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CONF-810340--1

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This paper was prepared for submittal to the
Proceedings of the 7th International Conference on Magnet Technology
Karlsruhe, Federal Republic of Germany
March 30 - April 3, 1981

March 20, 1981

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OPERATION OF THE 8-T, 1-m-DIAMETER TEST FACILITY AT LAWRENCE LIVERMORE NATIONAL LABORATORY*

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ABSTRACT

The High-Field Test Facility (HFTF) being built at Lawrence Livermore National Laboratory (LLNL) consists of a set of four Nb-Ti coils, inside of which there is a pair of multifilamentary Nb_3Sn coils. The outer coils are designed to generate 8 T in the 1-m bore; the Nb_3Sn coils will boost this to 12 T in a 40-cm bore.

This paper describes the first operation of the complete set of Nb-Ti coils and describes and gives results from the data acquisition and analysis system that was used during the test.

INTRODUCTION

The coils for the High-Field Test Facility (HFTF), now being built at the Lawrence Livermore National Laboratory (LLNL), consist of two concentric sets of superconducting coils; the outer set is composed of four Nb-Ti solenoids, and the inner set is a pair of solenoids made of cryogenically-stabilized, multifilamentary Nb_3Sn conductor [1]. Although the Nb_3Sn coils are still in fabrication, the Nb-Ti coils have been wound and tested in our facility at LLNL. A previous paper [2] presented the construction details of the Nb-Ti coils; in this paper we discuss the operation of these coils and also present some details of our newly-commissioned data acquisition and analysis system.

EXPERIMENTAL DETAILS

Figure 1 shows the Nb-Ti coils being rigged for installation in the cryostat. The clear bore of the coil assembly is 1 m, the winding o.d. is approximately 1.72 m, and the overall length is 1.25 m. The total mass that must be cooled is 11.8 tonne.

Two power-supply systems were used to energize and protect the coils, one for the two end solenoids and the other for the pair in the middle. Figure 2 shows the essentials of the circuitry that was used. The master control can accommodate up to four power-supply systems. The 2000-A power supplies are the PWR,† Inc., "Genesis" model with filtering added to reduce the ripple current. Reconditioned circuit breakers were purchased for the protection circuitry; a four-pole 1000-V breaker was used for the middle pair of solenoids, and a three-pole 750-V breaker was used for the end coils. The Zener diode clamps on the power supplies limit the voltage at the power supplies to 175 volts, in case the arcs in the breakers are not extinguished simultaneously.

The quench detectors and vapor-cooled-lead fault detectors will trip out the entire 8-T system if they detect either a normal zone or a heated vapor-cooled lead. To protect the system from spurious signals, the input to the quench detector is filtered through a 1.0-Hz two-pole Bessel filter and the absolute value of the detected voltage must exceed a preset threshold, typically 200 mV, for a predetermined length of time, typically 1 s, before the trip command is set.

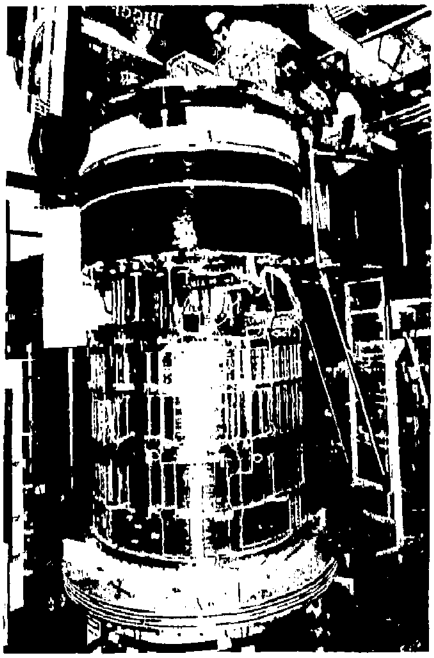

Fig. 1. Rigging the Nb-Ti coils for installation in the cryostat.

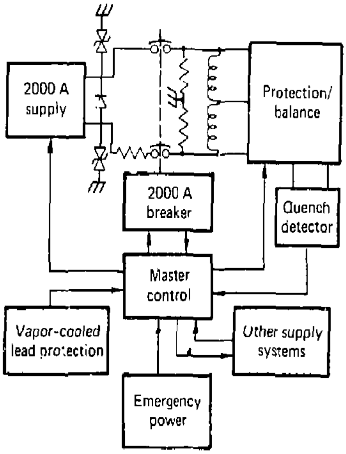

Fig. 2. HFTF control and protection systems.

The vapor-cooled-lead fault detectors are two-level devices. If, for example, the voltage drop

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Manuscript received March 31, 1980.

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†Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the US Department of Energy to the exclusion of others that may be suitable.

across the lead exceeds 50 mV, a warning buzzer is actuated, of if the level exceeds 75 mV the entire system is tripped out.

