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LDRD Final Report on Confinement of Cluster Fusion Plasmas with Magnetic Fields

Kenneth W. Struve, Jeffrey W. Argo, Roger D. Bengtson, Daniel I. Headley, Jeffrey W. Kellogg, Sean M. Lewis, John L. Porter, Hernan J. Quevedo, Mark E. Savage, Brian Stoltzfus, Caleb J. Waugh, and Matthew Wisher

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Department 1679, Z Operations
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS1194

Abstract

Two versions of a current driver for single-turn, single-use 1-cm diameter magnetic field coils have been built and tested at the Sandia National Laboratories for use with cluster fusion experiments at the University of Texas in Austin. These coils are used to provide axial magnetic fields to slow radial loss of electrons from laser-produced deuterium plasmas. Typical peak field strength achievable for the two-capacitor system is 50 T, and 200 T for the ten-capacitor system. Current rise time for both systems is about 1.7 μ s, with peak current of 500 kA and 2 MA, respectively. Because the coil must be brought to the laser, the driver needs to be portable and drive currents in vacuum. The drivers are complete but laser-plasma experiments are still in progress. Therefore, in this report, we focus on system design, initial tests, and performance characteristics of the two-capacitor and ten-capacitors systems.

CONTENTS

FIGURES.....	7
TABLES	8
1. INTRODUCTION	9
2. DRIVER DESIGN	11
2.1 Design Concept.....	11
2.2 Circuit Design.....	13
2.3 Hardware Details.....	17
3. 500-KA SYSTEM TEST RESULTS	23
3.1 Driver Validation	24
3.2 Coil Tests with the Two-Capacitor System	25
4. THE TEN-CAPACITOR, 2-MA SYSTEM	27
4.1 Ten-Capacitor System Driver Performance	28
4.2 Coil Tests at 1 MA.....	30
5. SUMMARY	33
6. REFERENCES	35
DISTRIBUTION	37

FIGURES

Figure 1.1. Neutron yield from deuterium cluster irradiation with various lasers. (Plot courtesy of Roger Bengston, University of Texas, Austin, used with permission.)	9
Figure 2.1. Capacitor and switch assembly with series water resistor. Area around switch is filled with SF ₆ at atmospheric pressure.....	11
Figure 2.2. Vacuum chamber (internal diameter 41 cm) with feed-through for the two-capacitor drive system.....	12
Figure 2.3. Conceptual coil connection. A single-turn coil is connected between the inner and outer lines.....	13
Figure 2.4. Bertha circuit model of the ten-capacitor system. Not shown are the charge circuit, dump relay, and trigger circuits, which are described in the text..	15
Figure. 2.5. Predicted current and insulator voltage.....	17
Figure 2.6. Implementation of the L3 Pulse Sciences T508 switch on the two-capacitor system.....	18
Figure 2.7. Implementation of the L3 Pulse Sciences 40364 switch on the two-capacitor system.....	18
Figure 2.8. Typical single-turn copper coil to be used for cluster-fusion experiments.....	20
Figure 2.9. Copper coil mounted to conical plates in the vacuum chamber.....	21
Figure 3.1. Two-capacitor, 500 kA system. The vacuum chamber is center front attached to the two capacitors with twelve coaxial cables. The blue cabinet contains the LabView control system, charging power supply and trigger generator. The Hoffman box behind the capacitors is filled with oil and contains the charging resistors, switch bias, and dump relay	23
Figure 3.2. Measured current into a coil with the two-capacitor system with a 100-kV charge voltage.....	24
Figure 4.1. The ten-capacitor system at the University of Texas where magnetic coil tests are being done. In this photo the vacuum chamber lid is removed, and one of the switch cans is open with cables not yet attached. Behind the capacitors are two oil-filled Hoffman boxes with the trigger bias, trigger switch,	

charging resistors, and dump relay. The LabView control system is in the smaller Hoffman box mounted in the blue rack. The trigger generator and charging power supply are also mounted in the rack.....27

Figure 4.2. Sixty coaxial cables from the capacitors connected to the tri-plate transmission lines of the vacuum chamber.....28

Figure 4.3. Measured current from a 50-kV charge, ten-capacitor shot into a short-circuit load. Peak current is 1.13 MA. Shown is the sum of the baseline corrected and integrated Bdot signals from each switch can. Switch jitter has smoothed a 0.5% ringing that is seen on each individual signal but is lost in the sum.....29

