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# TMX MAGNET CONTROL SYSTEM

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TMX MAGNET CONTROL SYSTEM

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A control system utilizing a microcomputer has been developed that controls the power supplies driving the Tandem Mirror Experiment (TMX) magnet set and monitors magnet coil operation. The magnet set consists of 18 magnet coils that are driven by 26 dc power supplies. There are two possible modes of operation with this system: a pulse mode where the coils are pulsed on for several seconds with a dc power consumption of 16 MW; and a continuous mode where the coils can run steady state at 10 percent of maximum current ratings. The processor has been given an active control role and serves as an interface between the operator and electronic circuitry that controls the magnet power supplies. This microcomputer also collects and processes data from many analog signal monitors in the coil circuits and numerous status signals from the supplies. Placing the microcomputer in an active control role has yielded a compact, cost effective system that simplifies the magnet system operation and has proven to be very reliable. This paper will describe the TMX magnet control system and discuss its development.

## Introduction

TMX is a facility constructed at LLL to test the Tandem Mirror approach to confining plasmas under the conditions necessary for controlled thermonuclear fusion. The magnet system is a major subsystem of TMX and the control system that evolved for the magnets reflects the objectives of the TMX project and the requirements of the magnet system.

One of the objectives of TMX is to make the shape of the magnetic field an adjustable parameter. With this capability, it is possible to do magnetic field scaling experiments and to study conditions for MHD stability and affects of varying mirror ratios. To realize this objective, the magnet control system had to allow for easy reconfiguration of the magnet set. Stepping through a sequence of different field shapes while other machine parameters remain constant had to be a routine procedure.

Since TMX is a relatively large and complex facility, it is separated into major subsystems such as magnets, neutral beams, and diagnostics that can operate individually or can be synchronized by a master timing system. The magnet control system must provide its own timing capabilities as well as data acquisition and processing capabilities for stand alone operation of the magnet system.

It was determined for reasons of cost and scheduling that the pulse length for the neutral beam system be 25 ms. The requirement for the magnet system is to provide a constant magnetic field during that time period. This led to a pulse mode of operation where the magnet coils are energized and allowed to reach steady state before plasma injection, and then are sequenced off. Another requirement for the magnet system is to allow for easy mapping of magnetic field lines and calibration of plasma diagnostics that are B field dependent. This led to a continuous mode of operation where the magnet set can be run indefinitely at reduced power levels.

It was first determined that the control system would include a processor to handle data collection and processing of magnet system measurements and to provide other general bookkeeping services. It was then decided that the processor and its equipment interfaces could be better utilized if they were given an active role in the control of the system. This would provide the versatility needed for different operating modes and would also centralize and simplify the operation of the magnets. The timing function needed for stand alone operation was absorbed by the processor. Because of the compactness of the processor interfaces, the size of the planned control circuitry was reduced from an estimated six equipment racks to a single rack. This idea resulted in a compact, cost effective system.

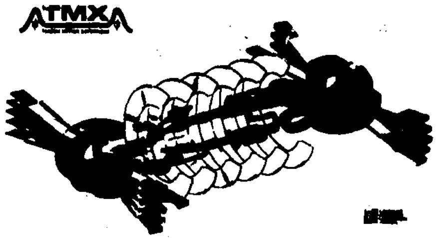

Fig. 1: TMX Magnet Coil Set

## General Description

### Magnet System

A tandem mirror consists of two high-field mirror machines (plugs) placed at either end of a large low-field solenoidal center cell as shown in Figure 1. Each plug consists of a coil resembling the seam of a baseball and two C-shaped coils located in the jaws of the baseball coil. Large ring-shaped coils form the central solenoid. Four transitional coils and a pair of octupole coils smooth the transition of magnetic field lines between the plugs and solenoid. Although the coils that make up the magnet system have a fixed physical geometry, they can produce a range of magnetic flux shapes by adjusting the current in individual coils. A typical flux shape is illustrated in the shaded area of Figure 1.

