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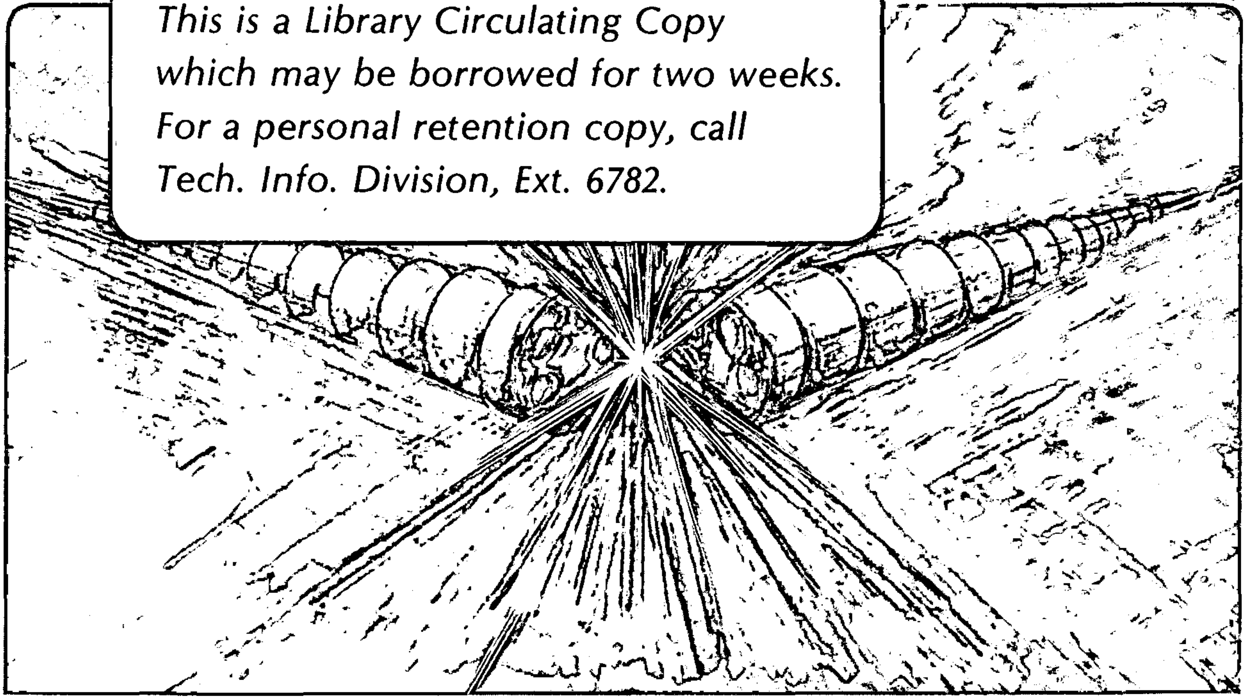

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CONTROL AND OPERATION COST OPTIMIZATION OF THE HISS CRYOGENIC SYSTEM*

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Summary

The Heavy Ion Spectrometer System (HISS) relies upon superconducting coils of cryostable design to provide a maximum particle bending field of 3 tesla. A previous paper describes the cryogenic facility including helium refrigeration and gas management. This paper discusses a control strategy which has allowed full time unattended operation, along with significant[a] nitrogen and power cost reductions. Reduction of liquid nitrogen consumption has been accomplished by making use of the sensible heat available in the cold exhaust gas. Measured nitrogen throughput agrees with calculations for sensible heat utilization of zero to 70%. Calculated consumption saving over this range is 40 liters per hour for conductive losses to the supports only. The measured throughput differential for the total system is higher.

Higher heat load on the helium system results from this, but non-linearity of the 4K refrigeration to compressor power input characteristics results in a 10% maximum power increment. Instrumentation allows proper tuning of the system.

Major power cost reductions[b] have been accomplished through negotiation with the utility for off peak, interruptible power.

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[a] Each 100 liters per hour of LN_2 costs \$8000 per month at current rates (7/83).
[b] \$.015/Kw-hr vs. \$.05 to .07/kw-hr.

Frequent manual bus transfer has been technically trouble free. 10,000 hours of assorted operation have been logged to date.

