Knoepfel.¹⁰

Much of our current work in flux compression development is devoted to plasma compression systems, some of which are outlined in reference 11. Systems suitable for other applications, such as solid state experiments, are also in a state of continuous development. More recent work on cylindrical flux compression systems is given in reference 12.

A few comments about our strip compression systems might be

of interest. Fig. 10 shows a sketch of a model developed in early 1962. The similarity with the "bellows system" developed independently by Herlach and Knoepfel¹³ may be noted. The first application we had for this system was that of creating a constant field for about 100 microseconds in a prescribed type of load. Figure 11 shows a field record obtained from one of these systems. By varying parameters such as the length of the system, thickness of explosive, size of load coil and initial magnetic field, the device could be tailored to make constant fields (to within 3%) for at least a hundred microseconds, or conversely rise to a field in the low megagauss range such as reported by Knoepfel and Herlach for their system. We also used this system to study some resistive effects. For example we were able to damp out the current completely by using 18-8 stainless steel for the top plate and lengthening the system to about 2 meters.

We have performed some experiments with systems of this type and with the bellows system of Herlach and Knoepfel. Both perform well. It might be remarked that access into the side of the load coil (for transverse field measurements as an example) is another advantage to these systems.

We have also devoted some effort to develop systems which will allow salvaging at least parts of an experimental system. A closely spaced transmission line separating the explosive section from the load coil, weighted with lead bricks (which, although battered, can be salvaged after a shot) has been useful here. Use of thinner dural plates has allowed a reduction in the amount of explosive required. Finally, we have found it somewhat easier to protect the load coil when the assembly is detonated from one side only.

We have had some doubts about pursuing these systems further for use as a small volume, high field experimental system since we feel that fields in the low megagauss range will soon be rather commonly available with non-explosive condenser bank systems. However, we now

question whether condenser bank operation will really be appreciably cheaper or quicker than the explosive method, particularly if it becomes possible to salvage most of the experimental gear associated with an explosive experiment. Of course, the availability of an explosive firing site is a requirement not easily met by many people.

Finally, various extensions of these systems for use in plasma compression devices are under development. We have been worried for some time that possible debris ejected into low density plasma from imploding liners or discharge tubes might cool the plasma too much. This problem would be avoided if the large fields are created in this manner, although, from our experience, very large fields (of order 10 megagauss) cannot at present be achieved in this fashion.

A few non-plasma experiments have been carried out in fields produced by strip and cylindrical systems; Zeeman spectra of several materials^{14,15} and Faraday rotation in quartz^{12,16} have been obtained in fields up to about 2.5 megagauss. With flux compression systems under development, we hope to extend these measurements to fields approaching 5 Megagauss with the same size experimental assemblies whose diameters have limited the fields to about 2.5 megagauss with previous systems.

Techniques suitable for other experiments, magnetic transitions, for example, are under development. Methods for matching field measuring probes have improved substantially. Small, glass transfer tubes have been developed, and we have now established the feasibility of making measurements at liquid helium temperatures.*

6. Possible Future Developments

In recent years, our thoughts have been directed increasingly to the possibilities of making "ultra-large" magnetic fields - fields of order 50 megagauss and higher. One of the reasons for trying this

*We have drawn upon the advice of H. L. Laquer, Los Alamos, and Bernd Mathias, University of California, San Diego in developing these systems.

Bernd T. Mathias

would be to see if there are natural limitations, such as resistivity, which preclude this. Another reason is that before too many years have passed, it is quite possible that fields of 5 megagauss will be achieved with very fast condenser banks, on a destructive basis, of course, but still over regions big enough for many experimental arrangements. Much discussion along these lines has been carried out with Professor Francis Bitter, MIT, who has been serving us as a consultant. He has recently described some of the problems to be expected in such a development, and sketched a few of the possible applications.¹⁷ Other applications have been described by Erber.¹⁸ Without going into further detail, it might be noted that the magnetic pressure of a 50 MG field is about 100 megabars, and that the magnetic energy density is nearly 100 ev per cubic Angstrom unit.

