Effects of room temperature aging on three cryogenic temperature sensor models used in aerospace applications

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Cryogenic temperature sensors used in aerospace applications are typically procured far in advance of the mission launch date. Depending upon the program the temperature sensors may be stored at room temperature for extended periods as installation and ground-based testing can take years before the actual flight. The effects of long term storage at room temperature are sometimes approximated by the use of accelerated aging at temperatures well above room temperature, but this can yield invalid results as the sensing material and/or electrical contacting method can be increasing unstable with higher temperature. To date, little data has been available on the effects of extended room temperature aging on sensors commonly used in aerospace applications. This research examines three such temperature sensor models – Lake Shore Cryotronics model Cernox, DT-470-SD, and DT-670-SD temperature sensors. Sample groups of each model type have been maintained for ten years or longer with room temperature storage between temperature calibrations. Stability data over this ten year time period is presented for each model.

Improved Capacitive Stress Transducers for use in High-Field Superconducting Magnets

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High-field (12-18 Tesla) superconducting magnets are required to enable an increase in the energy of future hadron colliders. Such field strength requires the use of Nb_3Sn superconductor, which has limited tolerance for compressive and shear strain. A strategy for stress management has been developed at Texas A&M University and is being implemented in TAMU3, a short-model 14 Tesla stress-managed Nb_3Sn block dipole. The strategy includes the use of laminar capacitive stress transducers to monitor the stresses within the coil package. We have developed fabrication techniques and fixtures which improve the reproducibility of the transducer response both at room temperature and during cryogenic operation. This is a report of the status of this transducer development.

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Operational experience and consolidations for the current lead control valves of the Large Hadron Collider

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The Large Hadron Collider superconducting magnets are powered by more than 1200 gas cooled HTS current leads ranging from 120 A to 13000 A. The gas flow required by the leads is controlled by solenoid proportional valves with dimensions from DN 1.8 mm to DN 10 mm. During the first months of operation, signs of premature wear were found in the active parts of the valves. This created major problems for the functioning of the current leads that was threatening the availability the LHC. Following the detection of the problems a series of measures were implemented to keep the LHC running, to launch a development program to solve the premature wear problem and to prepare for a global consolidation of the gas flow control system. This article describes first the difficulties encountered and the measures taken to ensure a continuous operation of the LHC during the first year of operation. The development of new friction free valves is then presented along with the consolidation program and the test equipment developed to validate the upgraded valves prior to their installation into the LHC.

Performance of classical Venturi tubes for applications in cryogenic facilities

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The measurement of the flow rate of coolant is very important for the reliable operation of cryogenic facilities. The selection of the proper instrument for cryogenic applications is governed by many variables, broad range of temperature, in addition with highest requirements on the leak tightness at applications in vacuum, low permanent pressure losses and huge pressure overloads capability. A favourite device in cryogenic facilities is the Venturi tube. A substantial advantage is there inherent stability over a long period of time, because the characteristics depend exclusively on their geometrical shape. Additional advantages are the simple installation and furthermore no additional installation space is needed. Using capillaries for measurement of the pressure head there are no electrical components integrated in the devices. High energy recovery makes the Venturi tube suitable where only small pressure head pressure losses are preferred. In case of long time operation and large mass flows; the permanent pressure losses becomes more and more important. The additional energy cost resulting from the permanent pressure loss is a factor in cryogenics, much more than in other fields of applications. Furthermore, there are specific experimental conditions where a measurement of the flow rate in opposite directions is required. The contribution handles the specific issues in respect to long time operation of cryogenic facilities operating superconducting magnets.

A method for estimating cryogenic load in optical payload system

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A method of estimating cryogenic load of an optical payload system for space applications is presented. Commercially available thermal analysis tool (Thermal Desktop 5.3) is used for the analysis. This method incorporates a CAD-based finite difference scheme and oct-tree accelerated Monte-Carlo ray tracing algorithm to solve first principle energy equations using a nodal network. In this paper, a generic spacecraft with an optical payload system is developed using surfaces, node conductances and capacitances to generate SINDA/FLUINT input files. The proposed method captures radiation and conduction parasitic loads in the focal plane assembly (FPA) and incorporates grey body radiation couplings between surfaces as well as heating rates resulting from environmental heating fluxes (such as Solar, Earth IR, and Albedo). An example of how this method applies to a typical space flight application is described and presented using the developed thermal model. The predicted FPA and Optical Bench Assembly cooling loads are presented for various beta angle orbits and operating temperatures. The results indicate that the proposed methodology can accurately predict cryogenic load in optical payload systems for use in defining requirements in the initial stages of a program.

A versatile apparatus for the measurements of thermal conductivity, thermal expansion and specific heat based on GM cryocooler

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The thermophysical properties of matters are extremely important for engineering and materials science. This paper describes a multifunctional apparatus based on GM cryocooler for the measurement of thermal conductivity, thermal expansion and specific heat using longitudinal heat flow steady-state method, strain gauge technique and adiabatic pulse heating method respectively in the temperature range from 15K to 300K. The sample holder is changeable, and there are several different sample holders for different measurements of the above properties. The measurements are rapidly and accurately carried out at different temperatures. A set of stability criteria has been followed during the measurements to ensure the accuracy of the experimental data. The setup of the apparatus is calibrated with stainless steel and the experimental results are within 8% of the published results given in the literatures.

Keywords: thermal conductivity, thermal expansion, specific heat, GM cryocooler

Critical current of small Y-Ba-Cu-O racetrack coils and short samples

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Racetrack coils based on Y-Ba-Cu-O (YBCO) coated conductors are under investigation as an insert option for Nb_3Sn dipole magnets at Berkeley Lab. As opposed to the Nb_3Sn magnets based on the stranded Rutherford cable, the current-carrying capability of YBCO racetrack coils is not readily available from the short sample due to the anisotropic performance of the tape-form conductor. In addition, an expected coil performance is necessary to be established to assess and improve the "react-and-wind" coil fabrication techniques. To address these questions, a 2D electromagnetic model is used to compute the expected racetrack performance based on short sample performance measured in different background fields. Details and limitations of the model are discussed. Critical current of small YBCO racetrack coils are measured at 77 K and 4.2 K, self-field and are compared to the expected values given by the model.

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Effect of coil current sweep cycle and temperature change cycle on the screening current-induced magnetic field for YBCO-coated conductor coils

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YBCO-coated conductors are promising for NMR, MRI, high field magnets and accelerators due to their high tensile strength, typically >700 MPa. These conductors allow for dramatically smaller high current density magnets. One of the major problems presented by the YBCO-coated conductor coil is the screening current-induced magnetic field, induced by the radial component of the magnetic field of the coil [1]. This induced magnetic field reduces the central magnetic field intensity by <20% and causes temporal drift of the magnetic field due to relaxation of the screening current [2]. We investigated the effect of current cycle and temperature cycle on the intensity and temporal drift of the screening current-induced field for YBCO coated conductor coils. Experimental results for an YBCO double pancake coil are compared with numerical simulations using the superconductor thin strip model [1,3]. The topics investigated are (a) effect of current sweep cycles such as the current sweep reversal method [3] or demagnetizing method and (b) effect of temperature cycle of the coil, which is available if we use a cryocooler cooled YBCO magnet.

