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STATUS OF THE 2 MA DRIVER FOR CREATING 2 MG MAGNETIC FIELDS FOR CLUSTER FUSION EXPERIMENTS

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Abstract

Now that the 400 kA version of a pulsed-power driver for magnetic coils for cluster fusion experiments has been completed, we are currently assembling a 2 MA version for generating magnetic fields up to 2 MG. Both versions are intended to drive single-turn, single-use 1-cm diameter magnetic field coils that enclose laser-produced, high-density deuterium cluster plasmas in vacuum. The driver is being built at the Sandia National Laboratories and laser-plasma experiments are being done at the University of Texas in Austin. The coils provide axial magnetic fields to slow radial loss of electrons from the plasma. Peak field with the 400 kA system is about 40 T, and will be up to 200 T for the 2 MA upgrade, with a current rise time of 1.7 μs for both systems. For these experiments the driver output must pass through a vacuum feed-through to couple to a short transmission line in vacuum that is terminated with a single-turn coil. This is done with a cylindrical insulator and conical transmission lines. A description of the device, and results of initial tests of the high-current version of the driver is given.

I. 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. [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 (~ 10^{19} /cm^3) and temperatures (~ 10 keV) of these plasmas, a 200 T magnetic field is needed to balance 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. The goal of this work is therefore to introduce sufficiently strong axial magnetic fields into cluster fusion experiments to slow radial expansion of the cluster plasmas to potentially increase neutron yield.

With field strengths of 200 T (2 MG) only single-use magnetic field coils are feasible since magnetic pressure exceeds tensile strength of any material that could be used for coil construction. A single-turn, 1-cm diameter coil, requires a drive current of up to 2.2 MA for this field. Multiple-turn or smaller diameter coils can lessen this requirement. But with the need to replace the coil with each shot it makes sense to keep coil design as simple as possible, thereby motivating single-turn coil use. Drivers that can supply this current are either not portable or they do not couple to coils in vacuum. For the cluster fusion experiments we need a driver that can be moved to a laser facility and that can deliver 2.2 MA to a coil in a vacuum chamber at the laser focus.

Two versions of a current driver for cm-sized magnetic field coils have built and tested at Sandia for the cluster fusion experiments at the University of Texas in Austin. Field strength for the two-capacitor system is in the range of 50 T, and up to 200 T for the ten-capacitor system. Current rise time for both systems is ~ 1.7 μs, with peak current of 500 kA and 2.5 MA, respectively.

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The 500-kA system has been built and is currently being used to test coil and cluster-fusion gas gun configurations at UT. The 2-MA system is also complete, has been tested at full voltage with two of its ten capacitors, and has been shipped to UT where it is being reassembled.

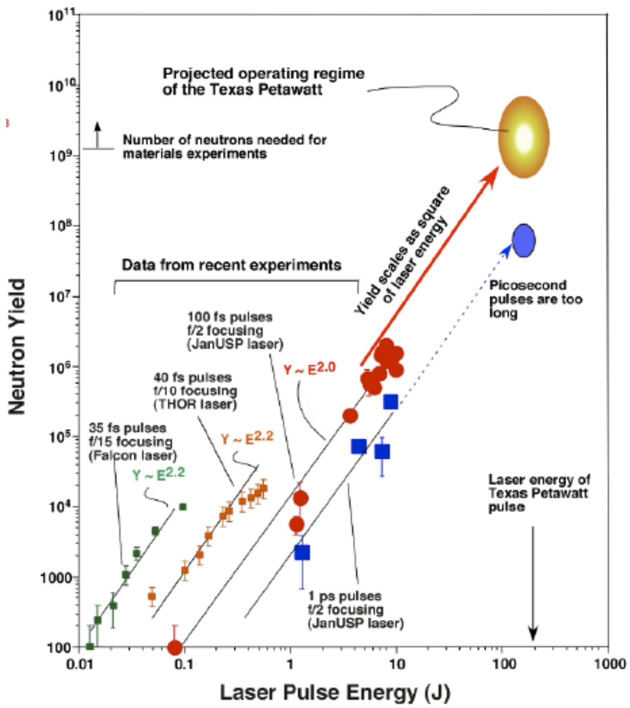

Figure 1. Neutron yield from deuterium cluster irradiation with various lasers. Plot courtesy Roger Bengston, Univ. of Texas, Austin.

