Final Design Report

for the M.I.C.E.

2 slot VLPC Cryocooler Cryostat

D-ZERO ENGINEERING NOTE # 3823.000-EN-579

Dec. 13, 2005

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Introduction

A special purpose cryostat has been designed and built for cooling the MICE photo-sensors to an operating temperature of approximately 9.0 K +/- 0.1 K. The sensors are visible light photon counter (VLPC) chips. They are used for readout of the MICE scintillating fiber trackers.

The cryostat has 2 cassette slots which accept Fermilab/D0 built 1024 channel VLPC cassettes. A two stage, commercial cryocooler located between the two cassette slots provides heat intercepting and cooling of the cassettes to operating temperature.

The cryostat was commissioned at Fermilab in the Spring of 2005. Modifications were made during the commissioning period and concluded with a successful final design. The cryostat was successfully operated at Fermilab for several months and for several thermal cycles. It was then shipped overseas and operated successfully at KEK in Japan. This engineering note documents the final design of the cryostat.

Design Performance Summary

Table 1 gives a summary of the measured thermal performance of the cryo-system and table 2 shows the design heat load estimates. Figures 1-3 show the operational parameters and graphical data for the system. Figure 4 shows the system in operation at KEK.

Table 1. Summary of thermal performance.

Parameter	**Measured values April 28, 2005**	**Design Values**
Cryocooler stage 1 lowest temperature	**47 Kelvin**	**45 Kelvin**
Cryocooler stage 1 heat load	**55 Watts**	**50 Watts**
Cryocooler stage 2 lowest temperature	**5.3 Kelvin**	**5.5 Kelvin**
Cryocooler stage 2 heat load	**3 to 4 Watts**	**3 Watts**
Cassette #105 temp, Slot 1, no heater	**7.5 Kelvin**	**8 Kelvin**
Cassette #111 temp, Slot 2, no heater	**7.1 Kelvin**	**8 Kelvin**

Table 2. Design heat load estimates

	Stage 1 (about 50 K)	Stage 2 (about 6 K)
Cassette	7.7 Watts	0.82 Watts
Envelope & stiffener panels	15.0 Watts	0.45 Watts
Radiation, miscellaneous	2 Watts	0.10 Watts
Total per slot	25 Watts	1.4 Watts
Total for cryocooler	**50 Watts**	**2.8 Watts**