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[1] Y. Koyama et al., *Physica C*, 469, 694-701(2009)
[2] Y. Yanagisawa et al., *IEEE Trans. Appl. Supercond.*, 20, 744-747 (2010)
[3] Y. Yanagisawa et al., *Physica C*, 469,1996–1999 (2009)

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Normal zone propagation in a 50 Tesla YBCO coated conductor solenoid – FEM modeling

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YBCO coated conductors are of interest in a number of possible high-energy physics applications, including high field solenoids for muon colliders. The heat and quench propagation, and conductor protection are highly important in these applications. In the past we measured the thermal conductivity and heat propagation in YBCO CC pancake coils as well as in stacks of several YBCO CC tapes, simulating parts of magnet windings. In the present contribution we performed a numerical Finite Element Method (FEM) modeling of heating and quench propagation in a 50 Tesla solenoid immersed in liquid helium bath. It was supposed to be wound of a cable made of YBCO CC tapes. A full heat transfer curve in the whole temperature range (up to 300 K) for liquid helium was used. A macroscopic anisotropic model for thermal propagation was adopted. Temperature dependent parameters, such as electrical and thermal conductivities, heat capacities etc., taken from experiment, were considered. Quite a high degree of stability of the 50 Tesla solenoid was found, with significant heat conduction across the winding.

Stability and Quench Propagation in YBCO Coated Conductor Coils at 4.2 K and Subjected to High Applied Magnetic Fields - Measurements and FEM Modeling

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New high energy physics magnets require increasingly high magnetic fields, demanding the use of new superconducting materials. YBCO is of interest in a number of possible HEP application areas, including high field solenoids for muon colliders. The thermal propagation, quench propagation, and conductor protection are very important in these applications. In the present work we have measured the thermal conductivity and heat propagation in several YBCO coated conductor pancake coils simulating parts of magnet windings. The measurements have been performed in liquid helium bath. The coils were wound using YBCO tape 1 cm wide and instrumented for voltage and temperature measurements at several places around the winding, such that both radial and azimuthal quench propagation could be measured. A heater was included for both quench initiation and thermal gradient measurement. After this the coil was epoxy impregnated. The coil was then placed in an applied magnetic field up to 14 Tesla in pool boiling liquid helium. Transport DC currents were applied to some fraction of I_c, after which a current pulse was applied to the heater, and NZP values were measured in radial and azimuthal directions using a real time DAQ system. Numerical Finite Element Method (FEM) modeling of heating and current sharing effects in such coils in liquid He was also performed. The results can be used as input to a model for quenching in a solenoid magnet.

Development of coil technology for HEP high field magnets using $YBa_2Cu_3O_{7-\delta}$ Coated Tapes

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The final beam cooling stages of a Muon Collider may require DC solenoid magnets with magnetic fields of 20-50 T. In this paper we present progress in coil technology development using commercially available $YBa_2Cu_3O_{7-\delta}$ Coated Conductor. Technological aspects covered in the development include turn to turn insulation, coil impregnation and coil manufacturing and testing. A dedicated winding fixture has been specifically designed for the co-winding of conductor and insulation. Test results of double pancake coils operated in liquid nitrogen and liquid helium are presented and compared with the performance of $YBa_2Cu_3O_{7-\delta}$ tape short samples.

Application of SuperPower 2G HTS wire to various coil applications

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Developments in 2G HTS conductor performance continue to drive the limits of magnet performance. The design, modeling and fabrication technology of 2G HTS coils are presented, highlighting the ability of 2G HTS wire to function under a wide range of operating conditions. The challenges of using 2G HTS wire in various coil constructions and applications are discussed. The ability of the conductor to operate under high stress levels has been demonstrated in both direct sample measurement and test coils. The architecture of SuperPower 2G HTS wire provides flexibility to address applications that require fault current limiting performance, low ac losses, high stresses or other demanding requirements.

Driving Stability of Superconducting Magnetic Bearing System

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A superconducting bearing system including a disk shaped rotor is stabilized by using superconducting magnetic levitation combination. The 7.5 kg rotor is stabilized in a way that the majority of the rotor mas are lifted via permanent magnets and stability is provided by superconductors. The stability tests are performed via obtaining levitation force characteristic. Preliminary levitation force results show that the system is stable and robust; indicating the rotor mass can be increased more without loosing efficiency. Dynamic tests are performed while driving the designed bearing system. The resonance behaviour of the system indicates that the bearing is not vulnerable to high speed.

Abstract for the CEC'11 conference

LHC cryogenics: The first year of operation for physics as a validation of the operation and support strategy

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The Large Hadron Collider (LHC) was successfully turned on for physics in 2010 for a complete year of operation. The cryogenic system has demonstrated availability above expectations, with particular care on energy savings and cryogen handling.
The methodology and results for operation and support are presented in this paper, including the identification and treatment of early weak points.
Perspectives for the coming years will be discussed.

Category: CEC-02, Large Scale Cryogen Systems and Test Facilities

Type of presentation: oral

Corresponding author: To be decided, Serge Claudet as fallback

Presenting author: To be decided

Operational Experience with the Supercritical Helium during the TF coils Tests campaign of SST-1

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Abstract

Presently, cold testing of the Toroidal field (TF) magnets of the Steady State Superconducting Tokamak (SST-1) is ongoing employing forced flow supercritical helium at nominal 4 bar (a), 4.5 K at the Institute for Plasma Research under an intensive SST-1 Mission program aimed at the SST-1 refurbishment. The TF magnets test campaign have begun in a dedicated experimental cryostat since mid of 2010 with the SST-1 Helium cryogenics facility, which is a 1.3 kW helium refrigerator-cum-liquefier (HRL) system. Till date, fifteen numbers of TF superconducting coils have been successfully tested for its rated parameters of 10,000 A. With HRL, ~300 g s^{-1} supercritical helium can be generated using the cold circulator to enable SST 1 magnet operation. For single TF coil testing, HRL process parameter can be manipulated to produce the required amount of supercritical helium even without the cold circulator. In this paper, the complete processes describing the Process Flow Diagram (PFD) of 1.3 kW at 4.5 K HRL to generate supercritical helium without the cold-circulator has been discussed. The maximum supercritical helium mass flow rate of ~ 60 g s^{-1} can be attained in this mode of operation. In the SST-1 TF campaigns, safe operation of supercritical helium has been demonstrated successfully. The results of the cool-down characteristics, two-phase helium and supercritical helium operations will be discussed in this paper.

Acknowledgements

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ITER Cryogenic System validation tests at HELIOS Test Facility

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The ITER cryogenic system will have to cope with substantial dynamic heat loads due to magnetic field variation and neutron production generated during the fusion reaction. Refrigerators used in this respect are not designed to accept large cooling power variations in time. The HELIOS test facility, developed at CEA-Grenoble and initially designed to study the pulse mitigation of the JT-60SA central solenoid cooling circuit, was adapted to the ITER cooling loops requirements.

The paper will present the experimental results with different mitigation methods and discuss their effects on the refrigeration process.

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Submission category: CEC-02 Large-Scale Systems, Facilities, and Testing

Possible cryogenic configurations for the superconducting magnets of the damping rings of the Compact Linear Collider (CLIC)

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The Compact Linear Collider is a future high energy electron-positron linear collider currently under study. Before being injected into the main linear accelerating structures, both the electron and the positron beams must pass through damping rings that will drastically reduce their emittance in all three dimensions. The required emittance reduction is achieved by passing the particle beams through alternating magnetic fields in superconducting wiggler magnets that result in the emission of intense synchrotron radiation. This article describes possible cooling schemes and possible cryogenic configurations to keep the magnets at operating temperature while removing the heat generated by the synchrotron radiation.