II. 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, [7] and Mielke at the Los Alamos National Laboratory (LANL). [8] 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.

A. 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. [8] 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. 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.

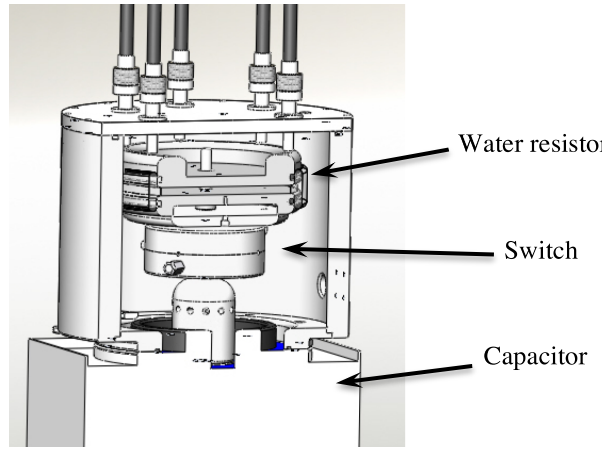

Figure 2. Capacitor and switch assembly with series water resistor. Area around switch is filled with SF_6 at atmospheric pressure.

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. This approach is shown in fig. 3. 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. 4.

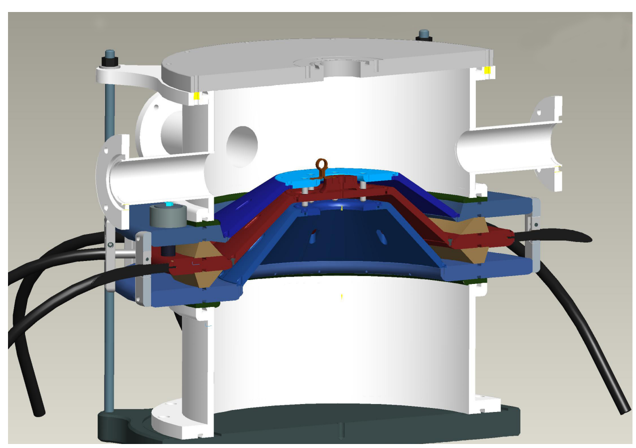

Figure 3. Vacuum chamber (internal diameter 41 cm) with feed-through for the two-capacitor drive system.

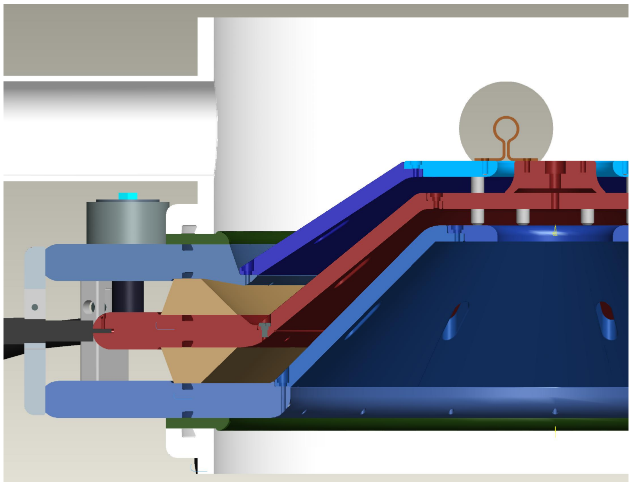

Figure 4. Conceptual coil connection. A single-turn coil is connected between the inner and outer lines.

B. 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 show in table 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 1. System inductance estimates.

	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 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. 5. Parameters for the components in the circuit are given in table 2. Predicted peak current, magnetic field, and magnetic pressure are given in table 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. [9] Predicted current, and voltage at the insulator are shown in fig. 6.