Cooldown time: About 24 hours **Warm up time:** About 48 hours

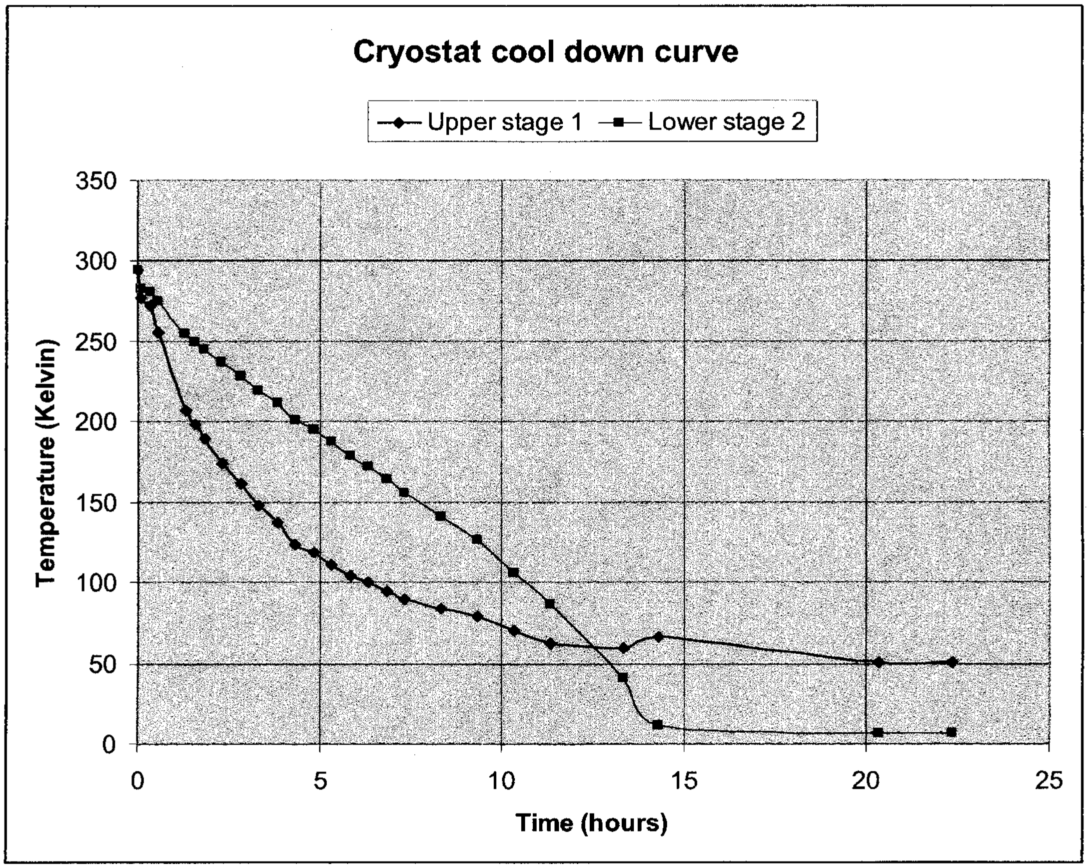


Figure 1. Cool down curve for the cryostat. Data from April 28, 2005 cool down

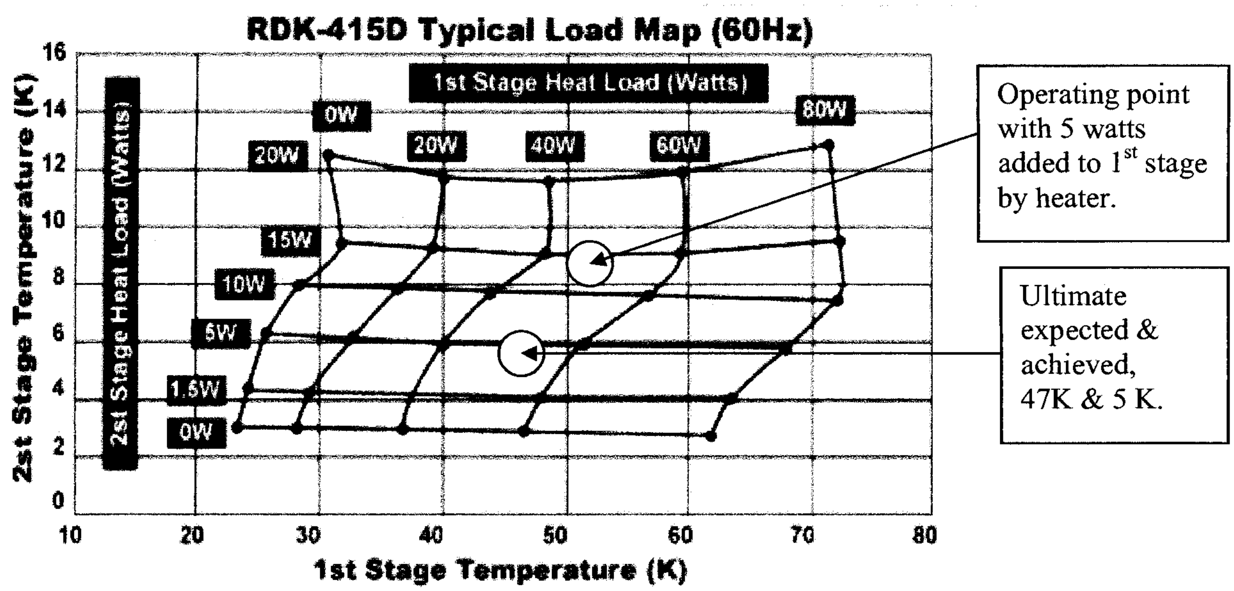
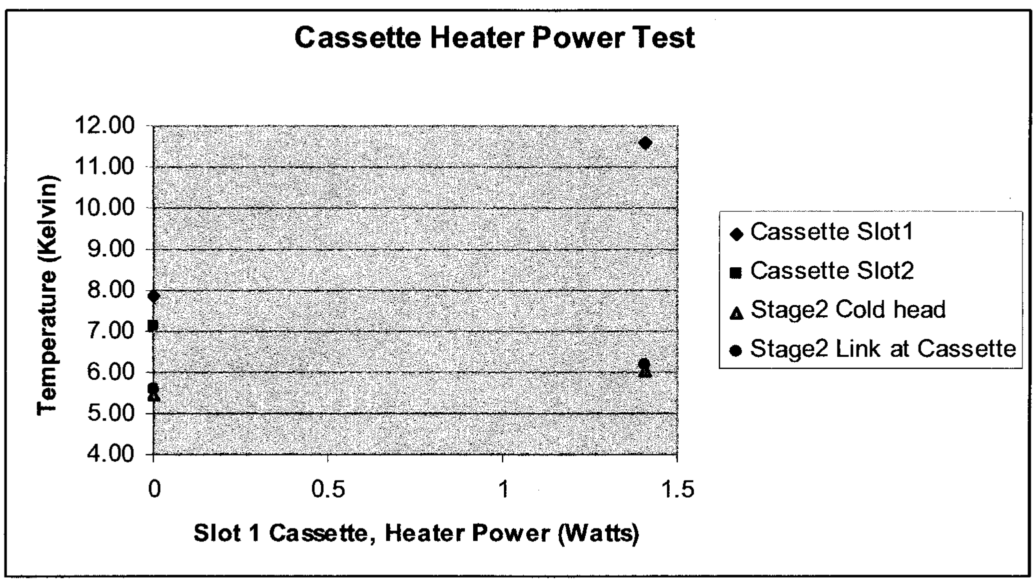


Figure 2. Refrigeration load map of cryocooler and cryostat operating point.



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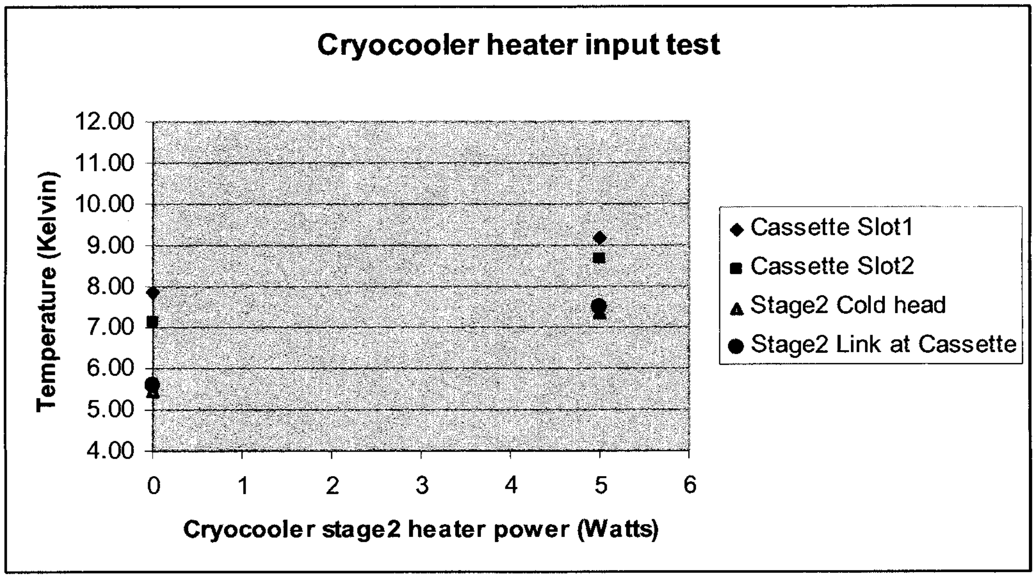


(b)

Figure 3. Temperatures of the cassettes and cryocooler stage 2 cold head and stage 2 thermal link when heater power was added by a.) the cassette in slot 1 (upper graph) and b.) the control heater banded to stage 2 of the cryocooler (lower graph).

