Fermi National Accelerator Laboratory
P.O. Box 500 · Batavia, Illinois · 60510

TD-99-039
08/19/1999

Critical Current Measurements of Superconducting Cables at the National High Magnetic Field Laboratory - Documentation / User Guide Version 1.0

P. Bauer, D. Dietderich

Abstract:

The National High Magnetic Field Laboratory (NHMFL) in Tallahassee (Florida) offers the possibility to measure the critical current of superconducting cables in high magnetic background fields as a function of a variable pressure load on the sample. The NHMFL test-station uses a split solenoid, designed to produce a 14 T field in its 150 mm high field region. The radial access-port can accommodate sample-holders of 30 mm x 70 mm cross-section and ~1 m length. The characteristic feature of the NHMFL Ic test facility is that it provides the possibility to apply high tensile stress as well as transverse pressure on the sample. The cryostat is structurally designed to be capable of transmitting high mechanical loads. The current leads are designed for 10 kA. This document describes the NHMFL critical current test-station and summarizes all the information necessary for the operation of the machine.

1) NHMFL 14T TEST FACILITY – GENERAL DESCRIPTION

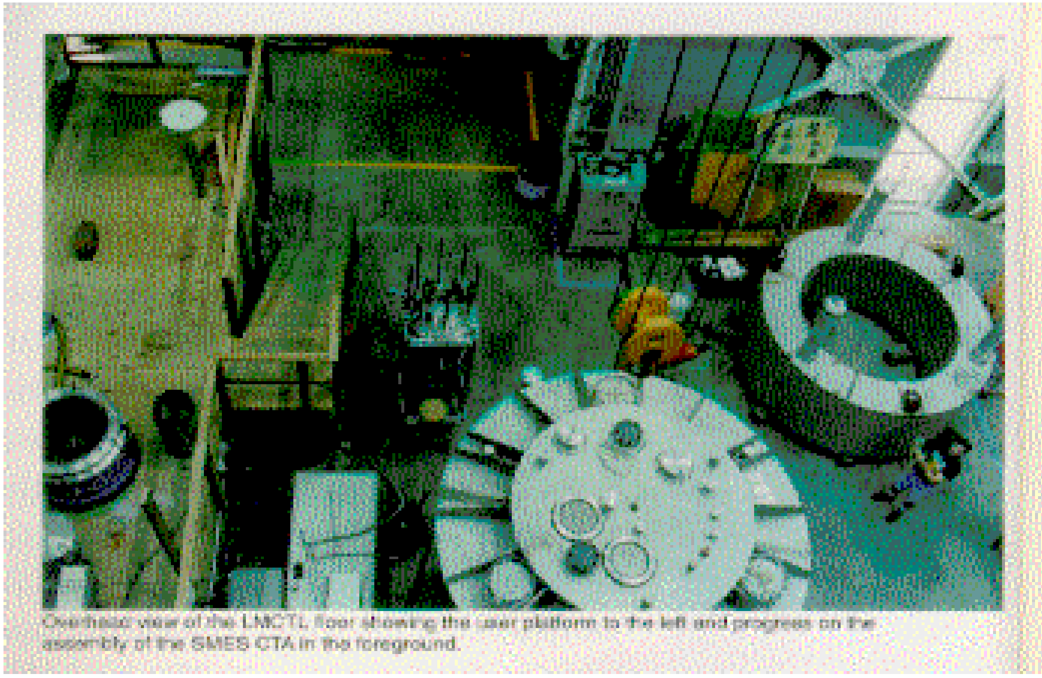
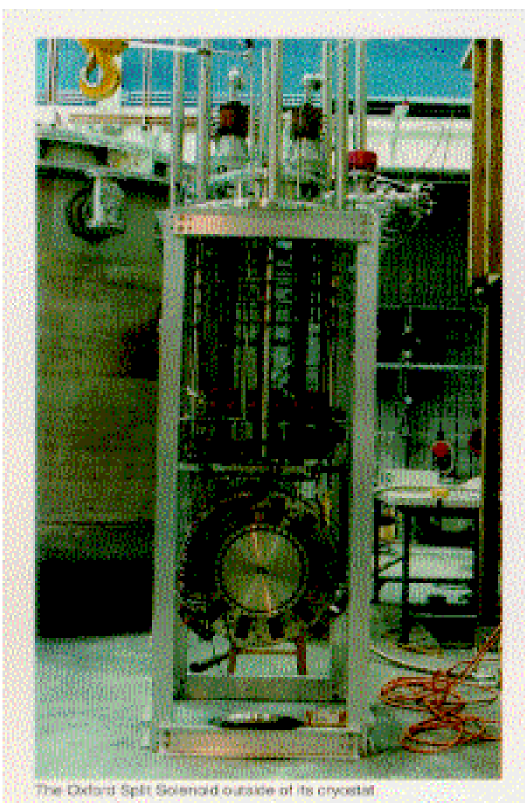


Figure 1: Overview of cell 16 at the NHMFL. Ic-test cryostat on the wooden platform (left).



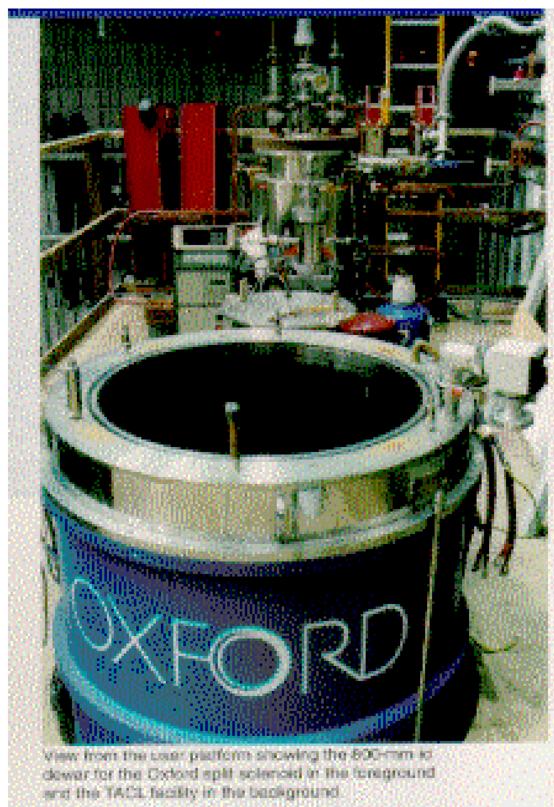


Figure 2: Ic test station: insert with current leads and split-solenoid (left), cryostat (right).