Only rarely have field multiplications in excess of 200 been achieved here with multiple detonator ring charge systems, and these only in unslotted, resistive liners, where perturbations are kept to a minimum. Even allowing for some improvement through use of cylindrical lenses, it is clear that initial fields should be well in excess of 150,000 gauss. This requirement, coupled with other geometric requirements, indicates the need for a large power source, as pointed out by Bitter¹⁷. Even omitting considerations of resistive and stability limitations, a number of calculations show that 50 MG fields cannot be achieved with any reasonable cylindrical implosion system, even with our most powerful explosives. It is clear then, that aside from the power supply requirements, an extensive explosive design program would be required, and from our previous experience, the utmost care would have to be taken to keep perturbations reduced to a minimum.

The possibilities of physical limitations are almost as interesting as achievement of the fields. Intimately involved in considerations of this type are the properties of materials under very high pressures and temperatures, the problem of stability of the imploding liner, and the

dependence of electrical resistivity under implosion conditions. A bibliography of recent work in these areas is available in reference 10.

One comment on a possible manifestation of instabilities may be made. In one of our stainless steel liner systems, which we expect to peak in at a little over three megagauss for a given probe radius and initial field, occasionally an anomalously high value, such as 5 megagauss will be achieved. At present we are unable to tell whether the peak field values are limited by mechanical perturbations or perhaps by growth of instabilities such as described by Linhart.¹⁹

Aside from conveniences listed in reference 16, another reason for using stainless steel systems is that we would expect to see significant flux leakage with this material more easily than with a copper liner, for example. Although some higher initial field experiments are imminent, which may clarify this question; at the time of writing we have not as yet been able to establish unequivocally any significant flux loss for this system, owing to the occasional large field values observed and to the inability to observe the liner at large compression stages.

We have given some thought to using multi-megagauss fields to confine and further compress the plasmas produced from high-power laser pulse heated solid matter. A recent theoretical discussion containing references to earlier work is given by Dawson.²⁰ Early experimental work with a low energy laser is described by Linlor.²¹ Recent work by P. Mace and R. Putzi²² at Los Alamos has extended Linlor's work and, although the power level of the laser used is still quite low, the results appear encouraging. Aside from additional adiabatic compression from field increases, mere confinement of the plasmas offers some significant advantages, in principle. First, more efficient use of the absorbed laser energy should result, in that the plasma kinetic energy of expansion is curtailed. Perhaps of more significance is the reduction in the laser power requirement.

For an unconfined plasma, the decrease in particle density accompanying expansion ultimately leads to an effective absorption cutoff. For this reason, to heat unconfined plasmas to the kilovolt level, predicted laser power output requirements get fantastically large. With confined plasmas, if only in the radial direction in cylindrical geometry, the power requirements should be considerably relaxed.

Some final remarks may be made about our 1958-1960 results in which magnetic fields in the 10-15 megagauss range were reported. As is evident from the contents of this paper, our experimental program has not been directed towards the production of fields in this range, but more towards development of reliable systems at necessarily lower fields (forced by the electrical energy sources available). Our feeling until fairly recently was that until successful experiments have become routine in the 1-5 megagauss range, there was little reason to exploit the larger values. Several factors have arisen to cause us to consider this early work in more detail, and particularly to start development of experimental systems in higher field ranges.

A careful examination of the records from these early shots has shown that the scope traces from only a handful of the fifty or more shots fired would be considered acceptable with the modern scopes now available. We have concluded that the systems with internal coils under the implosion region, used then, are too erratic in performance to be useful. After weeding out the questionable records, only shots with explosive widths comparable to the liner diameter (3" wide) gave acceptable records. It is also likely that in the successful shots much of the gross motion of the liner near the tangential slot, as well as that of the internal coils, was minimized by accidentally firing before the field peaks, caused by delayed condenser bank firing. Short of repeating this series, a long, tedious operation, our best judgment is that copper and brass liners still behave about alike. However, we would be forced to increase our stated limits

of accuracy, 15%, to perhaps 25%. In short, we still believe that fields in excess of 10 megagauss were obtained, but that the system used is not reliable.

It is clear, however, that quite aside from the controversy now existing, the matter cannot be left in this state because fundamental questions of resistivity remain, and in particular, the possibility of making ultra high fields rests squarely upon this question. We have, therefore, started a program to investigate this problem, and it is hoped that preliminary results will be available at this conference.

