Superconducting Magnet Development Capability of the LLNL High Field Test Facility

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Introduction

The High-Field Test Facility (HFTF), located at Lawrence Livermore National Laboratory (LLNL), is uniquely capable of meeting testing requirements for development of the large-scale magnets for the International Thermonuclear Experimental Reactor (ITER). The centerpieces of this facility are the Fusion Engineering International Experimental (FENIX) Magnet Facility and the HFTF 2-m Solenoid Facility. Operated by LLNL's Superconducting Magnet Development Group (SCMDG), these and other supporting facilities of the HFTF are used by researchers for the development of cryogenic materials, large magnet components, and superconducting magnet systems.

The HFTF 2-m Solenoid Facility, now in operation, is a six-coil set with an axial entry test well. As presently configured, it can provide a uniform 11-T field over a sample volume approximately 0.32 m in diameter. Power supplies are available to deliver sample current up to 40 kA. Higher currents are possible by inductive means. An effective cryostat design allows continuous availability for testing in the 2-m Solenoid Facility for extended periods using a single helium liquefier. The facility was designed with separate magnet and test-well cryostats; therefore, rapid exchange of test articles is possible without disruption of the magnet's cryogenic environment. The 2-m Solenoid Facility, which has been in service since 1981, is scheduled for a major upgrade in 1991 that will increase the field to 15 T in a 0.36-m-diameter volume.

The FENIX Magnet Facility, which is presently under construction, will be fully operational in late 1990. It is a split-solenoid configuration that will provide experimenters with radial access to transverse magnetic fields up to 14 T in a uniform high-field region approximately 0.4 m in length. The access gap between solenoid halves is variable, but the initial setup will include a cryogenically isolated test well with a 100 mm $\times$ 150 mm cross-section in the high-field region. Sample currents as high as 40 kA are possible, using power supplies that are presently available. The thermally isolated sample test well allows rapid specimen change-out and independent control of the sample temperature during tests.

Also supporting the development of large-scale conductors and coil components, the HFTF has a number of other unique facilities for the characterization of cryogenic materials and components. For example, magnet structural alloys and insulations can be mechanically tested at temperatures down to 4.2 K; and small superconducting-magnet test stands allow characterization of superconducting wires, cables, and sub-sized conductors at fields up to 15 T and 12 kA of current. Wires, cables, and conductors can be tested using hybrid electro-mechanical test facilities that can simultaneously

apply high-field (15-T), high-current, longitudinal (200 kN), and/or transverse (100 kN) loads. Heat-treatment and metallurgical-characterization facilities are available.

Both the large magnet systems and the materials test facilities are supported by a multi-channel data acquisition and analysis system. This system, comprising HP-330 and 360 computers and HP-3852 data acquisition units, provides real-time data display and control but is also integrated with the LLL VAX 8600 and the Cray machines of the MFENET for effective data manipulation, analysis, and transport.

All cryogenic test stands and liquefier/refrigerators in the HFTF are supported by an automated Helium Gas Management System (HGMS) that manages the recovery, purification, storage, and delivery of helium to various parts of the facility. To provide for possibly large refrigeration needs of future projects, 3-kW and 8-kW units at the nearby MFTF-B facility can, in principle, be made available. Large cryostats/vacuum vessels exist on site, including the 2- and 4-m-diameter vessels that house the 2-m Solenoid and FENIX, respectively, and the end-cell sections of the MFTF-B vacuum vessel.

Details of LLNL's magnet development facilities are described in the following pages. For further systems specifications and equipment availability, contact Dr. J.R. Miller (415) 422-0679 or Dr. S.S. Shen (415) 423-4826, Lawrence Livermore National Laboratory, P.O. Box 5511, L-643, Livermore, CA 94551, USA.

