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THE SUPERCONDUCTING UNDULATOR PROTOTYPE TEST FACILITY AT BROOKHAVEN NATIONAL LABORATORY

J. Skaritka, D. Harder, M. Lehecka, P. Mortazavi, G. Rakowsky,
NSLS, Brookhaven National Laboratory, P.O. Box 5000, Upton, New York 11973

Abstract

Users of Modern third generation Synchrotron Light Sources require ever brighter X-ray beams to perform their research. The beam brightness is controller by accelerator capability and the parameters of the undulator magnets used in the insertion devices. Parameters such as very short magnetic period length (1-2 cm), small magnetic gap (0.5-1 cm), very high magnetic fields (1.5-2 tesla), and a wide tuning range of magnetic field strength (more than 4:1) are required to achieve this next level of machine brightness. This combination of requirements can only be met with superconducting magnet technology. However, third generation light sources generate substantial heat from image currents of the high-power electron beam, as well as from intense synchrotron radiation from upstream magnets may limit the performance of superconducting insertion devices.[1] To meet the challenges of SCU undulator design and testing, BNL has entered into a collaboration with three other US National Laboratories. The goal of this collaboration is to develop SCU technology that will successfully address the high heat load, the above desired parameters and SCU field correction.[2] BNL's contribution to the collaboration is for the NSLS to build a cryogenic test facility for comprehensive calorimetric as well as magnetic measurements of short SCU prototypes up to about 0.5m long. This SCU "vertical test facility" (VTF) is uniquely designed to test SCU models under realistic operating conditions with simulated beam heating loads up to 100 watts/m of length.

1. Introduction

Undulator magnets are used in high-energy electron accelerators, like synchrotrons or electron storage rings ("synchrotron light sources"), to generate extremely intense, nearly monochromatic x-ray beams, which are used in many fields of basic research, including material science, chemistry and, most recently, in the decoding and 3-dimensional imaging of complex biological molecules.

To date, most undulators have been assembled from permanent magnets; however, this technology is mature and near its theoretical limits. Modern "third generation" synchrotron light sources require undulators with a combination of very short magnetic period length (1-2 cm), small magnetic gap (0.5-1 cm), very high magnetic fields (1.5-2 tesla), and a wide tuning range of magnetic field strength (more than 4:1). This combination of requirements can only be met with superconducting (SC) magnet technology. In a superconducting undulator (SCU), coils or windings of superconducting wire, carrying currents in excess of 1,000 amperes per square millimeter (A/mm^2) of conductor cross-section, are wound around or between ferromagnetic poles. SCU's wound with the commonly available niobium-titanium (NbTi) superconductors have been demonstrated recently. However, the higher performance requirements described above call for even higher current densities, necessitating use of more exotic SC materials like Nb_3Sn, NbAl or NbTi with artificial pinning centers (APC-NbTi).

As in all superconducting magnets, the SC wire must be cooled to a temperature below its "critical temperature " (T_c), typically a few degrees Kelvin. Modern cryostat designs can limit heat transfer from the environment to the superconductor to the order of 1 watt at 4K, which can readily be removed by a cryocooler or by a liquid helium refrigerator. However, third generation light sources may generate substantial additional heat from image currents of the high-power electron beam, as well as from intense synchrotron radiation from upstream magnets, and other beam-related effects. This heat appears in the walls of the evacuated beam tube which is situated between the magnet arrays and provides a flight path for the electron beam through the undulator's magnetic field. (Note that a beam tube is generally required to isolate the ultrahigh vacuum of the electron storage ring from the SC magnet coils which are typically insulated with organic materials and are not compatible with ultrahigh vacuum.) This heat must be removed, otherwise it may warm the SC wire above T_c, causing it to suddenly become normal conducting ("quench") and resulting in collapse of the magnetic field at best, or, at worst, in catastrophic failure of the magnet. An efficient system of thermal management and cryogenic cooling is needed for superconducting undulators to be used in the newest and proposed synchrotron light sources.

