SENSEI Technical Design Report Version 00

Michael B. Crisler, Greg Derylo, Javier Tiffenberg
Fermi National Accelerator Laboratory
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1.0 Introduction

SENSEI is a Direct Detection Dark Matter Search Experiment that will use ultra-low noise “Skipper” CCD sensors capable of detecting electron recoils induced by dark matter interactions. The current generation of dark matter search experiments focuses on the detection of nuclear recoils and will be sensitive to dark matter masses greater than ~1 GeV/c^2. Detection through electron recoils will allow for unprecedented sensitivity to a multitude of Hidden-Sector and Ultralight DM candidates with eV-to-GeV masses. The SENSEI acronym “**S**ub **E**lectron **N**oise **S**kipper-CCD **E**xperimental **I**nstrument” refers to the enabling Skipper CCD readout technology that allows for repeated oversampling of each pixel charge measurement, resulting in a noise figure of 0.06 electrons. It is this extraordinarily low charge noise that allows for the detection of electron recoils from dark matter.

The goal of the SENSEI experiment is to deploy CCD sensors adding up to a total silicon target mass of 100 grams in a low background deep underground site and to run for 1 year.

1.1 The Physics of SENSEI

Identifying the nature of dark matter is an urgent priority for particle physics. The current generation of direct detection experiments has focused on the detection of nuclear recoils induced by the elastic scattering of dark matter particles. The kinematics of dark matter scattering and the sensitivity of existing detector technologies has limited the reach of nuclear recoil based direct detection experiments to dark matter masses greater than ~1 GeV/ c^2 even for the lightest available target nuclei.

Direct detection experiments sensitive to recoiling electrons would provide an extraordinary new window into hidden sector and light dark matter candidates with eV to GeV masses, but such experiments have not been possible up to now owing to the exceptionally small signals produced by dark matter particles scattering on electrons. Such interactions result in ~eV level deposited energy and in the liberation of very small numbers of individual electrons.

The SENSEI collaboration has developed a new sensor, the “skipper” CCD, which is able to make thousands of repeated lossless measurements of the charge on each individual CCD pixel. The resulting signal averaging results in sub-electron noise levels ~0.06 electrons per pixel. This extraordinary noise level, coupled with the extremely low dark current in silicon, allows for meaningful physics sensitivity for signals as small as a single electron. The skipper CCD is the empowering technology that allows us to propose the development of SENSEI, the “**S**ub **E**lectron **N**oise **S**kipper-CCD **E**xperimental **I**nstrument” to search for dark matter interactions with electrons. The goal of the SENSEI experiment is to deploy CCD sensors adding up to a total silicon target mass of 100 grams in a low background deep underground site and to run for 1 year.

Details of the theoretical foundations of Dark Matter – electron scattering, demonstrations of the technical capability of the SENSEI Skipper-CCD sensors, and physics results to date are included in the references below:

1) *Theoretical Foundation of dark matter/electron scattering*: Direct Detection of sub-GEV Dark Matter, R. Essig et al., Phys. Rev. D85, 076007.
2) *Demonstration of Skipper CCD resolution*: Single-Electron and Single-Photon sensitivity with a Silicon Skipper CCD, Javier Tiffenberg et al., PRL **119**, 131802 (2017).
3) *Physics Results from Surface Sensor Tests*: SENSEI: First Direct-Detection Constraints on Sub-GeV Dark Matter, M. Crisler et al., PRL **121**, 061803 (2018)
4) *Physics Results from Sensor Tests Underground*: SENSEI: Direct-Detection Constraints on Sub-GeV Dark Matter from a Shallow Underground Run Using a Prototype Skipper CCD, Orr Abramoff et al., Phys. Rev. Lett. **122**, 161801 (2019)

The basic unit of the sensei experiment is a CCD sensor, laminated to a pitch-adapter board that is in turn laminated to a copper-on-Kapton flex cable that carries signal and control lines to external electronics. The goal of SENSEI is to construct an array of 48 skipper CCD sensors with a total active target mass of 100 grams of silicon. In this Technical Design Report, we provide the details of the mechanical design of the components that will support the sensors and keep the electrically and thermally isolated, cooled to the appropriate operating temperature, and shielded from radiation.

Additionally, details are provided for the auxiliary experimental infrastructure including shielding, cabling and readout electronics, chiller and thermal control system, and vacuum system.

2.0 SKIPPER CCD SENSORS

This chapter introduces the Skipper CCD technology and briefly presents the working principle and capabilities of the sensors.

3.1 Skipper CCD

The readout noise of previous silicon CCD detectors was about 2e − , requiring a threshold of Q ≥ 11e − (E r ≥ 40 eV). Instead, the Skipper CCDs have a readout noise of 0.068e − , allowing a precise and accurate measurement of the charge in each pixel, See Figure 2.1.1.

The readout stage of the Skipper CCD has a small-capacitance sense node and it’s isolated from parasitic noise sources in order to perform multiple, independent, non-destructive measurements of the charge in a single pixel. urate single-electron measurement in a large-format (4126 × 866 pix) silicon detector. The low readout noise achieved by Skipper CCDs, coupled with a stable linear gain, allows charge measurement at the accuracy of individual electrons simultaneously in pixels with single electrons and thousands of electrons. This makes the Skipper CCD the most sensitive and robust electromagnetic calorimeter that can operate at temperatures above that of liquid nitrogen. Because non-destructive readout is achieved without any major modifications to the CCD fabrication process, this new technology can be immediately implemented in existing CCD manufacturing facilities at low cost.

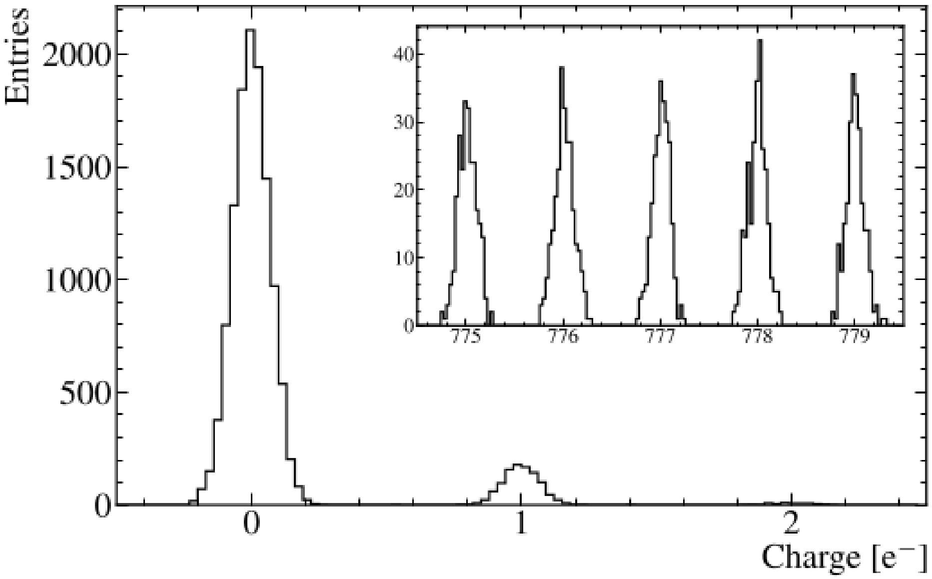


Figure 2.1.1: Single-electron charge resolution using a Skipper CCD.

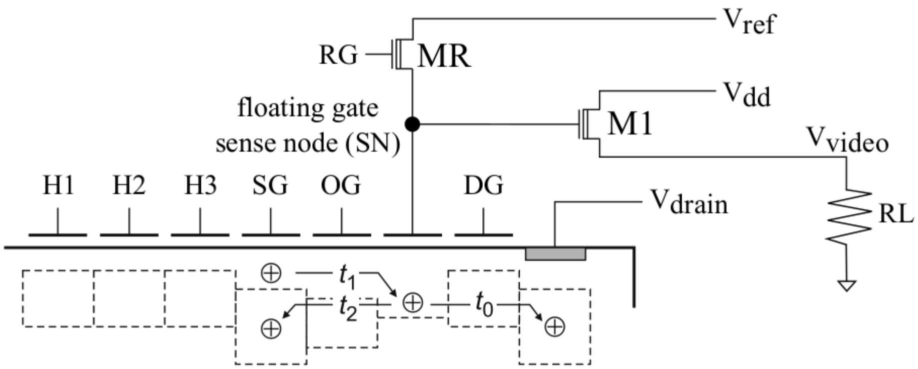


Figure 2.1.2: Schematic of the Skipper CCD output stage.