Overview of the Cryogenic System for the ARIEL e-linac at TRIUMF

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The Advanced Rare IsotopE Laboratory (ARIEL) is a major upgrade of the existing ISAC radioactive beam facility. After completion, ARIEL will triple TRIUMF's capability of the rare isotope production for the needs of the international scientific community. The key feature of this upgrade is the 50 MeV 10 mA continuous-wave (CW) electron linear accelerator (e-linac) based on 1.3 GHz TTF-style 2K superconducting technology. This paper presents the proposed layout of the e-linac cryogenic system including details of the accelerator cryomodules, calculated heat load of the helium refrigerator, and the description of the helium and LN2 storage and distribution systems.

Design, Construction and Test of a Cryogenic Test Station for MICE Coupling Solenoid Magnets

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In order to carry out the performance test for prototype coils and superconducting coupling magnets for the Muon Ionization Cooling Experiment (MICE), a cryogenic test station was designed and constructed in the Harbin Institute of Technology. It mainly consists of a 4.5 K refrigeration system, a cryogen distribution valve box, two cryostats, vacuum-jacketed transfer lines as well as measurement and PLC control system. The 4.5 K refrigeration system is composed of a recycle helium compressor with input power of 132 kW, a cold box with expansion turbines, an internal helium purifier, a helium gas recovery and storage system and its own control system. The refrigeration system can provide the cooling capacity of 150W at 4.5K with liquid nitrogen precooling, and of 80W at 4.5K without liquid nitrogen precooling. A liquid helium dewar placed inside the cryogen distribution valve box is to provide the liquid helium to cool the magnets by thermosyphon-driven method. The main parameters including the temperature, pressure, liquid level, voltage along magnets and current leads during cool down and magnet training are to be monitored. The paper describes the design, construction and commissioning of the cryogenic test station in details.

Up-gradation of helium refrigeration capacity and modification of helium cooling network for Superconducting Linear accelerator at IUAC

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Cryogenic system for Superconducting linear Accelerator at IUAC was commissioned earlier with 500 W capacity helium refrigerator of makes M/s CCI. USA. The quarter wave bulk niobium cavities are distributed in five beam line cryomodules which are integrated with refrigerator through helium distribution line and valve boxes. Considering capacity degradation of existing refrigerator over the years and additional demand for superconducting quadrupole magnet, it is proposed to have an additional refrigerator of guaranteed capacity of 750 W at 4.2 K. A separate valve box with all necessary transfer lines between refrigerator and existing liquid helium distribution line for linac is designed without dismantling the old refrigerator. The new refrigerator from M/s Linde is planned to have additional 10 K helium gas cooling provision for initial cool down of linac. The present paper will be highlighting the critical features of the new machine along with proposed cooling methodology of full Linac through new junction box and transfer line

Design of the New Muon Lab Helium Refrigeration System for SRF cavities and cryomodules

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The Fermilab Test Facility at New Muon Lab (NML) provides a test bed to measure the performance of superconducting radiofrequency (SRF) cavities and cryomodules (CM). These SRF components form the basic building blocks of future high intensity accelerators such as Project X, International Linear Collider (ILC), and a Muon Collider. Linde Kryotechnik AG has designed superfluid helium refrigerator needed to support SRF component testing at the NML Test Facility. The hybrid refrigerator is designed to operate in a variety of modes under a wide range of boundary conditions down to 1.8 Kelvin set by CM design. Special features of the refrigerator include use of warm and cold compression and high efficient turbo expanders. This paper gives an overview on the wide range of the cooling requirements and the design of the proposed cryogenic system.

Turbo-Brayton Cryocoolers for Space-Borne Cryogen Storage Applications

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Future space exploration missions may require cryocoolers to reduce boil-off and pressure control of cryogens. The applications include planetary and extraterrestrial exploration missions, extended-life orbital transfer vehicles, and in-space propellant depots. The cooling requirements for these applications will range from 10 to 50 W at temperatures between 20 and 120 K depending on the size of the dewar and the cryogen. Turbo-Brayton cryocoolers are ideal for these systems because they are lightweight, compact and very efficient at high cooling loads, in addition to their inherent attributes of high reliability; long, maintenance-free lifetimes; and ability to cool broad areas with minimal performance penalties. To date, space-borne turbo-Brayton technology has been developed for modest cooling loads. More recently, we started the development of a high capacity cryocooler that provides 5-20 W of refrigeration at 20 K. In this paper, we will review the cryocooler design and features, and present test results from cryogenic testing of a 20 K turbine.

Development of high frequency pulse tube cryocoolers for space applications

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This paper reviews recent advances in high frequency pulse tube cryocoolers developed to provide high reliability, low-noise and long life cooling for potential space applications. Three typical arrangements, U-type, coaxial and in-line, are all involved while the latter two become the study focus. The operating temperatures cover from 30 to 200 K, in which the region of 50-100K are emphasized, and the cooling capacity ranges from hundreds of milliwatts to around 20 W. The inertance tubes, due to its stable performance and wide phase-shifting ability, have been adopted as the main phase-shifting approach and investigated theoretically and experimentally. Recent advances in understanding the operating mechanism of the coolers and minimizing irreversible losses in various components are described that have made a great contribution to the improved efficiencies, which include the optimizations on dimensional and operating parameters, the design of novel heat exchangers, and the optimal matching between the cold fingers and the compressors, etc. The design approaches, the cooler characteristics, and the proposed applications are presented. The major problems associated with the coolers and the progress in overcoming them, and the efforts to realize space qualified cryocooler technologies are discussed.

Low cost split stirling cryogenic cooler for aerospace applications

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Cryogenic coolers are used in the modern spacecraft for maintaining the sensitive electronics and sensors of military, commercial or scientific payloads at low (cryogenic) temperatures. The general requirements associated with their use in a space mission are high power efficiency, low vibration export, high reliability, ability to survive launch vibration/shock and long-term exposure to space radiation.

A long standing paradigm of using exclusively space heritage derivatives of "Oxford" cryocoolers featuring linear "moving coil" or "moving magnet" actuators, flexural bearings, contactless piston/cylinder and bushing /plunger seals and active vibration cancellation is so far a best known practice aiming at delivering high reliability components for the critical and quite expensive space missions.

The recent tendency of developing mini and micro satellites for the relatively inexpensive missions has spurred attempts based on adaptation of the leading-edge tactical cryogenic coolers for the space requirements.

The authors are disclosing some theoretical and practical aspects of collaborative efforts on developing a space qualified cryogenic refrigerator based on the tactical cooler model Ricor K527 technology and Iris Technology radiation hardened control/drive electronics .

The initially targeted applications are cost-sensitive flight experiments, but should the results show promise, some long-life “traditional” cryocooler missions may well be satisfied by this approach.

Low vibration split Stirling cryogenic cooler for aerospace applications

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The cryogenically cooled space-borne instrumentation is usually susceptive to the cryocooler induced vibration, the major portion of which is contained at the driving frequency and typically low power higher-order harmonics.
Attenuation of the above vibration export over the typical wide frequency range is normally accomplished by using the principle of active multi-tonal momentum cancellation under supervision of dedicated feedforward DSP controller, where the error signals are delivered by the vibration sensors (accelerometers or load cells). The attenuation of vibration export originated from the expander is normally achieved by using the auxiliary active counter-balancer, while the vibration export from typical dual-piston compressor is closely controlled by active synchronizing the motion of piston assemblies.
This results in added components and complexity within both the electronics module and the cryocooler itself, negatively impacting cost and reliability.
The authors are advocating the purely passive approach relying on the combined principle of tuned dynamic absorber and low frequency vibration isolator delivering essential suppression of vibration export at the driving frequency and over the typical high frequency range.
Experimental testing of a Ricor model K527 split Stirling cryogenic cooler was performed using both the standard Ricor control electronics and open-architecture cryocooler electronics developed by Iris Technology. The presented test results fully support the theoretically predicted performance.