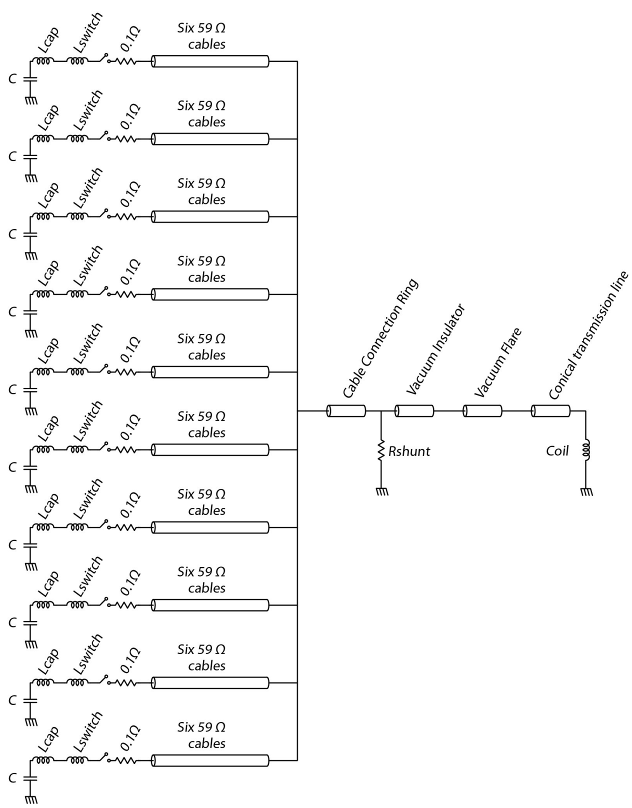

Figure 5. Bertha circuit model of the ten-capacitor system. Not shown is the charge circuit and relay tank, and the trigger circuit.

Table 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 (mΩ)	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 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) (= $B^2/2m_o$)
25	0.55	49	0.97
50	1.1	98	3.9
75	1.6	150	8.7
100	2.2	200	15

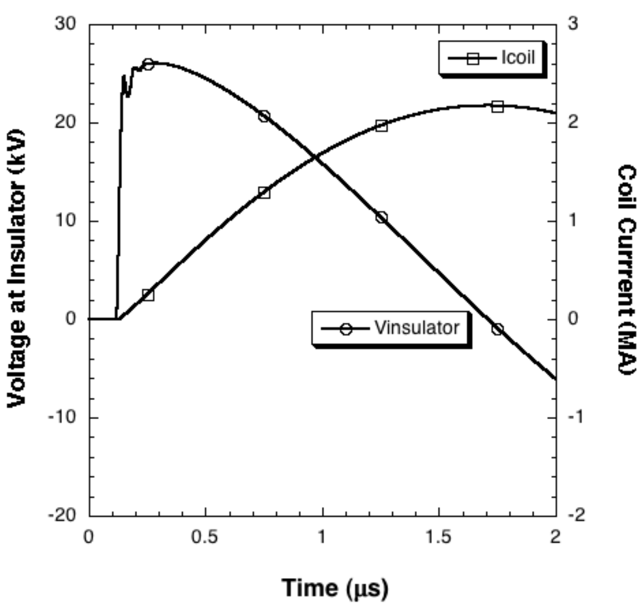

Fig. 6. Predicted current and insulator voltage.

C. 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 Communications. [10] 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 drivers. The switches are filled with dry air at 20 to 30 psia (130 to 200 kPa.)

A metal return-current can mounts to the top of the capacitor and is filled with sulfur hexafluoride, as shown in fig. 2. 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, [11] 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, [12] with power divided by 30 kΩ HVR [13] 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) [14] 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) [14] that is amplified by a Maxwell 40168 trigger amplifier. [10] 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 ½ the gap of the switches on the capacitors so that it fires at the same gas pressure.

The vacuum chamber, as shown in fig. 3, 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. Thus, the peak electric field at the airside of each insulator is 14 kV/cm.

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. 7. 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. This sheet must be cut away at this location 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

$$\frac{B(n)}{B(1)} = n\sqrt{\frac{\alpha+1}{\alpha+n^2}} \xrightarrow[as\ n\to\infty]{} \sqrt{\alpha+1} \qquad (1)$$

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.