High-Field Test Facility Equipment at LLNL

Large Magnet Test Facilities

FENIX Magnet Facility

High-Field Test Facility (HFTF) 2-m Solenoid

Component and Materials

Research and Development

Cryogenic Mechanical Test Facility

Electro-Mechanical Test Conductor Apparatus

Electro-Mechanical Wire Test Apparatus

Supporting Technologies

High-speed, multi-channel data acquisition and analysis system

VAX and National Magnetic Fusion Energy Computer Center (NMFECC) Cray support for computation and data analysis

Semi-automatic Helium Gas Management System (HGMS)

Airco liquefier

CTI 2800 and 1400 liquefiers

3-kW and 8-kW MFTF-B liquefiers

2-m-diameter, 4-m-diameter, and MFTF-B cryostat/vacuum vessels for coil and conductor tests

Coil-winding equipment

FENIX Magnet Facility

General Description

Magnet configuration: Two independent units, each comprising a Nb₃Sn insert and a NbTi outsert. Each coil is separately encased.

Gap width: 100 mm

High-field winding, i.d: 360 mm

Uniform high-field region: 150-mm diameter

Maximum field in test volume: 14.0 T (100-mm gap, iron cores)

Total cold mass: Approximately 75 tonnes

Total stored energy: Approximately 180 MJ

Test Sample Information

Configuration: Straight lengths or pancakes can be accommodated

Sample inlet pressure: 0.5 to 3.0 MPa, adjustable

Inlet temperature: 3.5 to 10 K; 3.5 K by pumping on test well, 4.3 K using atmospheric test well, and higher temperatures using heater and bypass circuits

Flow rate: 30 g s⁻¹ total for all paths with 0.5 MPa pressure at the test coil outlet—maximum flow is proportional to pressure

Maximum sample current: 40 kA

Duty cycle: Continuous with 40-kA conductors for several hours—helium supply supplemented using an existing 10-kL dewar

FENIX Magnet Facility

The Fusion Engineering International Experimental (FENIX) Magnet Facility, shown in the 4-m cryostat, is presently under construction. Planned to begin operation in the fall of 1990, FENIX will be capable of testing full-size ITER conductors.

High-Field Test Facility (HFTF) 2-m Solenoid

The High-Field Test Facility (HFTF) 2-m Solenoid provides a high backing field for testing large conductors, test coils, and magnets. The high-field capabilities of HFTF will be upgraded in 1991 with the addition of the Proof-of-Principal (PoP) coil to the magnet stack.

	NbTi Coils	Nb ₃ Sn Coils
Number of coils	4	2
Winding i.d.	1.05 m	0.4 m
Winding o.d.	1.71 m	0.86 m
Operating current	1.2 kA	5.0 kA
Winding pack current density	32 A mm ⁻²	33 A mm ⁻²

$B_{\text{max}} = 11 \text{ T}$ (15 T with PoP coil upgrade)

Bore diameter = 36 cm

Thermally isolated sample cryostat

Maximum sample current = 40 kA

$E_{\text{stored}} = \text{MJ}$ (57 MJ with PoP coil)

Cryogenic Mechanical Test Facility

Mechanical testing of structural alloys and magnet insulation can be performed in this facility. This photo shows the lower end of the compression column where specimens are attached, and the upper portion of the sample cryostat.

- LHe, LN₂, and room temperature operation
- Load, stroke, or strain control
- Loads to 100 kN
- Total stroke of 100 mm
- Cyclic loading with variable wave forms
- Accommodates the following ASTM specimen types
 - Flat tensile
 - Round tensile
 - Compact Tension
- Highly efficient cryostat design for long-duration fatigue testing.

Electro-Mechanical Conductor Test Apparatus

High fields, current, and both longitudinal and transverse loads can be individually or simultaneously applied to large Nb_3Sn conductors.

- Load, stroke, or strain control for longitudinal tension
- Load control only for transverse compression
- Longitudinal tension to 200 kN
- Capable of cyclic loading with variable wave forms
- Sample lengths of 300 mm (50 mm in high field)
- Maximum sample cross section 10×20 mm
- Fields to 15 T (12.5 T for transverse load)
- Current to 12 kA

Electro-Mechanical Wire Test Apparatus

Electro-Mechanical Wire Test Apparatus for strain vs J_c tests and mechanical properties measurements of Nb_3Sn superconducting wires.