Distributed Joule-Thomson microcooling for small detector arrays in space applications

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Vibration-free miniature Joule-Thomson (JT) coolers have a high potential for future space missions in cooling small detector arrays operating within the range 80-250 K. For this application, JT cooling has several advantages above other cooling cycles. JT cooler tips do not contain moving parts and therefore can be scaled to very small sizes. When combined with a sorption compressor, a closed-cycle cooler without moving parts can be obtained. Such a cooler is virtually vibration free and potentially has a long life-time. Also, a single compressor can be used to drive multiple JT cooler tips. This makes it possible to distribute the cooler tips over the satellite remote from the compressor. This allows for maximum flexibility in interfacing and satellite design.

Under ESA-contract, we investigated the integration of small detector arrays with miniature JT cooler tips. A conceptual design of a JT cooler tip - detector array system was made that focused on the interface between cooler tip and detector array and wiring of the array. A new generation of JT cooler tips was developed and the performance of these tips was measured while cooling a dummy detector array. Also, experiments were performed in which multiple miniature cooler tips were driven by a single compressor to obtain distributed microcooling. In this paper, the conceptual JT cooler tip - detector array system design will be discussed and the results of the experiments will be presented.

Remote Cooling Circulator with Cold Valves

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A fluid loop can be effective for cooling some distance from a pulse tube cooler or in applications that require vibration isolation from the cooled object. Space pulse tube coolers are very efficient, but like all regenerative high frequency Stirling and pulse tube coolers, the cold head needs to be located near the compressor in order to minimize the input power to the cooler. To provide the directional gas flow from the oscillating flow pulse tube cooler we added cold reed valves to the pulse tube cold block of our flight proven high efficiency cooler (HEC) so that cold gas could be circulated without the need for an additional circulation pump and additional heat exchangers to cool the gas. In this test an improved smaller cold valve than that previously reported was installed and the remote cooling and the parasitic heat loads were measured. The measurements are compared to those of our previously reported cold valve tests as well as warm reed valve tests that used a second circulator compressor and recuperative heat exchanger. The large improvement in remote cooling power relative to the previous cold valve tests will be described.

Design and characterization of very high frequency pulse tube prototypes

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Weight and size are important features of a cryocooler when it comes to space applications. Given their reliability and low level of exported vibrations (due to the absence of moving cold parts), pulse tubes are good candidates for spatial purposes and their miniaturization has been the focus of many studies. We report on the design and performance of three small-scale very high frequency pulse tube prototypes. One was numerically optimized to work with an inertance and the other to work in an active phase shift configuration, but they were both tested in both modes. These results allowed us to verify our simulation code and gave us clues to the construction of a third prototype that will also be tested in those two configurations.

Cryogenic Emissivity Properties of Ball InfraRed Black™, A New Thermal Control Coating

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Ball Aerospace and Technologies Corporation (BATC) developed a unique thermal control coating named Ball InfraRed Black™ (BIRB™). The coating generates a highly diffuse surface with a large effective surface area ideal for thermal radiative applications. Independent testing has been performed which demonstrates excellent total hemispherical emissivity properties across the cryogenic region and especially at temperatures below 50K where other products tend to roll off. Emissivity in this region far exceeds that of other commercially available thermal control coatings. Comparable performance is only achieved with significant mass and volume impacts. The proprietary coating was developed for use on spacecraft thermal radiators, but also has application to terrestrial cryogenic and vacuum systems. The coating is qualified for spaceflight, demonstrating outstanding adhesion after thermal cycling and vibration testing. Critical thermal, physical, and mechanical properties for BIRB™ are characterized, and extensive processing expertise demonstrates that BIRB™ is durable and cleanable with proper handling. BIRB™ has the additional benefit of being static-dissipative, making it ideal for direct exposure to the space environment. Additionally, contamination control properties are optimized, achieving low total outgassing rates and demonstrating particle cleanliness to meet stringent requirements for optical instruments. Thermal systems realize enhanced performance and/or substantial mass savings by applying BIRB™ to the radiator surface. To date, BIRB™ has been applied to several large cryogenic radiators for use on space-based thermal control systems.

High-emissivity paints are commonly used on thermal control system components. The total hemispheric emissivity values of such paints are typically high (nearly 1) at temperatures above about 100 Kelvin, but they drop off steeply at lower temperatures. A precise knowledge of this temperature-dependence is critical to designing passively-cooled components with low operating temperatures. Notable examples are the coatings on thermal radiators used to cool space-flight instruments to temperatures below 40 Kelvin. Past measurements of low-temperature paint emissivity have been challenging, often requiring large thermal chambers and typically producing data with high uncertainties below about 100 Kelvin. We describe a relatively inexpensive method of performing high-resolution emissivity measurements in a small cryostat. We present the results of such a measurement on Ball InfraRed Black™ (BIRB™), a proprietary surface coating produced by Ball Aerospace and Technologies Corp (BATC), which is used in space-flight applications. We also describe a thermal model used in the error analysis.

Use of Cold Radiometers in Several Thermal/Vacuum Tests

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We have developed a low cost low temperature broadband radiometer for use with low temperature tests as a diagnostic tool for measuring stray thermal radiation and remote measurement of material properties. So far these radiometers have been used in two large thermal/vacuum tests for the James Webb Space Telescope (JWST) Project. In the first test the radiometers measured stray radiation in a test of part of the JWST sunshield, and in the second test the radiometers were used to measure the reflectivity and specularity of black Z307 painted aluminum walls on a 25 K cooled shroud. These results will be presented as well as plans for future tests to measure the residual energy through a baffled aperture in the shroud and other stray thermal energy measurements.

THERMAL ANALYSIS OF LOW LAYER DENSITY MULTILAYER INSULATION TEST RESULTS

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Investigation of the thermal performance of low layer density multilayer insulations is important for designing long-duration space exploration missions involving the storage of cryogenic propellants. Theoretical calculations show an analytical optimal layer density, as widely reported in the literature. However, the appropriate test data by which to evaluate these calculations have been only recently obtained. As part of a recent research project, NASA procured several multilayer insulation test coupons for calorimeter testing. These coupons were configured to allow for the layer density to be varied from 0.5 to 2.5 layer/mm. The coupon testing was completed using the cylindrical Cryostat-100 apparatus by the Cryogenics Test Laboratory at Kennedy Space Center. The results show the properties of the insulation as a function of layer density for multiple points. Overlaying these new results with data from the literature reveals a minimum layer density; however, the value is higher than predicted. Additionally, the data show that the transition region between high vacuum and no vacuum is dependent on the spacing of the reflective layers. Historically this spacing has not been taken into account as thermal performance was calculated as a function of pressure and temperature only, however the recent testing shows that the data is dependent on the Knudsen number which takes into account pressure, temperature, and layer spacing. These results aid in the understanding of the performance parameters of MLI and help to complete the body of literature on the topic.