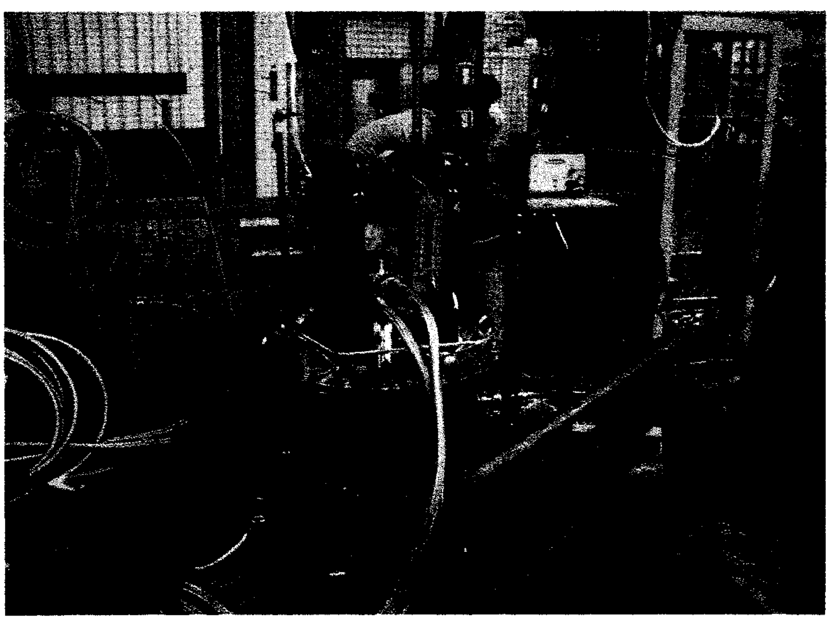


Figure 4. This is a picture of the cryostat in use by the MICE collaboration at KEK in Tsukuba, Ibaraki, Japan.

Design Specifics
The details of the design are discussed in this section.

Vacuum Can
The insulating vacuum vessel container is constructed from a 609 mm outside diameter (24" schedule 10 pipe size), with an o-ring groove flange ring at the top and a flat 20 mm thick bottom plate welded to the bottom (Figure 5). The internal depth of the vacuum container is 405 mm. The material is type 304 stainless steel. Insulating vacuum pump out and vacuum gauge ports are located on either side of the shell. The surfaces of the vacuum shell were electro-polished for a low emissivity finish. Four short support legs are welded to the outside of the container to put the top lid at a convenient elevation. I note that the assembled cryostat has a mass of 300 kg.

Figure 5. A picture of the empty vacuum can. Picture provided by Koji Yoshimura (KEK).

Top Lid
The top lid is the main structure that everything bolts to (Figure 6). There are quite a few features and machining in the top lid. The lid flange is 24 mm thick by 750 mm outside diameter. It is made from a type 304 stainless steel plate. An o-ring flanged "top hat" port in the center of the plate mates to the commercial cryocooler. Two cassette slots 35 mm wide by 425 mm long are located on either side of the cryocooler flange. The spacing of the cassette slots (266.7 mm center to center) is set by the pitch of the VLPC cassette analog front end (AFE) backplane. A 3.5 mm wide by 3.5 mm deep heater groove is machined into the lid in a serpentine pattern around the cassette slots. A 0.5 Watt/cm (rated capacity) cable heater is epoxied into that groove and provides about 50 watts (50% rated capacity) of heater power during operation so that the lid temperature is not depressed below room temperature. Stresses in the lid due to vacuum loading were calculated to be less than 34 MPa (5 ksi). Maximum deflections due to vacuum were estimated and measured to be about 0.15 mm. The surface finish at sealing surfaces was specified at 1.6 micrometers. The VLPC cassette assembly contains a polyurethane gasket which seals to the top side slot perimeter. An invar box (envelope) flange with o-

ring groove bolts to the underside of each slot perimeter. Three KF40 size ports are located on the lid for an instrumentation feed through, a control heater feed through, and secondary vacuum instrumentation. After all parts are assembled, the lid is mated to the vacuum can.