To meet the challenges of SCU undulator design and testing, we are constructing at NSLS a cryogenic test facility for comprehensive calorimetric as well as magnetic measurements of short SCU prototypes up to about 0.4m long. This SCU "vertical test facility" (VTF) is uniquely designed to test SCU models under realistic operating conditions with simulated beam heating loads up to 100 watts/m of length.SCU Magnet Development and the US Intra-laboratory Collaboration

BNL has proposed to build NSLS II , a ultra high brightness medium energy short pulse Synchrotron Radiation Facility, Various phenomenon have been identified that contribute to the cryogenic heat load deposited into the cold mass of the SCU. Cold mass heat loads as high as 5 watts per meter of SCU length have been estimated. The history of synchrotron radiation sources show that dramatic improvement in brightness often occurs over time. Using BNL's NSLS as an example X-ray brightness has increased by a factor of more than a 1000 since operation began over twenty years ago.

When NSLS II commissioning is complete, it is expected that X-ray beam brightness will be $\geq 10^{21}$ [photons/sec -0.1% bw-mn^2-mrad^2] Photons. After commissioning it is anticipated that brightness may be increased as technology evolves over the useable life of the new light source, so that it may continue to offer it's users the brightest beams for as long as possible. It would be unfortunate for any facility to have its brightness and flux limited by the thermal restrictions of its insertion devices. It would be desirable for the SCU to be a robust device with ample thermal operating margin, so the insertion devices will not impede upgradeability in the years to come. A thermal safety factor of at least an order of magnitude is highly desirable to accommodate the uncertainties of the heat load estimates and to assure reliability over the course of machine operation.

BNL is currently involved in intra-laboratory collaboration to develop SCU technology addressing the ultra high cryogenic heat loads that will be present in future high brightness synchrotron radiation sources. Three avenues of SCU research are being investigated by the intra-laboratory collaboration.

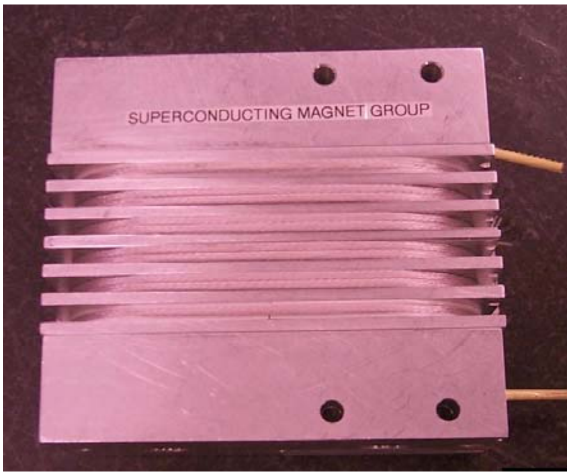


Fig 1 – 3 period, Undulator Prototype fabricated by LBL

Lawrence Berkeley Laboratory has produced and tested the first prototype undulator magnets utilizing Nb_3Sn superconducting cable [3] Nb_3Sn has a higher critical current density then conventional NbTi superconductors and it will maintain adequate current carrying capacity at temperatures of 8K see Figure 1. At this temperature, commercially available cryo-coolers can extract heat loads in excess of 5 watts from a cold mass.

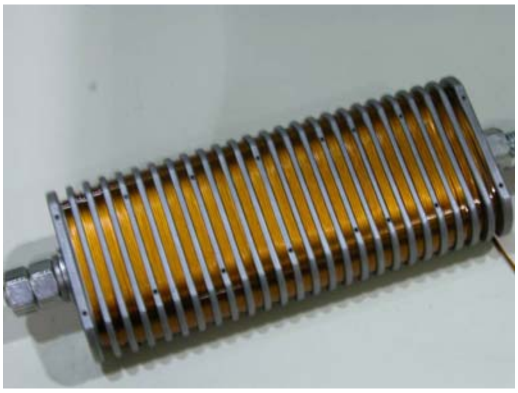


Figure 2 – The ANL 12 Period Undulator Prototype

Argonne National Laboratory has produced a segment of undulator yoke using conventional NbTi superconductor [4]. Liquid helium cooling tubes are used to cool the iron yoke of the magnet. It is proposed to use a helium refrigerator to circulate liquid helium through the yoke. Refrigerators can be obtained with adequate cooling capacity to maintain the cold mass temperature at approximately 4K see Figure 2.