Figure 4.4. Measured and simulated current for a 50-kV charge voltage shot with a 1 cm diameter coil. Peak current 1.03 MA.....30

Figure 4.5. Image of the exploded coil from the 1-MA coil shot.....31

Figure 4.6. Coil fragments from the 1-MA coil shot.....32

TABLES

Table 2.1. Estimated system inductance. Actual inductance is somewhat higher (see discussion in section 4.).....14

Table 2.2. Parameters used for circuit-code calculations.....16

Table 2.3. Predicted peak current, magnetic field, and pressure for the ten-capacitor system.....16

1. INTRODUCTION

Experiments have shown that intense ultra-fast lasers can ionize small solid-density deuterium clusters to produce high ion-temperature plasmas and fusion neutrons, as first described Ditmire, *et. al.* [1] When chilled deuterium gas is puffed into vacuum, a cloud of solid density droplets or clusters is formed, with each cluster consisting of 100 to 1000 molecules. When irradiated with an intense laser the clusters are ionized and electrons expelled, resulting in multiple near solid density ion cores each surrounded by an electron cloud. Electrostatic forces accelerate the ions to 10's of keV energies. [2,3] Collisions with other ions in the cluster and nearby clusters result in fusion reactions, producing up to 10^6 neutrons per shot, as shown in fig. 1.1. [4] The neutron output scales nearly as the square of the laser energy. The yield, however, is likely limited by the fast disassembly time (< 100 ps) of the deuterium plasma. Yield might be increased if plasma expansion could be slowed with an external magnetic field. Initial calculations suggest that neutron production can be increased by three or more orders of magnitude by creating clusters in a 200 T axial magnetic field. [5,6] At the densities ($\sim 10^{19}$ /cm³) and temperatures (~ 10 keV) of these plasmas, magnetic field in the range of 100-200 T is needed to counteract plasma pressure. With the lasers currently available at the University of Texas (UT) and Sandia, it is conceivable that we could produce 10^{10} to 10^{12} neutrons per shot from these plasmas if axial confinement is successful.

Fig. 1.1. Neutron yield from deuterium cluster irradiation with various lasers.
(Plot courtesy of Roger Bengston, Univ. of Texas, Austin, used with permission.)

The goal of this work has therefore been to introduce sufficiently strong axial magnetic fields into cluster fusion experiments to slow radial expansion of the cluster plasmas and thereby potentially increase neutron yield. A secondary benefit is that this technique produces high-density hot plasmas with embedded magnetic fields that can be useful for investigating plasma effects relevant to high energy density plasma research. Specific tasks were (1) to produce 200 T magnetic fields in vacuum with a pair of single-turn, 5-mm radius coils separated by 5 mm driven with 1.1 MA through each coil, (2) produce 10-keV cluster fusion plasmas with laser irradiation but without magnetic fields, and (3) to add 200-T magnetic fields to determine the effects of radial transport in the presence of these intense fields. The first task has been completed to the point of producing 125 T magnetic fields with a driver that has yet to be charged to more than $\frac{1}{2}$ peak voltage. The second task is part of a successful continuing series of experiments at UT revalidating neutron production with the Texas Petawatt.[7] The third will be achieved next spring as this device is coupled to the laser.

With field strengths of 200 T (2 MG) only single-use, single-turn magnetic field coils are feasible. Such coils require drive current of up to 2 MA for cm-size coils. Drivers at other high-field facilities [8] are either not portable, that is, they cannot be easily moved to a laser, or they do not generate fields in vacuum volumes of sufficient size to allow for injection and laser irradiation of deuterium clusters. For cluster fusion experiments the driver needs to generate 2 MA for the 200 T coils to be used with the Texas Petawatt and potentially the Z Petawatt [9] lasers.

Two versions of a current driver for single-turn, single-use, cm-sized magnetic field coils were built and tested at Sandia for the cluster fusion experiments at the University of Texas in Austin. Field strengths for the two-capacitor system approach 50 T, and up to 200 T for the ten-capacitor system. Current rise time for both systems is $\sim 1.7 \mu\text{s}$, with peak current of 500 kA and 2 MA, respectively. The drivers have been completed and are now being operated at the university. Magnetic field experiments are continuing, with cluster fusion experiments at peak fields with the Texas Petawatt laser scheduled for spring 2012. With the LDRD we have funded development of the driver at Sandia, and coil and laser experiments at the university. Since the magnetic field experiments are still taking place through additional non-LDRD funding we will concentrate on the design of the system in this report, and only show initial magnetic field experiment results.