The magnet coils are all fabricated of square, hollow, copper conductor suitably insulated and bound into an epoxy/glass/copper - composite structure. With the exception of the six solenoidal coils, all the coils are inside the TMX vacuum vessel. The internal coils are jacketed in stainless steel to eliminate outgassing of the conductor bundle. The average current densities achieved during a pulse shot vary from coil to coil up to a maximum of 5000 $A/cm^2$. Continuously circulating low-conductivity water cools the coils during the 2-minute period between pulses.

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Twenty-six dc power supplies drive the TMX magnets. These supplies are current-regulating so that a voltage reference as input to a supply provides a constant current output from the supply. The feedback network and regulating circuitry are at the supply. Typically, these supplies can be pulsed at near rated output voltage for output currents up to 2.5 times rating, while operating at 80 percent conversion efficiencies. The power supply system provides 16 MW of dc power to the magnet coils during a normal pulse of several seconds.

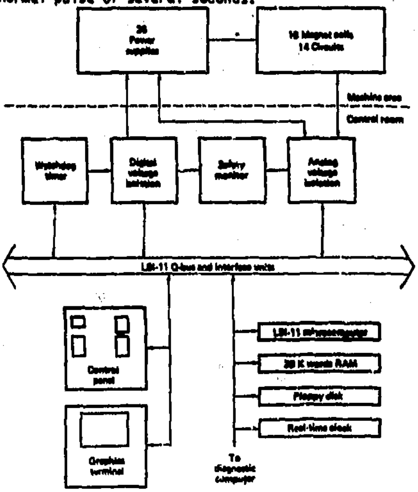


Fig. 2: Magnet Control System Block Diagram

Control System

The control system monitors magnet coil operation and controls the power supplies that drive the magnets. Figure 2 is a block diagram of the control system. At the center of the system is an LSI-11[1] microcomputer that links the operator and the electronic circuitry that exercises the actual control of the power supplies. The primary operator interface is a special purpose control panel with function labelled command buttons. The operator controls the magnet system by entering numerical information through a keyboard on the panel and depressing the appropriate command buttons. The processor receives, interprets, and executes these commands. In return, information is collected by sensors on each magnet circuit and is processed and displayed through annunciator panels and numerical readouts on the control panel. In addition, a graphics CRT terminal is used to present explanations for certain processor actions and to display diagrams, maps, and charts that summarize the status of the system.

[1]LSI-11 is a trademark of Digital Equipment Corporation, Maynard, Massachusetts. Reference to a company or product name does not imply approval or recommendation of the product by the authors, the University of California, or the U.S. Department of Energy to the exclusion of others that may be suitable.

As mentioned previously, there are two basic modes of operation for the magnet system; a full power pulse mode and a low level continuous mode. To run a pulse shot the operator sets up the desired configuration by selecting certain coils and current levels. The processor examines the status of the requested coil circuits and power supplies to determine that the system can be run. Once a pulse sequence is initiated no more operator inputs are accepted until the shot is completed. During this period the processor collects data from various sensors and executes the timing that sequences on and off the power supplies. In continuous mode the operator is allowed to interact with the system since there is no timing function involved. The operator is free to turn on or off any coils or adjust current levels while the rest of the system is energized. Continuous mode running is possible only at low power levels (1 percent) where the cooling rate of the circulating water exceeds the heating rate ($I^2R$) of the magnet coils.

The timing of a pulse sequence is implemented in the system software. The requirement is to energize the coils so that a constant magnetic field exists for 1 s prior to plasma injection. Because of the different L/R time constants for various coils, each is energized at a prescribed time so that all magnets reach steady state condition simultaneously. To reduce transients on the primary ac power lines at the end of a shot, the 26 power supplies are turned off at 100 ms intervals. The sequence in which coils are de-energized is determined by the heating rates of different coils. The coils operating at the highest current densities are shut off first. Between pulse shots the processor monitors coil temperatures and will prevent further shots until the coils have cooled sufficiently.

After a shot, the important system parameters are automatically stored on floppy disk memory. Any system failures are recognized immediately by the processor and brought to the attention of the operator. The operator is free to examine the status of the system through control panel displays or by use of soft maps on the graphics terminal. If no failures are detected, operator intervention is not necessary.