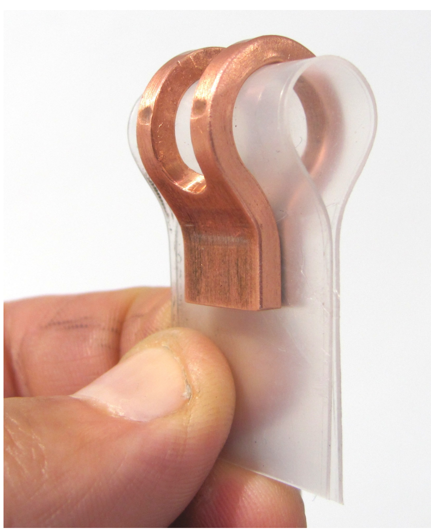

Fig. 7. Typical single-turn copper coil to be used for cluster-fusion experiments.

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. 8. 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.

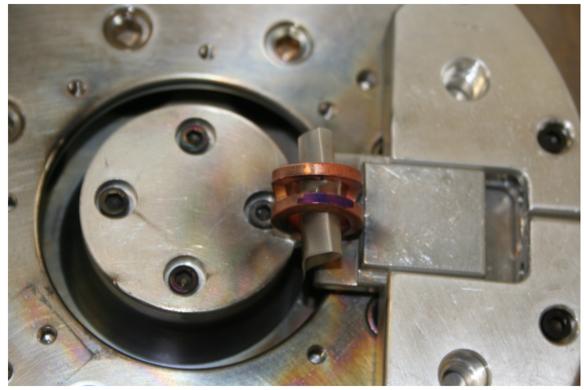

Fig. 8. Copper coil mounted to conical plates in the vacuum chamber.

III. 500-kA SYSTEM TEST RESULTS

The two-capacitor, 500-kA version 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. Driver Validation

Multiple shots were taken with the two-capacitor system into a low-inductance coil with a charge voltage of 100 kV. Peak current was 490 kA, as seen in fig. 9. 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.

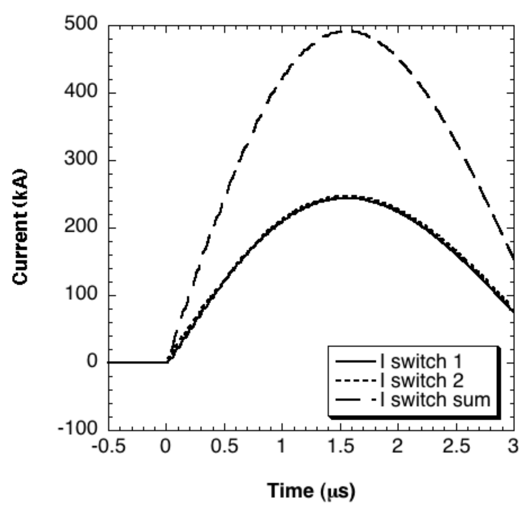

Fig. 9. Measured current into a coil with the two-capacitor system with a 100-kV charge voltage.

B. Coil Testing

The magnetic field coils depicted in figs. 7 and 8 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. But we are concerned about damage to the cluster gas gun nozzle, which must be close to the coil. Scoring the outer diameter of the coil may encourage coil breakup at specific locations to mitigate this potential damage. Other efforts will be taken to contain debris from the exploding coils.

IV. STATUS OF THE 2-MA SYSTEM

The ten-capacitor, 2-MA system has also been built and has completed preliminary testing at Sandia. It has also been shipped to UT, and is now in the process of being set up and tested at full current level. We anticipate tests with coils up to 200 T this fall, with special emphasis placed on debris mitigation, magnetic field measurement, and initial low-field tests with deuterium clusters on a lower power laser. In the spring of 2012 we plan to move the device to the Texas Petawatt laser 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.

V. SUMMARY

A 50-T, 400 kA prototype magnetic field driver system has been completed and used at the University of Texas in Austin. The system has been operated up to 100 kV, 490 kA. It is now being used for cluster fusion tests in vacuum with a lower-power laser system to investigate cluster injection into small magnetic field coils. Initial problems with shorting of the magnetic field coil with cluster injection have been solved by using an insulator inside the coil. These tests have confirmed that clusters are filling the space inside the insulator. A 200-T, 2 MA system has been constructed, has completed initial testing, and is being setup at the university. We anticipate operation at full current with single-turn, magnetic field coils early this fall, with 200 T experiments on the Texas Petawatt laser in the spring of 2012.

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