BNL has proposed to construct an undulator utilizing advanced pinning center NbTi superconductor. This type of superconductor has a current density similar to that of NbSn. Methods of field correction and shimming will also be investigated and developed by the participating laboratories. See Figure 2.

2. Vertical Test Facility

A test facility is being fabricated to evaluate the prototype undulators produced by collaboration. members. The test facility is designed to simulate the environment and heat loads that could be present in an actual undulator.

Magnetic Measurements and System Controls

Three measurement methods of are being developed for incorporation into the test facility. The primary field measurement system will be an array of hall probes. Six precisely positioned hall probes mounted to a substrate will map the field of the undulator. See Figure 3. The center hall probe measures peak field. The outer two hall probes detect field flatness and symmetry. The second set of three probes confirms the readings of the first set. A stepper motor drive system positions the array along the axis of the undulator.

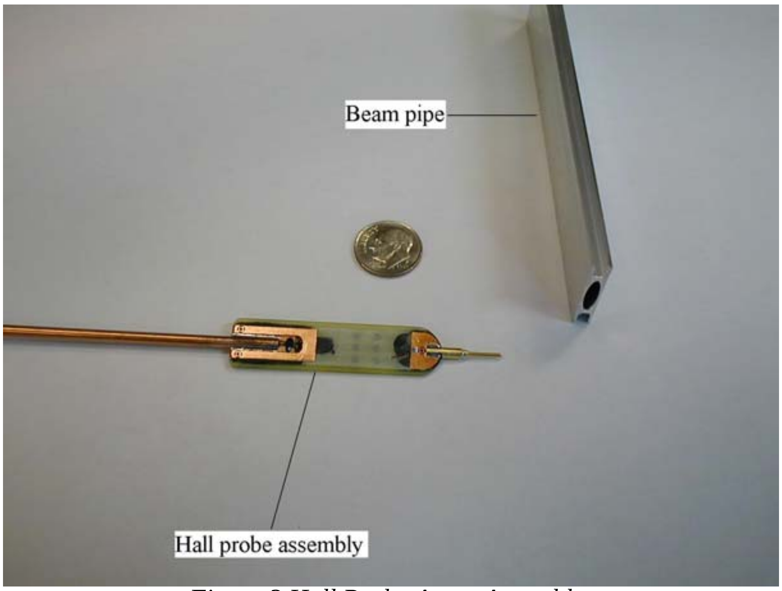


Figure 3 Hall Probe Array Assembly

A vertical pulsed wire system is being developed to perform integral field mapping and particle trajectory measurements. The pulse wire system may be altered to allow vibrating wire operation. Complementary field measurement methods will be used to fully categorize the magnetic field in the aperture of the SCU.

The unique nature of the Vertical Test Facility is evident in the type and variety of tests conditions required to simulate SCU operation. LBL and ANL prototype magnets are first tested by the respective institutions in the conventional manner utilizing pool boiling liquid helium. The magnet's performance will be evaluated and a baseline performance will be established.

The mechanical, magnetic and operational constraints on an actual insertion device indicate that liquid helium free operation is highly desirable; therefore, a cryogen free magnet performance measurement is designed into the (VTF).

Upon receiving the SCU at BNL A special point field magnet will be surveyed and fixed to the magnet yoke. The point field magnet will produce a field maximum on the magnet's geometric center axis; its position will be verified by warm pulsed wire bench tests prior to the installation into the VTF. A second point magnet is fixed to the Heimholz coil assembly which is aligned at room temperature and fixed to the bottom face of the SCU. The magnet will then be installed in the VTF. A liquid nitrogen pre-cooling, followed by a helium gas pump and purge sequence will bring the magnet and VTF components to cryogenic temperatures. Liquid helium will be transferred into the test dewar until all cold surfaces are submerged. The magnet can be tested with a current of up to 1000 amperes to re-establish the base line operating performance. The hall probe assembly will first be *insitu* calibrated using a superconducting Heimholz coil located below the SCU magnet.