The test-station was originally designed for testing the effect of strain on the Ic of strands and cable-in-conduit samples for the 45 T hybrid magnet, which is now in the final stage of assembly at NHMFL[1,2]. Figure 1 and Figure 2 show the laboratory environment, the magnet insert plus current leads and the cryostat. Figure 3 shows a schematic of the test-station including dimensions. Table 1 lists the most important parameters of the test-facility. The test-facility consists of a cryostat containing a 14 T Oxford split solenoid superconducting magnet system. The bore diameter of the solenoid is 150 mm. The radial access port for the sample measures 70 mm x 30 mm. However, the access in the piston housing is smaller, such that, the (maximum) sample dimensions should be 68 mm x (26 mm +1.5/-0 mm). The magnet is oriented such that the sample is introduced vertically into the access port between the 2 coils of the split solenoid, its bore being perpendicular to the cryostat axis. The facility is designed to operate in boiling liquid helium at 4.2 K.

ITEM	RANGE	COMMENT
Magnet		Split solenoid
Magnetic field	0-14 T	14 T reached only with Ho insert
Bore size	150 mm	
High field region in radial access mode	150 mm	where port & solenoid bore cross
Access port dimensions	30 x 70 mm	
Operating temperature	4.2 K	Magnet and sample in same bath
Sample-Power Supply		Centrally controled
Current rating	20 kA	
Protection resistor	22.043 mΩ	in parallel with teststation
Cryostat current leads		Vapor cooled Cu/NbTi leads
Max. current	10 kA	13 kA for short times
Pressurization device		
Transverse load rating	10-500 kN	He-gas from bottle pushes piston
Access port dimensions at piston housing	68 x 27.5 mm	determines sample dimensions
Position of piston with respect to sample	transversal	
Length of sample pushed by piston	~122 mm	Positioned in solenoid bore
Sampleholder		Mechanically supported by
Total length	~915 mm	pessurization system
Max dimensions	27.5 x 68 mm	Given by piston housing dim.
Length of Ic measurement section	150 mm	Given by high field region

Table 1: Data-sheet of the NHMFL superconducting cable characterization test-facility.

The liquid helium is supplied in dewars by the NHMFL liquefier department or purchased from an outside supplier. The vapor cooled copper/NbTi current leads are designed for 10 kA, but for short periods the leads have worked at 13kA.

---

[1] *"A Facility for the Characterization of the Critical Current of Superconductors as a Function of Strain and Magnetic Field", L. Summers, R. Walsh, J. Miller, IEEE Transactions on Applied Superconductivity, Vol. 5, No. 2, p. 1896, June 1995*

[2] *"Characterization of High-Current Nb_3Sn Cable-In-Conduit Conductors vs Applied Sheath Strain", J. Miller, R. Walsh, M. Haslow, W. Kenney, G. Miller, Proceedings of the 1997 CEC/ICMC Portland,OR*