Introduction

The heavy ion spectrometer was conceived as a user oriented facility for a wide variety of physics experiments. Available equipment includes a sophisticated computer facility for on line data analysis, fast counting equipment backing a variety of particle detectors including time of flight walls and drift chambers on a scale commensurate with the 1 m magnet gap. The Bevalac beam delivery system (protons to Uranium) incorporates a swivel section in conjunction with 360° magnet rotation capability for flexibility. This emphasis on flexibility allows physics ranging from simple projectile fragmentation to low energy pion production and neutron/gamma studies. Reliability and ease of operation have been primary design parameters in hardware selection and control philosophy because of scheduling logistics and the high cost of downtime.

The cryogenic system for the series flow pool boiling coils consists of a power lead feedthrough vessel, a 400 watt Claude cycle helium refrigerator and a nitrogen system to provide heat intercepts on the coil support cylinders. The leads feedthrough vessel doubles as a liquid helium reservoir with a capacity of 600 liters. Coil capacity is 500 liters. Many modes of operation exist - four basic cooldown phases, three circuit options at the magnet and three practical refrigeration options during steady state have emerged as useful.

Heat Balance

The heat load, as determined from boiloff data, is 120 watts at 4K for the coil system alone. The coil support cylinder thermally couples the 4K system tightly to the 80K system - the cross section (Fig. 1) is as slender as possible yet able to resist the 10^6 kg force generated at full field. A circumferential heat intercept is cooled with forced flow LN_2 - a maximum of 3000 watts is intercepted at this band. The 4K system heat load is directly proportional to the temperature at which the LN_2 cooled heat intercept is held - it is thus possible to juggle the energy absorption between the helium and nitrogen circuits by operating the intercept temp at some value above 80K, thus taking advantage of the sensible heat available in the cold gas (47 watt-hr/liter). The upper limit LN_2 heat load (3000 watts) assumes liquid or saturated vapor in the full intercept circuit (piping is brazed onto the 304 LN support cylinder). Consumption at this condition is 70 liter/hr[c]. This agrees with the measured exhaust throughput rate.