The hall probe array is injected into the cold beam tube. A diagram showing this operation is shown is Figure 4. The array reading is taken and then the array is moved to the second point magnet. The hall probe array (HPA) slides without clearance on the inside of an extruded aluminum tube. A horizontal probe position will be adjusted using a linear stage located at the top of the VTF. An electric contact at the end of the probe indicates the extreme position of the HPA. The stepping motor drive system will then pull the probe up through the 4.2K beam tube past the Heimholz calibration coil and the first point magnet. The hall voltage will be monitored and a maximum on the probe will indicate the hall probe chip is at its nearest approach to the point magnet. The axial position of the point magnet is fixed with respect to the first pole of the SCU. The axial position of the hall probe is accurately known relative to the magnet iron geometry. The HPA will be drawn through the magnet until it reaches the second point magnet. The axial positions of the two are controlled by Zerodur rods which are in turn fixed to the outside of the magnet. Knowing the exact distance between the point magnets and their relative position with respect to the SCU prototype assures that we will have hall probe positioning which is essentially independent of temperature gradients and the corresponding length uncertainties in the HPA drive shaft.

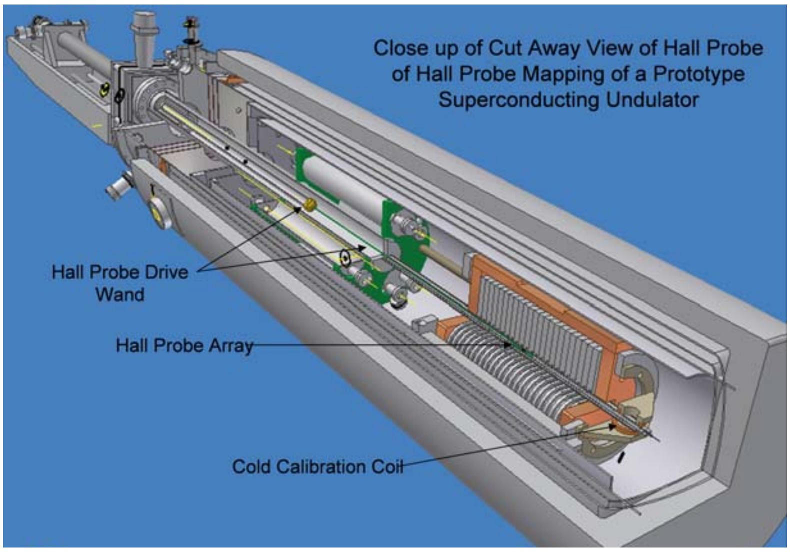


Figure 4

Upon completion of initial field mapping and baseline performance testing, the VTF will be pressurized with helium gas and the liquid helium that does not boil away will be transferred back into the storage dewar. A heater at the base of the VTF will assure that all liquid is boiled away. The fill/extension transfer line will be valved off and the transfer is withdrawn from the dewar.