A number of treatments of resistivity limitations, employing various degrees of sophistication, have appeared recently. With some of these treatments, it appears that flux losses varying from 25% to 50% might be expected for our earlier systems in agreement with some of our own calculations, although others are not so optimistic. In our opinion, the problem at this time is an experimental one. There are basic questions involved in the equation of state of liner materials, and the dependence of resistivity on such variables as electric and magnetic fields as well as metal density and temperature.

ACKNOWLEDGMENTS

We would like to give special acknowledgment to three men who have worked with us on a sustained basis for varying times: Paul Sisneros, our firing point supervisor; E. J. Rodriguez, who has joined him more recently; and K. J. Ewing of group GMX-3, who has served as a liaison between us and that group, and has also undertaken the design of several of our experimental and explosive systems.

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Figure 1. Explosive deuterium jet assembly shown here with two magnetic signal detectors for jet velocity measurements (not to scale).

THIN WALLED
AL TUBE

"DEUTERIUM" JET TUBE

Figure 2. Sweeping image photograph of a "deuterium" jet. Time increases from top to bottom. The space view is of a narrow, uncovered viewing slit running horizontally along the entire length of the large glass tube of Fig. 1. The equally spaced vertical stripes are premeasured reference marks taped on the glass tube.

Figure 3. The upper traces are electrical signals from the pickup loops shown in Fig. 1 as the ionized jet passes through them. Jet velocities are determined from the distance of pickup loop separation and the signal time differences, as determined from the lower traces.

Figure 4. Time resolved sweep spectrogram obtained from jet of the assembly shown in Fig. 1. The spectrograph viewed a fixed, small area of the glass tube. Time increases from right to left on the figure.

AL II 6243
AL II 6231
AL II 6226

NI 5553

AL III 5723
AL III 5696

AL II 5593

NI 5172

CI 5040

AL II 4663

AL III 4529
AL III 4512
AL III 4480

AK II 450
SI II 428-801

AL I 3981
AL I 3948
AL II 3901
NI 3834-3818
OH 3739-3722

Figure 5. The normalized relative motion of two parallel plates under the action of sinusoidal currents is compared to the fields developed between the plates. It is noted particularly that large displacements develop as time increases near peak, although the fields are changing very little. Bank capacitance is denoted by C and bank charging voltage by V_0 .

1.5

1.0

.5

0

1.0

0.9

0.5

0

DISPLACEMENT, X ,
 SCALES WITH $C^2 V_0^2 / \text{MASS}$

B/B_M

B/B_{MAX}	θ	X
0.9	64°	0.45
1.0	90°	1.47
0.9	116°	3.30
-1.0	270°	21.3

90°

90°

180°

Figure 6. Two views of the protective, low inductance, mousetrap. In the closed position (lower view) the mousetrap serves as a protective shunt across the main load. Upon receiving the shot trigger signal, the mousetrap opens (upper view) and subsequently produces a second signal from the upper relay which initiates the shot time signal chain. (The lower relay controls an "on light" in the firing bunker to assure that the mousetrap is cocked.)

Figure 7. Schematic view of a condenser bank energized plate-driving system. Projectile plate velocities may be determined from framing camera observation of the plates compared with suitable space reference coordinates.

Figure 8. "Flash X-ray photograph obtained from "Phermex," of a stainless steel liner at an instant during the implosion resulting from a cylindrical charge detonated by a ring of detonators.

Figure 9. Flash X-ray photograph, obtained from Phermex, of an aluminum liner at an instant during the implosion resulting from a cylindrical lens system.

Figure 10. Schematic of a strip flux compression system. Several parameters can be varied easily.

STRIP FLUX COMPRESSION ASSEMBLY

VARIATIONS OF THIS EXPERIMENT CAN
PRODUCE FIELDS EXCEEDING A MEGAGUSS

Figure 11. Lower traces: Magnetic field signals obtained from probe in load coil of Fig. 10, at two scope sensitivities. Middle and upper traces give voltage calibrations and time marks (10 and 100 μ sec intervals).