A schematic of the Skipper CCD output stage is shown in Figure 2.1.2 At t0 , all charge is drained from the sense node (SN) to V drain by applying a pulse to the dump gate (DG), and the SN voltage is restored to V ref with a pulse to the reset gate (RG). At t1 , raising the summing-well gate (SG) phase transfers the charge packet to the SN, concluding the readout of the first sample. To take the second sample, the output gate (OG) and SG phase are lowered at t2 , moving the charge packet in the SN back under the SG phase. A pulse to the RG restores the SN reference voltage. This cycle is repeated to remeasure the same charge packet.

2.2 Skipper CCD sensors used in the SENSEI experiment

The Skipper CCD sensors used in the SENSEI experiment are fabricated using Ultra High Resistivity silicon. In contrast with Skipper CCD sensors used for imaging applications, SENSEI sensors are not thinned and do not have any antireflecting coating that may be a source of radioactive contamination.
All the sensors needed for the construction of the experiment have been fabricated and are currently at Fermilab. Figure 2.2.1 shows an storage box with a diced silicon wafer.

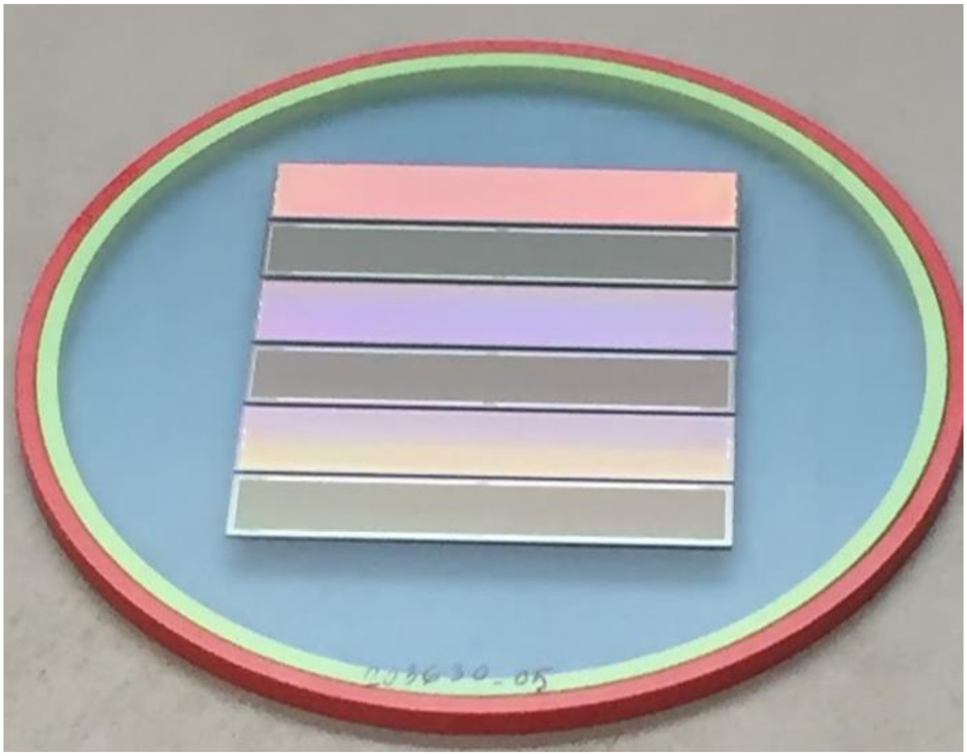


Figure 2.1.2: SENSEI sensors before packaging.

3.0 SENSOR MODULE

This chapter presents the layout of the sensor module, which is a term referring to an integrated assembly that that mechanically and thermally supports a CCD sensor (described in Section 2) and provides an electrical interface to the data acquisition system. As described below, a set of four CCD modules is then grouped into a single mechanical assembly that comprises what is referred to as a supermodule.

3.1 Pitch Adapter

In the module, it is important to support the sensor in a way that provides mechanical support without stressing the sensor, provides a thermal contact to allow for operation at the operating temperature, utilizes materials with similar thermal expansion characteristics to the sensor in order to minimize stresses resulting from thermal cooldown, and facilitates an electrical connection to the sensor's wirebond pads. These goals are achieved with the use of a "pitch adapter", which is a piece of silicon upon which is printed a one-layer electrical circuit in a thin layer of aluminum. Pads on the pitch adapter are wirebonded to the CCD sensor and to pads on the Kapton flex cable, thus allowing an electrical interface between the sensor and the readout system. A photo of a pitch adapter is shown in Figure 3.1.1, with CCD wirebond pads along the long edges and the flex cable bondpads shown towards the right. The extreme right end of the pitch adapter has no electrical traces on it, as this area will have the flex cable laminated to it.

Figure 3.1.1: Pitch adapter

The layout of the pitch adapter relative to the CCD is shown in Figure 3.1.2. The pitch adapter is slightly narrower than the sensor, thus allowing the exposed CCD wirebond pads along its long edges to protrude out from underneath the pitch adapter. An automatic wirebonding machine can then be used to electrically connect the exposed CCD pads to their corresponding pads on the top surface of the pitch adapter. The pitch adapter is also longer than the CCD sensor itself. This allows supporting the module by the pitch adapter to prevent the need to directly contact the CCD itself and also provides real estate for the interface with the readout cable. Epoxied onto the surface of the pitch adapter are two small blank pieces of silicon. These allow the module to be held in the supermodule frame described below without having the electrically-conducting copper frame directly contact the fragile electrical circuitry printed on the surface of the pitch adapter. By using silicon material for these spacers and for the pitch adapter itself, thermal distortion stresses that could be transmitted into the sensor are minimized.

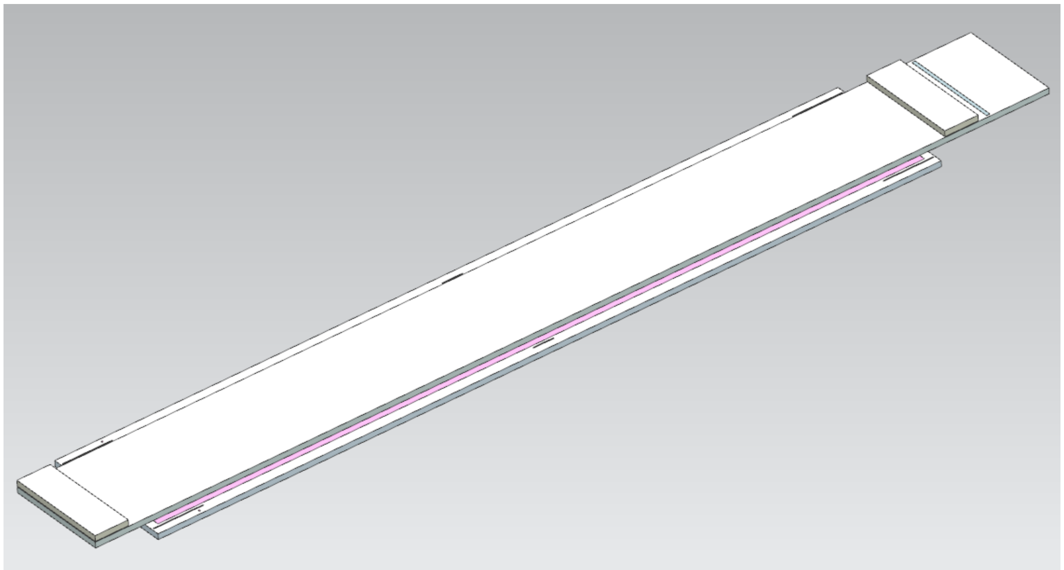


Figure 3.1.2: Pitch adapter with its two spacers positioned on top of CCD sensor

3.2 Flex Cable and Connector

The flex cable connects the pitch adapter to the readout system via a connector at its far end. The cable is long (about 2 feet) in order to route through the internal shielding within the vessel (see Section 6). The end of the cable is laminated to the pitch adapter using a film adhesive, as described in Section 3.3. The cable has a window in its bottom surface that allows its ground mesh to be clamped directly against the copper of the supermodule frame when the cable is sandwiched between the frame top & bottom plates. This direct contact aids to more directly thermally short the cable to the supermodule frame, this minimizing the heat that is conducted through the cable to the pitch adapter and CCD module. An electrical break in the cable's ground mesh allows the supermodule frame to be in good thermal contact with the cable while electrical isolation of the ground plane is still preserved.