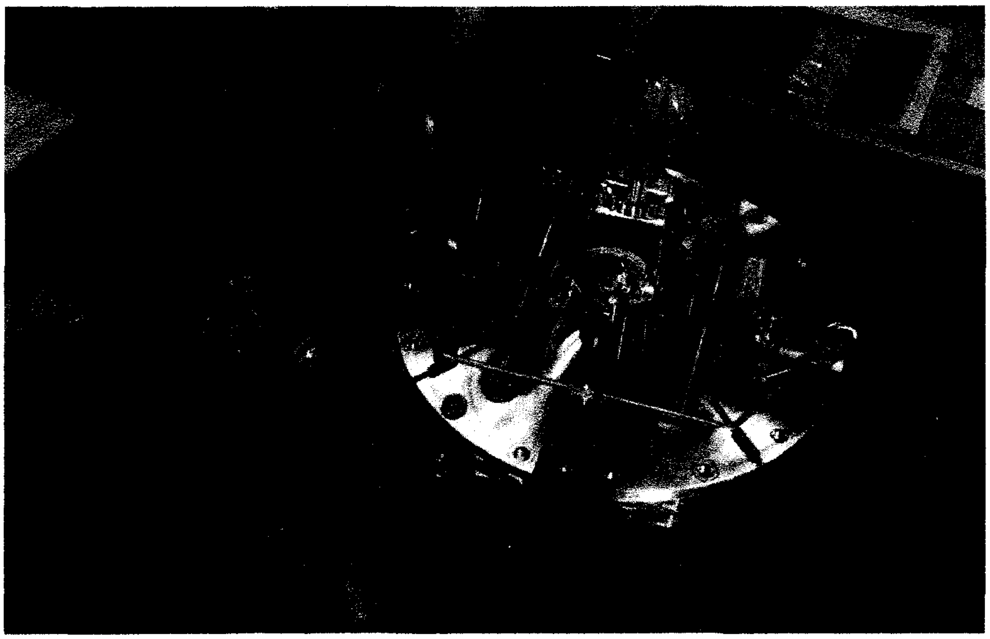


Figure 6. Top view of cryostat lid without cassettes installed. The cryocooler is mounted in the center with cassettes slots 1 and 2 on either side. The mechanical engineer and author of this note, Russ Rucinski is on the left.

Cassette Envelope

The cassette envelope is a low conductivity, low thermal expansion box that seals to the underside of the top lid (Figure 7). Insulating vacuum is on the outside of the envelope and gas helium and the VLPC cassette is on the inside. The nominal internal clearance inside to the cassette is made tight at 0.6 mm (0.024" clearance). The wall thickness, 0.38 mm (0.015") was minimized for heat conduction purposes. This was the minimum practical thickness for fabrication. The material of the box is "Invar 36", a 36% Nickel, balance Iron alloy known for its low thermal expansion properties. This property was a necessity to reduce thermal stresses to an acceptable level. The envelope flange at the underside of the lid is locked in by the lid heater to about 288 Kelvin while just 50 mm lower, the envelope temperature is locked in to about 70 Kelvin by stage 1 of the cryocooler. This is a huge, 4.36 Kelvin/mm temperature gradient!

The envelope was made by bending a thin sheet of invar into a rectangular box with one vertical fusion edge weld on the short edge. The 12 mm thick invar top flange and 12 mm thick invar bottom piece had weld preparations machined into them so that the box perimeter could be edge fusion welded to them as well.

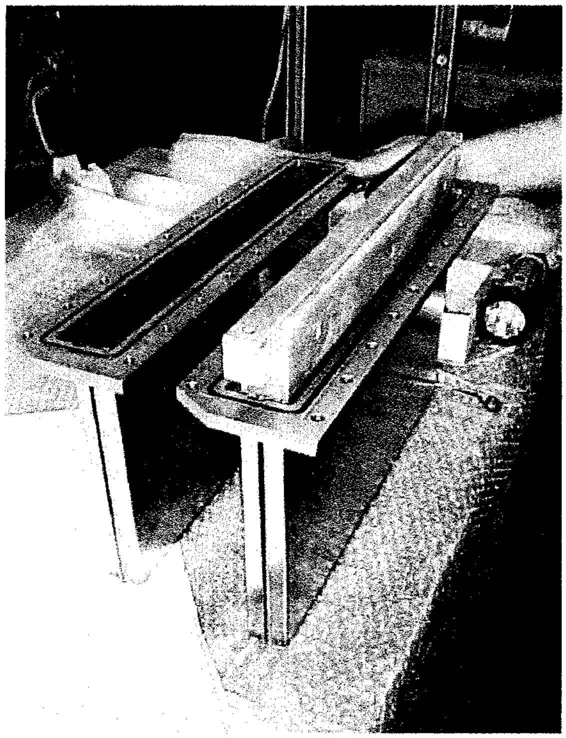
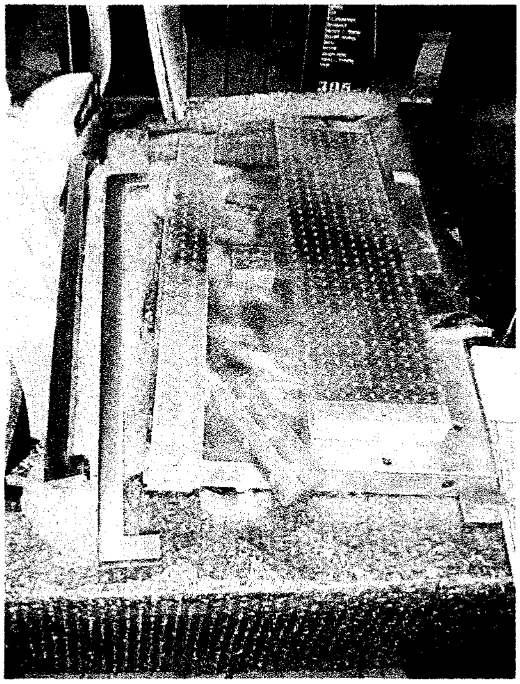


Figure 7. Picture of the Invar envelopes prior to bolting to the underside of the top lid. The o-ring seal in the top flange and vertical edge weld seam can be seen. The envelope on the right has a size checking fixture inserted into it.

