CRYOGENIC SYSTEM FOR A SUPERCONDUCTING SPECTROMETER*

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Summary

The Heavy Ion Spectrometer System (HISS) relies upon superconducting coils of cryostable, pool boiling design to provide a maximum particle bending field of 3 tesla. This paper describes the cryogenic facility including helium refrigeration, gas management, liquid nitrogen system, and the overall control strategy.

The system normally operates with a 4K heat load of 150 watts; the LN_2 circuits absorb an additional 4000 watts. 80K intercept control is by an LSI 11 computer. Total available refrigeration at 4K is 400 watts using reciprocating expanders at the 20K and 4K level. The minicomputer has the capability of optimizing overall utility input cost by varying operating points. A hybrid of pneumatic, analog, and digital control is successful in providing full time unattended operation. The 7m diameter magnet/cryostat assembly is rotatable through 180 degrees to provide a variety of spectrometer orientations.

Introduction

The HISS facility was conceived in the mid 1970's; construction was completed in early 1980, and after a one year shakedown period (7000 hours) the facility is operating smoothly. Full field has yet to be achieved because of operational requirements. Measured strains in the coil support cylinders at 2.0 tesla field agree with calculations. The load on the supports is 10^6 kg at 3 Tesla.

The cryogenic system for the series flow pool boiling coils consists of a charge leads feedthrough vessel, a Claude cycle helium refrigerator, and a liquid nitrogen system to provide heat intercepts on the coil support cylinders. The leads feedthrough vessel doubles as a liquid reservoir with a capacity of 600 liters. Coil capacity is 500 liters. Many modes of operation exist-4 basic cooldown phases, 3 circuit options at the magnet and 3 practical refrigeration options during steady state operation have emerged as useful.

Calculated heat load for the coil package is 70 watts assuming a 85K (saturated liquid at 17 psig) heat intercept temperature. Heat transfer limitations at this intercept prevent realization of such a heat load. Boil-off data indicate a minimum of 120 watts for the coil package alone. The load on the 4K system is thus most strongly affected by the LN_2 flowrate to the intercept. A Cryogenic Consultants Inc (CCI) coldbox with 200 watts nominal capacity was coupled with a Sullair C20 series screw compressor (50 gram per second, 18 ATM) for initial operation. Four stages of oil removal (bulk, Balston DX, BX, type JXC charcoal) and a final 50 micron filter are successful in stopping oil carryover. Cooldown and reliability experience with this initial capacity led to the addition of a reciprocating expander at the 4K level in parallel with the Joule-Thompson (JT) valve. The JT remains operational for cooldown and times during which the 4K expander is not operational. Measured capacity with isenthalpic expansion (JT) is 300 watts for short time periods only. Expander lifetime is short at this level. Output with isentropic expansion at 4K is above 400 watts. Steady state operation with a load of 150 watts thus requires about 40% of maximum available refrigeration and allows easy running of the compressor and expanders - expander speed is roughly 40% of maximum as one would expect assuming constant pressure ratios. Reliability at this speed has been good, although development and rework has been required to achieve this end.

Cooling the 10^4 kg cold mass takes about 3 weeks. The cooling rate is limited by the winding tension of the Nb-Ti/copper cryostable superconductor on the 304 stainless steel bobbin - cooling the winding 20K below the bobbin temp strains the copper to its yield point, resulting in loss of tension when the bobbin/winding package equilibrates at 4K. Initial winding tension was 200 kg on the 0.46 cm^2 composite cross-section.

The fact that the magnet rotates through 180^o for assorted spectrometer orientations necessitiated rotatable piping. Initial operation was with an ambient temperature rotateable joint, with the coldbox located atop the 8 m tall magnet. Operational inconvenience (including radiation) led to moving the coldbox to ground level and construction of transfer lines with standard bayonets and a 12' flexible section at the magnet centerline for rotation/translation. We are thus able to rotate the magnet "full" without interrupting helium flow by loosening the bayonets slightly.

Flow continues to the lower coil directly during cooldown or through a heat exchanger within the charge leads feedthrough vessel to improve liquid delivery quality during steady state when the vessel is partially full of liquid. A useful design addition for similar systems would be the capability of flowing directly into the leads vessel, so that the liquid reservoir could be "released" into the magnet at desired times (such as initial filling). Boiloff from the series piped coils is taken from the top of the upper coil and routed to the base of the leads feedthrough - most of this 4K vapor flows thru perforations into the reservoir vessel and out the top to suction. This piping assures that the cold ends of the feedthrough receives good 4K vapor flow. Charge leads feedthrough are of LBL ESCAR design.

The suction side of the coldbox is bypassed during most of the cooldown. No internal suction side bypasses exist making cooldown below 15K very awkward. Suction bypasses to the intermediate temperature levels are very desireable for cooling large masses.