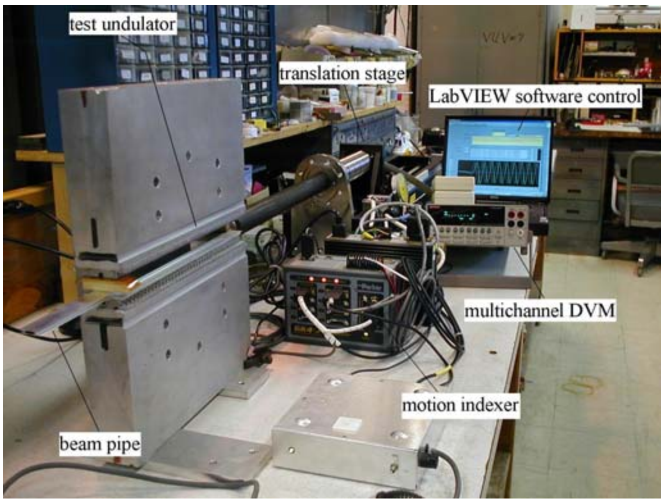
The next operation is highly dependent on the design of the magnet and the specific cooling concept. In the case of LBL SCU prototype, a copper cooling plate may be affixed to the magnet iron so that heat may be removed from the magnet by conduction between the chill plate and the magnet iron liquid helium or cold helium gas at ≈ 8K can be circulated through the chill plate. The ANL SCU prototype cooling tube in the yoke will extract heat by convection from the inside of the yoke. A helium cooling line attached to the cold mass will allow liquid helium with a temperature range of 3.2 to 5.2K to be supplied to the cold mass. A precision heater is affixed to the surface of the HPA tube. When the heater is turned on the heat generated will simulate the heat deposited into the actual beam tube from eddy currents, gas beam scattering and stray synchrotron radiation. The heater is designed to deliver up to 100 watts/meter to the gap of the SCU prototype.

There are up to 3 cooling loops that can supply liquid or cold helium gas to the magnets cold mass to evaluate magnet cooling concepts. Calorimeters are located in the flow path just down stream of the cold mass. The calorimeters are extremely important to determine the heat that is deposited in the cold mass and the effectiveness of the magnet's cooling concept.

Hall Probe Mapping Assembly

The Hall Probe Mapping Assembly consists of a 6 element printed circuit Hall array secured to a copper support tube, which is affixed to a Z-axis stage. The individual Hall elements are tiny surface mount devices, which have an active area approximately 125 microns by 125 microns. They are arranged in two rows of three elements, thus on-axis and off-axis data can be taken in a single scan. The twisted-pair wires which deliver the excitation current to the sensors and transport the detected Hall signals run along the inside of the copper support tube to provide shielding from electromagnetic interference.

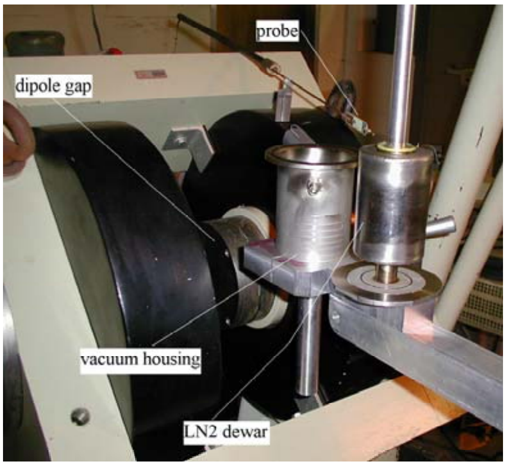
The Hall signals from the 6 sensors are sampled by a high precision, programmable, externally triggered, multi-channel voltmeter with a large buffer. The Z-axis stage is driven by a motor, which is software controlled.



The Hall probe scan is done "on-the-fly": the Z-axis stage is homed precisely, the motor is instructed to move at constant velocity and the voltmeter is periodically triggered by the divided motor step signal to scan sequentially to buffer all 6 channels. The "on-the-fly" scanning speed is constrained by the spatial field resolution required--the number of samples per undulator period--and the integration time of the measurement to achieve the desired accuracy, which is constrained by the interference in the Hall signals. Typically a full scan--1/2 meter--can be done in about 4 minutes. The Hall voltage data is converted into magnetic field information by post-processing with respect to the polynomial fitting of the NMR calibration data for each sensor.