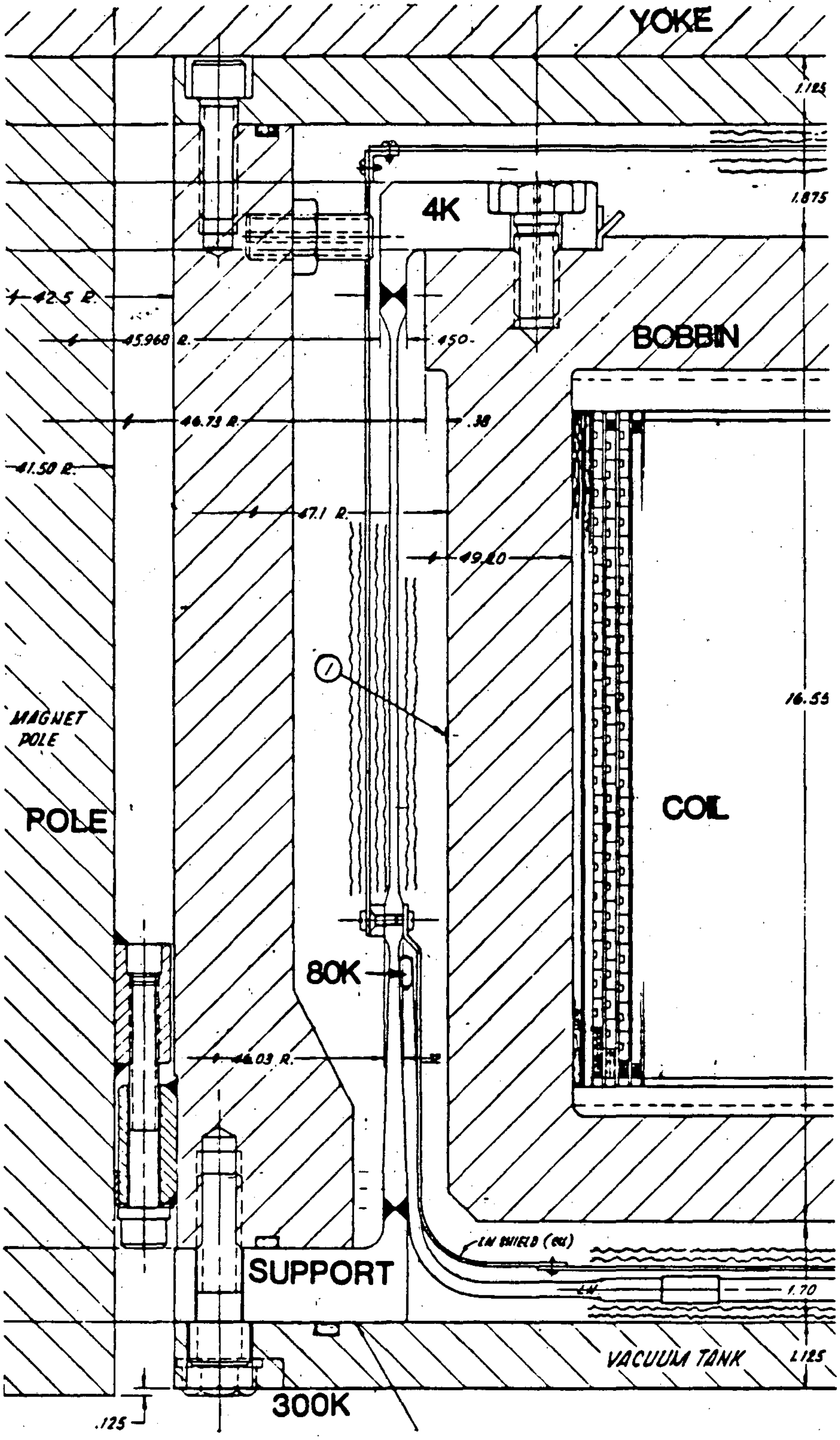

Fig. 1 XBL 838-10973

The increased heat load on the helium system is compensated for by higher throughput. The compressor used in this system (Sullair C-20 screw type) has variable mass throughput of 10 to 55 grams/sec and a discharge pressure range of 9 atm. to 18 atm. The resulting power consumption is 130 kW to 280 kW with a pronounced upward slope in power consumption at about 35 grams/sec. Operation at 150% of the minimum 4K heat load (~200 watts total) requires mass flow of less than 35 grams per second assuming isentropic 4K expansion and a healthy 20K engine. An instrumented orifice plate on the bypass circuit makes feedback control of mass flow possible.

Figure 2 shows the heat load and temperature profile of the circumferential heat intercept as a function of exhaust temperature.

Table 1 shows some calculated operating points using zero to 100% of the sensible heat in LN_2. In reality we have throttled the flow back to 25 liters per hour without adverse affects. Operation at high field requires a colder support for strength.

An upper limit on support temperature exists at present because the nitrogen exhaust at the control input sensing point can approach ambient - control is then affected by fluctuations in ambient temp and supply pressure. We are at present moving the control input sensors to a colder location.

Total elimination of nitrogren flow results in measured cylinder temps of 200K at the intercept. The resulting heat load on the helium system is greater than 400 watts. This number is interesting because it defines the lower limit on nitrogen cirucit heat load - zero watts at intercept temperature 200K.

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[c]3000 watts/40 liter-hr (Assume 90% quality) = 70 liter/hr.

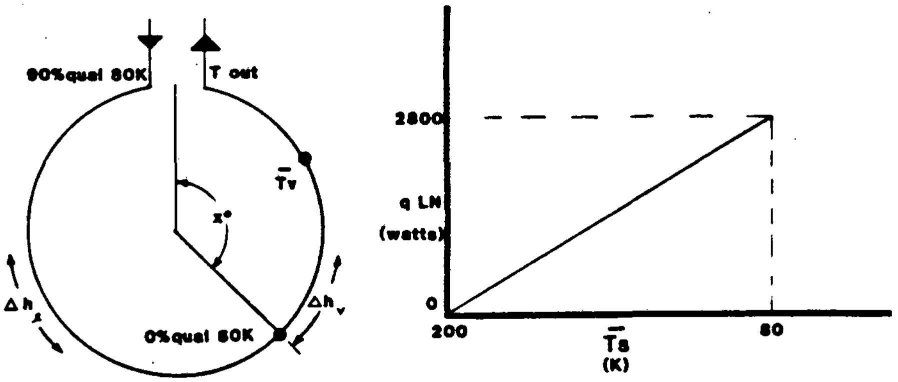

Fig. 2

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Nitrogen consumption at the cold box during stable operation is 32 liter/hour. This can be eliminated by boosting expander throughput about 60%. Future plans call for use of our "spare" 20K expansion engine in parallel with the on line 9.5 cm bore 7.5 cm stroke engine for increased throughput at low reciprocating speed (for long life). This additional expansion capacity will greatly enhance cooldown performance. The payback period for this modification is quite short.