Control

Smooth suction pressure control is a key to quiescent volumes of liquid helium, and ambient helium regulation is designed with smooth, simple unattended operation is mind. The overall strategy can be broken into two basic units - those functions which are strictly pneumatic or analog, and those

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which are digitized, with conventional back-up in most cases. An LSI 11 type minicomputer is the only dedicated processor for cryogenic control. Links to other HISS facility computers provide video displays (PDP 34) and data storage/manipulation (VAX 11/78). Most of the basic helium circuit controls are penumatic/analog. Those functions which are useful as digital control inputs are monitored with transducers or linear temperature sensors and ADC's.

Makeup gas can come from either a high pressure source (2500 psi tube trailers) or a 16000 gallon medium pressure tank, both via two stages of backpressure regulation. Makeup has two circuits of flow logic - high flow for startup and rapid liquifaction; low flow for cooldown and steady state. High suction pressure from excessive boiloff or transients is countered by dumping high side gas to storage via two echelons of control. A proportional controller and proper needle valves for dome pressure control handle the wide range of flow required of this circuit. Rapid liquid boil-off can result from either loss of insulating vacuum or inductive energy release if the coils should go normal (55 MJ). While this circuit cannot be sized to handle 100% of the gas generated by these events, it can almost handle full compressor discharge. We have found it useful to trim suction occasionally with a manually actuated slide type solenoid valve.

Rapid boiloff resulting from loss of insulating vacuum or normalization of windings is handled by three unique relief valves. Very large flow area is exposed at low ΔP above the release point to minimize cryostat pressure. Apertures deep within the magnet produce sonic flow in the relief stream, and the maximum ΔP across the relief is a function of the maximum allowable pressure of the cryostat. The design is essentially a linear bearing guided flat lift plate with a very long, weak spring having preload such that the lift required (3 cm.) to expose full effective piping area is achieved at pressure only 20% above the release pressure. Fundamental design aspects limit cryostat operating pressure to 2.3 atm. absolute. Note that helium becomes supercritical at 2.3 atm. and its heat transfer coefficient decreases orders of magnitude under this condition.

Compressor discharge pressure is controlled by a diaphragm loaded bypass to the suction side. Discharge pressure is 105% of this dome pressure and is controlled manually during the startup/cooldown phase, and by a proportional analog type controller or the LSI 11 minicomputer during steady state. Solenoid valves and micrometer handled needle valves allow repeatable tuning of this system for active regulation of liquid helium level. The response of the system to a rise in suction pressure is to boost discharge, thereby increasing the amount of refrigeration available and thus liquify more gas. Low suction pressure likewise triggers reduced discharge pressure, thus allowing some liquid to boil off. Proportioning and proper throttling allows almost imperceptible changes at steady state, yet allows continuous compensation for changing heat load or refrigeration degradation. Our suction pressure deadband is usually .1 psi. This system operates unattended, and reliability has been outstanding. It has not been practical to allow the system to fill completely with liquid - high heat loads and uncontrollable thermal oscillations result.

Compressor throughput determines within certain limits the motor (400 HP) power consumption. The coldbox consumes 20 to 50 grams per second as a function of load - the balance of compressor output flows through the bypass. The compressor inlet slide valve is moved to minimize bypass flow using an orifice plate/transducer in the bypass circuit as input. The current draw can thus be varied from 200 to 350 amps.

A primary function of any control strategy is the presentation of data in such a manner that operation is simplified. A dedicated control shack around the coldbox with a workable layout has been built. Data display of all digitized functions is handled by a touch panel with assorted menus. Certain graphics/data displays make temperature or pressure orientations easily understood - one menu contains a checkerboard of locally updateable numbers which determine the set points, deadband, slopes and time constants of the 15 available control outputs. Choice of digital control of the LN_2 circuits has opened the door to automation of cooldown, basic operation, and unique optimization. In the case of parallel two phase nitrogen control, the combination of very long time constants, and the degree of flexibility desired made a small computer a logical choice. Smooth control of these temperatures are fundamental to a controllable 4K system.

The flash boiling style LN_2 circuits comprising the coil heat intercepts have been difficult to control. The switch to digital/servo actuated globe valves on the LN_2 exhaust, using exhaust temperature as the control input has enabled us to reduce LN_2 consumption dramatically and stabilize the 4K heat load. The exhaust temperature can be smoothly varied from 80K to 250K, allowing a useful consumption range of almost a factor of 2. The result of this is that we are able to choose the 4K to 80K heat load balance as a function of utility input costs. In our unique case, electrical power costs range from 1 to 7.5 cents per kW-hr. in 2 discrete steps. When operating on inexpensive power, it behooves us to minimize LN_2 use and put more load on the compressor expander package. Note that the baseline utility costs for this facility (at $.05 per kW hr.) is $15,000 per month.

It is possible to operate the Claude cycle refrigerator without LN_2 precool by boosting both compressor output and expander speed about 30%. Steady state coldbox LN_2 consumption is 35 liters per hour. We are currently mapping power input as a function of LN_2 consumption in these different modes.

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