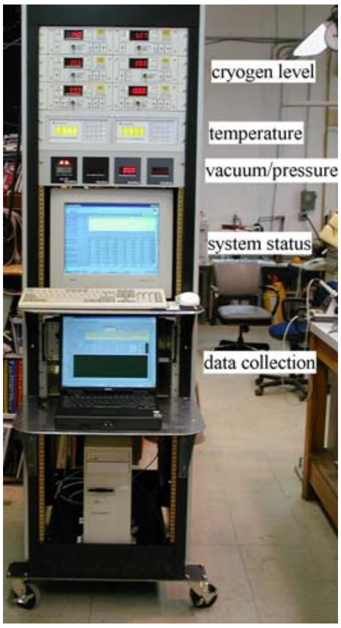
Hall Probe NMR Cold Calibration

All six of the Hall sensors on the Hall probe assembly were calibrated in the NMR at room temperature and then at 77 * Kelvin over a field range of + and – 1.1 Tesla. The cold calibration was done by submerging the probe in liquid nitrogen, which was contained in a small dewar, which was inserted into the NMR field. The dewar was designed to fit along with the NMR probe in the 1 ½ inches (38mm) gap between the NMR calibration magnet poles.



Vertical Test Assembly Instrumentation

The Vertical Test Assembly Instrumentation rack configuration was designed to be robust and portable. Using National Instruments LabVIEW software, all of the critical system parameters are monitored and controlled, like temperature, vacuum and pressure, cryogen level and flow, superconducting current path resistance, and embedded heating elements. All of the monitored parameters are displayed close to real-time, so that the state of the system is well defined at any given time, and so that calorimetry and heat loading calculations can be performed. Also, the information is continuously logged to spreadsheet for post-processing and analysis.



Calorimeter Operation

The purpose of the calorimeter is to determine how much heat has entered a particular liquid helium flow stream. This is necessary to determine the effectiveness of SCU cooling methods. There are three calorimeter cans in the VTF, one per each possible helium flow path. Each calorimeter is composed of a cylindrical tank with a volume of approximately 1 Lt. with an accurate inside diameter. A helium liquid lever probe runs the length of the can. A calibrated Cernox temperature sensor is positioned in the helium flow stream just below the can. A 100 watt heater is located in a separate line near the bottom of the can, but is isolated from the Cernox probe. A second Cernox probe is located in the flow path just prior to entering the cold mass.

The principle of operation can be formulated as:

$$Q = Mcp\Delta T$$

Q = Heat
M = Mass flow rate
cp = Specific heat
ΔT = Change in temperature

A precision pressure transducer measures the pressure of the gas flow down stream of the calorimeter can. Specific heat "cp" can be deduced by knowing the temperature and pressure of the helium flow. The liquid level sensor monitors the change in liquid level inside the calorimeter can. ΔT is the change in the helium flow temperature across the cold mass. Q in watts may be obtained by monitoring the above parameters and applying the formula. One drawback to the design is that it is a batch process. Once the helium can is full the heater is turned on to boil the liquid until the level in the can is nearly empty, but it is an accurate alternative to highly expensive liquid helium flow meters that will have significant error for this application. The pressure control valve has been designed to accommodate the increase of helium flow during boil off, and a check valve in the line between the cold mass and the calorimeter prevents the back flow of warm gas back through the cold mass.

