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THE DB/DT SYSTEM
HARDWARE AND PROTOCOL FOR INVESTIGATING THE HEALTH
EFFECTS OF RAPIDLY CHANGING MAGNETIC FIELDS

R. Bordow
(M.S. Thesis)

December 1983
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THE DB/DT SYSTEM

HARDWARE AND PROTOCOL FOR INVESTIGATING THE HEALTH EFFECTS OF RAPIDLY CHANGING MAGNETIC FIELDS

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Fall 1983
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ABSTRACT

The increased use of rapidly changing magnetic fields in areas such as medical imaging has sparked interest in the possible health effects of exposure to such fields. Two known physiological effects are the induction of magnetophosphenes (visual flashes of light), and enhanced bone healing and growth. A dB/dt (rate of change of magnetic field with time) of as small as 5 T/sec can be sufficient to induce magnetophosphenes. Since growing cells show particular sensitivity to rapidly changing magnetic fields, it is likely that more serious health effects may be observed in mice exposed during embryogenesis. This paper details the hardware and protocol developed to investigate these possible health effects.
A. System Overview

The purpose of the DB/DT* system is to provide the hardware and operating system necessary for investigations into the health effects of rapidly changing magnetic fields. The goal of the design was to produce a peak dB/dt of at least 5 T/sec, a peak field strength of at least 10 mT, and a repetition rate of up to 30 times per second. These minimum specifications were chosen because they were known to be sufficient for the magnetic induction of phosphenes. An investigation into the effects of such changing fields on mouse embryogenesis requires 24-hour/day exposure for periods of up to 4 weeks. Thus, reliability and safety were also major design considerations.

There were several constraints on the design. The coil driver had to be a general power amplifier to allow experimentation with various waveforms. It was desired to make use of readily available components: transformers, rectifiers, output transistors, and the coil. An unsafe and unreliable prototype capable of generating about 3.5 T/sec had been constructed previously. Thus, the objective was to build a safe and reliable system out of the existing components which more than doubled the performance of the prototype while keeping costs to a minimum.

The present system meets or exceeds all the above specifications. It now generates a peak dB/dt of 8 T/sec and reaches a peak B field of 39 mT at a repetition rate of 15 per second.

* The system name is a reference to dB/dt; the rate of change of magnetic field with time.
The remainder of this report is in four sections. Section B describes the system characteristics and capabilities; Section C, the experiments for which the system was designed; Section D the hardware; and Section E, alternate designs.
B. SYSTEM CAPABILITIES

B.1 Review of Inductors and Magnetic Fields

The DB/DT system is essentially a voltage source applied to an inductor and resistor in series (Fig. 1).

![Diagram of DB/DT system](image)

Figure 1. Model of DB/DT system.

The resistor is the resistance of the coil itself. At the low frequencies involved these elements are lumped and obey Kirchhoff's voltage law.

\[
\epsilon(t) + Ri(t) + L \frac{di(t)}{dt}
\]

When the applied voltage is a step function, this differential equation has the solution

\[
(B2) \quad i(t) = \frac{\epsilon}{R} (1 - e^{-Rt/L})
\]

When the source steps down to zero at time \( t_1 \), the new solution becomes:

\[
(B3) \quad \frac{di(t)}{dt} = \frac{\epsilon}{L} e^{-Rt/L}
\]
Current through an inductor gives rise to a magnetic field $B$ which is directly proportional to that current. Thus, the waveforms for $i(t)$ and $di(t)/dt$ also describe $B(t)$ and $dB(t)/dt$, respectively. Note from Eq. B3 that the maximum obtainable value for $di/dt$ and thus for $dB/dt$ is determined by $\varepsilon/L$.

The most commonly used waveform in the system is an asymmetric triangle wave. To obtain the solution to Eq. B1, we define the voltage across $L$ and $R$ as follows:
(B6) \( \epsilon(t) = V_1 t \) for \( t = 0 \) to \( t_1 \)

(B7) \( \epsilon(t) = \epsilon_m - V_2 (t - t_1) \) for \( t_1 \) to \( t_2 \)

where \( \epsilon_m \) is the maximum voltage attained = \( V_1 t_1 \)

\( V_1 \) is the slope of the rise = \( \epsilon_m / t_1 \)

\( V_2 \) is the absolute value of the slope of the fall = \( |\epsilon_m / (t_2 - t_1)| \)

Then it can be shown (see Appendix I) that the solution to Eq. B1 becomes

(B8) \[ i(t) = \frac{V_1 t}{R} + \frac{V_1 L}{R^2} \left( e^{-\frac{Rt}{L}} - 1 \right) \]

for \( t_0 \) to \( t_1 \)

(B9) \[ \frac{di(t)}{dt} = \frac{V_1}{R} \left( 1 - e^{-\frac{Rt}{L}} \right) \]

(B10) \[ i(t) = \frac{\epsilon_m}{R} + \frac{L V_2}{R^2} - \frac{V_2 (t-t_1)}{R} - \frac{L}{R} \left[ \frac{di(t_1)}{dt} + \frac{V_2}{R} \right] e^{-\frac{R(t-t_1)}{L}} \]

for \( t_1 \) to \( t_2 \)

(B11) \[ \frac{di(t)}{dt} = \left[ \frac{di(t_1)}{dt} + \frac{V_2}{R} \right] e^{-\frac{R(t-t_1)}{L}} - \frac{V_2}{R} \]

After the voltage reaches zero at time \( t_2 \), the solution reverts to Eqs. (B4) and (B5). Thus, the general appearance of the waveforms is as in Fig. 3.
Figure 3. LR circuit response to triangle wave.

B and i are related by a constant, so that

(B12) \[ B = Ki \]

For an ideal solenoid, the formula for \( K \) along the central axis of the coil is

(B13) \[
K(Z) = \frac{\mu_0 N}{2\pi T} \left\{ \left( \frac{r}{2} - Z \right) \ln \left[ \frac{r + \sqrt{r^2 + \left( \frac{r}{2} - Z \right)^2}}{(r - T) + \sqrt{(r - T)^2 + \left( \frac{r}{2} - Z \right)^2}} \right] + \left( \frac{r}{2} + Z \right) \ln \left[ \frac{r + \sqrt{r^2 + \left( \frac{r}{2} + Z \right)^2}}{(r - T) + \sqrt{(r - T)^2 + \left( \frac{r}{2} + Z \right)^2}} \right] \right\}
\]

where, if \( B = \) field strength \((T)\) and \( i = \) current through each turn \((A)\),
\[ \mu_0 = \text{permeability constant} = 1.26 \times 10^{-6} \text{ H/m} \]

\[ N = \text{number of turns} \]

\[ l = \text{coil length (m)} \]

\[ r = \text{outside radius (m)} \]

\[ T = \text{thickness of coil wall (m)} \]

\[ Z = \text{axial distance from coil center (m)} \]

For the same coil we can write

\[ (B14) \quad \frac{dB}{dt} = K \frac{di}{dt} \]

When a coil is placed in a changing magnetic field, the voltage induced on it is

\[ (B15) \quad \varepsilon = N\pi r^2 \frac{dB}{dt} \]

where \( \varepsilon \) is the voltage (\( \text{v} \))

\( N \) is the number of turns

\( r \) is the radius (m)

\( \frac{dB}{dt} \) is the rate (T/sec)

B.2 Predicting and Measuring System Performance

Determining what the system capabilities are consisted of using a combination of physical measurements and mathematical predictions. From measurements of coil resistance and inductance, current and rate of change of current can be predicted with Eqs. B4-B11. Use of Eq. B13 together with measurements of the physical dimensions of the coil gives
the constant that relates field strength and current. This constant can be determined directly by measurement of $B$ and $i$ with a gaussmeter and current meter. If the diameter of a coil and the voltage induced on it when placed in the system coil are measured, Eq. B15 can be used to get $dB/dt$. A third determination of the constant that relates $B$ and $i$ can be made by use of this value of $dB/dt$ and the value of $di/dt$ calculated above.