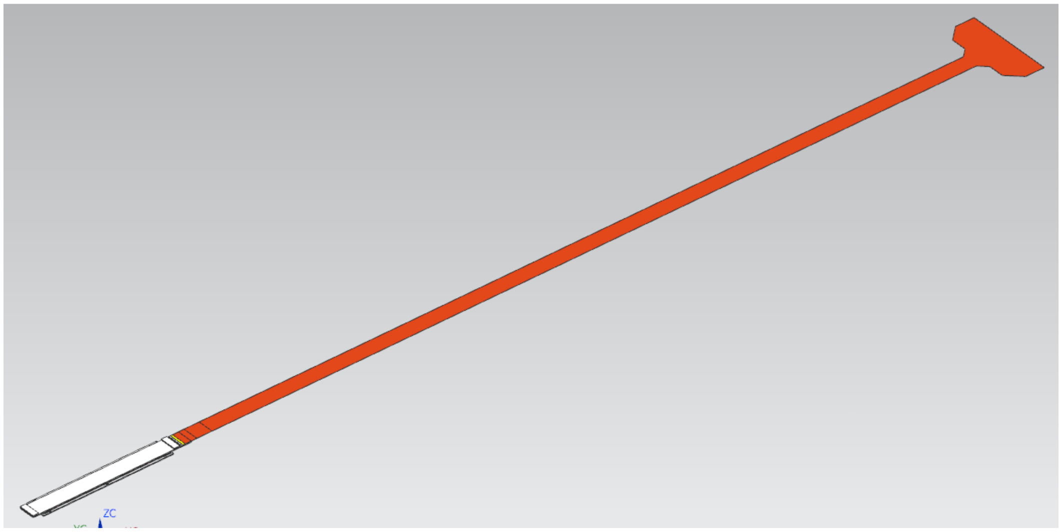


Figure 3.1.2: Module cable

3.3 Sensor Assembly and Fixturing

It takes several steps to assemble a module, as outlined below. A written procedure is used define the steps for the technician performing the work.

1. Epoxy silicon spacers to the pitch adapter – A simple guide (Figure 3.3.1) is used to help position the spacers on top of the pitch adapter. The epoxy used is Epotek 301-2.

2. Laminate the flex cable to the pitch adapter – A simple fixture (Figure 3.3.2) is used to hold the pitch adapter in place while the flex cable is positioned. This positioning is aided with the help of tabs with precision holes in them that are built into the cable. These tabs are used only during module construction and are simply cut off with scissors when module fabrication is complete. The Pyralux-LF film adhesive is held in place, sandwiched between the pitch adapter and flex cable with a clamp that applies pressure while the assembly is cooked in an oven to cure the adhesive.

3. Wirebond the cable to the pitch adapter – After lamination, the fixture is transferred to the wirebonding machine where the bonds are added between the cable and the pitch adapter.

4. Epoxy the CCD to the pitch adapter – This step is achieved by holding the pitch adapter with vacuum to a top plate and the CCD to a bottom plate, and mating the plates together with precision spacers to set a small gap between them that is then filled with the very-low-viscosity Epotek 301-2 epoxy, which wicks into the gap via capillary action. The top and bottom plate are shown in Figure 3.3.3.

5. Wirebond the CCD to the pitch adapter – After the CCD epoxy has cured, the top plate vacuum is released and the plate removed. The bottom plate is then transferred to the wirebonding machine where the bonds are added between the CCD and the pitch adapter.

6. Transfer the module into a storage case for testing – A simplified copper storage frame is used to house a single module during the module's electrical testing. This storage frame is based on the design of the supermodule (Section 3.4) and provides the necessary mechanical support and thermal interface.

During module fabrication, a module Traveler is used to document the assembly steps, keep track of individual part serials numbers, and record any irregularities in the assembly process. After assembly, these Travelers will be scanned and archived in the project's Fermilab-based document database.