Sub-cooler Operation

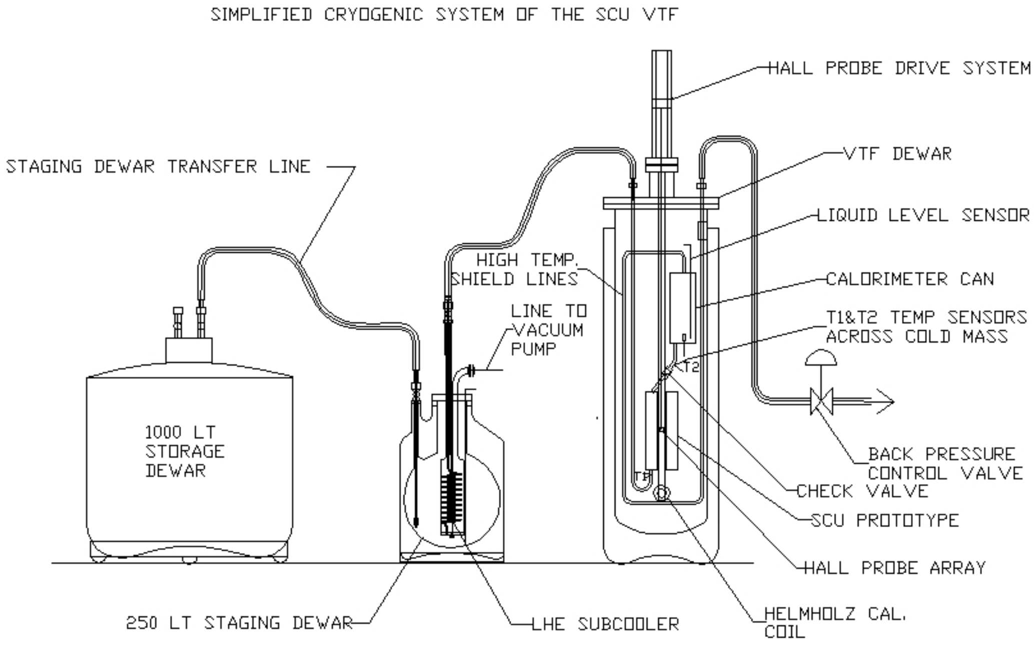
To perform effective calorimetric measurements helium liquid must be sub-cooled to allow a template rise with out phase change. To control the temperature of liquid helium, a sub-cooler insert will be installed in the high pressure staging dewar. The staging dewar is designed to have an operating pressure up to 50 psig. By pressurizing the staging dewar, the temperature of the liquid could be increased to the critical point of ≈ 5.3K. The sub-cooler is a small vessel with valves in the 250 Lt. helium staging dewar. When the valve is opened, liquid enters the sub-cooler vessel. A liquid lever sensor monitors the level until the level covers and heat exchanger coil. The valve is then closed and a partial vacuum is applied to the sub-cooler vessel. The vacuum allows the helium to boil, and the temperature can be dropped to as low as 2.5K. Helium in the high pressure vessel is then allowed to flow through the heat exchanger coil in the sub-cooler. A calibrated Cernox sensor at the exit of the heat exchanger coil monitors the liquid temperature. The overall flow is controlled by the pressure control valve and a valve at the base of the liquid helium transfer line between the sub-cooler and the VTF test dewar.

3. Detailed description of VTF operation

The cryo system of the VTF has three open loop helium flow paths. At its maximum the system is composed of the following:

- two each 1000 LT portable dewars,
- three 250 Lt. pressuerizable staging dewars.
- A sub cooling heat exchanger is located in each 250 LT dewar
- Liquid helium transfer lines for each staging dewar
- Liquid helium lines for each supply dewar
- transfer line stabs
- re-sealable feed throughs located on the top hat plate of the VTF

A simplified diagram of a single helium flow path and system components is shown below in Figure 5.



Stainless steel plumbing lines direct liquid cryogens to the following locations within the VTF:

1. The base of the helium dewar.
2. The independent helium reservoir of the pair of 1000 amp vapor cooled leads.
3. The HPA tube vacuum chamber.
4. The helium cooled magnet cold mass chill plate or vessel.
5. Magnet cold mass cooling lines.

The helium lines pass through the beam tube and cold mass plumbing into calorimeter cans. The flow path exits the calorimeter cans and enters lines that run through a low temperature aluminum shield. Up to two flow paths can run through the shield so that helium exhaust gas is always cooling the shield.

After leaving the shield the gas flow path enters a thermal heat stationing ring. This copper ring rests against the wall of the vertical test dewar. Its' purpose is to intercept heat entering through the top of the dewar and traveling down the dewar's inner wall. The heat stationing ring in effect establishes a high temperature heat shield, so that a liquid nitrogen bath on the out side of the dewar's vacuum envelope is no longer needed. This greatly simplifies cryogen handling, safety and space issues around the test dewar.