By these techniques, the constant relating $B$ and $i$ was determined to within ±7 percent of the exact value to be $1.4 \times 10^{-4}$ T/A. Actual values of $dB/dt$ can be determined to within 2 percent. For a detailed discussion on how the measurements were made, see Appendix II.

A plot predicting system behavior for a voltage rising to 33 V in 3.2 msec and falling back to zero in an additional 24 msec is shown in Figure B4. The predicted peak value of $dB/dt$ is 7.72 T/sec. The predicted maximum current is 306 A, which gives a $B$ of 43 mT.

Figure B5 is the system's actual response to the same input. The measured values indicated a peak $dB/dt$ of 7.69 T/sec and a peak current of 300 A. Both are within 2 percent of the prediction. This agreement adds confidence to any other predictions made for different rise and fall times.

### 8.3 System Limitations

Since both $B$ and $dB/dt$ are directly affected by the voltage applied to the coil, we could in principle get any value of $dB/dt$ by varying the voltage, except that the system's limitations prevent it in practice. The output transistors of the coil driver are limited by their reverse breakdown voltage and their secondary breakdown
Fig B.4

Response of L-R circuit to triangle voltage input (see Eq. B1, B5, B8 - B11)

\[ E_m = 35V \quad R = 0.64\Omega \quad L = 489\mu H \quad t_0 = 0 \]
\[ t_1 = 5.2\text{ms} \quad t_2 = 27.2\text{ms} \]
\[ V_i = 10312.5\text{V/s} \quad V_o = 1575\text{V/s} \]
Figure B5. System response to triangle wave.

characteristic. There is a limit on their current-carrying capability, but the secondary breakdown characteristic is the overriding factor. The rectifiers, the wiring, and the connections are limited by how much average current they can safely handle. The power transformers are limited both by how much current they can handle and by their output voltage (turns ratio).

*Nominal scale values for Trace A and B were 20 V/div and 20 mV/div. Values shown in the caption were determined from Trace C, which was accurately calibrated.

**2.40 div x 20.8 mV/div x 300 A/50 mV = 300 A.

***2.72 div x 0.100 V/div x 28.3 T/V = 7.69 T/sec.
In terms of system performance, the limitations on the components have the following implications. The maximum obtainable operating voltage is 33 V. The maximum safe operating current is 100 A average, 490 A peak, which yields maximum $B = 68$ mT and $dB/dt = 9.45$ T/sec. In addition, the limitation on average current puts a limitation on the repetition rate of the waveform for a given field strength.

Slower rise and fall times result in a lower peak $dB/dt$, but one that is sustained for a longer time. In addition, slower rise and fall times result in greater current flow and field strength. Since the maximum repetition rate is the reciprocal of the period, longer rise and fall times imply a lower repetition rate. Figure B6 shows the relationship between $dB/dt$ and the length of time it can be sustained. Figure B7 shows the effect of variations in voltage waveform on $B$ and $dT/dt$.

Thus, to achieve a peak $dB/dt$ of 8 T/sec and maintain a repetition rate of 15 per second, the maximum $B$ field that can be safely generated is 42 mT (Fig. B5).
Figure B6. dB/dt vs sustain time.

Input voltage 20 V/div 
rise times of 5 msec, 
12 msec, 24 msec, 35 msec 

Induced voltage on search 
coil 50 mV/div representing 
peak dB/dt of 7.6 T/sec, 
4.9 T/sec, 3.1 T/s, 2.3 T/s.

Time base = 10 msec/div

Figure B7. Effect of rise time on dB/dt.
C. DB/DT EXPERIMENTS

C.1 Overview

Living tissue exposed to a changing magnetic field has a voltage induced on it that in turn causes a current to flow. The DB/DT experiments are designed to investigate the physiological effects of such currents.

The absolute value of the voltage induced around a loop in a changing magnetic field is given by

\[ \varepsilon = \pi r^2 \frac{dB}{dt} \]

where \( \varepsilon \) = induced voltage (V)
\( r \) = radius (m)
\( \frac{dB}{dt} \) = rate of change of field (T/sec)

The strength of the electric field generated is given by

\[ E = \frac{\varepsilon}{2\pi r} = r \frac{dB}{dt} \]

where \( E \) is the field (V/m).

The current density is given by

\[ J = Es \]

where \( s \) is tissue conductivity (ohms\(^{-1}\))
\( J \) is current density (A/m\(^2\))

An order-of-magnitude relation between \( J \) and \( \frac{dB}{dt} \) of 1 \( \mu \)A/cm\(^2\) for 1 T/sec has been established [1,2,3].
Two well-known physiological effects of currents induced by changing magnetic fields are the enhancement of bone healing and the induction of magnetophosphenes.

The former has been accomplished by induction of current densities of $10 \, \mu A/cm^2$ at a repetition rate of 30 to 60 per second by the use of a coil near the fracture. It has been shown that asymmetric waveforms produce results and sinusoidal waveforms do not [4,5].

These facts provide the groundwork for the main set of experiments on mouse embryogenesis. If asymmetric waveforms induce changes in the growth pattern of bone cells, they are likely to have some effects on embryogenesis. In our experiments, each mouse develops from a single cell to hundreds of millions of cells during three weeks of constant exposure to $8 \, T/sec$ field changes repeated 15 times per second.

The second well-known effect is that of induced visual light flashes known as magnetophosphenes. Previous studies have shown a threshold for humans of 2 to 5 $T/sec$ provided that a minimum field strength of $10 \, mT$ is reached [6,7,8]. Our intention was simply to verify this threshold level.

C.2 Mouse Embryogenesis

The purpose of this set of experiments is to document any gross physical effects in mouse pups which have been exposed to a rapidly changing magnetic field continuously from conception to birth.

During the spring of 1983 an informal prototype experiment was carried out to develop and refine protocol for the series of experiments to follow. Sixteen litters were used, eight of which were
exposed to a field change of 3.6 T/sec at a repetition rate of 4 sec$^{-1}$ for nine hours per day, from conception to birth. The remaining eight litters were controls. Comparisons between the two groups included litter size and sex ratio. Careful physical inspections for gross physical abnormalities were made. Finally, x-ray films were made to look for obvious bone deformities.

The results of this experiment can be seen in the histograms in Fig. C1. No statistically significant differences were noted between the active and control groups. The examinations and x-rays also yielded no differences.