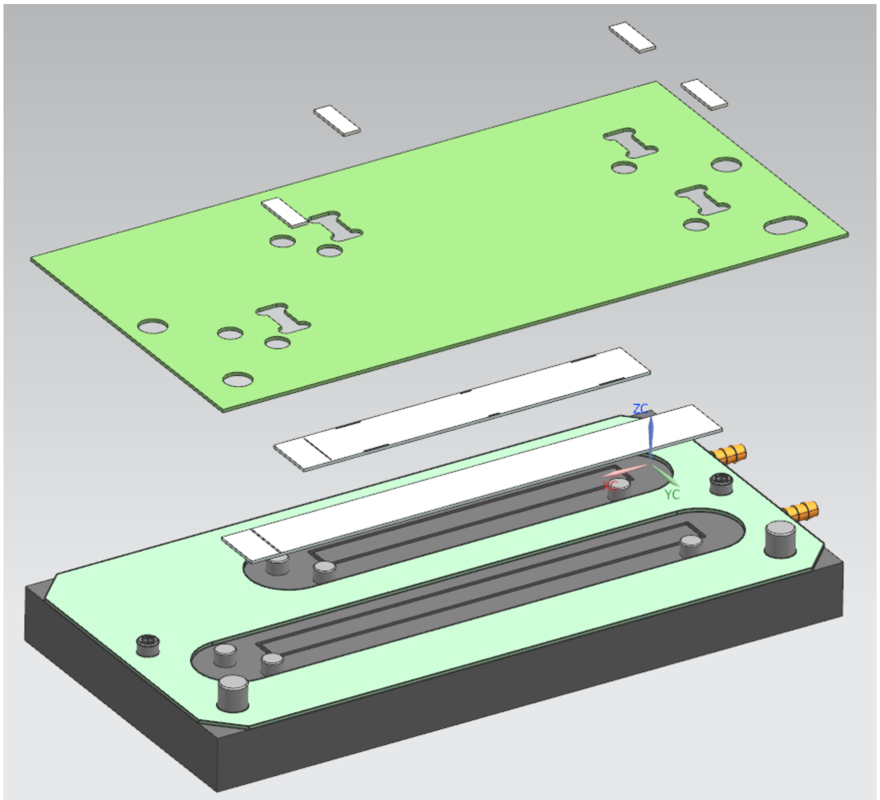


Figure 3.3.1: Fixture for positioning silicon spacers on top of pitch adapters

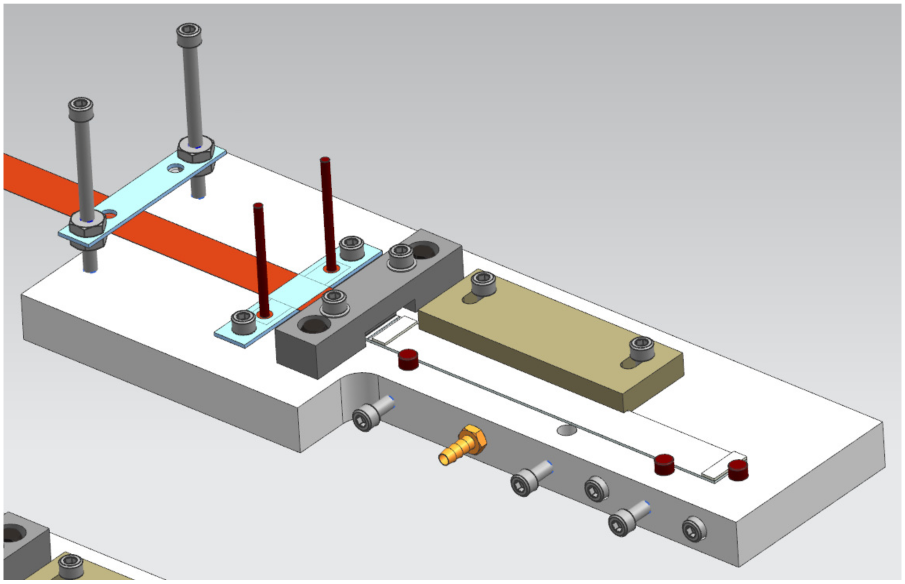


Figure 3.3.2: Fixture for flex cable lamination to the pitch adapter

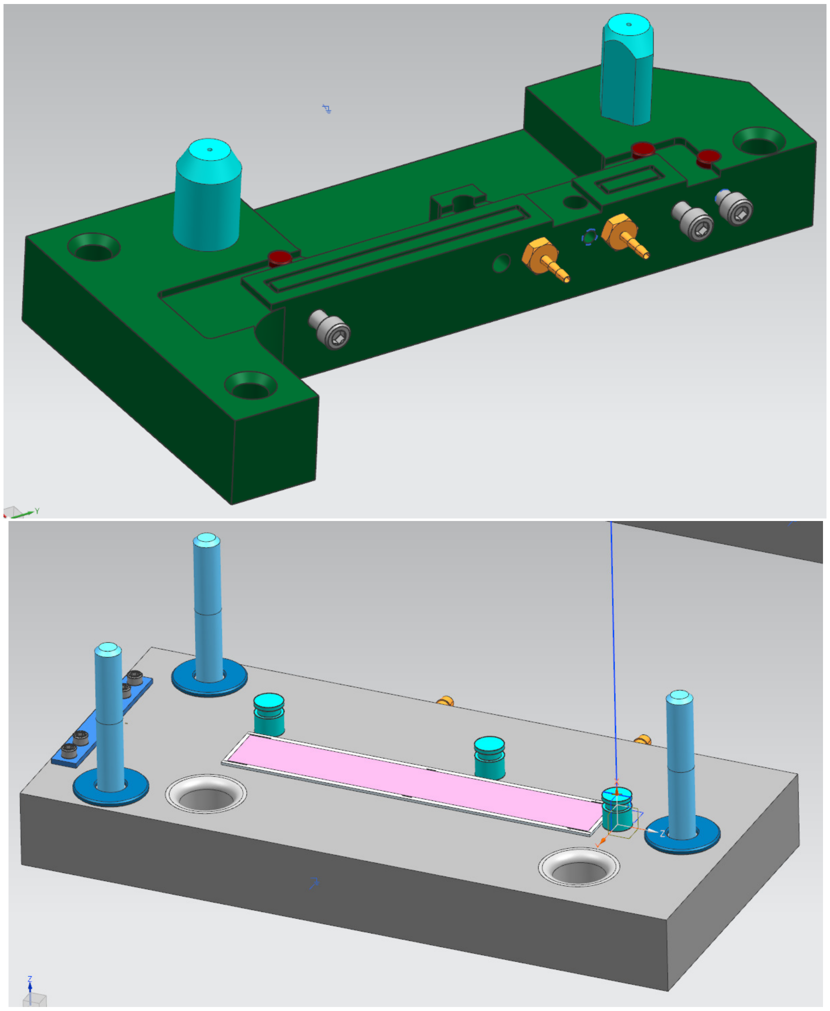


Figure 3.3.3: CCD gluing fixture top & bottom plates

3.4 Sensor Supermodule

The CCD modules described above must be housed in a frame that allows for physical handling, mechanical mounting in the detector, thermal connection with path to the cryocooler, and strain relief of the cables. This task is achieved with a copper frame assembly that houses four CCD modules and is referred to as a supermodule. The supermodule layout is shown in Figures 3.4.1 through 3.4.3 and has a copper base plate, copper top plate, four CCD modules, and the stainless-steel screws and lock washers to fasten the top plate to the base plate. The copper to be used is C101 OFHC.