Upon leaving the heat stationing ring the flow path exits through a re-entrant feed through out of the vacuum/helium space of the dewar, through its top hat. A flexible metal hose directs the flow to the CPC cryo lab pressure control valve. This back pressure control valve controls the pressure through the VTF's cryogenic system. Upon exiting the control valve the helium flow enters the building 902 Magcool refrigerators helium recovery system. After cleaning, compression, and liquefaction the helium liquid fills the 1000 lt. storage dewars.

4. VTF Testing Procedures

The magnet and beam tube assembly is brought to liquid helium temperature and base line performance is re-established. Liquid helium flow rate through the sub-coolers, cold mass and calorimeters is established and stabilized base line conditions. The magnet is brought to the desire field level and magnetic measurement utilizing the hall probe array and/or pulsed wire system is performed. After the magnet field is fully measured, thermal studies are started. The beam tube heater is turned on. The calorimeter on the beam tube cooling line is monitored to determine the total heat load deposited in the beam tube. Temperature sensors on the magnet iron and the cold mass calorimeter are monitored to detect heat being transferred into the cold mass and determine the cooling capacity of the respective cold mass cooling system. Magnet voltages are monitored to detect quench onset. This operation is performed until a stable heat transfer condition is established in the beam tube magnet cold mass assembly. If this state is re-established, this would mean, the magnet cooling system is supplying an adequate heat removal capability. Upon completion of this step additional current is applied to the heater in the beam tube. All systems are monitored to determine if the heat loads in the beam tube and cold mass are understood and if the magnet is nearing a quench threshold at this additional heat load. This step is repeated until quench or a near quench threshold event occurs. When a quench is determined the current on the magnet is dumped to a resistor by the magnet's quench protection system. The test may be repeated with different temperature and or flow rates of liquid helium through the cold mass to determine the total thermal operating envelope of the prototype magnets cryogenic cooling system. Magnetic measurements may be performed to determine if any field changes occur at these extreme conditions.

Once the prototype has completed these tests it will be removed from the VTF and returned to the contributing institution and the next prototype will be made ready for magnetic and thermal measurements. This operation will be repeated for all the undulators BNL and/or the collaboration members' supply for testing. Higher temperature operation can be achieved for testing Nb_3Sn coil undulators by running cold helium gas to the magnet cold mass a beam tube. The sub-cooler will be fitted with a heater to vaporize the liquid helium flow. Cold gas will then be transferred through the magnet cold mass. The calorimeters' temperature sensors will be used to determine the change in temperature of the gas stream across the cold mass .A calibrated helium mass flow meter will be installed into the flow path down stream of the VTF. The precision flow meter operates at near room temperature so the gas stream must first pass through a gas or air heat exchanger prior entering the flow meter. At the completion of the SCU prototype program, several different SCU magnet and cooling concepts will be characterized experimentally. Confirming the thermal operational envelope will allow engineers to make appropriate selection of specific cryogenic systems to maintain the operating parameters of selected magnets.

When the initial cryogenic magnetic measurements program is completed, the VTF is planned to be modified to incorporate a cryo-cooler and closed loop helium circuit flow components to allow the testing of proposed cryogenic systems as well as the magnet. A cryo-cooler or liquid helium heat exchanger would occupy the same location that the magnetic measurements systems currently occupy. The VTF can then test components of integrated system to demonstrate their performance prior to or in parallel with full scale insertion device development.

5. Conclusion

A Vertical Test Facility capable of simulating the heat load of current and future high brightness synchrotron radiation sources is being assembled by the NSLS Department at the Brookhaven National Laboratory. The facility will be able to fully measure and categorize the field of a superconducting undulator magnet up to 0.5 meters in length using several field measuring methods, which includes a hall probe array, a pulsed wire and possibly a vibrating wire system. The system will be able to measure the heat load deposited in the magnets' cold mass from a heater in the magnet gap, which simulates image currents, synchrotron radiation, and other phenomena up to 100 watts per meter can be simulated by this system so that the thermal operating envelope of perspective SCU designs may be experimentally conferred and /or evaluated so that appropriate cryogenic refrigeration systems may be selected.

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