Non-compacting Aerogel Insulation for Cryogenic Tanks

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Space exploration requires new technologies for long-term cryogenic storage applications on-orbit, on the lunar surface, and on the Earth. Long term storage (6 months or more) of cryogens on the lunar surface is required to support space power systems, spaceports, spacesuits, lunar habitation systems, robotics, and in situ propellant systems. Long term, minimal-loss storage on the surface of the Earth is also required to support launch operations.

Aerogels have a unique combination of properties making them exceptionally good cryogenic insulation materials. However, mechanical properties of aerogel materials need to be improved before they can be used in applications requiring higher strengths such as in the intertank region between liquid oxygen and liquid hydrogen tanks of launch vehicles. Improving the strength of aerogels to develop non-compacting aerogel insulation that could be used to insulate cryogenic tanks for both Earth and space-based applications is the subject of this research investigation. The basic approach is to incorporate an organic crosslinking agent into the aerogel to increase its mechanical properties while maintaining the inherently low thermal conductivities. Aspen Aerogels has prepared crosslinked aerogels that are stronger than silica aerogels with comparable densities. We have determined the thermal conductivities and mechanical properties of these crosslinked aerogels and will present the methods used to prepare the aerogels. Efforts to optimize the properties of the novel crosslinked hybrid aerogels for use in cryogenic thermal insulation systems will be discussed.

Thermal properties of thermal links used for coupling of active cooled thermal shields with cooling process lines.

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Some middle and large scale cryogenic helium systems can be provided with thermal shields actively cooled by process lines through thermal links. The thermal link should be characterized with high thermal conductance and mechanical elasticity. Therefore the thermal links usually consists flexible copper braids which ends are fixed to the matrix. Such pre-prepared links are connected to the process line and the thermal shields. Due to difference in material of the thermal links, the process lines and the thermal shield it is necessary to apply brazing in one of connection step: connection of the braids to the matrix or the matrix to the process line/thermal shield. The main disadvantage of the brazing is difficulty in precise cleaning of a brazing flux after a fixation process. Some remains of flux or cleaning substance can results in them strong outgassing to an insulation vacuum during the system operation. Some new perspective, free form above mentioned disadvantage, is given by material connection with explosive method. With this method copper- aluminum and copper – stainless steel flux – free matrixes can be fabricated. It allows to realize a matrix – process line/thermal shield connection with more vacuum clean, welding method. The paper presents discussion concerning critical issues and an optimization of the thermal links design. An experimental set-up for an investigation of a thermal performance of the links is described. A few different design thermal links performance, included the links with matrixes fabricated with explosive method, in a 40 – 80K temperature range is compared.

CEC-19 Thermal Insulation Systems

Using a Multi-Parameter Monitoring Methodology to Predict Failures in the Cryogenic Plant of the Cold Neutron Source at Australia's OPAL Reactor

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A 5 kW Brayton-cycle helium refrigeration plant provides cooling at 20 K to the Cold Neutron Source (CNS) at Australia's OPAL Reactor. The cryogenic plant consists of two screw compressors in parallel, an oil removal skid, a two-stage heat exchanger, a turbine and the CNS In-Pile where the helium gas removes 4 kW of nuclear radiation heat. The plant was installed in 2005 and commissioned in 2007. During several years of operation to the present day, the plant has experienced an unusually high number of turbine and compressor failures. The root cause for some of the failures is known, but for others remains to be determined. It has been identified that all of the turbine failures were caused by contaminants that were produced in the compressor oil. All of the failures were catastrophic without any prior warning from standard industrial monitoring based on singular process variables such as temperature, pressure or vibration. The failures and the down time they caused have been very costly to the CNS facility.

As the operator of the plant, we have developed a multi-parameter monitoring (MPM) methodology to track the performance of the equipment. The methodology utilises indicators obtained from a combination of process variables based on their thermodynamic relations. By studying the historical trends of appropriate indicators, especially during the past failures, we have found some indicators that would be able to predict future failures. In this paper, specific examples using the MPM methodology related to turbine and compressor failures will be presented.

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Helium Refrigerator Maintenance and Reliability at the OPAL Cold Neutron Source

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Australia's first Cold Neutron Source (CNS) is a major asset in Australia's nuclear research program. The CNS and the associated helium refrigerator is operated at the Open Pool Light Water Reactor (OPAL) and was commissioned in 2006. Since that time the facility has been in full power operation and relevant experience from helium refrigerator operation, maintenance and repair is presented below.

The OPAL Cold Neutron Source operates a 5 kW, 20 K Brayton cycle helium refrigerator. The refrigerator is used to cool a 20-litre single phase liquid deuterium source, located close to the nuclear core, and hence deliver a 10^9 n/cm^2·s cold flux to the end of several neutron guides.

The CNS cryogenic system has a unique design feature that allows for system maintenance without interrupting the reactor operation. This is achieved by ensuring continuous helium flow to reactor components close to the nuclear core (ie the deuterium source), whether the turbine is in operation or not. One of the consequences of this warm (ie turbine by-passed) 'maintenance mode' has been that OPAL has been able to detect and study changes in contamination levels, and the consequential risk to refrigerator reliability.

In this paper the lessons learnt by OPAL, from a series of refrigerator failures, are presented. Turbine failure due to volatile organic species is discussed along with the associated compressor oil degradation mechanisms. Observations on oil separation efficiency are also noted, along with experience in screw compressor operation and failure modes. Recommendations for helium refrigerator operators, to optimize refrigerator reliability, are summarized.

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RAMI analysis of the ITER cryoplant and cryodistribution systems

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The ITER cryogenic system is now entering the procurement phase in the framework of a large international collaboration. It will be operated for the first cool-down at Cadarache, south of France in 2019.
The cryoplant consists of three 4.5 K refrigerators and two 80 K helium loops coupled with two LN_2 modules providing an equivalent refrigeration capacity of 65 kW at 4.5 K and 1300 kW at 80 K. The associated cryodistribution system allows distributing the cooling power at 4.5 K to the magnets, cryopumps and pellet injection system and at 80 K to the thermal shields. The cryodistribution system consits of one cryoplant termination cold box, one cold compressor box, 5 auxiliary cold boxes including cold circulators and two redundancy 80 K cold boxes.
According to the project requirement document, ITER is designed to reach a global inherent availability of 60 %. The tokamak shall be operated 365 days per year and it is anticipated that plasma physics will be performed during 11 consecutive days in plasma operation state (POS) and then followed by 3 days break in short term maintenance (STM). This period of plasma campaign will be followed by a major shutdown of 8 months during the long term maintenance (LTM) state for further installation and commissioning.
In order to reach this requirement, a specific reliability, availability, maintenability and inspectability (RAMI) analysis has been performed. The risks related to the failure modes of the cryogenic subsystems have been assessed, their contributions to ITER machine unavailability have been estimated and the necessary recommendations in terms of Design, Testing, Maintenance and Operation has been issued.
Considering both inactive (hydrogen, deuterium) and active (deuterium-tritium) phases as defined by the ITER scientific program, this paper will present the RAMI results and mitigation actions applied.