Recall that insulating vacuum is on the outside of the box, and a positive pressure of gas helium is on the inside. The design pressure differential is 145 kPa (21 psid) with the actual internal operating pressure about 110 kPa (1.5 psig = 16 psia). Because the envelope material thickness was minimized for heat conduction purposes, external mechanical support is needed to withstand the pressure differential across the wall. The external support provides point contact support spaced at 12.5 mm centers. Calculated stress due to pressure loading for this spacing is 46 Mpa (6.7 ksi). The allowable stress for the invar is 234 MPa (34 ksi).

G-10 stiffener panels

Stiff panels 25 mm thick provide external support for the thin envelope wall with minimal self deflection (Figure 8). The panels have 2.5 mm sized dimples machined onto the contact face with a 12.5 mm pitch. The panel material is G-10 CR grade. This material was chosen because of it's low thermal conductivity, suitability for cryogenic temperature, and strength. The long span panels are bolted to each other using stainless steel bolts and Belleville washers that keep the panels tight even after thermal contraction due to cool down. The short side panels are held in place by stainless steel tie bars which bolt into the ends of the long side panels. The panels are segmented in the vertical direction to break the heat conduction path. To reduce radiation heat load, the emissivity of the G-10 is reduced from about 0.9 to 0.1 by applying highly reflective 3M tape to the external surfaces.



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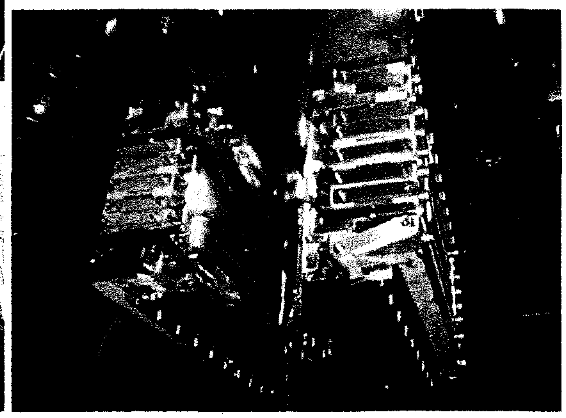

(b)

Figure 8. (a) G-10 Stiffener panel pieces are pictured. This picture was taken prior to the commissioning tests. Panels were later segmented in the heat flow direction to segments containing only two rows of dimples, (b) Shows the underside of the cryostat lid showing the support structure fastened around the invar box. Copper thermal links and the now segmented G-10 panels are coated with low emissivity tape

Thermal links

Thermal links provide the conduction heat transfer path between the two stages of the cryocooler and the cassette. The thermal links are made from oxygen free high purity copper (OFHC), UNS grade C10100. The thermal links are 10 mm thick solid copper pieces with a short flexible segment to accommodate 2 mm of movement due to thermal contraction. The flexible segment is constructed of 35 individual 0.13 mm (0.005") thick pieces of high purity copper foil soldered to the solid segments. It takes about 90 N (20 lbf) force to flex the 2 mm distance. The upper thermal link (Figure 9) operates at a temperature of around 45 to 50 Kelvin and has a temperature gradient of 1.0 Kelvin from the cryocooler connection to the envelope connection. The lower thermal link (Figure 10) operates at temperatures in the area of 6 to 8 Kelvin and has a calculated 0.1 Kelvin temperature drop from the cryocooler to the envelope. The two upper thermal links transfer 55 Watts to stage 1 of the cryocooler. The two lower thermal links transfer around 4 to 6 Watts (depends on cassette heater power) to the cryocooler stage 2.

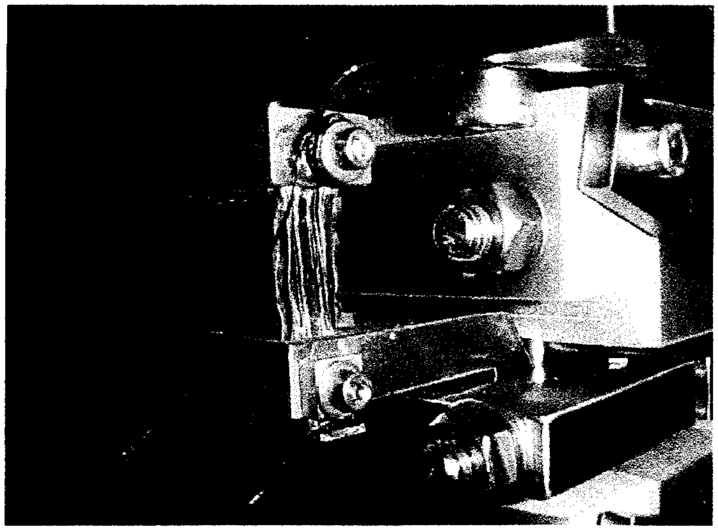

Figure 9. This a close up of the flexible segment at the upper stage 1 thermal link. The silicon temperature sensor (lower, envelope side of link) and heat sinking bobbin (upper cryocooler side of the link) are also seen.

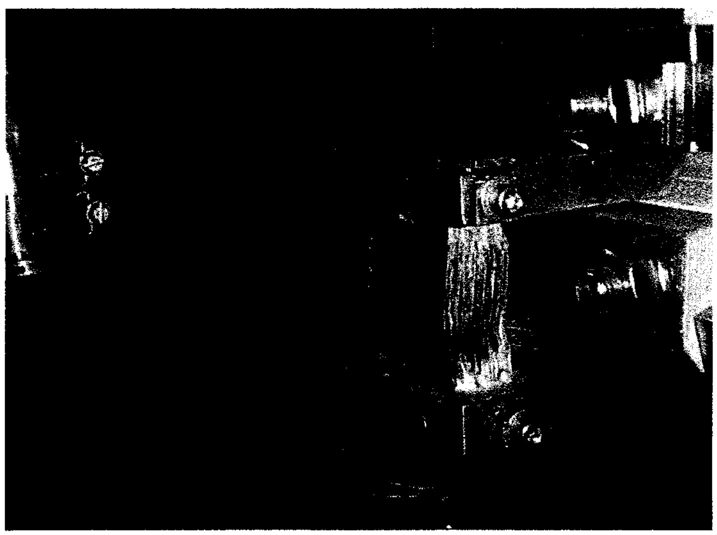

Figure 10. This is a close up of the lower thermal link flexible section. The Cernox temperature sensor is mounted to the envelope side of the link. A heat sink bobbin is on the cryocooler side of the link. The hose clamps on the left are securing the stage 2 heater which is wrapped under a piece of thin copper sheet.