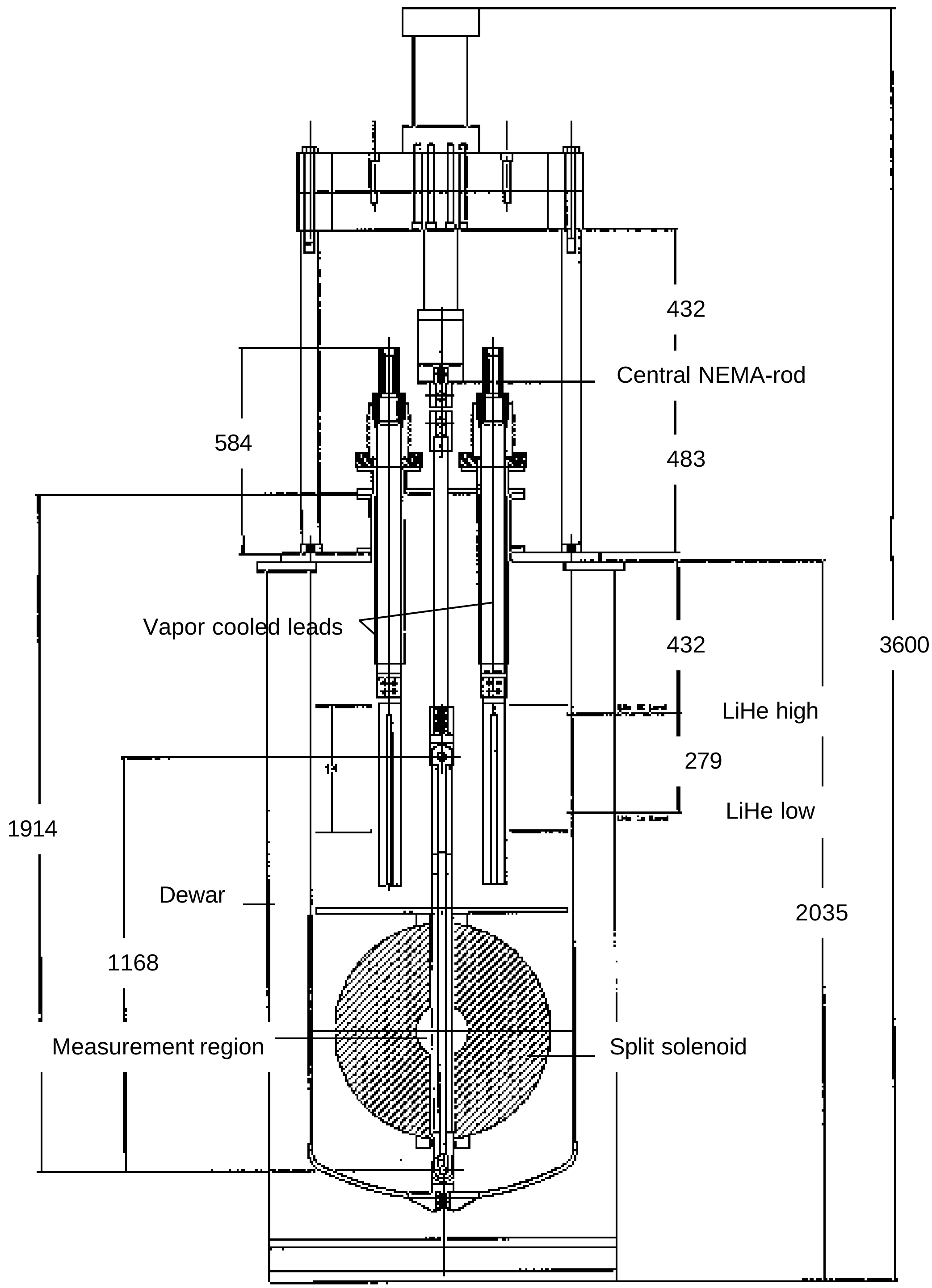


Figure 3: Schematic of the NHMFL 13T Split Solenoid Large Conductor test-facility, meas. in mm.

The sample current is provided by a 20 kA power supply (and the water-cooled 20 kA bus-work) of the regular NHMFL "laboratory equipment". The characteristic feature of the test-station is a piston, fed through the solenoid bore, which fixes the sample and allows producing up to 500 kN transverse load on the sampleholder in the 150 mm high field region. The piston is pressurized by helium from a standard helium-gas bottle. The data acquisition system consists of a set of high sensitivity digital voltmeters and a Labview based data acquisition software, which reads the data through the GPIB bus. An analog quench detector (threshold voltage in highest sensitivity level: 500µV) protects the sample from damage during a quench.
Resuming, the test-station is capable of Ic measurements for typical accelerator magnet cables at 4.2 K and in fields of up to 13 T. State of the art Nb_3Sn is specified to reach 2000 A/mm^2 at 12 T and 1000 A/mm^2 at 15 T (4.2 K). A hypothetical Rutherford type cable with thirty 1mm diameter strands (with 50% Nb_3Sn) would require 16 kA at 14 T, 20 kA at 13 T and 24 kA at 12 T. This is unfortunately out of the scope of this test-station, unless an upgrade of the current lead capability occurs. Some of today's conductors, and especially those forseen for Fermilab's React & Wind study program have sufficiently low critical currents to be within the scope of the NHMFL facility.

2) Ic SAMPLE-HOLDER

A topview-drawing of the sample-holder (including one Cu mounting block for the NbTi ropes) is shown in Figure 4. A sketch of the sample-holder is given in Figure 5 .

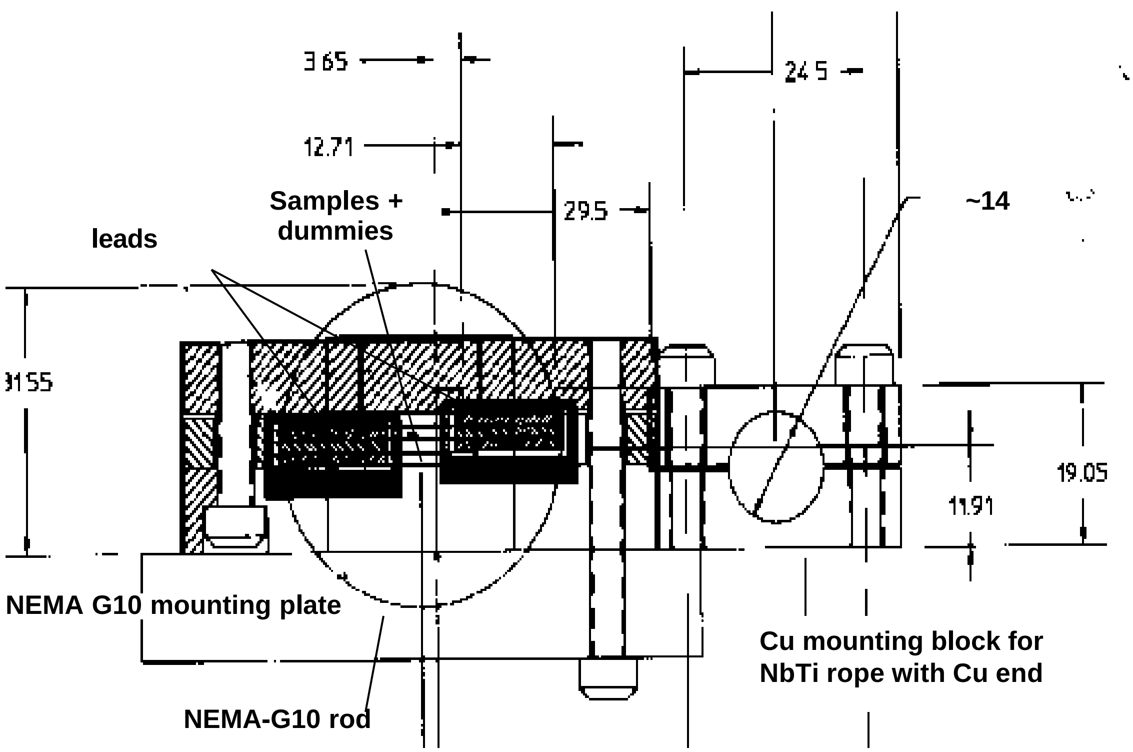


Figure 4: Top view of LBNL cable-Ic-sample holder for the NHMFL test-station, dim. in mm.