Risk analysis of the ITER cryogenic system

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ITER cryogenic system belongs to the most complicated ever built and will contain over 20 tons of helium, mostly in high density cold phases. The reliability of the tokamak strongly depends on the safe and uninterrupted operation of the cryogenic system. The objective of this risk analysis is to identify all risks to personnel, equipment and environment resulting from cryogenic system failures that might accidentally occur within the cryogenic system of ITER tokamak in any phase of the machine operation, and that could not be eliminated by design. The analysis methodology is based on the Failure Mode and Effects Analysis FMEA, a procedure by which each potential failure mode in a system is analyzed to determine its effects and then classified according to its severity and the probability of occurrence. The ITER cryogenic system is treated as composed of separated helium enclosures – so called cryogenic nodes. Each cryogenic node can be characterized in terms of helium quantities, helium thermodynamic parameters, the volume of corresponding insulation vacuum, instrumentation and special equipment. Additionally, the volume of a potential confinement where the node is located is taken into account. The Pareto-Lorentz analysis has ranked all the identified defects. For the most credible scenarios the dynamic simulations of the helium outflows from the system to the related confinements were performed. Conclusions concerning the system safe operation, remedial actions and mitigations of the most credible incidents have been formulated.

Dynamics of a Liquid Helium I SRF Cryostat at the Canadian Light Source

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The Canadian Light Source (CLS) is a third-generation synchrotron located in Saskatoon, Canada. A superconducting radio frequency (SRF) cavity contained in a 4.43 K liquid helium I cryostat is used at the CLS to replenish energy loss in the electron beam. A dynamic simulation of this cryostat has been generated to examine pressure and level fluctuations due to variations in heat loading or other system parameters. This simulator has led to some interesting observations in system behavior, which have been shown to occur in the actual system as well. For example, mass rates of vaporization appear to drop as heat loading increases under certain conditions. Also, the relationship between pressure and SRF tuning characteristics is examined, and the abilities and limitations of the simulator are presented.

Transient Effects of Sudden Catastrophic Loss of Vacuum on a Scaled Superconducting Radio Frequency Cryomodule

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Superconducting radio frequency (SRF) cavities for particle acceleration require protection from sudden catastrophic loss of vacuum (SCLV) adjacent to liquid helium spaces and associated dangers. To aid in the design of SRF systems, a scaled SRF cavity experiment is being developed to measure the longitudinal effects of SCLV along the beam line. The experiment consists of six scaled mock SRF cavities arranged in a scaled cryomodule. Each mock cavity includes one segment of beam tube within a liquid helium vessel, and a riser pipe connecting the liquid helium vessel to a larger helium gas header. Between cavities there are low flow orifice plate flow meters to estimate which cavities are vaporizing liquid at any given time. Each cavity is instrumented with Validyne pressure transducers and Cernox thermometers. There is also a master flow meter near the exit of the experiment to measure the total venting flow once the relief blows at approximately 0.4 MPa absolute. The assembly is made of stainless steel, with each beam cavity in direct contact with sub-atmospheric liquid helium at 2 K initially. It is the goal of this experiment to quantify the time required to fully spoil the beam vacuum and measure the transient effects that the time-varying temperature and pressure front have on the vaporization of liquid helium in the system and on the pressurization and relief parameters. Details of the experimental design and preliminary results are presented.

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A survey of pressure vessel code compliance methods for superconducting radio frequency cryomodules

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Superconducting radio frequency (RF) cavities made from niobium and cooled with liquid helium are becoming key components of many particle accelerators. The helium vessels surrounding the RF cavities, portions of the niobium cavities themselves, and also possibly the vacuum vessels containing these assemblies, generally fall under the scope of local and national pressure vessel codes. In the U.S., Department of Energy rules require national laboratories to follow national consensus pressure vessel standards or to show "a level of safety greater than or equal to" that of the applicable standard. Thus, while used for its superconducting properties, niobium ends up being treated as a low-temperature pressure vessel material. Niobium material is not a code listed material and therefore requires the designer to understand the mechanical properties for material used in each pressure vessel fabrication; compliance with pressure vessel codes therefore becomes a problem. This report summarizes the approaches that various institutions have taken in order to bring superconducting RF cryomodules into compliance with pressure vessel codes.

Intermediate Quality control tests in the development of a Superconducting RF Cryomodule for CW operation

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Through an international cryomodule collaboration, ASTeC at Daresbury Laboratory has taken primary responsibility in leading the development of an optimised Superconducting RF(SRF) cryomodule, operating in CW mode for energy recovery facilities and other high duty cycle accelerators. For high beam current operation, Higher Order Mode (HOM) absorbers are critical components of the SRF Cryomodule, ensuring excessive heating of the accelerating structures and beam instabilities are effectively managed. This paper describes some of the cold tests conducted on the ferrite HOMs and other critical components during the construction phase, to ensure that the quality and reliable cryomodule performance is maintained.

CEC-ICMC_Purification of Argon from a diluted stream

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Argon is a powerful scintillator and an excellent medium for detection of ionization. Its high discrimination power against minimum ionization tracks, in favor of selection of nuclear recoils, makes it an attractive medium for direct detection of WIMP dark matter. Atmospheric Argon contains the radioactive isotope ^{39}Ar, formed by the interaction of cosmic rays on ^{40}Ar. ^{39}Ar is a beta emitter that limits the size of the detector due to signal pile-up. We have identified an underground source of CO_2 containing traces (~ 500 ppm) of Argon depleted in ^{39}Ar. The gas needs to be purified to remove all non-Argon contaminants. The first purification step produces a crude Argon stream, containing 3-5% of Argon with a balance of Helium and Nitrogen. We have designed and built a cryogenic distillation column to remove the residual Helium and Nitrogen and produce Argon with residual contaminations at or below 1 ppm. The key element is the vertical separation column filled with packing material and along which a controlled temperature gradient is established. The feed gas mixture is partially liquefied and enters the column at the half-height point. The more volatile components, Helium and Nitrogen, rise to the top of the column and are vented in the gas phase through the `condenser', while the less volatile component, Argon, is collected in the liquid phase at the bottom, inside the `reboiler'. This presentation will detail the requirements, design, construction, and initial performance of the cryogenic distillation column. The column could also be used to purify other targets used in direct dark matter searches (Xenon in particular). Its development is crucial for the scaling in mass of high sensitivity direct searches for dark matter, allowing the development of ton-sized detectors.

EXTREME LIQUID ARGON PURITY IN A LARGE, NON-EVACUATED CRYOSTAT

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Liquid Argon Time Projection Chambers (TPCs) show promise as scalable devices for the large detectors needed for long-baseline neutrino oscillation physics. Over the last several years at Fermilab a staged approach to developing the technology for large detectors has been developed. The TPC detectors require ultra-pure liquid argon with respect to electronegative contaminants such as oxygen and water. The tolerable electronegative contamination level is equivalent to 30 parts per trillion of oxygen. Three liquid argon cryostats operated at Fermilab have achieved the extreme purity required by TPCs. These three cryostats used evacuation to remove atmospheric contaminants as the first purification step prior to filling with liquid argon. Future physics experiments may require very large detectors with tens of kilotonnes of liquid argon mass. The capability to evacuate such large cryostats adds significant cost to the cryostat itself in addition to the cost of a large scale vacuum pumping system. This paper describes a 30 tonne liquid argon cryostat at Fermilab which uses purging to remove atmospheric contaminants instead of evacuation as the first purification step. The results of this liquid argon purity demonstration will strongly influence the design of future TPC cryostats.