One of the distinct advantages of having the processor in an active control role is the ease in which the operation of the magnet set can be changed. Configurations of the system are stored on floppy disk and can be recalled at any time. These configurations contain information that determines which coils are on-line and what current levels they will run at. Once recalled, this information controls the parameters of the next pulse. Using this feature, it is a simple matter to do B-field scaling experiments or to duplicate conditions of past magnet runs.

With the processor being an active component of the magnet controls, much concern was shown for machine and personnel safety. The development of the system followed the prudent policy that no magnet or human safety would depend on the magnet control processor or its software. In regard to this, a special chassis was constructed to provide the primary safety function for the magnet coils. As can be seen in Figure 2, this chassis forms a closed loop between the digital isolation chassis, power supplies, magnet coils, and analog isolation chassis. The safety chassis monitors the sensor signals from the magnet coils, and should any error condition occur, acts independently from the processor to remove control power from the magnet supplies. Considerable effort was given in designing this chassis to analyzing failure modes and their consequences. Additional coil protection is provided by the watchdog timer (also shown in Figure 2) which insures that the system software continues to be executed. If the processor is not heard from as expected, control power is removed from the magnet supplies.

To help check and maintain the control system a special magnet simulator was developed. Though not an integral part of the system, the simulator can connect to the control system and act in the manner of any of the real magnet circuits. With the simulator a complete checkout of the control system hardware and software can be done routinely. This chassis played a crucial role in developing the control system software and is useful in periodic maintenance and calibration of the control system hardware.

## Hardware Description

The compactness and cost effectiveness of the control system is due in a large part to the capabilities of the equipment interfaces that are used. For communicating with the power supplies, a large number of input and output lines are required. In this application 64 line parallel TTL I/O boards are used. To monitor the numerous magnet sensor signals we use 64 channel multiplexed A/D converters. Both types of interface boards that are used fit directly into the backplane of the LSI-11.

Three chassis that help make up the control system are devoted entirely to protecting the sensitive signals in the control room from the harsh environment of the machine area. These chassis serve to eliminate any electrical paths between the processor interfaces and the magnet system equipment. The digital isolation chassis passes on-off signals through optical isolators between the processor and the power supplies. Two separate analog isolation chassis couple analog voltage signals from the magnet sensors to the A/D converters in the processor. These analog signals are relatively slow time-varying voltages representing magnet system parameters as depicted in Figure 3. The isolation in these chassis is accomplished by modulating the amplitude of incoming signals with a 100 kHz square wave, coupling through transformers with 2.5 kV dc isolation and then demodulating to return the original signal.

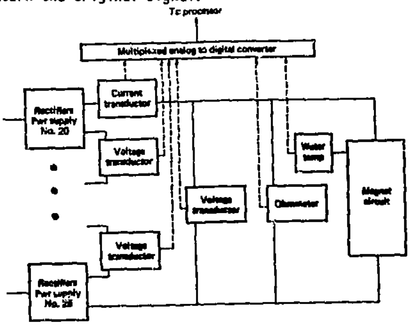


Fig. 3: Block Diagram
Of Magnet Circuit Sensors

Since the analog signals are crucial to the safety of the magnet coils added care was taken in handling them. Output signals from the analog isolation chassis are monitored by both the safety chassis and the processor. These signals are used by the safety chassis to determine if the system is operating correctly. Two analog isolation chassis are used to provide separate signal paths for certain critical signals. These separate paths are carried on into the safety chassis as well. In the event of a major chassis failure resulting in a loss of some sensor signals, the safety of the magnet coils will be insured.

of Magnet Circuit Sensors

With the magnet coils and power supplies that make up the magnet system it is not possible to overpower a coil. The real danger to a magnet occurs if the power supply fails to turn off after a period of time, or if a short occurs between the coil and its case. The safety chassis has the responsibility to see that this does not happen. The safety monitor detects a threshold current or voltage level (typically 10 percent of rated current or voltage) and uses this measurement to switch on individual timing circuits. Each timer is preset according to the allowed "on" time for individual coil circuits. Should current or voltage above the threshold exist longer than safe operation allows, the coil circuit is immediately de-energized. The safety chassis also monitors the current flowing from coil windings to coil casings which are at ground potential. If a ground fault current exceeds a predetermined threshold (typically 50 mA), the coil circuit is de-energized.