- Computer control and data acquisition using an HP 9000 series 330
- Load or stroke control
- Loads to 2 kN
- 300-mm sample length with 50 mm in high field
- Current to 2 kA
- Fields to 15 T

FENIX/HFTF Data System and Network Topology

All experiments in the HFTF facility, including FENIX, are integrated with a computerized data acquisition and analysis system. Active experiment control and real-time data analysis are possible. The FENIX HFTF computers are networked to the NMFECC system.

Data Acquisition and Analysis

- Hewlett-Packard (HP) 360 computer with HP 3852 data acquisition units
- Analog inputs available for the sample fixture
 - (1) 20 channels, maximum sample rate 40 ch/s,
6-digit integrating voltmeter
 - (2) 50 channels, maximum sample rate 20,000 ch/s,
13-bit analog/digital converter
- 20 Preston 8300 differential input isolation amplifiers, 1000 Vdc_{cm}.
Gain: 1—1000, bandwidth: 1—1000 Hz
- Several current sources available for transducer signal conditioning—
ranging from 1 μ A to 50 A.
- Real-time data displays and recorders during sample runs, with plotted
raw data available after each run
- Data transferred to the LLL VAX 8600 for archiving in MDS database
- Data processing, analysis, and plotting with IDL software on the LLL VAX
- Data processing and analysis using the (NMFECC) Cray computers

Helium Gas Management System (HGMS)

This semi-automated, closed-loop system provides liquid helium to all experiments through the liquefiers or by batch transfer from 10-kL and 500-L dewars. Boil-off gas is reprocessed for storage as gas for make-up supply to a variety of liquefiers.

- Hewlett-Packard computer and control interface
- Unattended operation, 24 hr/day
- Processing speed: 630 equivalent liquid liters of helium gas per hour
- Output purity: <5 PPM total impurities
- Cryogen storage capacities
 - 19000 equivalent liquid liters helium as gas
 - 12000 liters of helium as liquid
 - 30000 liters of nitrogen as liquid

Airco Helium Liquefier/Refrigerator

This liquefier, which uses a single turbo expander, has proven performance of over 60 L h^{-1} or 200 W at 4.5 K. The Airco provides liquid to the HFTF Solenoid. The liquefier can also be put on line to a 10-kL storage dewar, which is used for batch transfer of liquid to the HFTF test well.

CTI 2800 Helium Liquefier

This liquefier has two turbo expanders and two oil-bathed screw compressors for a liquefaction rate of 50 L h^{-1} or approximately 150 W at 4.5 K . The CTI 2800 is capable of using as many as four compressors for increased performance.

In addition to the Airco and CTI 2800 liquefiers, a CTI 1400 with a make rate of 20 L h^{-1} supports small-scale experiments. Also available are the 3-kW and 8-kW helium liquefiers previously used during testing of the Mirror Fusion Test Facility-B (MFTF-B).

MFTF-B/ITER Magnet Test Facility

The end cells of the Mirror Fusion Test Facility (MFTF-B) vacuum vessel are shown in a configuration that depicts possible methods of testing full-scale ITER central-solenoid magnets. The MFTF-B end-cell vacuum vessels, cryogenic equipment, power supplies, and other utilities are presently idle and can, in principle, be made available to test extremely large components.

The superconducting magnet development program at the Lawrence Livermore National Laboratory is a multidisciplinary effort to address engineering and design issues of large magnets. The High-Field Test Facility (HFTF) has a wide range of test capabilities, such as the 2-m Solenoid Facility, the FENIX magnet facility, advanced computational capabilities, and cryogenic materials and component testing equipment. Supporting technologies and services are available to meet both large- and small-scale test requirements. HFTF, with its unique test facilities, is fully ready to support ITER magnet development and to assist with international collaborative research.