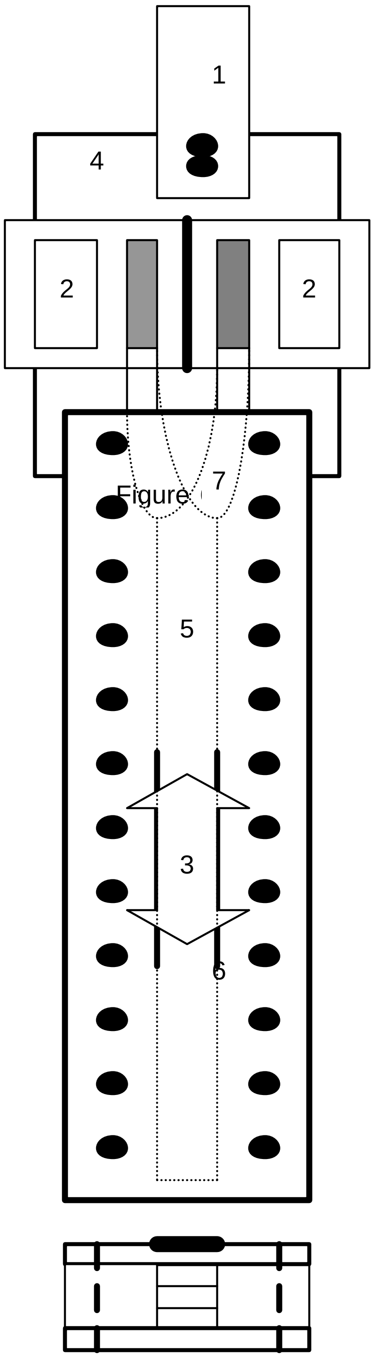


Figure 5: sample-holder sketch

The sample-holder consists of three parts:

- The non-magnetic stainless-steel (304 S.S.) sample holder which consists of top-and bottom plates and 2 side rails (+ shims) to contain the sample-loop (and eventually some dummy cables). The sample holder has to contain the considerable Lorentz-forces, which become shear forces when the cable broad-face is oriented perpendicular to the magnetic field (so called “face loaded” assembly). The sample holder dimensions (st. steel part only) are: 915 mm long, cross-section (<68 mm) x (**26-27.5)** mm. The cross-sectional dimension is determined by the size of the pressure priston housing window (68 x 28 mm), which is centered within the radial access-port (70x30 mm). The thickness of the sample-holder is taking into account the geometrical constraints of the pressure system, such that it easily fits into the pressurization device without leaving a gap larger than 3mm at the pressure piston window (to avoid overextension of the bellows).
- The connection to the current leads (copper mounting block (2)), which in the LBL sample-holder design consists of two copper connection blocks attached to a G10 plate. The copper blocks have a groove into which the cable is soldered (or a current lead to the sample) and a specially shaped bolted clamp to attach it to a NbTi rope which is soldered into a hollow copper tube. The NbTi bundles are connected to the vapor cooled leads of the test-facility. Using indium foil the current leads are soft-soldered to the connector with the pressure generated by bolting the two halves of the clamp together.
- The G10 plate (4), which holds sample-holder and copper blocks together and attaches them to the central NEMA-G10 rod (1) running through the top-plate of the cryostat.

The sample-holder also serves as the impregnation fixture. The impregnation is done in an evacuated PVC-tube. To facilitate the disassembly the bolts/threads running along both sides of the sample holder and the sample-holder surface have to be protected with mold-release. The PVC-tube is destroyed during the extraction of the sample-holder afer impregnation. The sample-holder can contain more than 2 cables. LBNL uses dummy cables to simulate a “coil-environment”. Only the real sample carries the current up and down the holder. The cables (5) normally run on top of each other in the “face loaded assembly” (cable and sample-holder broad faces are parallel) and side by side in the “edge loaded assembly”. The lower (return) soldered joint is a twist pitch long and involves a copper solder box. The dummy cables are terminated before and therefore not included in the joint. The top joint is as well straight. At the top end of the sample-holder the cables are forced to separate to join into the grooves in the connection piece. This imposes a “hard-bend” on the cables in the flat assembly and a twist and a hard-bend in the upright assembly. LBNL solved this problem by using 2x2 NbTi/Cu cables (7) to cover the transition between the top joint and the copper connector block. In the edge loaded assembly the intermediate NbTi cables make the twist outside of the sampleholder. G10 spacers fill the gap opening where the connection cables split. The side rails, which are traversed by the bolts, have to adapt as well to the curved shape of the connection cables. There is a small gap between the connector and the straight part to let the cable twist by 90 degrees. At the change of the sample the connection cables are soldered/unsoldered at the top of the straight part of the sample-holder. This brings two solder joints in relative proximity (~30 cm) to the Ic measurement part. It has not been determined yet if the heat generated in these joints affects the measurement region (typical soldered joint contact resistance: <1mΩ). To apply the transverse pressure to the conductor pack the top part of the sample holder has two 170 mm long longitudinal EDM cuts (6), separated by exactly the width of the conductor block. Additionally a “dog-bone shaped” metal-piece (3) (the shaft being of the same width as the conductor pack) is placed on top of the sample-holder cover, such that the pressure piston presses the lamella formed by the two cuts into the soft conductor package. The sampleholders is thickest at the location of the dog-bone shaped metal piece. A small groove in the bottom part of the sample-holder along each side of the conductor pack holds the wires from the voltage taps. The voltage taps are brought out to a hypertronix pin connector (reference:LDMSTH, Mod D, male, 17 pin, 2 Unit, 50 micron, O1G-3).