In addition to the quench-detector and vapor-cooled-lead voltage taps, voltage taps were soldered to each of the double pancakes, the coil terminals, and across the bolted joints on the buss bars to monitor coil performance.

Linear potentiometers from Beckman Electronic Components were installed on the end flanges of each of the solenoids in an attempt to measure the axial compression of the coils as they were energized. The cermet resistance element of these potentiometers provides a continuously varying resistance with displacement, and the displacement resolution is essentially limited by the excitation/sensing electronics. For our case, the resolution was approximately 200 μm (0.0005 in.). The implementation of these gages is fairly straightforward--they must be disassembled, degreased, reassembled, calibrated at room temperature, and checked for LHe operation.

Platinum resistance thermometers from American Magnetics, Inc., and cryogenic linear temperature sensors from Micromeasurements, mounted on the stainless steel structure, were used to measure temperatures during cooldown.

Figure 3 shows the wiring diagram for the various diagnostic lead wires. In order to protect personnel and equipment, all sensors that could have a high common-mode voltage are routed through either isolation amplifiers or the protection relays. The amplifiers are floating, differential amplifiers, Preston Model 8300 XWB-A, which have been factory-modified to provide a 1000-V common-mode voltage protection. The gain is selectable with a front panel switch from 1 to 1000, and the bandwidth is 100 Hz. The peak-to-peak input noise with the amplifier input shorted is 5 μV R.T.I. The attenuator/amplifier combination allows voltage measurements to be made during the discharge. The protection relays are opened approximately 100 ms before the breaker opens, thus protecting the instrumentation and personnel. The signals through the protection relays, therefore, cannot be monitored during the discharge. The system has 104 channels, 48 of which are equipped with Preston amplifiers.

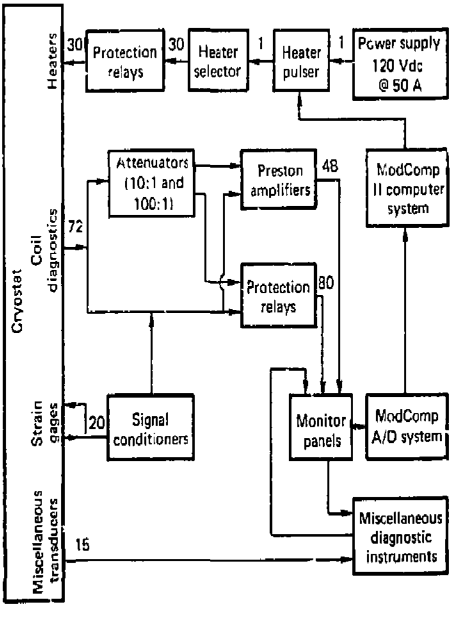

Fig. 3. HFTF diagnostic and heater systems.

Whenever possible, the signal leads were twisted, shielded pairs of conductors, with a voltage rating sufficient to withstand the expected common-mode voltages. At the coil, the low side of the signal lead was tied to the shield; at the amplifier end, the shield was connected to the guard.

In general, all the signals go into the computer system via the analog/digital converter (A/D). The monitor panel provides a break-out point where voltmeters, etc., can be used to monitor selected signals in real-time.

Figure 4 shows the configuration of the HFTF data system. During an experiment, the highest priority task of the system is to take data from the A/D subsystem, pass them through the core memory of the central processor unit, and then temporarily store them in partitions on the disk memory. When these partitions are filled, the data are read back into core, converted to floating point, demultiplexed, and then stored in other partitions on the disk. When the "floating-point" partitions are filled, the data are again read back into core, converted into engineering units by applying the necessary scale, offset, and gain factors, and then stored on magnetic tape. The data from a particular experiment will then consist of a series of files on the magnetic tape. Each record in the file will correspond to the data in a particular channel.

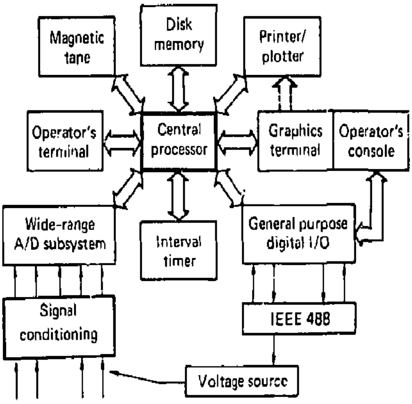

Fig. 4. HFTF data system.

Since buffered arrays and efficient operating codes are used for these data transfers, real-time plotting, which has a lower priority, can also be run. In this program, data is read out of core, converted into engineering units by applying the necessary scale, offset, and gain factors, and displayed on the graphics terminal.