Among the problems identified in the prototype experiment were the need for more careful control of breeding, handling, and the physical environment of both groups of mice. At that time 3.6 T/sec was the limit of the system. Since then, an advanced system was built with an upper limit of 9.45 T/sec. Since no effects were noted with the prototype, the exposure time has been raised to 24 hours/day. Additional measurements such as weight and crown to rump length have been included. Everything learned from the prototype was used to develop a new configuration (Fig. C2) and protocol for the experiment. The active and dummy coils are oriented at right angles to each other and are about 3 ft apart at their closest point. The field at the dummy coil is less than 1 percent of that of the active coil. The coils are identical in construction and both have water flowing through them.
Fig. C1  Histograms of Litter Size* & Sex Ratio for DB/DT Faramouse

Active Coil (DB/DT = 3.6 T/s) (rep rate = 4 Hz)

- Average Size: 11.8
- Std. Dev: 1.3

Active Coil

- Average % Male: 56.5%
- Std. Dev: 15.0%

Dummy Coil

- Average Size: 10.4
- Std. Dev: 2.76

Dummy Coil

- Average % Male: 52.5%
- Std. Dev: 14.46%
Figure C2. Coils, cage, and paraphernalia used in mouse embryogenesis experiments.

The water through the dummy coil is heated to the same temperature as the water through the active coil. The only difference between the two is that the active coil (seen at right) has the electrical connections to the coil driver, and a plexiglass shield over these connections.

The mouse cages and tops contain no metal except for the nipple of the water feeder. A mouse cage bottom, top, and food hopper can be seen on the table between the two coils. Cages are held inside the coil by the wooden platforms shown in the figure. The mice are handled only with gloves, also shown between the coils. The lighting in the room is controlled by a timer and is on for 12 hours, then off for 12 hours.

Preparation for the experiment includes obtaining 16 virgin sexually mature females, and 8 proven breeder males from ICR Simonsen. Each mouse is identifiable by notches in the ear. Males and females are housed in close proximity (but not together) for four days prior
to the experiment to acclimatize them and to induce estrus. The females are handled once each day with gloves to accustom them to that. The DB/DT system is turned on at least 24 hours prior to starting time to allow it to completely stabilize.

To begin the experiment, two cages are partitioned into four quadrants each. Two females and one male are placed in each quadrant. One cage is placed in the active coil, the other in the dummy. All females are inspected twice each day for vaginal plugs indicating pregnancy. Those with plugs are noted in the log. Each day the equipment is inspected for proper operation. Food and water supplies are maintained, and cages are cleaned. All mice are inspected for evidence of illness or fighting.

After six days, or until all females in both cages have been impregnated (whichever comes first), all males and partitions are removed from the cages. From this time on, cages are cleaned every three days, and females are weighed at set intervals. Females are still handled once each day.

On day seventeen of the pregnancy, each female is removed to a separate cage to prevent mixing of the litters. Cages are now cleaned every two days. Pups are weighed every two days. Crown to rump measurements are made at less frequent intervals. After six weeks, the pups are sexed and sacrificed. Data on sex ratio are recorded and x-rays are made to check for bone deformities.

The next three pages are the computer generated forms used to record data and check operation of the equipment as the experiment progresses.
MATING CAGE RECORD

Males and females proximate (not together) between __/___/___ and __/___/___
Date males and females put together in partitioned cage (and in coil) __/___
Placement diagram during breeding period. Colors on top match those on cage.

Red  | sire     | sire     | Brown
     | dam      | dam      |
     | P        | P        |
     | dam      | dam      |
     | P        | P        |

Black | sire     | sire     |
      | dam      | dam      |
      | P        | P        |

Note all unusual conditions in log. Y or N for (?) below. See checklist if *.
Inspection mice with clean equip. water, mice
              time date new plugs cage? OK* food? OK* comments

1A

1P

2A

2P

3A

3P

4A

4P

5A

5P

6A

6P

7P

7P
GROUP CAGE RECORD

Weigh each dam on days 6, 11, 15, and 20 of its gestation. Record on Single Cage Record.

Note all unusual conditions in log. Y or N for (?) below. See checklist if *.

date and time ID mice weighed clean equip. water, mice note initials of inspection (record on SCR) cage? OK?* food? OK?* in log?

---

Equipment checklist

---

water 20 psi on driver?
water 40 psi each coil?
function generator on?
driver on (check meter, white lite)?
transformer on (red telltale)?
scope on, scope traces correct?

room light timer working correctly?

check for water leaks

---

Mouse checklist

---

eyes open, bright, no deposits near or in eyes
whiskers, ears, tail and fur intact
fur smooth and clean vs matted and dirty
animal active in cage
SINGLE CAGE RECORD

dam ID _____ sire ID _____ date plug found __/__/__ (day 0)
dam weight: day 0 (__/__): _____, day 6 (__/__): _____
day 11 (__/__): _____, day 15 (__/__): _____, day 20 (__/__): _____

birth date __/__/__ # of pups in litter __ day 19: __/__/__

date time dam pup total ave. clean check: log initials
wt. ct. wt. wt. cage? eqip. cage note? 

---

---

---

---

---

---

---
C.3 Magnetophosphenes

This experiment was done to verify the threshold of dB/dt needed to induce visual flashes of light for human subjects. A simple protocol was followed.

Four male subjects were used. The value of dB/dt was set and measured using a search coil. This value was unknown to the subjects. Each subject inserted his head into the coil (Fig. C3).

After all the subjects had been exposed, each was queried as to what had been experienced. The level of dB/dt was then readjusted by the experimenter and the process repeated. It was found that the threshold varied slightly with repetition rate. Subjects were most sensitive to a repetition rate of 15 per second. At this repetition
rate, a dB/dt of 5 T/sec was required to cause the induction of phosphenes. These results verified those mentioned in the overview.

The subjects, who had their eyes open during exposure, reported seeing a dim but unmistakable shimmering field of light when dB/dt was turned up to 5 T/sec.
D. HARDWARE DESCRIPTION AND THEORY OF OPERATION

D.1 Block Description

An overview of the hardware reveals six physically separate components (see block diagram on the following page).

The transformer bank steps down the 208-V rms three-phase input to a 28-V rms three-phase output.

The air-cooled rectifier/filter converts the 28-V AC into an unregulated 40-V DC power supply for the coil driver.

The coil driver is a water-cooled, low-output-impedance power amplifier which provides voltage and current to the coil.

The waveform generator provides the triangle waves to be amplified by the coil driver.

The coil itself consists of two fifty-turn coils of copper tubing wound one over the other and connected in parallel. It is 37.4 cm in length and 30.4 cm in outer diameter. It is also water cooled.

The interlocks shut the system down if the flow of cooling water to the coil or coil driver is reduced below safe levels. (For a detailed description of each section as well as the way they interface and operate with each other, see the following sections and the corresponding illustrations in Appendix IV).

D.1.1 Transformer Bank (see Appendix IV-1)

This unit converts the 208-V three-phase input into a 28.6-V three-phase output. It consists of two three-phase transformers, two solid-state and two mechanical relays, three circuit breakers, a fan, indicator lamps, and input and output connectors.
Fig. D1  BLOCK DIAGRAM
The transformers are actually six single-phase transformers connected as two three-phase Wye-Wye transformers in parallel. The turns ratio for each of the six transformers is 120:16.5. The three-phase wye connection causes a factor of $\sqrt{3}$ to be introduced and thus the effective ratio is 208:28.6.