Thermal interfaces in the vacuum space

A light coating of Apiezon type "N" cryogenic grease is used at the interface of the copper thermal links to the copper cryocooler stages. The grease makes a solid conduction path at the interface. The grease works well where similar metals are joined. The interface where the copper link mates to the invar envelope was a bit trickier. It took a few iterations to make it work. The basic concept is that the copper thermal link is squeezed against the invar envelope using stainless steel clamping bars. The stainless bars are tightened with bolts (and Belleville washers) at each end. Initially, grease was used at the interface to provide a conduction path. This did not work. It was found during open bath liquid nitrogen tests that when the joint was cooled down, the copper shrinks longitudinally, pulling the invar envelope into a wavy pattern. The grease at the interface is brittle at liquid nitrogen temperature and crumbled away leaving a vacuum gap and no heat transfer. The solution used was to use indium (98% In, 2% Ag) at this interface (Figure 11). The invar envelope was pre-tinned with indium using Indalloy Flux #3 from Indium corporation of America. The contact surface of the copper thermal link also was pre-tinned. Then when making up the assembly, a 1.6 mm (0.0625") diameter, 355 mm long soft indium wire was inserted and then compressed at the interface. To date, this solution has worked well and has survived a half dozen thermal cycles without degradation of performance.

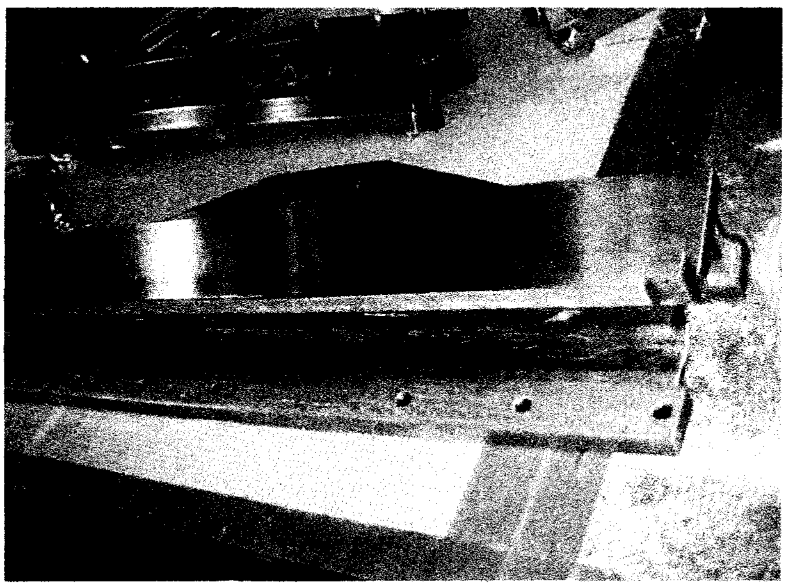

Figure 11. This is a picture of the lower thermal link (foreground) and upper thermal link (background) with indium coating at the interface surface that mates with the envelope.

Cryocooler

A commercial Sumitomo model SDRK-415D-A71A cryocooler is used. It is operating at about 60% of rated capacity at the two stages. The cryocooler along with air cooled helium compressor, gas flex lines, and control cables came as packaged system. It has worked flawlessly, giving very stable non-fluctuating temperatures for long operating periods (weeks).

Operation of the Sumitomo SRD-415D in Magnetic Fields

In order to keep the external fiber waveguides of the MICE tracker as short as possible, the VLPC cryo system described in this document will be located in the stray field of the tracker module solenoid. The manufacturer's specification for the SRD-415D is that the maximum magnetic field be limited to 700 gauss parallel to the axis of the unit's motor, and 500 gauss perpendicular to the axis of the motor. Calculations for the radial and axial stray field in the vicinity of where the cryo-cooler heads will be located are shown in figures 12 and 13.