The data system can be calibrated before running an experiment by connecting the output of the voltage standard to the desired inputs. The calibration software will program the voltage source, scan the data channels, calculate the measured gains, etc., and output the results to the operator's terminal and/or the printer.

The central processor is a Modcomp II/221 minicomputer manufactured by Modular Computer Systems. The Modcomp II is a 16-bit machine with 64K-word capacity of core memory, floating-point hardware, and a real-time clock. The disk memory has a 5M-word capacity with a 70-ms maximum access time, and the magnetic tape unit is nine-track with a speed of 45 in./s. The printer/plotter is a Versatec Model 1200A. The operator's terminal is an 11-in. CRT, a so-called "smart" terminal, Tektronics Model 4025. The graphics terminal is a storage-type CRT, Tektronics Model 4012. The operator's console is an LLNL-designed addition to the 4012 terminal and is used to control the data acquisition and select the method of real-time plotting via software interrupts. The wide range A/D subsystem, supplied by Modcomp, has 104 channels and is expandable to 128. The system has twelve programmable ranges, from ±5 mV to ±10.24 V, full scale. The maximum throughput of the system is 20 kHz; in the autoranging mode, the throughput rate is reduced to 6 kHz. The interval timer, supplied by Modcomp, has a 10 μs resolution and is used to provide an accurate time base for the data channels. The digital I/O system interfaces with the EDC 501J programmable voltage source, which is patched into the front end of the signal conditioners to calibrate the system.

DATA-ACQUISITION PROGRAM

Three modes of data acquisition are possible: normal, adaptive, and burst. In the normal mode, data from the set of desired channels (104 maximum) are scanned and stored at a constant rate. In the adaptive mode, 20 of the 104 channels can be designated as "trigger" channels; when this mode is used, data is taken at an adaptive scan rate for a certain period of time before and after each trigger event. In the burst mode, which is intended to be used with heater pulse tests, a limited number of channels (20 maximum) with fixed gain ranges on the A/D subsystem are scanned at the burst rate.

The first set of parameters that must be chosen when setting up the data system include:

- Number of samples per channel (4096 max).
- Normal scan rate per channel (0.006 Hz min to 50 Hz max).
- Adaptive scan rate per channel (0.006 Hz min to 50 Hz max).
- Burst scan rate per channel (2 Hz min to 333.3 Hz max).
- Time before adaptive trigger (0.77 s max at 50 Hz).
- Time after adaptive trigger (no limit).
- Burst duration (13.65 s max at 333.3 Hz).

The second set of parameters includes: the assignment of the various A/D channels to the corresponding computer (logical) channels; for each of the channels, a transducer code (three-digit number) for later identification, scale, offset, Preston amplifier gain, adaptive trigger type, and level; and A/D gain for the burst-mode channels.

The real-time plotter parameters are entered on the 4012 graphics terminal and include channels to be plotted, minimum and maximum values expected, and plot duration. The real-time display can be done in one of three ways: the first plots the data in engineering units for the desired channels vs time; the second plots the data vs channel number for successive times; the third provides a listing of the data on the graphics terminal. Push-buttons on the operator's console are used to select the desired option.

Information pertinent to the heater pulse tests is also entered on the 4012 terminal--the number of the next heater pulse, pulse voltage, pulse width, and a list of heaters to be pulsed (10 maximum). This information, along with the real time of the actual heater pulse, is stored for later use in data analysis. The desired heater voltage, time, and selector switches are set on the heater hardware in the equipment racks; depressing a push button on the operator's console starts the data scan and pulses the heater. Other push buttons on the operator's console stop and start the data-taking and allow selection of normal or adaptive rate.

DATA ANALYSIS PROGRAM

The routines in GPDAP (General Purpose Data Analysis Programs) [3], provide a comprehensive data analysis capability. Data channels can be manipulated in a variety of algebraic and arithmetic ways, integrated, differentiated, smoothed, etc. Data from a group of records with varying and different time bases can be compressed onto a single record, so that results of an experiment whose data span several records can be analyzed and presented.

An assortment of plotting routines allows data to be plotted vs time or vs data from another channel. Provision can also be made for making multicurve plots. The 4012 graphics terminal has a crosshair-type cursor that can be positioned on the data plot; depending on subsequent commands, the coordinates of the point will be listed or an enlargement made of the curve about the cursor position.

TESTING PROCEDURE AND RESULTS

The 8-T system was cooled to approximately 20 K in 120 hours with our Airco/80C turbo-expander helium liquifier. The coils were then submerged in liquid helium by transferring the liquid from a 10,000-ℓ storage Dewar that had been filled before cooldown.