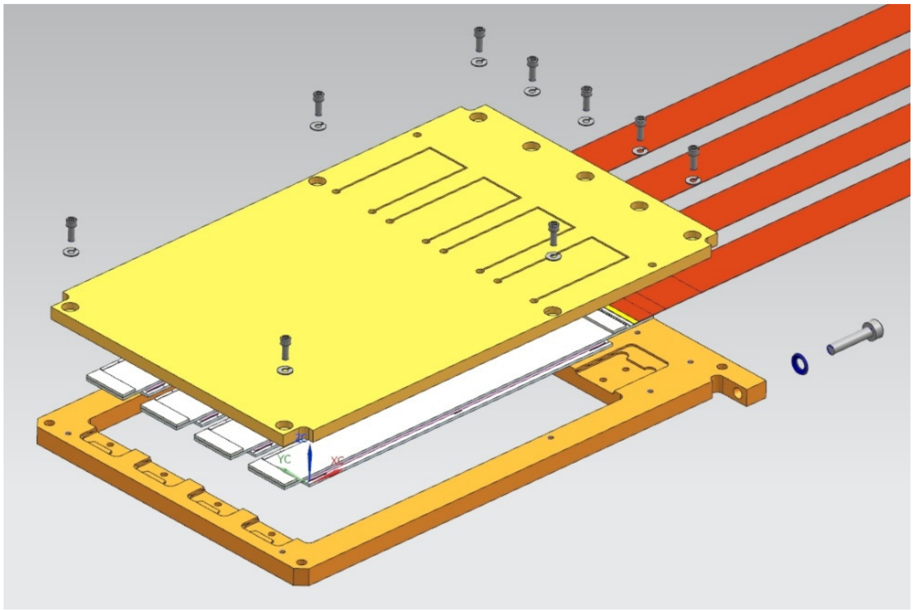


Figure 3.4.1: Supermodule layout exploded top view

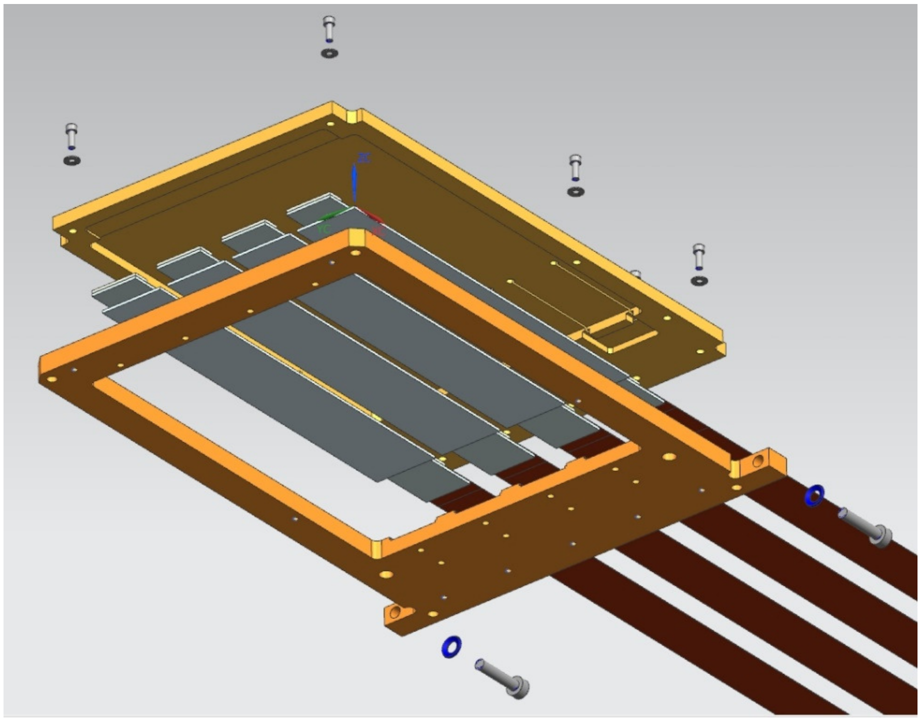


Figure 3.4.2: Supermodule layout exploded bottom view

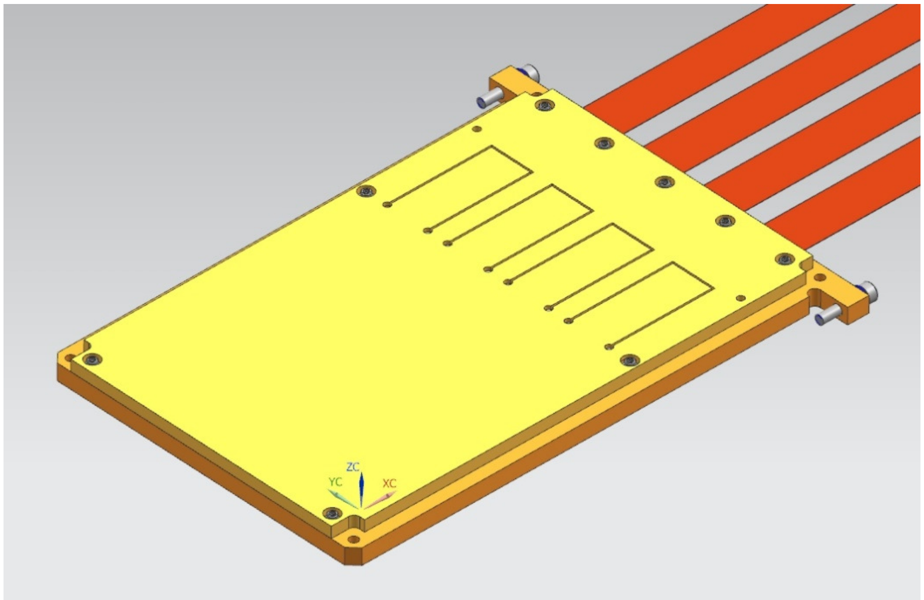


Figure 3.4.3: Supermodule layout assembled view

An important aspect of the supermodule design is the thermal grounding of the CCD module in a way that provides an effective thermal connection to the CCD without stressing the sensor, taking up excess space, or introducing additional material types into the design. This is achieved with use of thin leaf spring sections cut into the copper top plate itself, so no additional materials are added for this function. The end of each spring presses on the small blank silicon spacer glued to the top of the pitch adapter. This then presses the underside of the pitch adapter against the supermodule copper base plate in order to provide thermal contact. Across the width of the supermodule, the difference between deflections for each module as a result of large-scale top plate deformation is found to be small, as shown in Figure 3.4.4.

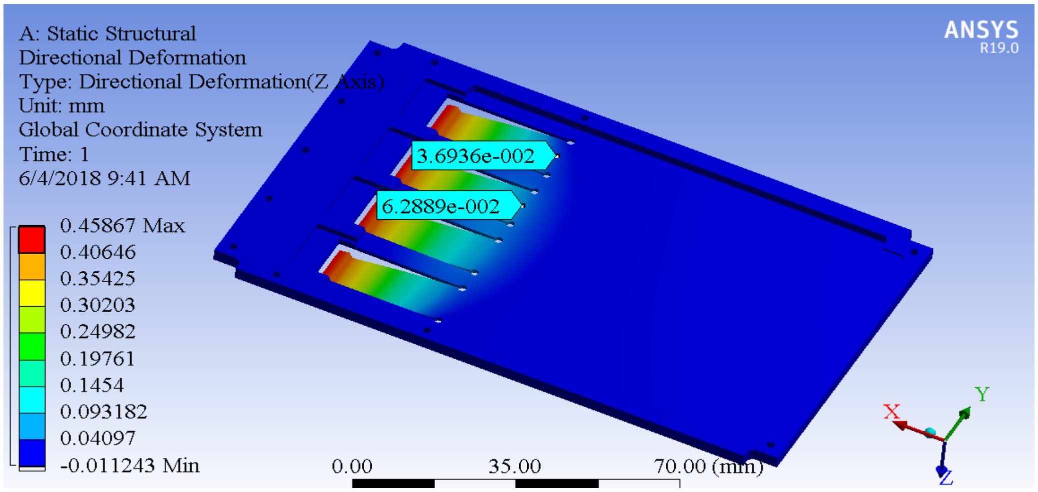


Figure 3.4.4: FEA of top copper plate showing uniformity of deflection across supermodule width

It should be noted that the CCDs are to be shipped from FNAL to SNOLAB as individual supermodules, not as part of the support box or vacuum vessel assemblies. During supermodule handling and shipping, the supermodule is mounted on a temporary bottom plate (Figure 3.4.5) since the supermodule otherwise has exposed CCDs visible from underneath.

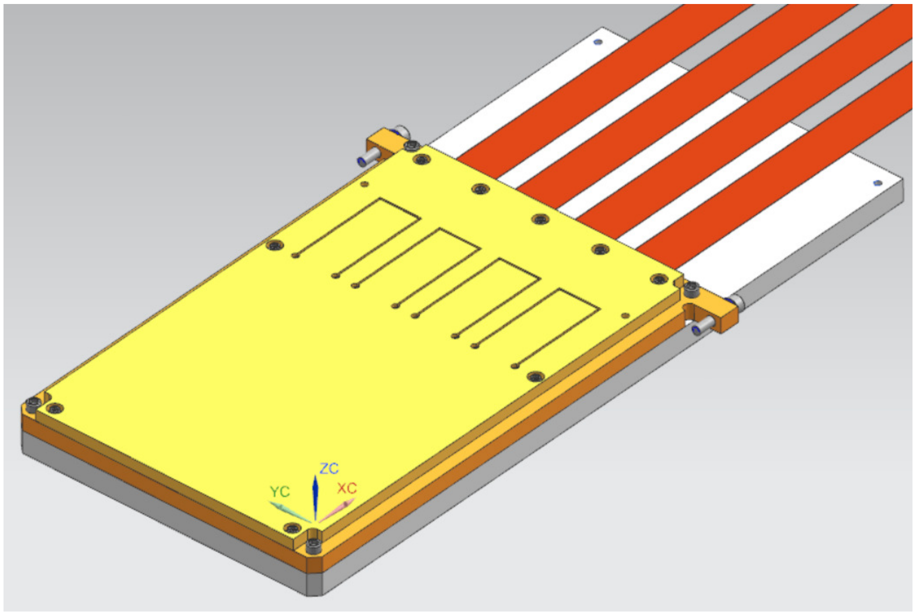


Figure 3.4.5: Supermodule with temporary bottom cover plate

4.0 SENSOR READOUT

This chapter introduces the Low Threshold Acquisition board developed for the SENSEI experiment. The SENSEI detector will use an array of these boards as DAQ and control system for the Skipper CCD sensors.

4.1 Low Threshold Acquisition board (LTA electronics)

Figure 4.1.1 shows a general block diagram of a CCD readout electronics. The charge of each pixel is transferred to the sense node (SN) for its measurement. C_{SN} models the capacitance of the sense node, and includes the parasitic capacitances of the transistors MR and M1. C_{SN} is of the order of ≈0.05pF , and hence is possible to achieve a sensitivity of ≈2μV /e −.

MR and M1 are PMOS transistor integrated in the CCD. M1 is in a source follower configuration used to sense the voltage of C_{SN} . In figure 1 there is a cartoon of the output signal every time that a pixel is read, called "video signal". The pixel charge is obtained from the difference between the signal level and the reset level. This method is called "Correlated Double Sampling (CDS)".