2. DRIVER DESIGN

The design of the cluster fusion high-field driver is based on similar machines developed by Portugall and colleagues at the Humboldt University, [10] and Mielke at the Los Alamos National Laboratory (LANL). [11] With both machines multi-megagauss fields are produced in 1 cm or smaller-diameter, single-turn coils, driven by multi-megampere currents. However, in our design we must provide both portability, and deliver current to a coil in vacuum.

2.1 Design Concept

For safety reasons we use a one-switch-per-capacitor scheme, and connect to an output transmission line using multiple cables per switch, thus copying the scheme of the Single Turn Facility at LANL. [11] Thus if one capacitor shorts out internally, only that capacitor's energy is dissipated, rather than energy from the entire bank. The multiple cables minimize inductance and provide flexibility in placement of the device near the laser. Each capacitor has a switch and series resistor, as shown in fig. 2.1. The resistor reduces voltage reversal on the capacitors but does take some energy from the forward-going pulse. The resistor output is connected to six high-voltage, high-current coaxial output cables.

Figure 2.1. Capacitor and switch assembly with series water resistor. Area around switch is filled with SF_6 at atmospheric pressure.

A major challenge is to get current to the coil in vacuum without a significant inductance penalty. Our approach is to connect the output cables from the capacitor-switch assemblies to a tri-plate transmission line that extends through a cylindrical insulator into the vacuum chamber, much as is done on the Z accelerator.[12] This approach is shown in fig. 2.2. The structure has very low inductance and delivers current to a coil in the center of the chamber. The transmission line is conically shaped to allow line-of-sight access for the laser. The coil, which explodes each shot, is connected to the transmission line as shown conceptually in fig. 2.3.

Figure 2.2. Vacuum chamber (internal diameter 41 cm) with feed-through for the two-capacitor drive system.

Figure 2.3. Conceptual coil connection. A single-turn coil is connected between the inner and outer lines.

2.2 Circuit Design

The driver is an LRC circuit with estimated system inductance of about 40 nH. Peak current scales as $V_o\sqrt{C/L}$ (neglecting series resistance), where V_o is charge voltage, C capacitance and L system inductance. Note that peak current scales linearly with capacitor charge voltage. Thus, for $V_o = 90$ kV, and $L = 40$ nH, the capacitance needed for 2.2 MA is 24 μF , or eight 3.1 μF / 100 kV capacitors. But to allow for series resistance losses and potentially higher inductance we are using ten capacitors. With these values the time to peak current, $T_p = (\pi/2)\sqrt{LC}$, is about 1.7 μs .

The system inductance is estimated as 38 nH, as shown in table 2.1. The bulk of the inductance is in the cables and the switch housing, with only about one-fourth of the total in the vacuum feed through, vacuum transmission lines, and coil.

Table 2.1. Estimated system inductance. Actual inductance is somewhat higher (see discussion in section 4.)

	Capacitor	Switch	Cables	Insulator and connection	Vacuum Line	Coil	Total
Per Line	40	70	148	1.5	3.7	5	268
Two-capacitor system	20	35	74	1.5	3.7	5	139
Ten-capacitor system	4	7	15	0.8	5.7	5	38

Both the two-capacitor prototype and the ten-capacitor system have been modeled with the Bertha circuit code [13] using actual transmission-line lengths, series resistance at the switch, and parallel resistance to ground at the vacuum insulator. Switch inductance depends on which switch is used. This circuit is shown in fig. 2.4. Parameters for the components in the circuit are given in table 2.2. Predicted peak current, magnetic field, and magnetic pressure are given in table 2.3. Note that the inductive components in the vacuum chamber are modeled as transmission lines, but their lengths are also so short that they can be considered as inductors. The series resistance minimizes ring-over of the capacitors. The shunt resistor, which is placed across the input to the vacuum insulator, limits ringing between the capacitor and the load. It also serves to damp late-time oscillations when the coil explodes and becomes non-conducting. If the coil were to open during peak current we could expect megavolt ringing at the coil. However, experience with other machines is that an arc forms in the exploding coil that maintains the current, and that large inductive voltages are not seen. [14] Predicted current, and voltage at the insulator are shown in fig. 2.5. Note that voltage at the insulator is small since most is dropped across the cable inductance.