The circuit breakers place a limit of 30 A on the current through the primaries to provide short-circuit protection. A 5-A breaker limits the current to the control circuitry.

The solid-state relays are part of the control path and interrupt power to the primaries if any of the interlocks are not closed. (For a detailed description of how this arrangement interacts with the other components, see the control theory of operation section D.2 and Appendix IV-5.)

D.1.2 Rectifier/Filter (see Appendix IV-2)

This unit converts the 28.6-V three-phase transformer voltage to a 40-V unregulated DC supply. It consists of two three-phase rectifiers, a bank of filter capacitors, a fan, and some protective circuitry. The rectifiers consist of six diodes each and are both mounted on the same heatsink. The heatsink is composed of two blocks of aluminum separated by an insulator. One block serves as the ground bus; the other is the power bus. The two types of diodes used, the 1N2063R and the 1N3739, are identical electrically but differ in the way they are mechanically mounted in their case. The cathode is connected to the threaded end
in the 1N2063R, which screws into the power bus. In the 1N3739 the threaded end is the anode and it screws into the ground bus.

The outputs of the two rectifiers are connected in parallel across the capacitor bank of twenty electrolytic capacitors, each valued at 15,000 μF, and rated for 50 V, for a total of 0.3 F. Each capacitor is connected to the power bus by a piece of No. 22 copper wire, which would act as a fuse if a capacitor were to short out. The filter charges up to the peak value of the input, which is $\sqrt{2} \times 28.6 = 40.4$ V. Because it is unregulated, this voltage falls to 35 V with maximum loading.

The protective circuitry consists of a shorting relay, with normally closed contacts, and a microswitch. When power is turned off, the shorting relay connects the filter output to the bleeder resistors to dissipate the power stored in it. The microswitch is held closed by the top cover of the box, and is part of the control path. If the cover is off, the system cannot be turned on. If the cover is removed while the system is on, it shuts off and the charge is bled off the filter.

The fan blows air across the fins of the heatsink to reduce the heating of the rectifiers. (For more detailed information of the role of this unit in the control path, see the control theory of operation section D.2 and Appendix IV-5).

D.1.3 Waveform Generator (see Appendix IV-3)

This unit generates the triangle voltage waveforms which are amplified by the coil driver. It consists of a ±15-V power supply, an
ICL 8038 waveform chip, two op-07 op amps, and associated resistors, capacitors, potentiometers, and switches.

The rise time, fall time, amplitude, and DC offset of the waveform are independently adjustable. The rise time can be set from 2.7 to 25 msec; the fall time, from 25 msec to 1 sec. The corresponding repetition rates range approximately from 1 to 33 per second. The amplitude is adjustable from zero to 15 V. The DC offset ranges from +10 to -10 V.

Switches S1 and S2 and two empty IC sockets have been provided to prevent user error during experiments. When S1 and S2 are in the FRONT position, the front panel controls described above are all operational. When S1 and S2 are thrown to the INTERNAL setting, the front panel controls are locked out. Rise time, fall time, amplitude, and offset are then determined by the components in the IC sockets. (Figure IV-3-3 in Appendix IV-3 shows which sockets affect which parameters.) At this writing, the internal settings provide a 2.7-msec rise from 0 to 3.9 V and a 24-msec fall back to 0. The offset is zero and the repetition rate is 15 per second. In between repetitions of the waveform, the output falls to -0.6 V, but it is only the positive portion of the waveform that is amplified by the coil driver.

The ±15-V power supply is a piece of surplus equipment; no schematic was available. However, it does have an adjustment potentiometer and can be varied from ±12 to ±15 V. Its outputs are always symmetric.
The heart of this unit is the ICL 8038 waveform generator. It is actually capable of delivering square, triangle, and sine outputs though only the triangle output is currently wired. External resistors and capacitors control the characteristics of the waveforms. The unit produces a triangle wave symmetrical in amplitude with respect to ground potential. Its output goes through the amplitude control to OP-07 No. 1, which is an inverting summing amplifier. The triangle wave is summed with the output of the DC offset controls. OP-07 No. 2 is an inverting clipping amplifier, which prevents the output from going below -0.6 V. The diode in the feedback path causes this effect. Thus, the voltage range of the output of the entire circuit is -0.6 to +15 V.

D.1.4 Coil Driver (see Appendix IV-4)

The main purpose of the coil driver is to amplify the signal from the waveform generator and apply it to the coil. The coil driver also serves as the center of the control circuitry. Its main components are the op amps and transistors of the signal path, and the switches, relay, and indicating lamps of the control path.

The signal path flows in the following manner. The output of the waveform generator feeds the current-amplitude potentiometer, which controls the level of the signal reaching the rest of the circuitry. From here the signal passes through the two op amp stages. Both these stages are inverting amplifiers. The first stage clips any negative going voltages. The second stage gets its negative feedback both from its own output and from the output of the entire coil driver. This
arrangement gives some limited protection against runaway gain occurring in some component further down the path. The signal then passes through two transistors, a 2N3019 and an MJE 2955. These two transistors act as a combination voltage and current amplifier. They use the 40-V DC supply, whereas the op amps use a ±15-V supply. The output of the MJE 2955 feeds each of the eight power transistor assemblies, which are in parallel. Each assembly consists of two pre-driver stages in series followed by ten drivers in parallel. All the transistors in the assembly are in the common-collector configuration; thus there is current gain but no voltage gain. This arrangement also implies that the maximum output voltage is the 40-V supply minus three p-n junction drops of approximately 0.7 V each, so that the lightly loaded output is about 38 V. Across each assembly is a set of three TranZorbs rated at 15 V each, to prevent any voltage transients from causing the voltage across the assembly to exceed 45 V. Across the outputs of the assemblies (and thus across the coil) are two diodes to short the freewheeling current from the coil and provide additional protection for the transistors. All the transistors on the assembly are 2N5885 NPN power transistors. Each assembly is individually water cooled.

Thus, we see that the output stage of the coil driver consists of 80 transistors in parallel, which may seem excessive, since each transistor is rated at 25 A maximum. There are two reasons it was necessary to use four times the number of transistors that are apparently needed for a 500-A output. The first reason is that all
the transistors are in parallel, and bipolar transistors in parallel
do not share current well. In fact, they tend to hog current. Any
current imbalance between two transistors becomes worse if left alone.
Thus, if any one of the eighty transistors exceeds its limit and
shorts, the entire coil driver is shorted and a major blowout occurs.
If a transistor opens, its share of the load must be carried by the
others, which brings them closer to their limit. To compensate, all
the transistors used were tested on a curve tracer. All the output
transistors on a given assembly have been matched for current gain to
minimize current hogging. The two pre-drivers on each assembly were
chosen to make all the assemblies match as closely as possible. A
potentiometer is in series between these two predrivers. By use of a
clamp-on current meter and a dummy load that draws 80 A, these pots
were adjusted so that each assembly put out 10 A.