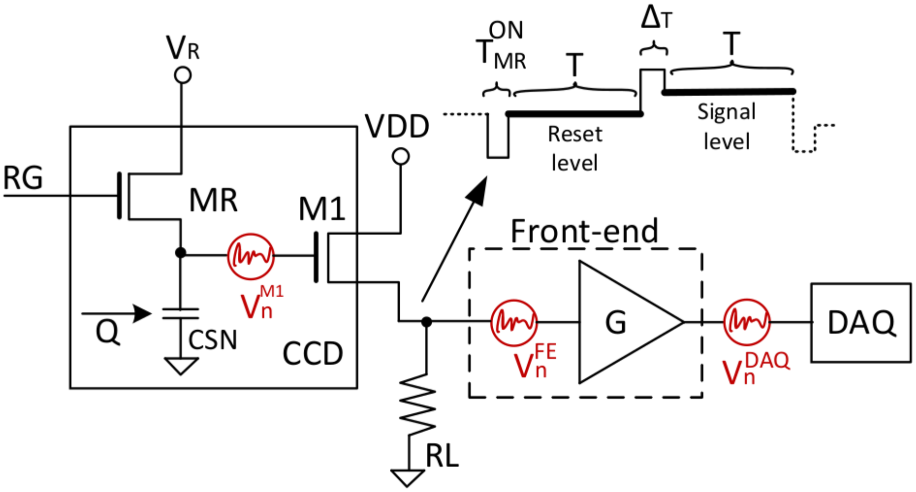


Figure 4.1.1: Block diagram of a CCD readout electronics.

Figure 4.1.2 is a block diagram of the LTA board. It was designed to fully digitize up to four video signals, and digital processing techniques can be applied in the FPGA Artix-7. The high and low level of all of the clock signals needed to control the CCD are provided by a digital to analog converter (AD5371), and the FPGA switch between this two values following the proper timing sequence. All the components are supplied from switching mode power supply, the switching frequency is over 1MHz to avoid its interference into the video signal bandwidth. All the communication with the board is made by a Ethernet interface. Figure 4.1.3 shows an LTA board being used at a prototype system currently running in the MINOS cavern at Fermilab.

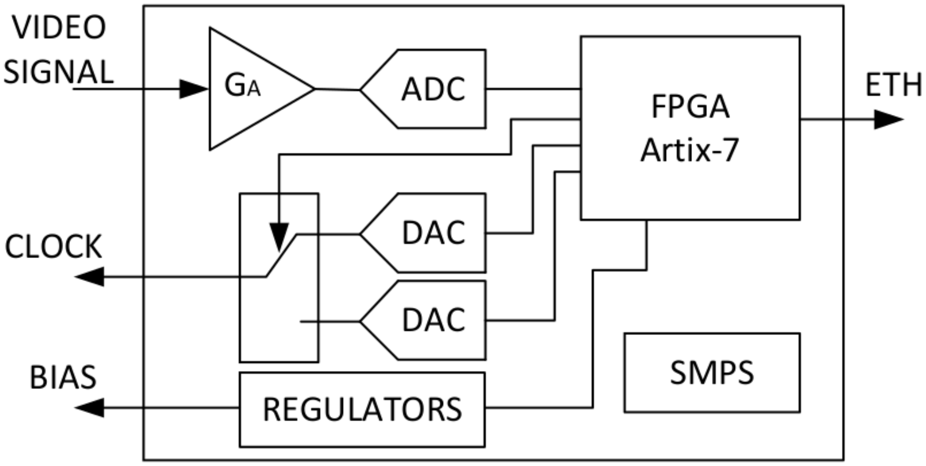


Figure 4.1.2: Block diagram of the readout system.

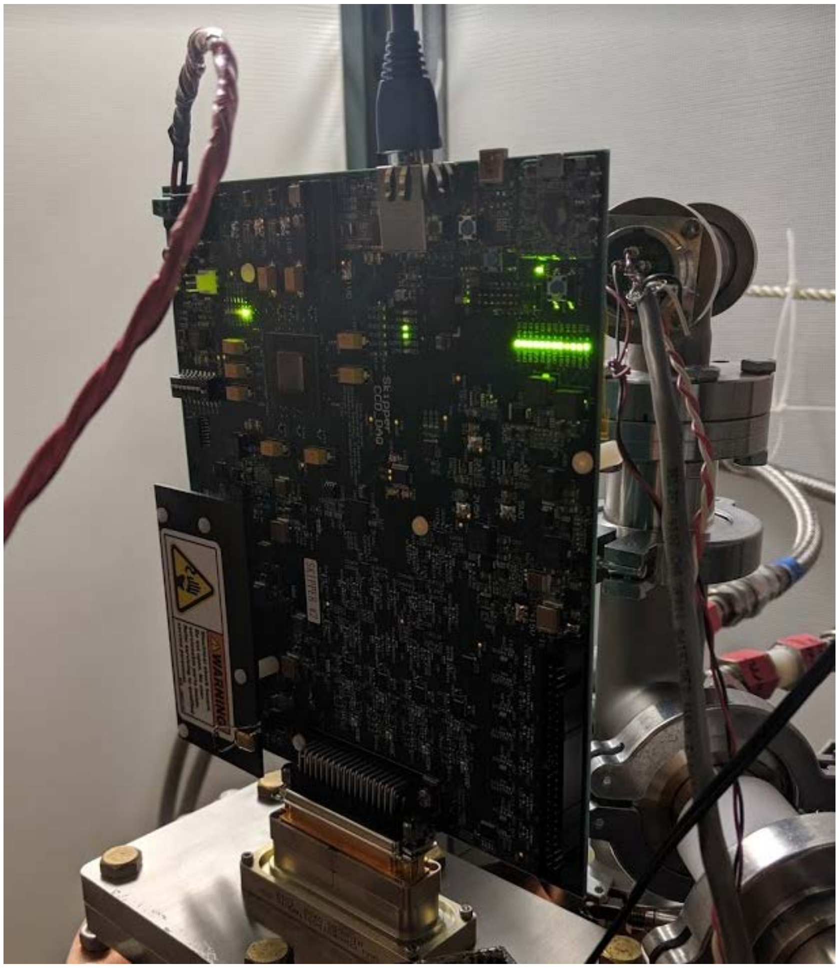


Figure 4.1.3: LTA board in operation

5.0 SENSOR MODULE SUPPORT BOX

This chapter presents the section of the detector design that provides a mechanical and thermal housing for the CCD supermodules. All the hardware described here is located inside the vacuum vessel, and additional copper shielding is included where possible, as described below.

5.1 Support Box

Similar to the configuration successfully utilized in the previous DAMIC and CONNIE CCD experiments, the supermodules will be inserted into sets of slots in a copper box, as shown in Figure 5.1.1, and the supermodule's wings are then fastened against the box's side plates. The support box is fabricated from electropolished C101 OFHC copper and assembled with stainless steel fasteners. Alternating supermodules in the stack will be flipped such that the exposed CCD sensors in neighboring modules will be facing each other with no intervening copper between them. This will also act to divide the cables into two equal groups, with half of the cables exiting each side of the box.