3) POWER SUPPLY AND ELECTRICAL NETWORK

The NHMFL user facility comprises four 20 kA power supplies. Their operating time has to be scheduled in advance. There are 4 shifts per day (9-12am, 12-4pm, 4-8pm, 8-12pm). The normal procedure is that the control room hands over control of the power supply (Labview window appears on screen) to the cell as soon as the system is set up. The power supply control panel allows one to choose peak current and ramp rate. The superconductor test facility in particular requires a manual reset of the PS in the control room after the quench detection system triggers a current supply ramp down. Figure 6 shows a sketch of the sample power supply network. A DCCT-signal (so called “process variable”) of 10V refers to a current of 20 kA. It has to be noted that the DCCT reads the total bus-current. To obtain the actual current in the sample the current through the 22 mΩ parallel protection circuit has to be

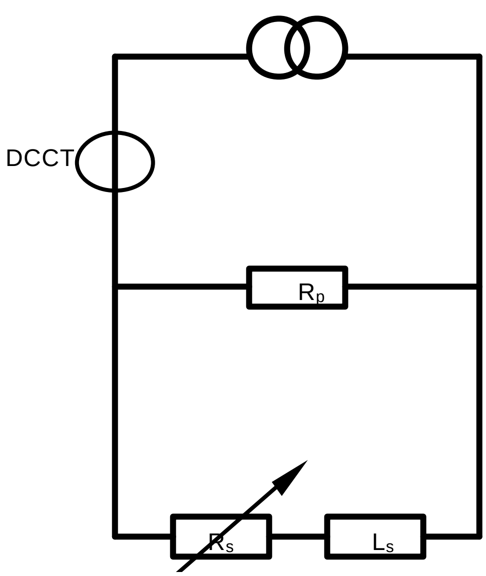


Figure 6: Sketch of sample powering system in the NHMFL cable test facility.

subtracted. Adequate wiring from the protection (“snake-“) resistor is provided. A close inspection reveals that the snake resistor is not suited to protect the sample effectively. A rough estimate of the normal state resistivity of 2 m of sample of 40 μΩ results in an estimated current in the snake-resistor of less than a 0.1% of the current in the sample. Usually non linear devices like diodes are better protection systems. Especially the brittle Nb_3Sn cables are very sensitive to thermomechanical shocks following thermal expansion along the quench front. Therefore an improved protection system could be useful.

4) MAGNET SYSTEM

The magnet system consists of 2 solenoids, capable of producing a peak field of 14 T in the 150 mm bore. The magnets are placed in the cryostat with their axis perpendicular to the cryostat axis. The sample is inserted via the vertical access port into the gap between the two solenoids. In this configuration the field is perpendicular to the samples. Figure 7 shows a field profile measurement across the solenoid bore at the center of the sample-holder (z=0). Actually, the magnet uses a Ho-insert to attain 14 T. Since the bore is occupied by the pressurization system the magnet has to operate without the Ho insert, reducing its peak-field to 13T. The two lines in the plot mark the boundaries of the high field region. Hand-taken dimensions of the magnet system are: 34.9 cm between center of bore and top of access-port, equal distance between center of magnet and bottom, 6.32 cm between bottom exit of access port and bottom of dewar, but only 4.5 cm clearance between access port bottom exit and center of the clevis rod. The magnet system is locally controlled by a standard Oxford magnet control hardware. A permanent resistance measurement (see voltmeter on top of magnet power supply) provides information about the magnet temperature. NHMFL has established a list of the ramp-rate settings for different peak fields. Low ramp-rates of a few A/m (100 A ~ 8.3T) are common rule. Don’t forget to activate the switch heater to disable the persistant mode. The magnet is automatically protected during a quench.

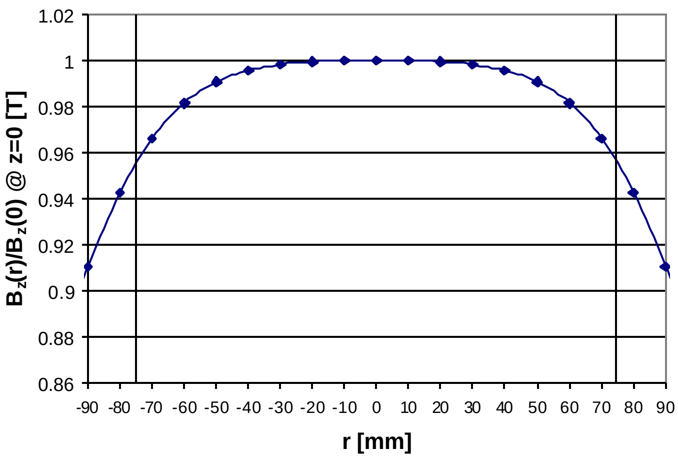


Figure 7: Magnetic field profile $B_z(r)$ normalized on peak field in solenoid bore (peak field: 12.3526 T) along the 150mm high field region (= across the solenoid bore)

5) PRESSURE PISTON

The major features of the NHMFL Ic test-facility is the transverse pressure mechanism: a self-contained structure, placed in the bore of the solenoid, puts the sample holder under transverse pressure by pressing it with a piston against a rigid Anvil back-plate. The sampleholder enters the piston housing structure through a window placed in the radial access port. Since the back-support sticks out of the magnet bore by 1mm the sample is kept apart from the magnet wall (so called “magnet former”). Eventually, an improved sample-holder design could make use of a spacer at the top to give additional mechanical support to the sample holder against the torque due to the Lorentz-force. A sketch of the pressurization system is given in Figure 8.