LN_2 Control

Smooth control of LN_2 flow is required to keep the 4K heat load smooth and hence manageable. An LSI11 microprocessor is used for open loop control of nitrogen flow. Long stem globe valves on the LN_2 exhaust lines are driven by low torque permanent magnet DC gear motors. A ten-turn potentiometer coupled to the motor shaft serves as an absolute position encoder for operator convenience. Control input is from exhaust temperature sensing only. A fifteen channel steppermotor control CAMAC module was modified to provide variable width square-wave outputs (rather than pulse trains) which are used to energize the DC motors for programmable lengths of time from 1 ms to 10 seconds.

Table 1

T_{out} K	h_{vapor} cal/g	X° circum	$\bar{T}s$ K	q_{LN_2} watts	$LN_{2\,Use}$ l/hour
80	0	0	80	2800	70.0
100	4.25	34.	81.	2777	62.7
140	12.7	87.	87.	2635	50.0
180	21.2	125	97.	2395	39.0
220	29.8	153	110	2100	30.
260	38.3	176	124	1775	22
300	50	200	136	1500	16

Where $$\bar{T}_s = \frac{80\ \Delta h}{\Delta h_v + h} + \frac{\Delta h_v\ (80 + T\ out)\ /2}{\Delta h_v + \Delta h} \qquad X = \frac{360^{\circ} \Delta h}{\Delta h_v + \Delta h}$$

The servo and monitoring amplifiers are housed in a standard rack bin. The front panel has switches to allow manual or computer control of each channel and bi-color LED's to indicate opening or closing motion. Batteries allow manual control during power outages.

Table 2 - Steady State Control

Function	Primary Control Type	Optional/ Backup Control	Input	Output
Helium level	analog - proportional	digital	suction	dome pressure
20K expander speed	pneumatic	digital*	expander inlet temperature	dynamic brake-SCR angle
4K expander speed	analog manual	digital*	primary set points	hydraulic brake pressure
JT valve	manual	digital	primary set points	
LN_2 flows	digital	manual	exhaust temperature	Square wave width
Slidevalve position	manual	digital	bypass mass flow - 2 grams/sec set	
Mix & bypass valves	manual	digital*		
Makeup	pneumatic	None	suction	dome pressure
Kickback	analog - proportional	pneumatic	suction	dome pressure

*required for cooldown automation

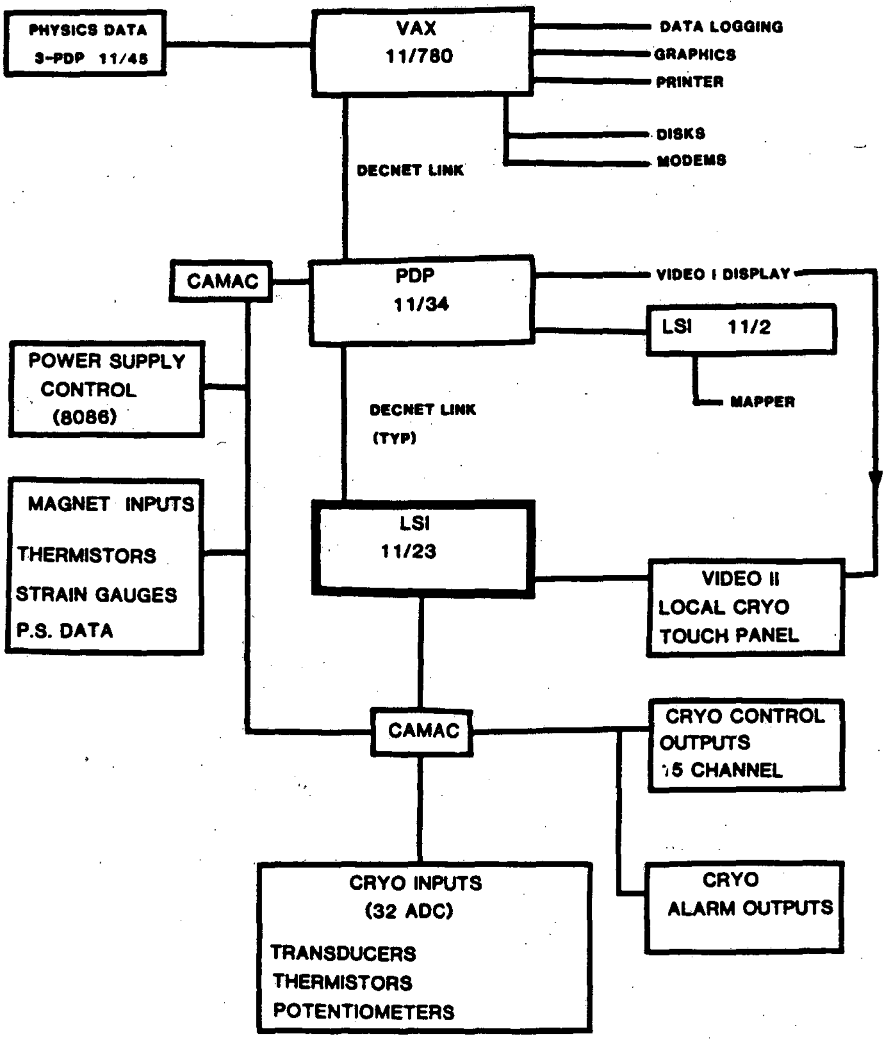
Temperature monitoring is done with thermistors which provide 1% linearity from 4K to 300K. A simple current source and differential amplifier circuit generates 24.42 mv/K such that the 10v/12 bit A to D converter in CAMAC reads exactly 0.1 deg per bit.