Figure 2.4. Bertha circuit model of the ten-capacitor system. Not shown are the charge circuit, dump relay, and trigger circuits. These are described in the text.

Table 2.2. Parameters used for circuit-code calculations.

C (μF)	3.1
Vcharge (kV)	85.0
L capacitor (nH)	40.0
L switch (nH)	70.0
R series ($\text{m}\Omega$)	100.0
Z cable (Ω)	59.0
Number of cables	6
Cable length (ns)	15.0
L connection ring (nH)	0.4
R shunt (Ω)	0.5
L insulator (nH)	0.2
L vacuum flare (nH)	0.2
L transmission line (nH)	6.0
L coil (nH)	5.0

Table 2.3. Predicted peak current, magnetic field, and pressure for the ten-capacitor system.

V_o (kV)	I_{peak} (MA)	B_{peak} (T) ($a = 5$ mm)	P_{peak} (GPa) ($= B^2/2\mu_o$)
25	0.55	49	0.97
50	1.1	98	3.9
75	1.6	150	8.7
100	2.2	200	15

Figure. 2.5. Predicted current and insulator voltage.

2.3 Hardware Details

With this scheme each switch must be able to hold off a 100 kV charge voltage, carry a peak current of 220 kA, and transfer 0.3 C in several microseconds. We evaluated two switches for this application that are rated for lower currents, but found that they can tolerate higher currents with minimal wear. These were the T-508 and the 40364 spark-gap gas switches, both from L-3 Pulse Sciences. [15] Both of these were used on the two-capacitor prototype system, as shown in figs. 2.6 and 2.7. Both are designed for peak currents of 100 kA. The T-508 is regularly used at 200 kV and 160 kA, whereas the 40364 is a 100-kV / 100-kA switch. With both switches electrode erosion is not severe and thus acceptable for our low shot rate. Because of its more compact, lower-inductance design, we chose the 40364 switch for the final design. The switches are filled with dry air at 20 to 30 psia (130 to 200 kPa.)

Figure 2.6. Implementation of the L3 Pulse Sciences T508 switch on the two-capacitor system.

Figure 2.7. Implementation of the L3 Pulse Sciences 40364 switch on the two-capacitor system.

A metal return-current and switch enclosure can mounts to the top of the capacitor and is filled with sulfur hexafluoride, as shown in fig. 2.1. Inside the can is also a series water resistor to which the six output cables are connected. The cables are Dielectric Sciences 2121 coaxial cables, [16] which are 59 Ω and DC rated for 150 kV. Also in the can is a spring-loaded shorting lever that grounds the capacitor when not retracted.

The capacitors are charged in parallel with a Glassman 125 kV/30 mA (model PK125R30) power supply, [17] with power divided by 30 k Ω HVR [18] ceramic resistors that isolate the capacitors from each other. This circuit is enclosed in an oil-filled Hoffman box and connected to ground through a normally-closed Ross relay (model E60-NC-80) [19] that is only open for charging and firing. The circuit thus prevents catastrophic dumping of the entire bank energy in the event of a single capacitor failure, and grounds capacitors when not in use. The circuit also provides a half-voltage bias for a separate trigger circuit, which is in a separate oil-filled Hoffman box, to charge the ten trigger cables for the capacitor switches.

The triggers for each switch are initiated by a ten-volt signal from a CompactRIO system (National Instruments cRIO-9012) [20] that is amplified by a Maxwell 40168 trigger amplifier. [16] The Maxwell output triggers a modified 40364 switch in the trigger box to short out the charged trigger cables, thus driving a pulse to the trigger electrodes in the ten switches. The trigger switch is modified to have $\frac{1}{2}$ the gap of the switches on the capacitors so that it fires at the same gas pressure as the other switches.

The vacuum chamber, as shown in fig. 2.2, has three 9.5-mm-thick conically shaped conductors that form two parallel transmissions lines. The two lines connect in parallel at a radius of 47 mm with posts through the center electrode. Each conductor consists of several concentric pieces with the innermost made of stainless steel, and the outer aluminum. The six output cables from each switch/capacitor combination connect to their outer diameter. Two 22-mm-thick rexolite (cross-linked polystyrene) insulators separate the lines, producing a gap of 19 mm outside the chamber, and 10 mm at their smallest radius. With these gaps and the predicted voltage from the circuit code we estimate a 14 kV/cm peak electric field at the insulator.