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<u>CEC Submission Category</u>

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Design and 1st year operating experience of the novel 30kW cooling system for the INFN Icarus project

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At NLGS INFN is studying neutrinos at the ICARUS project. A 600 Ton high purity liquid Argon bath, containing the Neutrino detector, is cooled with liquid Nitrogen with a total heat load of maximum 30kW at 89K. As the project is intended to operate non-stop for approximately 10 years and is located in a confined space (cave), reliability and redundancy of the cooling system is of the utmost importance. In 2007 SC designed a novel cooling system based on their SPC-4 cryogenerators, including tanks, heat exchangers, pumps and piping with extreme redundancy through decoupling of all components and smart design. All components operate completely individual and are designed in such way to always provide cooling to the project without any bulk supply back-up. The system does not have an overall control system.

This paper discusses the design and set up of this system, the commissioning in 2009 and the first year of operations.

Also the possibilities to use this concept on other demanding cooling systems like HTS power cables will be reviewed.

Taurus II Launch Vehicle LOX Subcooler

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The Orbital Sciences Taurus II medium lift launch vehicle utilizes first stage engines fueled by liquid oxygen and RP-1. Performance of the Taurus II is enhanced by densifying the liquid oxygen from a saturation temperature of 94 K to a subcooled temperature of 77.9 K. Subcooling the 75.07 kg/s liquid oxygen flow is accomplished in a 1.907 megawatt heat exchanger cooled by a flow of 9.62 kg/s ambient pressure liquid nitrogen. Design, fabrication, insulation and testing of the densification heat exchanger is described in this paper.

80 K Liquid Nitrogen (LN_2) Booster System for SST-1

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Abstract

The thermal shield in the Steady State Superconducting Tokamak (SST-1) at Institute for Plasma Research (IPR) is proposed to cool using forced flow single-phase liquid nitrogen at 80 K. These shields surround 5 K superconducting magnet system in order to reduce the heat load at 5 K. The 80 K double embossed bubble type thermal shield is designed to maintain a temperature uniformity of +/- 5 K over the shields surfaces for a designated nominal flow of ~1 kg s^{-1} at 7 bar (a). During normal operating conditions of SST-1, the heat loads acting on the 80 K shields is about 20 kW. The concept of forced flow sub-cooled LN_2 has been adopted to avoid uneven hydraulic distribution, pressure fluctuations, thermal runaway and vapor locking etc. The 80 K booster system consists of booster pumps, sub-cooler vessel, interconnecting vacuum jacket cryo lines and dummy load along with its ancillary components in a compact skid of 2.3 m x 2.3 m x 5 m height. During steady state operation, the basic function of the booster pump is to circulate the rated mass flow rate of LN_2 in closed loop so that the losses (Make up, net evaporation rate, dumped heat load from 80 K thermal shields system) are supplemented from the existing storage tanks. This paper describes the conceptual design along with the process flow diagram (PFD) along with process and instrumentation diagram (P & ID) of the 80 K booster system.

TEMPERATURE STABILITY OF THE TRITIUM SOURCE IN KATRIN

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Abstract

The Karlsruhe Tritium Neutrino Experiment (KATRIN) will measure the mass of the electron anti-neutrino, based on the precise measurement of the tritium β spectrum in a region close to the endpoint energy. The tritium source in KATRIN consists of a 10 m long beam tube with 90 mm inner diameter, in which gaseous tritium is injected through a central injection chamber. The tritium diffuses toward either tube end, providing 10^{11} β decay electrons per second. In order to reach the design sensitivity of 0.2 eV/c^2, the source temperature must be homogeneous and stable within 1 ‰ at 30 K. A thermosiphon cooling system operated with saturated neon was developed for this purpose, running all along the beam tube. The full-scale set-up was tested under the final operating conditions in the Tritium Laboratory Karlsruhe. Experimental results are presented, showing a temperature stability of better $\pm$0.003 K/h at 30 K.

KEYWORDS: Measurement, neon, Pt500, temperature stability, thermosiphon.

Operation of cryogenic facility in e-way at Tata Institute of Fundamental Research, Mumbai, INDIA

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In an attempt towards the development of modern, model & paperless cryogenic facility, the Low Temperature Facility of Tata Institute of Fundamental Research, at Mumbai, India; carried out many automation works using PLC and other modern electronic tools, with the objective of bringing the entire plant operation to your palm whenever and wherever you are.

Efficiency in the plant operation by keeping a watch on the plant healthiness, advance indication about the possible plant problem by means of pre-warning/alarms, so that the remedial action can be taken well prior to the actual failure affects the plant operation, reduction is plant down time were achieved by the automation works.

Large size in our cryogen production, controlling the complicated helium liquefier, meeting the uninterrupted supply of cryogen to the users on "any time availability basis", safety in handling cryogens & high pressure gas, effective usage of limited skilled manpower etc., all these requirements call for the definite need of modern electronic gears & gadgets.

The talk will describe in details about the automation works carried out at our cryogenic facility at TIFR.

Abstract CEC/ICMC 2011

Basic Considerations of Small to Medium Size Helium Liquefaction System

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The basic requirements for a user to size and design small to medium helium liquefaction systems are quite multilayer. The feed gas composition, for example, defines whether impurities can be removed by an internal adsorber system or if a purifier (internal or external) is required and if the purification operation is a continuous or batch process.

The liquefaction rate of the system furthermore is dependant on the running time, e.g. if the system is operated during the whole week or stopped on weekends and if a turn-down of the system is required. This will also determine the size of the liquid dewar and storage tank.

Another important issue is the availability of liquid nitrogen for pre-cooling purposes. In the US liquid nitrogen is a commodity with a liter price equal to the price for a kW hour of electricity, whereas in Europe LN is more expensive and used only if necessary or easily available. In case LN is used the components like compressor and coldbox can be smaller with less consumption of electric power.

The presentation will cover a number of issues showing important considerations in specifying a helium liquefaction system.

Performance versus coldhead orientation for large 50K 'pulse-tube' cryocooler

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Recently, one of us reported on a coaxial pulse-tube cooler with 30W cooling capacity at 50K from 2.1 kWe input*. In that work, the coldhead was always in a vertical orientation, cold-end down. At the same conference, Greg Swift described a newly published theory** describing under what conditions a pulse-tube cooler should work when tipped. Intuitively one would expect worse performance when a pulse tube is oriented cold-end up or sideways, but our own experience with small cryocoolers, as well as the theory of Swift and Backhaus**, suggest that when the oscillating frequency and amplitude are high enough, the gas column in the pulse tube remains convectively stable. However, as pulse tube coolers increase in capacity at the same frequency, the pulse tubes tend to be larger diameter but about the same length, making them more susceptible to convection. To our knowledge, no data are available for a tipped pulse tube as large as our 50K cooler, and there are applications for which cold-end down orientation cannot be maintained. In this paper we will present performance measurements on the 30W-at-50K cryocooler with its coldhead in various orientations, and compare the results to the predictions of the Swift/Backhaus theory.

This work is supported by the U.S. Air Force and Cryoconcept/Cryomagnetics, Inc.

* Spoor, P.S., "30W at 50K Single-Stage Coaxial Pulse-Tube cooler with Tapered Buffer tube," in *Cryocoolers 16*, ed. S.D. Miller and R.G. Ross, Jr., ICC Press, Boulder, CO, 2010, pp 163–166.
** Swift, G.W. and Backhaus, S., "Why High-Frequency Pulse Tubes Can Be Tipped," in *Cryocoolers 16*, ed. S.D. Miller and R.G. Ross, Jr., ICC Press, Boulder, CO, 2010, pp 183–192.