In order to check out both the coils and the diagnostics system, a cautious test program was undertaken. The goal was to eventually charge the entire system to 1200 A. The middle coils were energized first, with the end coils open-circuited. The current was limited to 500 A, and the coils were discharged with the protection resistor. The tests were then repeated with the end coils energized and the middle coils open-circuited. During these tests, it was discovered that the amplifiers in the A/D system would not autorange properly for certain input conditions and the computer output would then appear noisy. This problem was corrected by the computer manufacturer.

After we were satisfied that the coils and the data-acquisition system were operating properly, the same procedure was used to charge the coils separately to 1200 A. In order to not needlessly place a high voltage on the system, the coils were not tripped from currents above 800 A. The calculated inductance values are 24.3 H for the middle coils, 11.4 H for the end coils, and 10.8 H for the mutuals. The inductances deduced from charge/discharge rate data agreed with the calculated values to within 5%.

After the individual systems had been energized to 1200 A, the entire system was charged to 1200 A. The charging voltages of the two coil systems were adjusted such that di/dt was the same for each. The charging rate was 17.2 A/min to 1000 A and 8.3 A/min to 1200 A. Voltage spikes, presumably caused by conductor motion, were observed occasionally as the coils were being charged, but no quenches or training occurred. The deviation between calculated field values and those measured with calibrated magnetoresistance probes from American Magnetics was approximately 2%. The peak conductor field was 8 T and the stored magnetic energy was 40 MJ. The coils were slowly discharged to approximately 600 A and then quickly discharged through the protection resistors. Figure 5 shows the current decay of the two coil systems. Except for some initial spikes, the current traces decay in a smooth, exponential way, indicating that the discharge circuits are properly matched. The voltage traces were also quite smooth, indicating that there are no shorted turns.

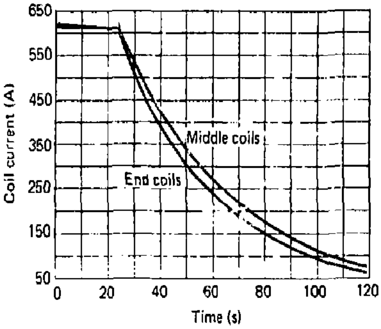

Fig. 5. HFTF fast discharge from 600 A.

Figure 6 shows the movement of the end flanges of one of the middle solenoids, measured by a linear potentiometer, as a function of coil current. The maximum deflection, approximately 1 mm, is close to the value expected on the basis of axial buildup measurements. The steps in the data are due to the resolution of the A/D subsystem. The compaction indicated in Fig. 6 was verified after warming the coils to room temperature, when it was found that the torque on the tension rods and jack bolts on the end flanges had decreased. In addition to our checkout testing, the facility was run a second time up to 1200 A to provide a background field for stability tests on a 1-m-diameter test coil for Los Alamos Scientific Laboratory (LASL).

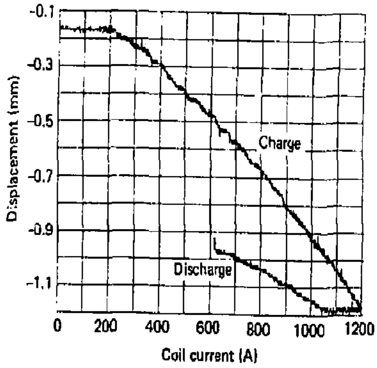

Fig. 6. HFTF axial compression.

The pulser chassis and data-acquisition program were used to energize a heater attached to the LASL test coil. Figure 7 shows a 1-s square-wave heater pulse and the resulting voltage drop across the heated section. In order to plot the heater and voltage tap signals on the same graph, the voltage values were multiplied by 100. As previously mentioned, the scan rate in this mode is 333.3 Hz maximum, so heater pulses of 50-ms duration can be rather accurately represented.

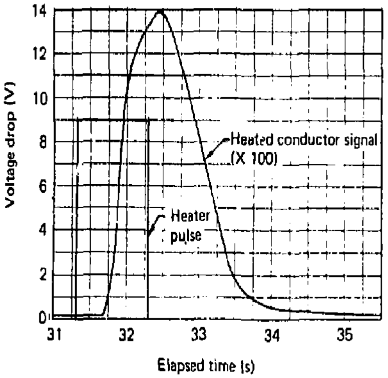

Fig. 7. Heater pulse test.

CONCLUSIONS

A rather large set of solenoids for the HFTF has been built and energized twice to the design current of 1200 A. The current density in the winding bundle is 3200 A/cm^2, the peak conductor field is 8 T, and the usable maximum field in the bore is 7.5 T. The stored magnetic energy is 40 MJ.

The HFTF data system was used for the first time and was found to acquire, store, and analyze coil test data with relative ease.

ACKNOWLEDGEMENTS

The authors are indebted to T. A. Horillo for writing and implementing most of the software for the data system, to R. W. Hoard, P. R. Carnahan, and R. F. Gross for their efforts in operating and maintaining the cryogenic system. This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

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