Single-turn copper coils are mounted between the center conductor, which is the anode, and the upper plate, which is the cathode. A typical coil is shown in fig. 2.8. Sandwiched inside the coil is an insulating sheet (Mylar or Teflon) that prevents shorting. Note that the coil is split in the axial direction to allow cluster injection perpendicular to the axis of the coil. Thus this geometry approximates a Helmholtz coil configuration. The insulating sheet must be cut away between the loops to allow cluster injection.

Options to increase the magnetic field, without decreasing loop diameter, include constructing a multiple-turn coil. Using the scaling relations given earlier, and recalling that the inductance of a multi-turn coil scales as n^2 and that current decreases as coil inductance increases, we can estimate the increase in the magnetic field B as a function of n , where n is the number of turns of the coil. Ignoring shunt and series resistance, we find that

$$\frac{B(n)}{B(1)} = n \sqrt{\frac{\alpha + 1}{\alpha + n^2}} \xrightarrow{\text{as } n \rightarrow \infty} \sqrt{\alpha + 1} \quad (2.1)$$

where α is the ratio of the inductance of the circuit before the coil to the inductance of a single turn coil. Thus, the magnetic field scales nearly linearly with n , but quickly approaches a constant value for a large number of turns. For the parameters of our circuit we can only expect a maximum factor of 3 increase in the field by using multiple-turn coils.

Figure 2.8. Typical single-turn copper coil to be used for cluster-fusion experiments.

Several coil-mounting techniques have been tried, with the intention that the coil is easily replaced between shots. One of these mounting schemes is shown in fig. 2.9. Here the coil is compressed between plates that are mounted to the top of the anode and cathode. The electrical connection is a friction fit, with a wedge driven in behind the contact bar and its mounting flange to apply pressure to the joint.

Figure 2.9. Copper coil mounted to conical plates in the vacuum chamber.

3. 500-KA SYSTEM TEST RESULTS

A two-capacitor, 500-kA prototype was built and has been operating at UT for over a year, and has been used to verify driver design, test coil configurations, and to learn how to operate the system with cluster and gas injection inside the magnetic field coil. A picture of this device is shown in fig. 3.1.

Figure 3.1. Two-capacitor, 500 kA system. The vacuum chamber is center front attached to the two capacitors with twelve coaxial cables. The blue cabinet contains the LabView control system, charging power supply and trigger generator. The Hoffman box behind the capacitors is filled with oil and contains the charging resistors, switch bias, and dump relay.

3.1 Driver Validation

Multiple shots were taken with the two-capacitor system into a low-inductance coil with a charge voltage of up to 100 kV. With peak charge voltage the peak current was 490 kA, as seen in fig. 3.2. The dashed line is the sum of the two switch currents at the capacitors. The switch currents were measured with magnetic loops (Bdots) that were calibrated against a calibrated current-viewing resistor at the load position. An uncalibrated loop at the load gave an identical trace when overlayed with the sum, thus indicating that no breakdowns occurred between the switches and the load. The time to peak current was 1.5 μs , which implies a system inductance of about 150 nH.

Figure 3.2. Measured current into a coil with the two-capacitor system with a 100-kV charge voltage.

3.2 Coil Tests with the Two-Capacitor System

The magnetic field coils depicted in figs. 2.8 and 2.9 were tested at various peak currents and chamber gas pressures. As expected, when the chamber pressure approaches the Paschen minimum, arcing occurs either across the chamber's vacuum insulator, or at the throat of the coil. This was significant because it dictates the necessity to well insulate the inside of the coil to prevent its shorting when the cluster gun puffs microscopic, cooled clusters and neutral gas into this region. The concern is how to inject the clusters through a hole in the insulator without compromising the clusters, or providing a path to short out the coil. However, experiments with the two-capacitor system using an Nd/YAG laser to diagnose cluster formation have indicated that the clusters are not destroyed, and that the coil is not shorted. With these tests the laser light is absorbed when clusters are present, and passes through the coil if there is only neutral gas.

Calculations indicate that the coil diameter and bi-plate feed gap will expand by about 100 μm at peak current. So peak magnetic field will not be degraded during the pulse because of coil expansion. The thick copper coils used for these tests did not explode, so there was no damage to the cluster gas gun nozzle, which must be close to the coil. But we anticipate this could be a problem as higher currents are used. Therefore it will be necessary to implement containment and debris-shielding techniques to prevent damage from exploding coils.