Experiments with Linear Compressors for Phase Shifting in Pulse Tube Cryocoolers

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For the past year NIST has been investigating the use of mechanical phase shifters as warm expanders for pulse tube cryocoolers. Unlike inertance tubes, which have a limited phase shifting ability at low acoustic powers, mechanical phase shifters have the ability to provide nearly any phase angle between the mass flow and the pressure. We discuss our results with experiments and modeling on a commercially available miniature linear compressor operating as an expander on the warm end of a 4 K pulse tube, whose temperature is nominally about 35 K. We also present results on experiments with a linear compressor operating at room temperature but coupled to the 4 K stage through secondary regenerators and secondary pulse tubes. Experiments on a small pulse tube test apparatus with both ^{4}He and ^{3}He showed improved efficiency when using the mechanical expander over that of inertance tubes. Phase locking techniques using function generators and power amplifiers for phase angle control are detailed. The use of expanders demonstrates flexible control in optimizing phase angles for improved cryocooler performance.

CEC-07

Analytical Model for a Pulse Tube Cryocooler Bellows Phase Shifter and Experimental Results

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Losses within a pulse tube cryocooler (PTC) are dominated by losses within the regenerator that scale directly with the magnitude of the mass flow rate within the regenerator. Therefore, in order to maximize PTC performance it is necessary to minimize the mass flow rate in the regenerator, which occurs when the phase between the mass flow rate and the pressure variation at the center of the regenerator is zero. The phase between the mass flow rate and the pressure in a pulse tube refrigerator is controlled by a phase shifting device installed at the warm end of the pulse tube component. The three phase shifting mechanisms used for pulse tubes are the orifice, double inlet, and inertance tube; the inertance tube is the most commonly used device. Each of these shifting devices have significant disadvantages including limited achievable phase angles and large mass and volume. Also all of these devices are non-tunable once the mechanism is installed. The inertance tube works as an acoustic RLC circuit where the resistance is provided by the wall friction, the inertance is provided by gas inertia, and the capacitance is provided by a gas reservoir. It has been proposed that this acoustic circuit be replaced with a hybrid mechanical/electrical system where the damping is provided by a non-contact eddy current damper, the inductance is provided by a mass attached to the end of a metal bellows, and the capacitance is provided by the mechanical stiffness of the bellows. A significant advantage of the hybrid mechanism is that the damping provided by the eddy current damper can be controlled via an applied external magnetic field. By changing the amount of damping, active real-time control of the phase between the mass flow rate and the pressure can be achieved. This paper presents a one-dimensional analytical model of a bellows phase shifting mechanism for use at the warm end of the pulse tube component of a PTC. The model is used to determine properties of the phase shifting mechanism (volume, mass, spring constant, damping force, etc.) based on typical PTC operating conditions. Initial experimental results are also presented.

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The performance of a linear compressor with triangle flexure bearings

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Abstract: This paper reports on the performance of the first self-fabricated moving coil linear compressor at Zhejiang University. The efficiency of the compressor is testing using the RC load method. From the experimental results, its resonant frequency is below 30Hz. When combined with a pulse tube cryocooler working at 40Hz, the minimum temperature is 49.1K, the cooling power at 80K is 4.5W, and the electricity power input is 540W. From the RC load experiment, the efficiency of this compressor is only 30% at 40Hz. Therefore, we are considering using the compressor to drive a three stage pulse tube cryocooler at liquid helium temperatures, by running at 25Hz or lower.

Keywords: Linear Compressor   Triangle Flexure Bearings   RC load method   Pulse Tube Cryocooler

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Using RC load method to test the performance of linear compressors

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Abstract: The efficiency of linear compressor is taken as the ratio of PV power to electrical input power. In order to determine the acoustic power transferred to the hot end of regenerator, this paper discussed the RC load method to test the performance of five different linear compressors. Phasor diagram is employed to analysis the efficiency influenced by the operation and structure parameters. Fluid network theory is employed to simulate the pulse tube by using the valve impedance R and reservoir capacitance C and to test the efficiency of linear compressor. In the experiment, the efficiency of the self-made linear compressor is about 60% if it works at 25Hz with the maximum opening valve. This experimental rig is simple and easy to carry out, thus, this method could be widely used to detect the efficiency of the linear compressor without position sensor.

Keywords: Linear Compressor   RC load measurement   PV power   Efficiency

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Measurement of flow resistance coefficient on resistance component in pulse tube cryocooler

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Abstract:

Flow resistance coefficient is a key parameter in the design of pulse tube cryocooler. An indirect quantitative approach to measure and compute flow resistance coefficient is introduced. Flow resistance coefficient of resistance component is obtained by established resistance coefficient testing system, which provides important reference on the process of designing pulse tube cryocooler and improving cryocooler's performance.

The resistance coefficient testing system is composed of gas storage, pressure sensor, flow meter and switch valve. Resistance component which is used in multi-bypass pulse tube cryocooler is connected at the end of the system. After switching the valve on, time is recorded when pressure in the system drops from p1 to p2, and the resistance coefficient can be deduced . The performance of multi-bypass pulse tube cryocooler badly depends on multi-bypass orifice resistance component .By optimizing orifice resistance component ,the lowest temperature 22.8K is gotten, which is the lowest temperature one stage multi-pass pulse tube cryocooler has ever reached.

Performance studies of single and two-stage Pulse Tube Cryocoolers under different interspace vacuum levels with and without thermal radiation shields

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The objective of this work is to evaluate the performances of single and two-stage Pulse Tube Cryocoolers (PTCs) under the possible conditions of loss of inter-space vacuum with and without thermal radiation shields. Towards the above, both single and two-stage Pulse tube Cryocoolers (PTCs) have been designed and fabricated. The single stage system reaches the no-load temperature of ~ 30K at its cold end. On the other hand, the two-stage PTC reaches ~ 2.5K at its second stage cold end and ~60 K in its first stage. Stainless steel meshes (size 200) along with Lead (Pb) granules are used as the first stage regenerator materials. On the other hand, combinations of Lead (Pb) with Er_3Ni and $HoCu_2$ are used as the second stage regenerator materials in the above PTCs. The single stage PTC provides a cooling power of ~ 10W at 80K, while the two-stage PTC delivers a cooling power of ~ 250mW at 4.2K.

Experiments have been performed with the interspace of the vacuum jacket maintained at high vacuum while the PTCs are with or without thermal radiation shields. These results are used to estimate the radiation heat transfer to the system and the effective emissivities of the radiating surfaces. Experimental studies with deteriorating vacuum levels in the interspace with thermal radiation shields on PTCs have been conducted to simulate the practical conditions of loss of vacuum in the interspace of PTCs. These studies lead to estimates of gas conduction heat transfer and the effective thermal conductivities in such conditions. The detailed experimental studies along with the analysis of the results are discussed in this work.

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A helium liquefier/recondenser using three pulse tube cryocoolers

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We have developed a helium liquefaction unit which can be used for recondensing helium vapor in a liquid helium cryostat or liquefying helium gas for a storage dewar. This helium liquefier employs three 4 K pulse tube cryocoolers, Cryomech model PT415. Each PT415 provides ≥ 1.5W at 4.2K while consuming 10.5 kW electrical powers. The liquefier is installed with the remote motor cold heads to minimize the vibration. The liquefier can liquefy room temperature helium gas with a liquefaction rate of 56 Liter/day. When installing it in the cryostat, it can reliquefy and recondense helium vapor with a rate of 63 L/day. The liquefier will be installed in a gravitational wave detector in Brazil to recondense the helium boil off from the cryostats. When the detector is turned off, it will be used to liquefy helium gas for a 500L storage dewar.