The sample-holder top plate has two 170 mm long EDM cuts separated by the width of the sample. These longitudinal cuts produce a flexible beam which is supported at the

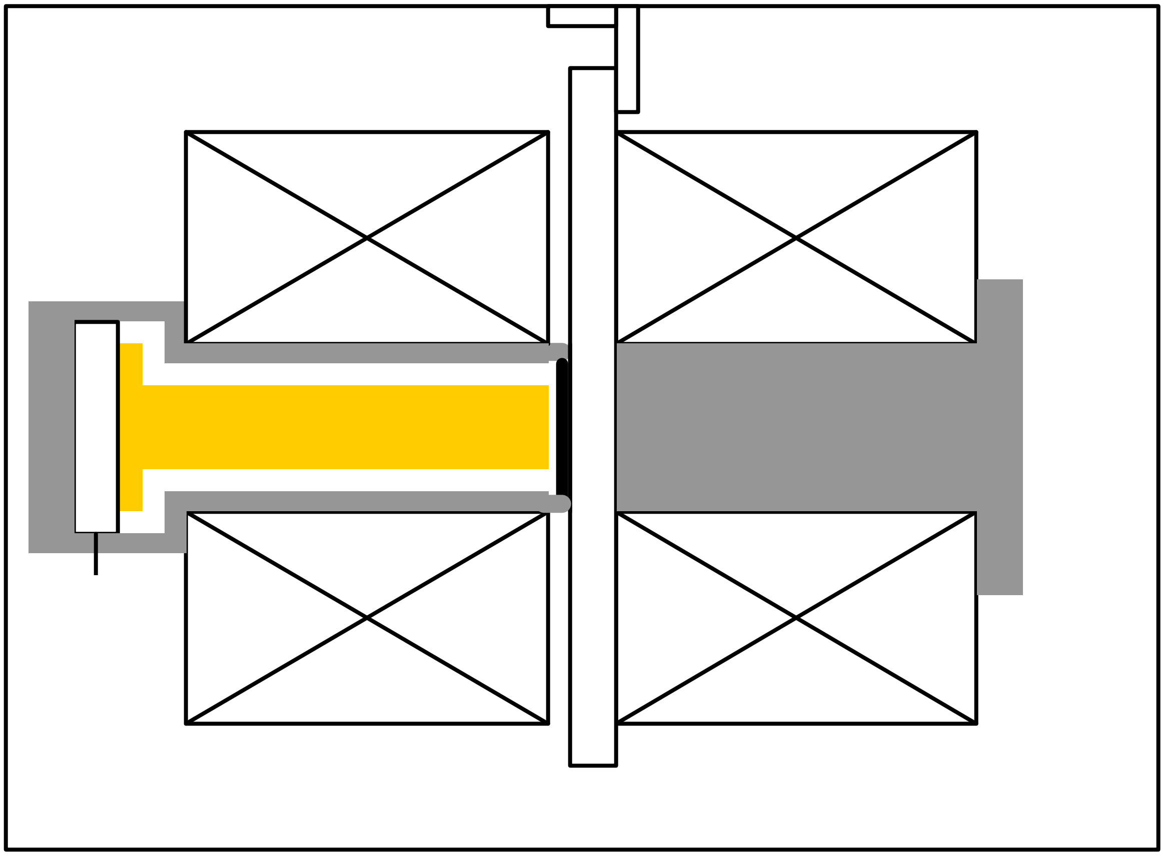


Figure 8: Sketch of the NHMFL transverse pressurization system.

ends (outside the piston region) and which can bend into the sample. A thin, flat “dog bone shaped” metal piece, with the same width as the sample and bolted to the sample-holder exactly on top of the sample-stack, channels the force onto the beam. Since the back-plate of the pressure system and the bottom plate of the sample holder are rigid the force from the piston mainly compresses the sample (strictly speaking: the beam deflects into the relatively “soft” sample). Finite element calculations showed that a 25µm deflection of the beam at the center of the piston results in a 100 MPa peak stress in the conductor package. Since the conductors are also strongly confined to the sides the sample will be squashed only parallely to the force. An experimental verification of the finite element modeling using a capacitor gauge in place with the conductor package confirmed the model to a 20 % level. Further tests should be conducted to improve the knowledge about the real stresses/strains on the sample. Measurements of the beam deflection with a bridge array of strain gages have been envisaged but not conducted yet. The pressure is generated by helium gas from a standard helium gas bottle and regulated

Stress Mpa	Pressure psig	Voltmeter Volts
0	0	0.5
10	37.7	0.584825
20	75.4	0.66965
30	113.1	0.754475
40	150.8	0.8393
50	188.5	0.924125
60	226.2	1.00895
70	263.9	1.093775
80	301.6	1.1786
90	339.3	1.263425
100	377	1.34825
110	414.7	1.433075
120	452.4	1.5179
130	490.1	1.602725
140	527.8	1.68755
150	565.5	1.772375
160	603.2	1.8572
170	640.9	1.942025
180	678.6	2.02685
190	716.3	2.111675
200	754	2.1965
210	791.7	2.281325
220	829.4	2.36615
230	867.1	2.450975
240	904.8	2.5358
250	942.5	2.620625
260	980.2	2.70545
270	1017.9	2.790275
280	1055.6	2.8751
290	1093.3	2.959925
300	1131	3.04475
310	1168.7	3.129575
320	1206.4	3.2144
330	1244.1	3.299225
340	1281.8	3.38405

Figure 9: Voltage pressure conversion for the transverse pressurization system of the NHMFL superconductor test-facility for one particular LBNL sample – active surface: 122 mmx15 mm. Piston diameter: 122 mm.

with the standard set of valves (fine and rough) attached to the bottle. The gas is precooled outside the cryostat by immersing some spirals of the stainless steel tubing in a liquid nitrogen dewar. The helium is directed into a system consisting of 2 parallel stainless steel (316) plates connected by a stainless steel bellow. The system extends and pushes the inner plate against a piston in the bore of the solenoid. The piston can travel 3mm. Therefore the total sample-holder thickness (incl.the bone-shaped extra-piece) should be in the 26-27.5 mm range (28mm is the clearance when the piston is fully retracted and 25 mm is the clearance when the bellow is fully extended. The other dimension of the piston housing window is 71mm, thus 1 mm larger than the access-port. The piston transmits the pressure to the sample, which is supported from the back by an anvil part. The anvil is part of the piston housing assembly. The bellows and piston are are inside this assembly. A cover plate with a diameter of 35 cm holds the bellows and piston in the assembly. The bellow is protected from overextending, nonetheless it is not advisable to build up pressure in the system without the sample in place. The pressure in the system is reduced by pumping (slowly open valve to pump). The default intial condition is with vacuum in the line (zero pressure). To maintain the default position the pump is working continuously. The line-pressure is measured in a transducer. The transducer signal is linearily proportional to the pressure. The voltage to pressure conversion table for one particular LBNL sample-holder is given in Figure 9. Note that the line-pressure has to be renormalized to the actual piston surface to active sample surface ratio to obtain the right voltage/pressure conversion. Note as well the offset in the voltage scale. The requirements for the transducer power supply are: 16V, the transducer current is normally in the-mA range. The upper pressure limit of the system is given when the helium starts to solidify in the bellows (~10MPa).