4. THE TEN-CAPACITOR, 2-MA SYSTEM

The ten-capacitor, 2-MA system was completed and delivered to the university in the summer of 2011. A picture of this system, as set up at the university, is shown in fig. 4.1. To accommodate the sixty cables needed for this configuration the outer flange of the vacuum chamber was modified, as shown in fig. 4.2. Coils are now being tested with this configuration, with emphasis placed on debris mitigation, magnetic field measurement, vacuum operation, and initial low-field testing with deuterium clusters with a lower power laser. This device will be moved to the Texas Petawatt laser in the spring of 2012 where full laser energy and peak magnetic field experiments will be done. Initial indication is that the hardware will fit in the laser bay without disruption.

Figure 4.1. The ten-capacitor system at the University of Texas where magnetic coil tests are being done. In this photo the vacuum chamber lid is removed, and one of the switch cans is open with cables not yet attached. Behind the capacitors are two oil-filled Hoffman boxes with the trigger bias, trigger switch, charging resistors, and dump relay. The LabView control system is in the smaller Hoffman box mounted in the blue rack. The trigger generator and charging power supply are also mounted in the rack.

Figure 4.2. Sixty coaxial cables from the capacitors connected to the tri-plate transmission lines of the vacuum chamber.

4.1 Ten-Capacitor System Driver Performance

Initial testing of the ten-capacitor system has begun, with capacitors yet only charged to half voltage, 50 kV. Higher voltage testing will continue as issues such as debris mitigation are addressed. Of particular concern is protection of the cluster-gun nozzle from the exploding coil. Since forces are radial, it is anticipated that scoring the outer surface of the coil may lead to preferential breakup of the coil, thus allowing placement of the cluster gun at a location that will not experience flying debris.

Tests with a 50 kV charge voltage have produced currents exceeding 1 MA in a short-circuit load, as shown in fig. 4.3. The current for this shot was determined by summing the current measurements of each of the ten lines. The current in each can was measured with a magnetic loop (Bdot) that was calibrated with a current-viewing resistor (CVR) at the load position. The shorting bar for this shot was ripped away from the plates, destroying a nearby Bdot. The time to peak of the signal was $1.87 \mu\text{s}$, which is one-fourth of the measured period. From this the system inductance was determined to be 45.6 nH. The L/R decay time is $4.37 \mu\text{s}$, consistent with a $104 \text{ m}\Omega$ average series resistor in each can. Both of these measurements are independent of calibration and thereby provide a level of confidence in these results.

Figure 4.3. Measured current from a 50-kV charge, ten-capacitor shot into a short-circuit load. Peak current is 1.13 MA. Shown is the sum of the baseline corrected and integrated Bdot signals from each switch can. Switch jitter has smoothed a 0.5% ringing that is seen on each individual signal but is lost in the sum.

The inductance determined from this shot is somewhat higher than expected. By comparing this shot with calibration shots it was determined that the inductance for each capacitor-switch and cable combination needed to be increased by 90 nH in the circuit code, and the inductance of the vacuum chamber and radial transmission lines by 6 nH. Part of that was that the cables are actually 17 ns, and not 15 ns long. The other part is related to changes in the design of the switch can to increase voltage hold-off that also increased inductance. The increased inductance in the vacuum chamber is related to the sixty-cable feed versus the twelve-cable feed. The net result is that we will need a nearly 100-kV charge voltage to get 2 MA to a coil in the vacuum chamber. Also, ringing noise that is seen on individual line signals is a result of not using the shunt resistor at the insulator. This has been left off because it does not appear to be a serious effect and can cause some current loss.

4.2 Coil Tests at 1 MA

Initial testing of magnetic field coils has also been done with the ten-capacitor system. First tests were done with the coil type that is shown in fig. 2.8, with the coil in air. The coil added an additional 5 nH inductance, which dropped the peak current to just above 1 MA, as shown in fig. 4.4. The measured current from this shot is compared with the circuit code with the changes discussed in the previous section. Note that the current matches the simulation until about 15 μs into the pulse, indicating that even with the coil exploding current was maintained through the coil. When the feed to the coil shorts we can expect a change in the period of the signal as is seen at late time. Furthermore, scaling the circuit code with charge voltage indicates that 97 kV is needed to get 2 MA to this coil.