The second reason it was necessary to use so many transistors is
the secondary breakdown characteristic of the transistors. Though they
are rated at 200 W each, there are certain combinations of collector-
to-emitter voltage and collector current that will cause breakdown at
much lower powers. Figure 5 of the 2N5885 specifications in Appendix
III-1 shows that with 50 V across it, as little as 1.7 A causes the
transistor to break down. Thus, we see that this problem compounds
(and is compounded by) the first problem of current hogging. Finally,
it was observed in the original prototype that a safety factor of 2 was
insufficient. Even with water cooling, we observed repeated breakdowns
of the device, usually within a few hours after it was turned up to
maximum output. The present design, with a safety factor of 4 and carefully matched transistors, has proved to be a good one. It has been successfully run at maximum output continuously for four weeks.

After passing through the coil, the current from the output stages passes through a shunt that is used to provide current monitoring. The shunt drops 50 mV when 300 A passes through it and is accurate to 0.25 percent. The voltage developed across the shunt is used to drive a current meter on the front panel. The 40-V DC supply is connected to a voltmeter, also on the front panel.

The control circuitry in the driver consists mainly of the on and off switches, a solid-state relay, and several indicator lamps. (For details on how this circuitry interacts with the other system components, refer to section D.2 on control theory of operation, and also to Appendix IV-5.)

D.1.5 Coil

The coil consists of two fifty-turn coils wound one over the other and connected across the coil driver in parallel. The job of the coil is to convert the voltage from the coil driver into a changing magnetic field.

The coil is 37.4 cm in length and 30.4 cm in outer diameter. The turns consist of 3/16" copper tubing wrapped around a lucite cylinder and separated and insulated by epoxy. The coil is cooled by water flowing through the tubing.
The resistance of the coil is 0.067Ω; its inductance is 489 μH; its L/R time constant is 7.6 msec. The coil generates a field of 1.4 \times 10^{-4} \text{T for each } 1 \text{ A of current through all the turns. (For more background on the implications of the coil parameters, refer to section B and section E.1.)}

**D.1.6 Interlocks**

The interlocks serve the purpose of providing an open set of contacts when the water flow through the coil and/or coil driver is insufficient for safe operation. When flow is sufficient, the contacts are closed. The coil and coil driver have separate water flow paths and separate interlocks. (For more detailed information on how the interlocks protect the system, refer to the next section on control theory of operation.)

**D.2 Control-theory of operation (see Appendix IV-5)**

The best way to understand the control aspects of the system is to take a step-by-step look at what happens when it is turned on and off. Assuming that the 208-V three-phase input is connected to the terminal strip in the transformer box, the first step is to close the three circuit breakers CB1, CB2, and CB3. Closing CB1 and CB2 simply transfers the three-phase voltage to the contacts of mechanical relays Re1 and Re2. Closing CB3 provides power to all the control circuitry. CB3 taps one 120-V leg of the three-phase input. This 120 V is applied to fan M and to one side of the coils of relays Re1 and Re2. Note that Re1 and Re2 do not turn on at this time because their coils get a ground through normally open solid-state relays Re3 and Re4.
The 120-V control voltage is also applied to contact A of connectors PG1 and PG2. A cable transfers this voltage to PG1 contact A on the coil driver. From here it is applied to the ±15-V power supply, contact 6 of the on switch, and the green control power indicator lamp. If the ±15-V power supply is in working order, it immediately supplies +15 V to contact 4 of the off switch, which causes the red indicator lamp in that switch button to light. To summarize, closing CB3 should cause the fan in the transformer box, and the green and red indicator lamps on the coil driver to turn on.

When the on button is pushed, the 120 V on contact 6 is transferred to contacts 2 and 3 of the on switch, contact C of PG1, and contact B of PG3. A cable from the coil driver to the rectifier/filter brings the voltage to the microswitch in the rectifier box. If this switch is closed (meaning the cover is on), the 120 V energizes the shorting relay in the rectifier box and removes the bleeder resistors from across the filter. It also transfers the voltage back to the coil driver through PG3 contact C. Thus, it can be seen that if this microswitch is open for any reason, the filter remains shorted, and the 120-V control voltage is not returned to the coil driver. Once returned to the coil driver, the control voltage is applied to the Gems Load-Pak, which is a contact-controlled solid-state relay. Contacts one and two are closed only if contacts three and four are shorted. Contacts three and four of the Load-Pak connect to contacts B and C of PG4. These contacts are connected in series with the two water-flow interlocks. Thus, we see that if either of the interlock contacts are
open, the Load-Pak does not transfer the control voltage to the rest of the control circuitry. Assuming the interlocks are all closed and the off button is not depressed, the control voltage is applied to a voltage divider, rectified, filtered to 22-V DC, and applied to contact D of PG1. Note that contacts B and E are neutral. This voltage on contact D is routed back to the transformer box, where it energizes solid-state relays Re3 and Re4. Closing the contacts of Re3 and Re4 provides a ground return for the control power through the coils of mechanical relays Rel and Re2, causing them to energize and close their contacts. When Rel and Re2 close, the three-phase power is applied to the primaries of the transformers. It is then stepped down, rectified, filtered, and applied to the coil driver, where it causes the white indicator lamp in the on button to light, and the voltmeter to indicate 40 V.

In addition, the closing of Rel and Re2 cause the red indicator lamps on the transformer box to light. To summarize, provided all the interlocks are closed and the circuit breakers have been closed, pushing the on button causes the red indicator on the transformer and the white indicator on the coil driver to turn on. In addition, power is applied to all the noncontrol circuitry. Note that everything stays on when the on button is released because once Rel is closed, control power has a path through PG1 contact C to contacts 2 and 3 on the on switch.
When the off button is pushed, power to Re3 and Re4 is interrupted, thus causing Re1 and Re2 to de-energize. This action in turn removes power from the primaries and causes the bleeder resistors to be applied across the filter. Note that any break in the interlock contacts while the system is on has the same effect.

D.3 Operating Procedures

D.3.1 Power-on Procedure

1. Turn water on to coil (40 psi) and coil driver (20 psi).
2. Switch on circuit breakers on transformer box.
   i) Green and Red indicators on coil driver should light.
3. Turn on waveform generator and scope. Adjust if needed.
4. Make sure current amplitude adjustment is set to zero.
5. Push on button
   i) A loud thunk indicates the shorting relay in the rectifier/filter box energizing
   ii) Red indicators on transformer box light.
   iii) The front panel voltmeter shows 40 V
6. Adjust current amplitude for no more than 100 A average. Peaks may reach 490 A.

D.3.2 Power-off Procedure

1. Adjust current amplitude to zero
2. Push the off button
   i) White indicator goes out
   ii) Voltmeter falls to zero
3. Turn off waveform generator and scope
4. Open circuit breakers on transformer box
5. Turn water off to coil and coil driver
E. ALTERNATE DESIGNS

The goal of any alternate design for this system is to be able to increase the maximum value of dB/dt while still maintaining some minimum value to which the B field must build. Safety and reliability must also be considered essential.

E.1 Prototype vs. Present Design

The prototype system contained all the same basic elements as the current system, but configured differently. In order to operate reliably, its maximum output was limited to less than half the current system capability. The output transistors, rectifier diodes, power transformers, and coil were the same as the ones currently being used. Yet there were several important differences.