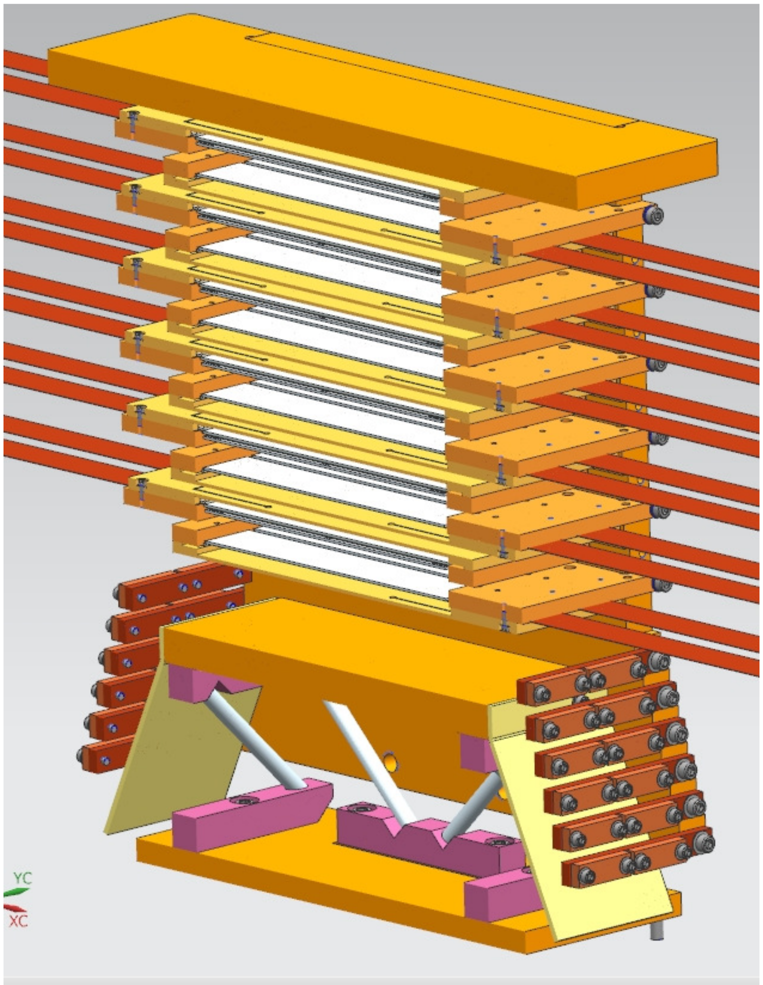


Figure 5.1.1 Support box cross section view

The cables are then clamped to bars attached to the box side plates in order to help intercept heat being conducted from the warm end of the cable to the colder sensor end. A thin copper end cap then covers the open end of the box to cover the cables and provide a thermal radiation barrier to the inside of the box, as shown in Figure 5.1.2.

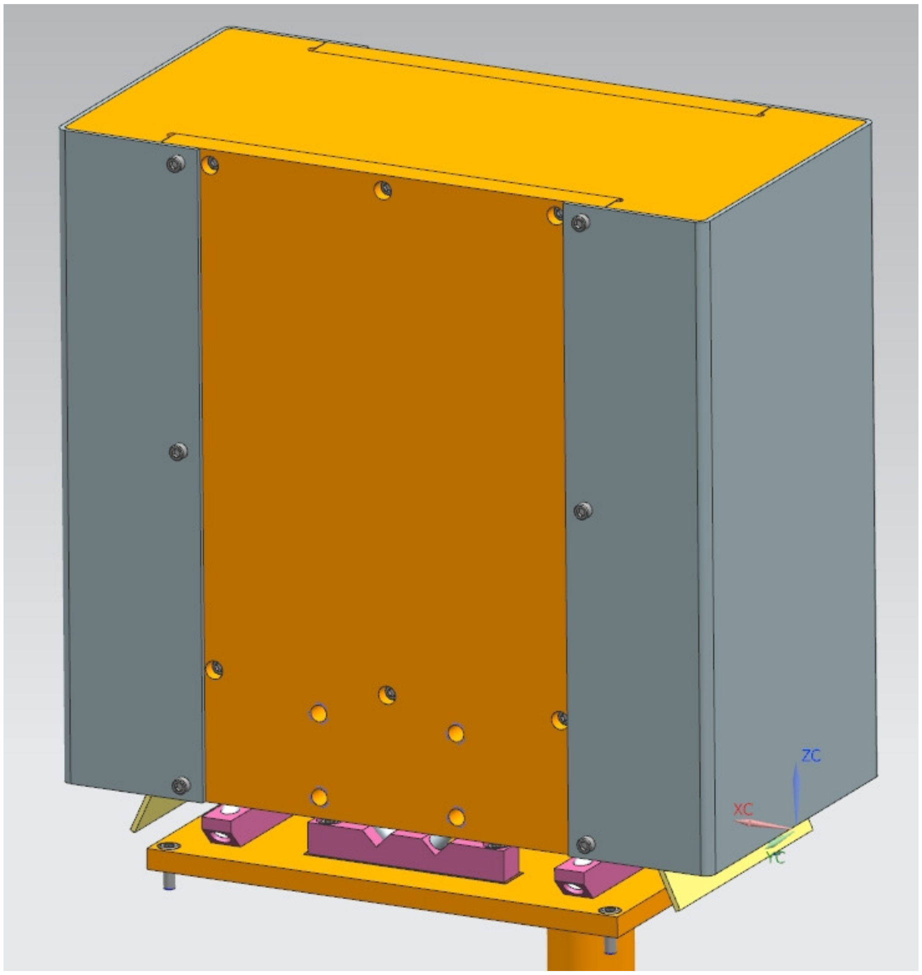


Figure 5.1.2: Support box with copper end caps

An additional thermal radiation shield is used to provide additional isolation between the support box and the surrounding, warmer environment. This shield is constructed from thin copper sheets fastened to reinforcing blocks that run along each edge of the shield (Figure 5.1.3). The joints will be both screwed and epoxied together for effective thermal joining and the shield will be isolated from the support box itself with thin-walled polyetheretherkeytone (PEEK) standoffs to maximize isolation. A copper strap will thermally ground the shield to the coldfinger mount block in order to thermally intercept the heat radiated from the surrounding warm surfaces and direct it to the coldfinger.

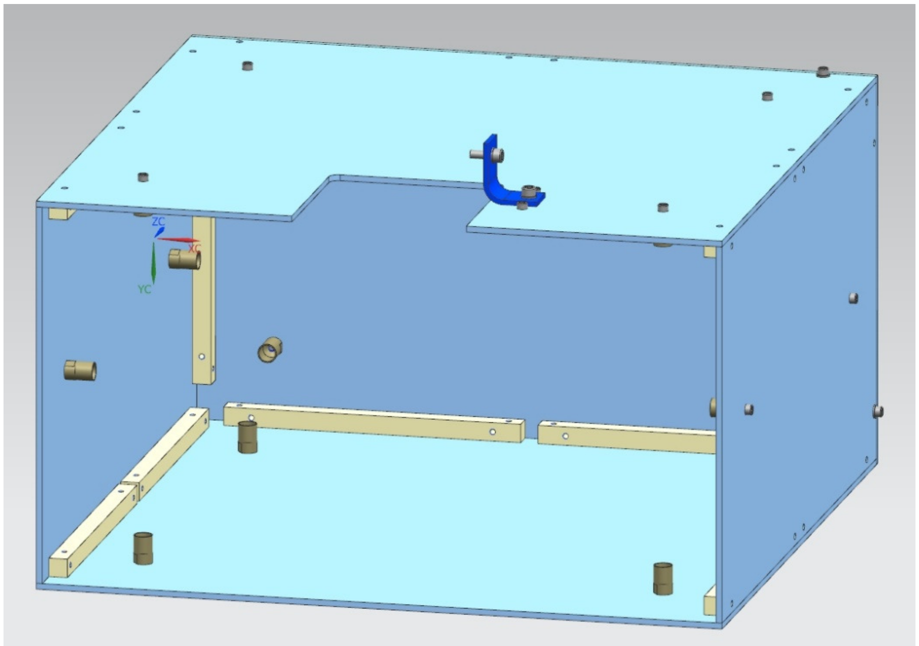


Figure 5.1.3: Support box thermal shield

The support box itself is thermally isolated from the hardware to which it mounts by use of relatively long supports made from low-conductivity stainless steel tubes with low cross-sectional area. These tubes are glued in pairs, and four sets of them are used for mounting of the coldbox, as shown in Figure 5.1.4. In addition to providing thermal isolation, use of a Kapton shim and nylon screw washers/sleeves also act to provide electrical isolation.