Figure 4.4. Measured and simulated current for a 50-kV charge voltage shot with a 1 cm diameter coil. Peak current 1.03 MA.

With the 1 MA coil shot peak magnetic field was estimated to be over 100 T, which is sufficient to explode the coil from the magnetic pressure. With this shot the coil debris blew through a polyethylene barrier placed over the coil, and scattered debris throughout the chamber. A photograph of the exploded coil remnants is shown in fig. 4.5. The coil did not release from its mounting, but fragmented and slapped the electrodes sufficiently to imbed copper in them. Remaining coil fragments are shown in fig. 4.6. At higher currents we can expect more damage.

Figure 4.5. Image of the exploded coil from the 1-MA coil shot.

Several things need to be done before fielding the magnetic coil experiment with a laser initiated cluster fusion experiment. As mentioned earlier, we need to determine if we can force current breakup in directions that avoid damage to a cluster-gun nozzle. The alternative is to replace the nozzle with each shot. Debris must also be contained within the vacuum chamber to avoid damage to other diagnostics and windows within the chamber. Of primary importance is measurement of the magnetic field strength. Initial tries with fielding magnetic field diagnostics near the coil have not been successful. But with the radial explosion of the coil it is possible to place diagnostics on the axis of the coil without damage.[21] Thus the university personnel will

be using magnetic loops, and Faraday rotation crystals and fibers. Also of importance is to verify operation in vacuum.

Figure 4.6. Coil fragments from the 1-MA coil shot.

5. SUMMARY

The questions of whether a 200 T magnetic field can retard the breakup of a cluster-fusion plasma, and whether this field can enhance neutron production have not yet been answered. However, tools have been developed that will enable producing the magnetic fields needed to answer these questions. These are a two-capacitor, 400-kA system that was delivered to the University of Texas in 2010, and a 2-MA ten-capacitor system delivered this year. The first system allowed initial testing, and the second system will be able to produce the 200 T magnetic fields needed for cluster fusion experiments with a petawatt laser.

The prototype 400-kA magnetic field driver system was designed and built to test the design concept for the system, and to verify that a portable driver system could be built that delivers current to a magnetic field coil in vacuum. This system was built copying a design from a fixed-facility, high-field machine at LANL, but made to be portable and to use a Z-machine-like vacuum insulator and vacuum transmission line. This system was sent to the University of Texas in Austin where magnetic fields up to 50 T have been produced in vacuum. Peak charge voltage and current for this system have been 100 kV and 490 kA. It was used this last year to verify injection of deuterium and surrogate clusters into these small, single-turn coils without shorting the coil. Initial test confirmed the need to insulate the inner surface of the coil, which requires that the clusters must be injected through small holes in an insulator. Tests with a low power laser confirmed that it is possible to inject clusters into the magnetic field coils through these holes without destroying the clusters. The university team also learned the necessity of maintaining good vacuum to avoid insulator, transmission line, and coil shorting.

A 200-T, 2 MA system was also constructed using the experience from the first design to make the pulsed-power system more robust. This machine is a copy of the prototype design, but with ten 100-kV capacitors versus the two used in the prototype. It has additional inductance in the switch/capacitor unit to avoid breakdown seen in the prototype design. It also has slightly more inductance at the cable connection to the vacuum chamber. With this design we have been able to demonstrate 1 MA current into a 1 cm diameter coil with the vacuum chamber at air pressure. Circuit code simulations, including the additional inductance with the new design, agree well with the measured current at a charge voltage of 40 kV with a short circuit load, and at 50 kV with a coil. The code also predicts that with a charge voltage of 97 kV we will be able to get 2 MA into a 1 cm diameter coil, which will be sufficient for 200 T fields. Smaller diameter or multiple-turn coils will be able to achieve even higher fields, or be able to achieve 200-T fields with lower charge voltage.

Work is now proceeding at the university under separate funding to verify operation at the 2-MA level, and to address issues of debris mitigation, measurement of the magnetic field, and operation in vacuum. We anticipate operation at full current with single-turn, magnetic field coils this fall, with 200 T experiments on the Texas Petawatt laser in the spring of 2012.

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University of Texas at Austin
Dept. of Physics, College of Natural Sciences
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Austin, TX 78712
- 1 Caleb J. Waugh
Massachusetts Institute of Technology
Nuclear Science and Engineering Dept., School of Engineering
77 Massachusetts Avenue
Cambridge, MA 02139

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