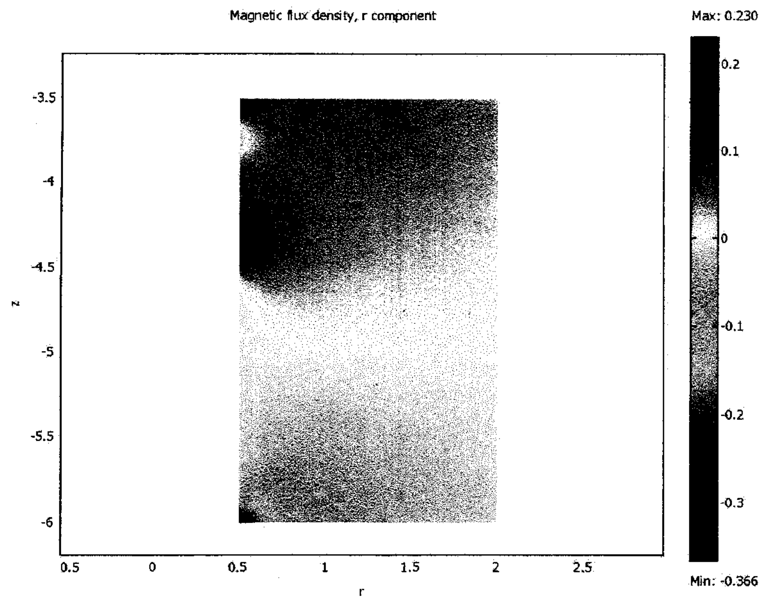

Figure 12. Radial component of stray magnetic field

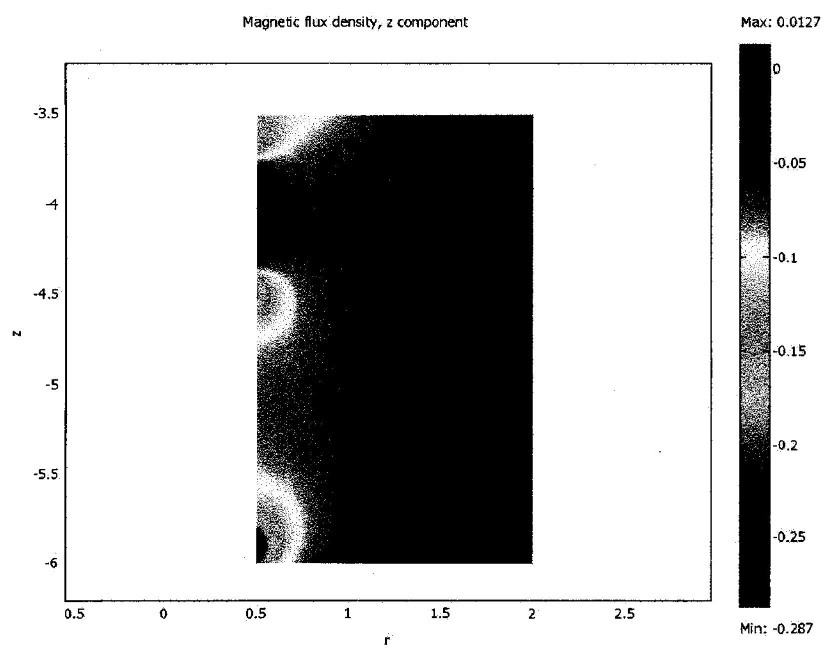

Figure 13. Axial component stray magnetic field

We anticipate that the cryo-cooler head will be at approximately 2 m radially from the center of MICE and located almost in-line with the end of the solenoid. At this position we anticipate no problem with operation of the Sumitomo SRD-415D.

50 Hz Operation of the Cryo-Cooler

Operating the cryo-cooler system at 50Hz will reduce the cooling capacity of the system by approximately 15%. This was the situation at KEK and we still had enough capacity to adequately cool the system. The use of water-cooled compressors will make the system insensitive to the ambient conditions in the MICE hall. At KEK the relatively high humidity and temperature in the hall (85% and 30C) produced an additional 10% drop in cooling capacity. The system was still able to adequately cool the VLPCs, as mentioned, even with this additional degradation.

Instrumentation and controls

Cernox temperature sensors from Lakeshore Cryogenics are mounted on the cold head of the cryocooler and the lower thermal link near the cassette envelope. A silicon diode temperature sensor from Oxford Instruments is used to measure the upper link temperature. A 100 ohm platinum resistor was also used during the commissioning tests. The sensors are mounted into small copper holders using GE-7031 varnish. The copper holders themselves are screwed to the surfaces with a #4-40 screw with Apiezon "N" grease at the interface. Cryogenic quad lead wire from the sensors is heat sinked to a small copper bobbin mounted nearby. Figures 9 and 10 show the sensors mounted on the thermal links. Readout and temperature control is via an Oxford instruments, ITC503 temperature controller. A flexible 36 ohm heater element from Minco is wrapped around the second stage of the cryocooler using high purity copper sheeting and hose clamps. The hose clamps and location of the heater can be seen on the left hand side of picture 8. The heat transfer surface of the heater is lightly coated with Apiezon grease. Up to 5 Watts of heat can be supplied by the heater to give gross temperature control for the cassette cold end. Each cassette also has individual heater control to adjust for fractional asymmetrical temperature differences.

Utilities

The volume inside the envelope containing the cassette is evacuated and backfilled five times with helium prior to cool down to reduce residual air contamination to less than 50 ppm. The gas helium acts a heat transfer medium between the cassette and envelope walls which are cooled by the cryocooler. The helium pressure is maintained just above atmospheric pressure, about 0.110 MPa (1.2 psig) by a low pressure regulator (Figure 14). As the cryostat cools, helium gas is added (see figure 3). Pressure relief valves set at 0.15 MPa (2 psig) protect the cassette space and relieve pressure during warm up. If the cassette space pressure ever went below atmospheric pressure, air and water contamination might occur since the VLPC cassette seal to atmosphere is not perfect, about (1E-3 cc/sec leak rate). To protect against this disaster, a low pressure switch and audible alarm is added to the cassette space piping.

A small Leybold TMP50 turbomolecular pump is mounted on the side of the insulating vacuum container. When the cryostat is warm the insulating vacuum space can easily be pumped to about 1E-4 Torr. The pressure drops to 1E-6 Torr when the cryostat is cold. A Hastings DV-6 thermocouple gage and MKS Instruments cold cathode gage model 421 is used to monitor insulating vacuum pressure.