The watchdog timer provides another level of safety protection by monitoring the operation of the processor and insuring that the system software continues to be executed. The watchdog timer is a pair of countdown timers that can be programmed to count down from 0 to 6.5 s in steps of 100 microseconds. The software periodically directs the processor to give the timers a value to count down from. In normal operation, a new time value will be given to the timers before they have finished counting down the last value. Should either timer count down to zero, it would indicate that the software is not being executed properly and control power is removed from the magnet supplies. In addition, the logical outputs from the separate counters are compared and if either timer

The control panel shown in Figure 4 is the primary interface between the operator and the processor. It presents the operator with a concise summary of magnet system status through annunciator panels and more detailed information about system performance through numerical LED readouts. These displays are processor driven through additional 64 bit parallel I/O boards. The keyboard and command buttons on this panel are monitored by a keyboard encoder. When a button is pushed the processor is interrupted and told which button it was. Later the software associated with that command is executed.

## Software Description

The magnet control software is written in Fortran with a top down, structured approach. Fortran was chosen because of the familiarity with it that the majority of scientists in the project shared. When speed was essential, like for sampling the A/D converters, special routines were written in assembly language. The main program is a single loop consisting of calls to separate subroutines that perform major functions. The entire loop is executed in about 100 ms. The functions performed by various subroutines are:

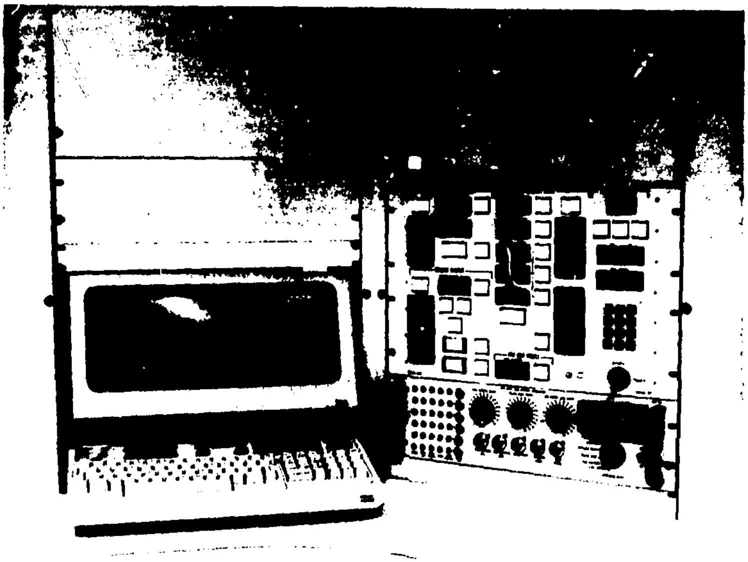

Fig. 4: Control Panel And Graphics Terminal
With Current Traces Displayed

- Sample analog signals
- Read binary inputs
- Process collected data
- Update system status information
- Display control panel quantities
- Process control panel inputs
- Display terminal screen maps
- Service diagnostic room requests
- Pulse magnet system, if desired
- Run magnets continuously, if desired

The capabilities of the software in displaying maps and charts on the graphics terminal can be a tremendous asset to the operator. On the terminal screen in Figure 4 is shown one possible display that plots current versus time for each of the 14 coil circuits. By using a fairly sophisticated terminal, a lot of information can be presented like this, and the operator is free to expand portions of the display for closer scrutiny.


## Summary

The magnet control system has proven to be a reliable and useful part of the TMX project. Placing the processor in an active control role resulted in a compact, cost effective, and versatile system. This system shows the trend toward more advanced controls as fusion energy experiments continue to increase in size and complexity.



## Acknowledgements

Much credit for this project goes to Keith Mortensen who did a great deal of the system analysis and circuit designs. Many thanks go to Al Waugh who developed the magnet power supply system, for his useful inputs to this project. Thanks also to Tom Kruckewitt who did much of the software programming and Jim Rycek who assisted in the checkout and debug of the system.