The coil driver was in a bipolar configuration. That is, there were really two coil drivers, one using a positive voltage and the other a negative. The coil itself is composed of two coils wound one over the other. The old system had them in series with the junction of the two connected to ground. The ends went to the outputs of the positive and negative coil drivers, respectively. Thus, the rectifier was really two rectifiers, and the transformer bank was two independent three-phase transformers rather than two in parallel. If the system had been capable of the power output of the present system, it would have given much the same results. Each of the two coils would still have about 33 V across it and the fields developed would still add. However, the old system used half as many output transistors, and half of the those were complementary PNP rather than NPN. The transistors
were never matched for each assembly, and no TranZorbs were used to suppress transients. The rectifier, filter, and coil driver were all contained in one very crowded enclosure.

The result was a system that failed often when brought up to desired power levels. The poor enclosure design made for very time-consuming repair work.

The major improvements made in the design were as follows. The number of output transistors was doubled and they were all made the same type (2N5885-NPN). The rectifier and filter were turned into a single positive supply and were removed to a separate enclosure. The transformers were connected in parallel instead of being isolated. These steps improved reliability, eased servicing, and eliminated possible asymmetries between the two supplies and drivers.

E.2 Coil

The design of the coil has a major impact on what values of $B$ and $dB/dt$ are obtained with a given coil driver. The constraints on any new coil design are that it should have approximately the same dimensions of length and diameter, it must not draw more current than the driver can supply, and it must attain a field strength of at least 10 mT. The physical dimensions cannot be made smaller without overcrowding the mice, and cannot be made larger without reducing the $dB/dt$ generated. The present system reaches a peak $dB/dt$ of about 8 T/sec and a peak field of about 39 mT with the input waveform we use. The system limits are 9.45 T/sec and 68 mT as rise time approaches zero and fall time approaches infinity. If we are willing to sacrifice
some field strength, a greater peak dB/dt can be obtained with a
different coil design. The average dB/dt can also be increased in
this manner, although it is then available for a shorter time period.

The proposal is to construct a coil with 25 turns of larger
diameter tubing, so that the length and diameter of the coil stay the
same. The resulting coil would have about the same resistance as the
two 50-turn coils in parallel. The inductance would be approximately
one quarter as great, so that the time constant of the coil L/R would
drop to one-quarter of its present value. The constant relating B and
i would be one half as great. Since the maximum attainable dB/dt is
that constant times the applied voltage divided by the inductance, the
maximum dB/dt is doubled.

Figure E.1 shows that with the same waveform we use now, this new
coil would produce roughly the same dB/dt but only about 2/3 of present
value of B. However, if the rise time is cut to 500 μsec, the peak
dB/dt becomes nearly double that of the present coil and the maximum
value of B still reaches 2/3 of the present value.

There is one important aspect of this modification, the
implications of which are not known. With the present coil, the peak
value of dB/dt occurs when B is about 14 mT. With the new design, B
is only about 4.5 mT at the time the peak dB/dt is reached, though the
value of B eventually reaches 28 mT.

These predictions are based on ideal behavior, but there are
second-order effects that should also be considered. The coil
resistance would be likely to drop if larger-diameter tubing is used.
FIG. E1  Comparison of present and proposed coil
The constant that relates $B$ and $i$ may drop by more than a factor of two because the windings would not be as closely spaced. A drop in resistance and the constant of 25 percent would yield a peak $dB/dt$ of about 12.5 T/sec.

Therefore, by changing only the coil we should be able to increase the peak $dB/dt$ of the system by a factor of 1.5-2. Before any construction is done, further research on the relationship between the spacing of the turns and the constant relating $B$ and $i$ should be done.

E.3 Increasing Power Output

If we wish to increase the $dB/dt$ available from the system without sacrificing the strength of the field, we must increase the power-handling capability of the system. Using the present coil, we should have to increase $E_{\text{max}}$ and the system's ability to handle the added current drawn. This change implies rebuilding or modifying the transformer bank, the rectifier/filter, and the coil driver. Probably the most promising approach for the coil driver is the use of power MOSFETs as the output stages.

E.3.1 HEXFET System

This proposal is for a system based on the IRF 150 HEXFET. It will handle three times as much current as the present system. This device has many features that make it desirable in this application. It has an on resistance of 0.055 $\Omega$, a breakdown voltage of 100 V, and a DC drain current capability of 40 A. The on resistance of the device increases with temperature, which causes devices in parallel to share current evenly. There is no secondary breakdown characteristic to
limit power-handling capability. (The complete specifications for the
device are given in Appendix III-11.)

The system would be based on an $E_{\text{max}}$ of 100 V. With the same
coil we have now, this change would cause a maximum current of
approximately 1500 A. The maximum dB/dt available would be 28 T/sec.
If it were run with the same rise and fall times used now it would
produce a peak of 24 T/sec.

To handle safely 1500 A for less than 100 msec at a time, at least
40 devices should be used for safety. The current drive required by
40 devices should be less than 10 mA for rise times of 250 usec or
longer. Therefore, the front end of the amplifier should not require
more than a single transistor stage. The devices come in a TO-3
package that is compatible with the water-cooled heat sinks we now use.
All the cabling inside the driver would have to be increased to handle
a greater average current.

The rectifier/filter would have to be rebuilt to accommodate the new
coil driver. The rectifiers are easily capable of handling the
anticipated 300-A average current as long as they are kept cool.
Though they are capable of withstanding temperatures of well over
100°C, they should be water cooled for reliability and safety. The
present rectifier is air cooled. The filter would have to be rebuilt
because the capacitors are only rated at 50 V. With the existing
filter, a voltage drop of 7 V occurs at maximum current drain. With
the new heavier drain, a larger filter will be required, at least
0.5 F. Once again, all system wiring and connections would have to be upgraded to handle the added current.

The transformer bank would have to be replaced by one with a higher turns ratio in order to get 100 V at the filter. The new turns ratio should be approximately 3:1. The existing waveform generator and interlocks could be used.

The estimated cost of the transistors plus twenty backups is approximately $3000. The filter capacitors would cost about $500. Labor costs for machining a water-cooled heatsink for the rectifiers plus putting everything together would be considerable.

E.3.2 Switched Capacitor System

This system would employ a large bank of capacitors that would be slowly charged by an external supply and then quickly discharged through the coil. This type of design would not allow experimentation with variously shaped waveforms. This fact, combined with the massive size of the capacitor bank required, and my inexperience with this type of design, constrains me to give it no more than this passing mention.
APPENDIX I

Proof of Solution of L-R Circuit with Triangle Voltage Input

For the solutions to be valid, the following boundary conditions must be met:

\[ \epsilon(t) = Ri(t) + L \frac{di(t)}{dt} \] for all \( t \)

\[ i(t^-) = i(t^+) \] for boundary times \( t_0, t_1, t_2 \)

\[ \frac{di(t^-)}{dt} \frac{di(t^+)}{dt} \] for boundary times \( t_0, t_1, t_2 \)

Then for \( t_0 \leq t \leq t_1 \) if we substitute

\[ i = \frac{V_1 t}{R} + \frac{V_1 L}{R^2} (e^{-Rt/L} - 1) \]

\[ \frac{di}{dt} = \frac{V_1}{R} (1 - e^{-Rt/L}) \]

\[ \epsilon = V_1 t \]

into

\[ \epsilon = Ri + L \frac{di}{dt} \]