6) QUENCH DETECTION CIRCUIT

Especially in brittle Nb_3Sn cables quench protection is a serious issue. The thermomechanical jolt the cable receives during normal zone formation and subsequent thermal expansion due to Joule heating of the current in the normalconducting matrix can disrupt the filaments. The quench detection system has been designed at NHMFL. It provides 4 channels with gains in the range 1-2000 and threshold voltages (after amplification) of 1 to 7 Volts. This sets the lowest possible quench detection voltage to 500 μV. Since this is relatively high, considering the short length of the sample, it is reasonable to operate with the highest possible sensitivity. Obviously one has to find a compromise in the tradeoff between noise and quench detection threshold. The quench detection voltage taps should cover the go and the return branch of the sample, the whole sample loop and the superconducting part of the current leads. When a quench is detected the device sends a quench signal to the power supply control unit. It would be advisable to reduce the quench detection threshold voltage by one order of magnitude.

7) MEASUREMENT HARDWARE

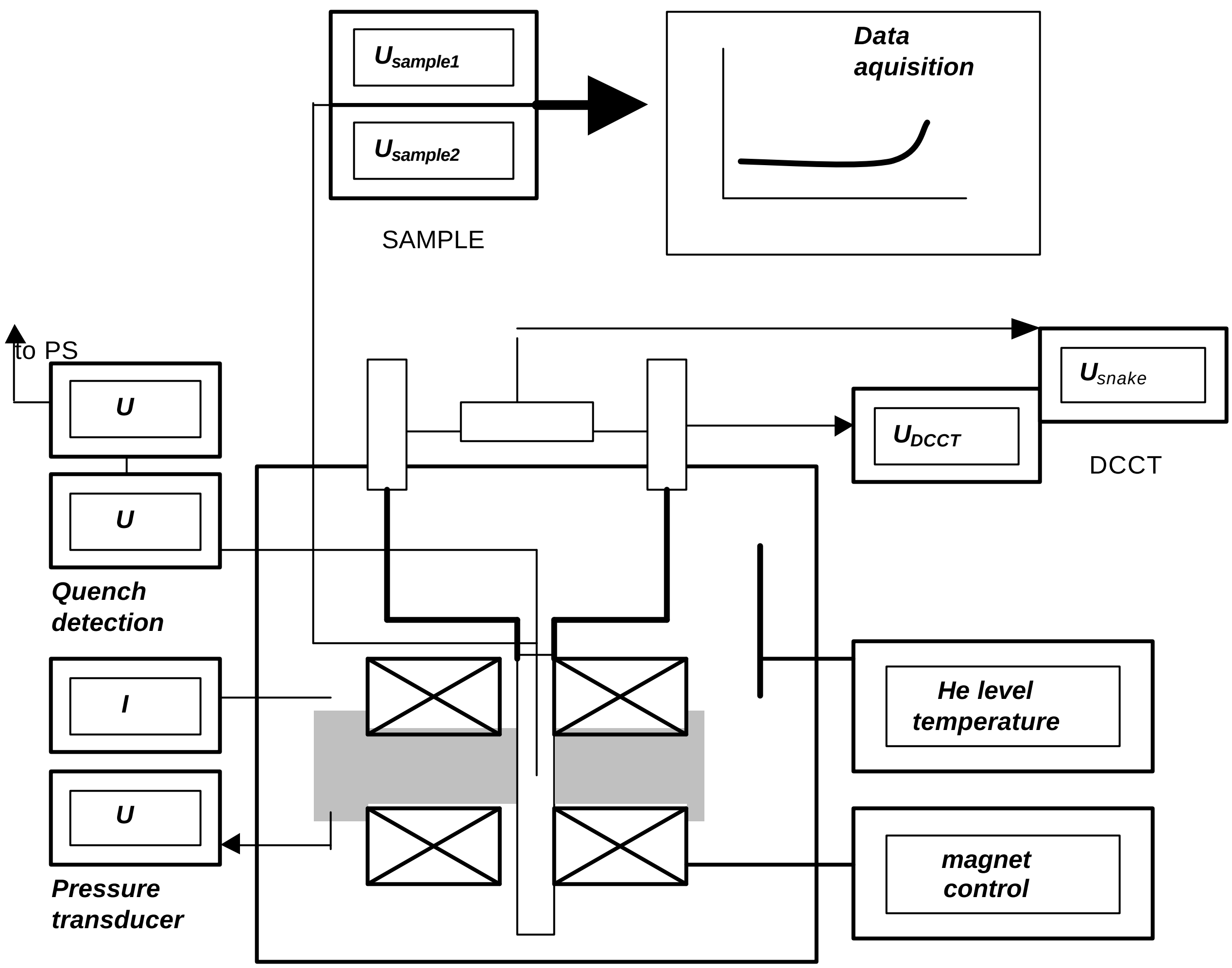


Figure 10: Schematic of the NHMFL Ic measurement set-up.