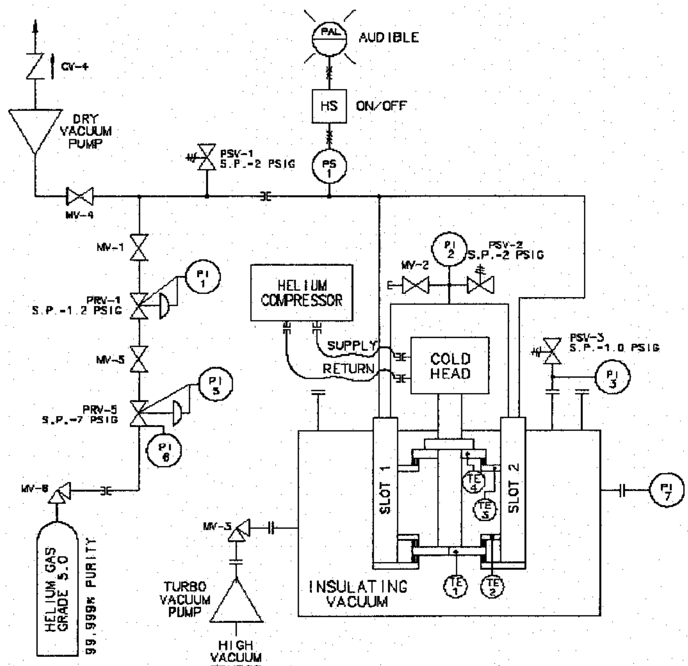

Figure 14. Flow Schematic of the cryogenic operating system

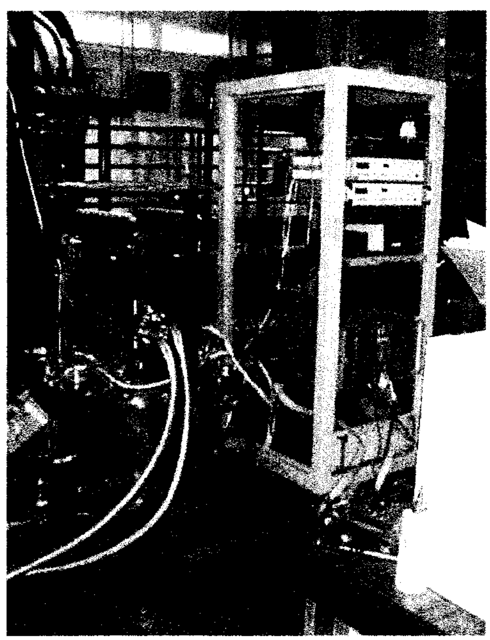

Figure 15. Picture of the cryostat in operation at the FNAL test stand. The cryogenic controls rack is on the right hand side.

Thermal-link design improvement

The thermal clamp connection to the invar envelope works, but is not an elegant, robust, dependable design. A different design which uses five copper studs brazed to the invar envelope is in test and development (Figure 16). The copper studs have a low profile head which is on the inside of the envelope in connection with the cassette intercept rail. The thermal link and clamping bar bolt to the studs in the vacuum space to complete the conduction path. This alternative design idea will be fully evaluated by the end of January, 2006.

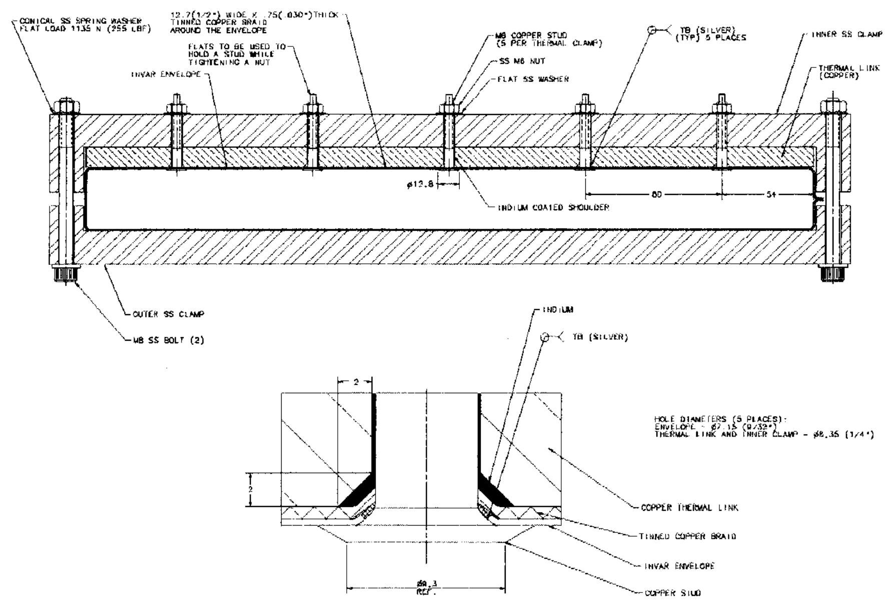

Figure 16. Design sketch of the improvement to the thermal link to envelope connection. This design idea is under test and evaluation at this time.

Acknowledgements

James E. Fagan (team leader), Robert Kubinski, Rolando Flores, and Chris Tolian comprised the technical staff that assembled the cryostat and helped make the modifications necessary during the assembly and commissioning of the cryostat. Several hurdles were overcome through their ingenuity and hard work. Alan Bross (FNAL), Koji Yoshimura (KEK), Shigeru Ishimoto (KEK), Mike Sarychev (FNAL), and Richard Schmitt (FNAL) also gave valuable advice and assistance during the commissioning period. Koji Yoshimura (KEK) and Shigeru Ishimoto (KEK) took care of the detail part fabrications by the Jecctorisha cryogenic company in Japan. Jack Mateski (FNAL) was my designer drafter who made the fabrication drawings. Alan, Shigeru, Koji, and other members of the M.I.C.E. collaboration also gave insightful commentary during the design phase of the project. Finally we wish to thank Holger Witte for providing the stray field maps.

This work done by Universities Research Association Inc. under contract No. DE-AC02-76CH03000 with the United States Department of Energy.

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