Then we have

\[ V_1 t = R \left[ \frac{V_1 t}{R} + \frac{V_1 L}{R^2} (e^{-Rt/L} - 1) \right] + L \left[ \frac{V_1}{R} (1 - e^{-Rt/L}) \right] \]

\[ V_1 t = V_1 t + \frac{V_1 L}{R} e^{-Rt/L} - \frac{V_1 L}{R} + \frac{V_1 L}{R} - \frac{V_1 L}{R} e^{-Rt/L} \]

\[ = V_1 t \]

\[ i(0^-) = 0, \quad i(0^+) = \frac{V_1(0)}{R} + \frac{V_1 L}{R^2} (e^0 - 1) = 0 + \frac{V_1 L}{R^2} (1 - 1) = 0 \]

\[ \frac{di}{dt} (0^-) = 0, \quad \frac{di(0^+)}{dt} = \frac{V_1}{R} (1 - e^0) = 0 \]
For \( t_1 \leq t \leq t_2 \) if we substitute

\[
i = \frac{\epsilon_m}{R} + \frac{LV_2}{R^2} - \frac{V_2(t-t_1)}{R} - \frac{L}{R} \left[ \frac{d\epsilon(t_1)}{dt} + \frac{V_2}{R} \right] e^{-\frac{R(t-t_1)}{L}}
\]

\[
\frac{d\epsilon}{dt} = \left[ \frac{d\epsilon}{dt(t_1)} + \frac{V_2}{R} \right] e^{-\frac{R(t-t_1)}{L}} - \frac{V_2}{R}
\]

\[
\epsilon = \epsilon_m - V_2(t - t_1)
\]

into \( \epsilon = Ri + L \frac{di}{dt} \), then we have

\[
\epsilon_m - V_2(t - t_1) = \epsilon_m + \frac{LV_2}{R} - V_2(t - t_1) - \frac{L}{R} \left[ \frac{d\epsilon(t_1)}{dt} + \frac{V_2}{R} \right] e^{-\frac{R(t-t_1)}{L}}
\]

\[
+ L \left[ \frac{d\epsilon(t_1)}{dt} + \frac{V_2}{R} \right] e^{-\frac{R(t-t_1)}{L}} - \frac{LV_2}{R}
\]

\[
\epsilon_m - V_2(t - t_1) = \epsilon_m - V_2(t - t_1)
\]

\[\frac{d\epsilon(t_1^-)}{dt_1} = \frac{V_1}{R} \left( 1 - e^{-\frac{R(t_1/L)}{L}} \right) , \quad \frac{d\epsilon}{dt} (t_1^+) = \left[ \frac{d\epsilon(t_1)}{dt} + \frac{V_2}{R} \right] e^{0} - \frac{V_2}{R}\]

\[
\frac{d\epsilon(t_1^-)}{dt} = \frac{d\epsilon(t_1^+)}{dt}
\]

\[
i(t_1^-) = \frac{V_1 t_1}{R} + \frac{V_1 L}{R^2} (e^{-\frac{R(t_1/L)}{L}} - 1) = \frac{\epsilon_m}{R} + \frac{V_1 L}{R^2} (e^{-\frac{R(t_1/L)}{L}} - 1)
\]
\[ i(t_1^+) = \frac{e_m}{R} + \frac{LV_2}{R^2} - \frac{V_2(0)}{R} - \frac{L}{R} \left[ \frac{di(t_1)}{dt} + \frac{V_2}{R} \right] e^0 \]

\[ = \frac{e_m}{R} + \frac{LV_2}{R^2} - \frac{L}{R} \left[ \frac{V_1}{R} (1 - e^{-Rt_1/L}) + \frac{V_2}{R} \right] \]

\[ = \frac{e_m}{R} + \frac{LV_2}{R^2} - \frac{LV_1}{R^2} + \frac{LV_1}{R^2} e^{-Rt_1/L} - \frac{LV_2}{R^2} \]

\[ i(t_1^+) = \frac{e_m}{R} + \frac{LV_1}{R^2} (e^{-Rt_1/L} - 1) = i(t_1^-) \]

For \( t > t_2 \). If we substitute

\[ i = i(t_2)e^\frac{-R(t-t_2)}{L}, \quad \frac{di}{dt} = \frac{Ri(t_2)}{L} e^\frac{-R(t-t_2)}{L}, \quad \epsilon = 0 \]

Into

\[ \epsilon = Ri + L \frac{di}{dt} \]

Then we have

\[ O = Ri(t_2)e^\frac{-R(t-t_2)}{L} + L \left[ \frac{-Ri(t_2)}{L} e^\frac{-R(t-t_2)}{L} \right] \]

\[ O = Ri(t_2) - Ri(t_2) \]

\[ i(t_2^+) = i(t_2)e^0 = i(t_2^-) \]

\[ \frac{di(t_2^-)}{dt} = \left[ \frac{di(t_1)}{dt} + \frac{V_2}{R} \right] e^\frac{-R(t_2-t_1)}{L} - \frac{V_2}{R} \]
\[
\frac{di(t_2^+)}{dt} = \frac{-Ri(t_2)}{L} e^0 = \frac{-R}{L} i(t_2)
\]
\[
= \frac{-R}{L} \left\{ \frac{\epsilon_m}{R} + \frac{LV_2}{R^2} - \frac{V_2(t_2-t_1)}{R} - \frac{L}{R} \left[ \frac{di(t_1)}{dt} + \frac{V_2}{R} \right] e^{\frac{-R(t_2-t_1)}{L}} \right\}
\]
\[
= \frac{-\epsilon_m}{L} - \frac{V_2}{R} + \frac{V_2(t_2-t_1)}{L} + \left[ \frac{di(t_1)}{dt} + \frac{V_2}{R} \right] e^{\frac{-R(t_2-t_1)}{L}}
\]

Note that \(V_2(t_2 - t_1) = \epsilon_m\). Thus,
\[
\frac{di(t_2^+)}{dt} = \left[ \frac{di(t_1)}{dt} + \frac{V_2}{R} \right] e^{\frac{-R(t_2-t_1)}{L}} - \frac{V_2}{R} = \frac{di(t_2^-)}{dt}
\]
APPENDIX II

Description of Measurement Techniques

In order to determine dB/dt to within 2 percent, 50 turns of No. 24 magnet wire were wrapped around a lucite center machined to 3.00 cm on a lathe. It was placed at various locations in the system coil and the voltage induced on it was measured with a calibrated channel of a Tektronics model 561A oscilloscope. From Eq. B15 it was determined that a dB/dt of 28.3 T/sec would induce 1.00 V.

The resistance and inductance of the coil were measured directly and indirectly. Direct measurement was made with an Electro-Scientific Industries model 252 RLC meter. On a 2-mH scale, inductance was measured to be 0.489 mH. On a 2-Ω scale, resistance was measured to be 0.09 Ω. The lack of a second significant figure on the resistance made that measurement highly questionable.