The control program has self checks to prevent false compensation in the event of input signal failure. Time constants and set points are readily accessible via a touch panel. Valves remain stationary during computer failure.

Helium System Control

Smooth suction pressure is a key to quiescent volumes of liquid helium. Our overall strategy is a combination of pneumatic, analog and digital control.

Steady state liquid level control is accomplished by modulating compressor discharge in response to suction pressure. The stable operating setpoint (.7 psi) is just above the gas makeup point (.6 psi) and well below the kickback point



XBL 838-10961

(4-psi generally). Compressor discharge pressure is controlled by a dome loaded bypass to the suction side. Discharge equals 105 % of this dome pressure and is controlled by a proportional analog controller or the LSI11 during steady state. Solenoid values and micrometer handled needle values allow repeatable fine tuning of the circuit. The response of the system to a rise in suction pressure is to boost discharge, thereby increasing the amount of available refrigeration. Low suction pressure triggers reduced discharge pressure allowing some liquid to boil off. Proportioning and proper throttling allows almost imperceptible changes at steady state and allows continuous compensation for changing heat load or refrigeration degrdation. Manual control is used during startup and cooldown.

Open or closed loop control of other helium system parameters is available (see table 2) but unnecessary during steady state. Automation of cooldown requires use of the digitized functions.

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 LN alloy 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.

Maintaining this ΔT limit requires continual mixing of ambient temp gas with stable 80K LN_2 cooled gas - expansion engines are started when the magnet is below 100K and the warm mix gas flow rate reaches zero at magnet temperatures below 40K.

Design

Figure 3 shows schematically the manner in which existing facility computers are linked to the LSI11 microprocessor to provide a powerful system. The framework exists for presentation, control and alarm changes as are deemed necessary by personnel and situation dynamics. Inputs are generally in the form of voltage signals from pressure transducers. Vapor bulb thermometry lends itself to this application but requires absolutely leaktight transducers. A more cost effective means of digitized thermometry is linear thermistors.

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 and pressure status 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. Digital control of the LN_2 circuits has opened the door to automation of cooldown, and 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.

Shakedown operation in 1981 indicated that the system is complex enough to warrant consideration of the operator. These include the following obvious but often overlooked items.

1. Minimization of overall utility and LN_2 operations cost.
2. Minimize manpower requirement.
3. Data presentation at some central location.
4. Comprehensive local alarm system with remote summation and general alarming to some constantly manned location. To accomplish these ends:
    1. Automate critical functions with redundancy
    2. Failsafe logic
    3. Remote control capability via modems.

Conclusion

Operational experience has been positive to date. Microprocessor control of flash boiling style nitrogen circuits has been virtually troublefree. Stand alone, compact controllers are possible without interfacing to larger machines as done at this facility. Variable throughput compressors have the advantage of high performance for cooldown and turndown capability for steady state. Most 4K systems have a distinct knee in the power input to refrigeration characteristic, and it behooves one adjust the intermediate temperature circuits to take advantage of this. It is cost effective in this system to eliminate LN_2 precool on the refrigerator during stable operation.

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