Item	Task	Location
6 Keithley 182 DVM	Sample voltages Pressure transducer voltage Process variable Snake resistor voltage	on shelf in electronics shop
4 channel quench detector	Quench detection	in principle for cell 16 only
16 V power supply	PS for pressure transducer	cell 14 or 16
PC	Measurement software	cell 16
Magnet control unit (PS, Voltmeter)	Set magnet, control magnet temperature	cell 16
He level control unit	Read He level in cryostat	cell 16
10 A power supply	Warm test of sample voltage taps	cell 14
Fluke handheld VM		cell 14
tooling		cell 14
cables	GPIB, Keithley, Banana	on shelf in electronics shop
Cryogenic plumbing	Helium transfers	cell 16, cell 14
He gas bottles		workshop near coffee machine
Liquid nitrogen		automatic filling station in corridor with odd numbered cells

Table 2: List of measurement devices, cell 16 refers to the Ic measurement lab, cell 14 is occupied by the same group which operates and supports operation of the Ic facility.

8) MEASUREMENT SOFTWARE

NHMFL provides a Labview based measurement software, which reads data from digital measurement devices through the GPIB bus. In the program a channel-list has to be defined – assigning GPIB addresses to the software placeholders of these devices. The data acquisition window allows monitoring live the different measured magnitudes. The measured magnitudes can be multiplied with proportionality factors. Unfortunately channel data cannot be combined (e.g. subtracting 2 channels from each other) in the live mode. The data are automatically stored in a text-file format (filename=generic name + run number). One channel can be defined as the timestamp using an internal clock. There are several trigger options. Since the PC is connected to the network the final data can easily be transferred by FTP. The data acquisition speed is of 4 readings per second. Eventually a better time-resolution can be achieved by reducing the transport current ramp rate at the approach of the transition.

9) CRYOGENIC SYSTEM

The cryogenic system for the NHMFL superconductor test facility is essentially manual: The liquid helium is supplied in 500 l dewars. Transfer-lines are available. The cryostat has a liquid nitrogen shield, which can be filled once the magnet has reached a low

temperature. Following local practice the magnet is as well precooled with liquid nitrogen. However, experience has shown that it is advisable to stop the nitrogen transfer above 77K to avoid later contamination of the system with nitrogen ice. After throrough purging with helium gas the transfer of liquid helium can start. Approximately 500 - 1000 l of liquid helium are necessary for the first cooldown. In the following the typical consumption is 500 l a measurement day. The dewars are pressurized with an electrical heater (4 or 8 psi) – in between rates can be set with a voltage divider. The helium dewars are parked (and connected) to the recovery line between cell 14 and cell 16. The current leads are vapor cooled and have to be connected to the recovery system as well. The sample can be changed in cold conditions, but it is advisable to reduce the liquid helium level as much as possible to avoid excessive turbulence. Following local usage the sample holder is precooled in liquid nitrogen before a cold sample change.
Two level gages indicate the liquid helium level in the cryostat. The lower gage reaches from underneath the magnet to about 2/3 of the magnet. The upper gage reaches from the top of the magnet to higher. The upper third of the magnet is a blind zone for the level meters. Typically the machine is operated at a 50% upper level. In this condition the dewar contains approximately 500 l of liquid helium. The cryostat is protected with at least two multiple saftey valves.

10) MEASUREMENT PREPARATION

TASK	DETAILS	TIME	COMMENT
Scheduling of measurement time	Power Supply-shifts	Weeks ahead	Contact M.A. Johnson
Scheduling of liqu. helium delivery	Confirm with J. Pucci	Weeks ahead	Contact M.A. Johnson
Inform concerned NHMFL staff of scheduled venue to the lab	J. Miller, B. Walsh, G. Miller and M. Haslow	Weeks ahead	
Prepare measurement hardware	Get Voltmeters, GPIB cables, Keithley cables from electronics pool	1-2days before measurement	
Prepare sample holder	After cleaning connection connect sample holder to sample insert (indium solder)	1-2days before measurement	
Electrical check of voltage tap	Run 1-10A through sample and check response of alle the voltage taps (underneath connector and above connector)	1-2days before measurement	
Check quench detection system	Feed known voltage into all channels of quench detector and test if it triggers	1-2days before measurement	
Cooldown 1	Start cooldown with liquid nitrogen (cryostat inside and jacket)	1 day before measurement	Stop before magnet reaches 77K.
Insert sample-holder into cryostat		evening before measurement	support needed
Cooldown 2	Start slow helium transfer (leave it overnight)	evening before measurement	
Cold electrical check	Check for “lost” voltage taps	morning before measurement	
Check pressurization system	Carefully build up pressure in	morning	

	pressure circuit – watch response of transducer	before measurement	
Start magnet ramp	As soon as 10% on upper helium gage is reached start magnet ramp	before measurement	
Prepare measurement software	Set channel list, test live data displays, set plots	before measurement	
Call control room	Test PS	measurement	
Start measurement			

Table 3: Checklist for the Ic measurement preparation in the NHMFL superconductor test facility.

11) USEFUL CONTACTS / DIRECTIONS

NAME	POSITION	TEL	E-MAIL	COMMENT
Steve Van Sciver	Head Magn.Scien.&Techn.Div.	0998	vnsciver@magnet.fsu.edu	
John Miller	Head Magnet Design Group	0929	miller@magnet.fsu.edu	
Robert Walsh	Material scientist	5088	walsh@magnet.fsu.edu	Best knowledge about Oxford test-station
Bruce Brandt	Director of operations	4068	brandt@magnet.fsu.edu	Scheduling of PS-time and test-station occupancy
M.A. Johnson	Secretary director of operations	6257	johnson@magnet.fsu.edu	Scheduling of PS-time and test-station occupancy
John Pucci	Responsible for helium delivery	8517	pucci@magnet.fsu.edu	Scheduling of helium dewar delivery
George Miller	Technician	2031	millerg@magnet.fsu.edu	Technical support
Michael Haslow	Technician	2819	haslow@magnet.fsu.edu	Cryogenic support
Andy Powell	Electronics Engineer	1910	powell@magnet.fsu.edu	Electronic support
Cell 16		3037		Test station
Control room		4416		Power supply control

Table 4: Useful telephone numbers (all numbers refer to the NHMFL Tel: (850) 644-xxxx)