Indirect measurement of R and L were made as follows. The voltage across the search coil mentioned above was used to determine when dB/dt (and thus di/dt) was zero; then the voltages across a shunt and across the coil were measured on the scope. The shunt is rated at 50 mV per 300 A and is accurate to within 0.25 percent. The scope can be read to within 2 percent. Since Ldi/dt is zero, from Eq. B1 we have ε = iR. By this method R was determined to be 0.0673 Ω. To obtain L, careful time measurements of the scope waveforms were made, and curve fitting to Eqs. B8-B11 were done. This method yielded a value for L of 506 µH, within 4 percent of the measured value of 489 µH.
Three determinations of the relation between $B$ and $i$ were made. With an F. W. Bell Model 811 gaussmeter and an Model HAK8-2508 x 10 axial probe, the field was measured while a DC current was measured with the shunt. This measurement yielded a value of $1.36 \times 10^{-4}$ T/A. Unfortunately the measurement of the current was only that flowing through one of the two coils that make up the system coil. Therefore, the accuracy of this measurement depends on the symmetry of the two coils. Given the relatively simple nature of the construction, this measurement is estimated to be accurate to about 5 percent.

A second determination was made from Eq. B8-B11 and best fit values of $R$ and $L$ to give $\frac{di}{dt}$, with the search coil used to get $\frac{dB}{dt}$. This measurement yielded a value of $1.45 \times 10^{-4}$ T/A, 6.6 percent higher than the first value.

A third determination was made from the coil dimensions as measured with a scale, and Eq. B13. This method yielded a value of $1.31 \times 10^{-4}$ T/A or 3.6 percent below the first value.

Thus, I settled on a value of $(1.4 \pm 0.1) \times 10^{-4}$ T/A as the value of $K$. The maximum uncertainty is about 7 percent.
APPENDIX III

Data Sheets of Key Semiconductors

III-1  2N5885 NPN High Power Transistor
III-2  1N3729-44 High Power Silicon Rectifier
III-3  1N6098 - Schottky Barrier Rectifier
III-4  2N3019 - NPN Transistor
III-5  MJE 2955 PNP High Power Transistor
III-6  OP-07 Low Offset Voltage Op Amp
III-7  ICL 8038 Waveform Generator
III-8  ICT Transient Suppressor Diode (TranZorb)
III-9  Gem Solid State Load Pack No. 26392
III-10 LED Solid State Relay No. 22329/06
III-11 IRF-150 HEXFET (Power MOSFET)
APPENDIX III. Pages 51-101

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APPENDIX IV

Hardware

Drawings, Photos, Schematics

IV-1  TRANSFORMER BANK
    Fig. IV-1-1 Top View
    Fig IV-1-2 Inside Top View
    Fig. IV-1-3 Rear View of Top Panel
    Drawing IV-1 Transformer Schematic

IV-2  RECTIFIER/FILTER
    Fig. IV-2-1 Top View
    Fig. IV-2-2 Rear View
    Drawing IV-2 Rectifier/Filter Schematic

IV-3  WAVEFORM GENERATOR
    Fig. IV-3-1 - Front Panel
    Fig. IV-3-2 - Top View
    Fig. IV-3-3 - Switch and Socket Detail
    Drawing IV-3 Waveform Generator Schematic

IV-4  COIL DRIVER
    Fig. IV-4-1 - Front Panel
    Fig IV-4-2 - Rear Panel
    Fig. IV-4-3 - Top View
    Drawing IV-4 Coil Driver Schematic
Fig. IV-5-1 - Waterflow Interlocks
Drawing IV-5 - Control Schematic
APPENDIX IV-1  TRANSFORMER BANK

FIG IV-1-1  TOP VIEW of TRANSFORMER ENCLOSURE
208 V Input Line

Secondary Outputs to Rectifier/Filter

Top Panel (see Fig. IV-1-3)

Mechanical Relay

Transformer

FIG IV-1-2 Inside of Transformer Bank
Solid State Relays

Circuit Breakers

Fan

PG1

PG2

Fuse

Terminal Strip

Indicator

FIG. IV-1-3 BACK VIEW OF FRONT PANEL
APPENDIX IV-2  RECTIFIER/FILTER

a) Top View

+40V Output Lug (top)
Gnd Lug (bottom)
Heatsink
Cooling Fins
Fan

REAR

Connectors to Transformers (below diodes)
Interlock Connector P63
6x IN2043R Diodes (top)
6x IN3739 Diodes (bottom)
Bleeder Resistors
Microswitch
Shorting Relay
20x 15000 uF Filter Capacitors
+40V Bus (top)
Gnd Bus (bottom)
#22 Wire Fuses

FRONT

DB/DT RECTIFIER/FILTER

b) Front View

FIG IV-2-1  RECTIFIER/FILTER  TOP,  FRONT  VIEWS
a) Rear Cover

b) cover removed

FIG IV-2-2 RECTIFIER/FILTER REAR VIEWS
APPENDIX IV-3 WAVEFORM GENERATOR

FIG IV-3-1 WAVEFORM GENERATOR FRONT PANEL

- Fuse
- +15V Power Supply

FIG IV-3-2 WAVEFORM GENERATOR TOP VIEW

- Switch S2
- Switch S1
- ICL8038
- Op Ø7 #1

XBB 830-10976

Power Supply Voltage Adjust
Socket 2
Socket 1
Op Ø7 #2
Top View

16 Pin DIP Sockets

Switch 2

Switch 1

Front

Note: Each portion of the socket has room for two series resistors. If only one resistor is used, a short must be placed in the other pair of holes. Resistors are oriented vertically when viewed as in this figure. The lines shown between the bottom holes are wires under the sockets which connect the two inserted resistors in series.

Fig IV-3-3 Waveform Generator Switch & Socket Detail
**APPENDIX IV-4  COIL DRIVER**

Volts - shows voltage from rectifier/filter

AC On - green indicator lit by 120V AC control power

Interlock - connector PG 4 cable from here to water-flow interlock

**Fig IV-4-1 COIL DRIVER FRONT PANEL**

AC IN (PG1) control power from transformer bank

Coil V+ - hot lead to coil

Coil Gnd - gnd lead to coil

PG3 Interlock cable to Rectifier/Filter

IN/OUT - water connections to each of 8 heatsink assemblies

Amps - indicates current through coil

Current Amplitude - to turn pot controls signal level to coil.

Input - bnc to waveform generator

Current Monitor - bnc to scope to see current waveform

OFF - push to turn off

ON - push to turn on

**Fig IV-4-2 COIL DRIVER REAR PANEL**

Water IN/OUT - main coil driver water cooling connections.

V+ IN - +40V unregulated from Rectifier/Filter

GND IN - Gnd connection from Rectifier/Filter.
Fig. IV-4-3 Top View of Coil Driver

- +40 connection from Rectifier (top)
- Gnd connection (bottom)
- +40 V cable
- Gnd cable
- Isolation resistors
- Braid from assembly to bus
- Power bus to Coil
- Load Pak
- +15V supply
- Interlock PGA

REAR
- +40 bus plate
- Gnd connection to Coil (bottom)
- +40 connection to coil (top)
- Heatsink assembly (2 deep)
- Bus output to coil
- Current balance adjust pot
- Gnd return from coil
- Current shunt
- System Gnd
- MJE transistor
- Rectifier/divider
- Op amp PC board

FRONT
- Voltmeter
- Off
- Current monitor output
- Current meter
APPENDIX IV-5  CONTROL

- Water Input
- Sensitivity Adjust
- Coil Driver Interlock
- Water Output

Cable to Coil Driver PG4

Water Input
Coil Interlock
Water Output

FIG. IV-5-1  WATERFLOW INTERLOCKS
REFERENCES


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