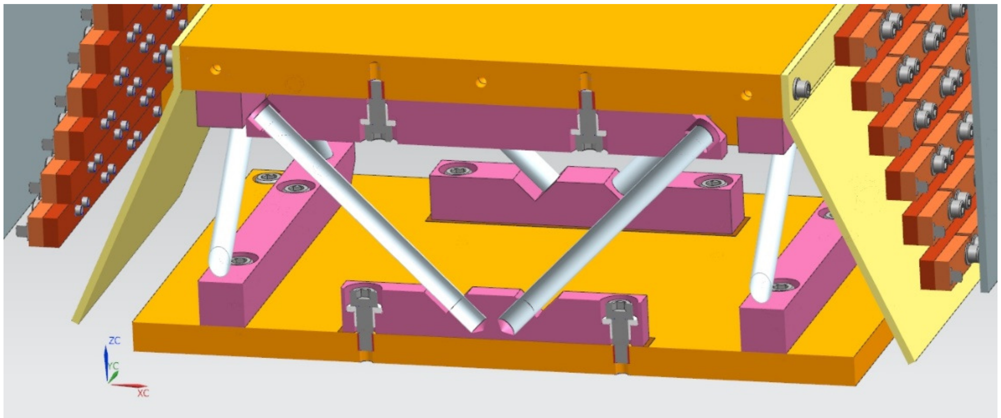


Figure 5.1.4: Support box thermal isolator mounts

In order to access the supermodules in the support box, it is necessary to remove several pieces of the support box. First, the support box thermal shield must have its copper grounding strap removed from the support box coldfinger mounting block. Then the shield can be lifted off the support box. One of both of box's end caps must then be removed, depending on the number of supermodule mounting slots it is necessary to access. The cable thermal intercept clamps must then be opened to allow access to that supermodule's cables. After working to install/remove the supermodule(s) in question, the process is revered to reassemble all the support box parts.

5.2 Coldfinger

A copper rod is used to thermally connect the support box to the cryocooler, as shown in Figure 5.2.1. At the upper end, this rod is welded into a block for optimal thermal contact. This block mounts to the side of the support box in a way that sandwiches a thin, 0.001"-thick Kapton film. Combined with the use of nylon isolators on each of the fasteners, this provides an electrical isolation for the support box desirable for detector grounding purposes.

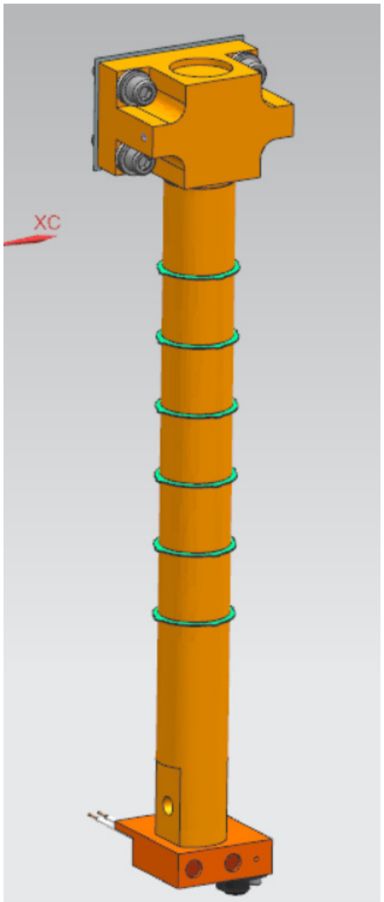


Figure 5.2.1: Support box coldfinger

At the lower end of the coldfinger there is a connection for a thermal strap that will thermally connect the coldfinger to the cryocooler. At this end of the coldfinger is also a heater block assembly that houses an RTD, electrical heater, and high-temperature safety cut-off. This block acts as the temperature controller for the support box by actively controlling heater power in response to the RTD measurements. The safety cut-off opens the electric heater circuit if the temperature were to rise above +65°C. Although desirable to control temperature as close to the point of interest as possible, the heater block here is located away from the support box, below the internal radiation shield, to prevent the introduction of additional materials near the sensors. This same approach was also utilized in the DAMIC experiment, and during initial system commissioning additional temporary RTDs will be used to help characterize the system performance.

Along the length of the coldfinger, thin G10 snap-rings are installed in place to ensure that there is no physical contact between the coldfinger and the copper shield through which it passes. These G10 rings have a profile that minimizes contact radially, have a long path length between contact points, and are made from thin material all in order to maximize their thermal resistance.

The cold mass of the copper, between the supermodules, support box, and coldfinger, is approximately 41 pounds. For an assumed 30W cooldown, reducing the temperature to 170K should take about 10 hours.

5.3 Internal Shield

Additional copper is used inside the vacuum to shield the support box from the surrounding environment. Underneath the support box, the copper shield is comprised of 6 one-inch-thick disks (see Figure 5.3.1) that help isolate the box from the rest of the vacuum vessel material. These plates have several features to note. First, there are two channels used to route the CCD module cables down from the support box to the connections in the lower volume of the vessel. Once the cables are in place, an additional piece of copper is used to seal off these channels to improve the shielding effectiveness. Each cable cover weighs 13 pounds and has a threaded hole in its top so a screw can be installed for use as a temporary handle when there is need to access the supermodule cables. In addition, there is a hole through these shield plates to allow the coldfinger to pass from the support box down through the shield to the lower volume of the vacuum vessel, as described in Section 5.2. A pair of copper rods that run through grooves machined in each of the six shield plates act to align the orientation of each plate, which helps keep the coldfinger clearance holes in line with each other. It is intended that this set of 6 plates will be shipped separately from the vacuum vessel for ease of handling, but once installed it is not necessary to handle these plates again.

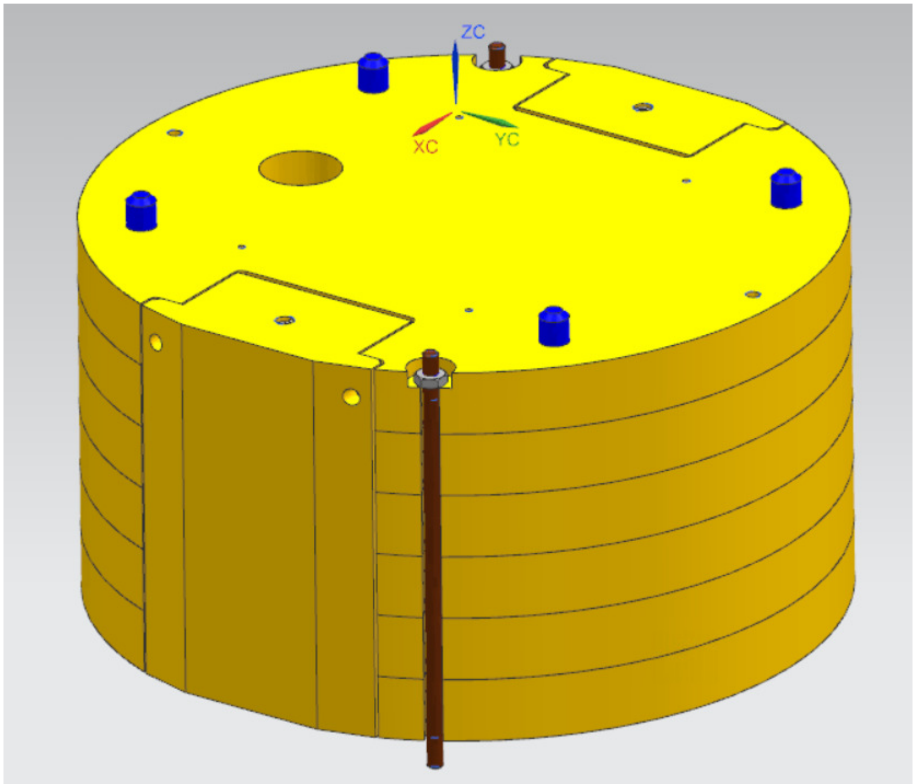


Figure 5.3.1: Copper shield underneath the module support box

The topmost one-inch plate is equipped with some plastic guide pins that are used to locate the upper side shields, which are shown in Figure 5.3.2. These copper plates fill some unused space inside the vessel but due to the available geometry they provide shielding in a non-uniform way, being several inches thick in some directions but providing no coverage at all in others. In order to provide stability, the tops of these two side blocks are tied together with a round top plate. The top plate center is removed to provide clearance for the support box. It is not possible, however, to open the support box to access the CCD modules while these upper sections of shield are in place since there are multiple fasteners than cannot be reached with this shield region in place. Therefore, these side plates and their upper round plate must each be removed every time the support box is to be accessed. Since the side plates weigh about 47 pounds each, installation is to be aided with the use of an overhead lifting device (SNOLAB RBK or equivalent), so threaded holes are added to allow a hoist ring to be temporarily installed in each block to aid handling.

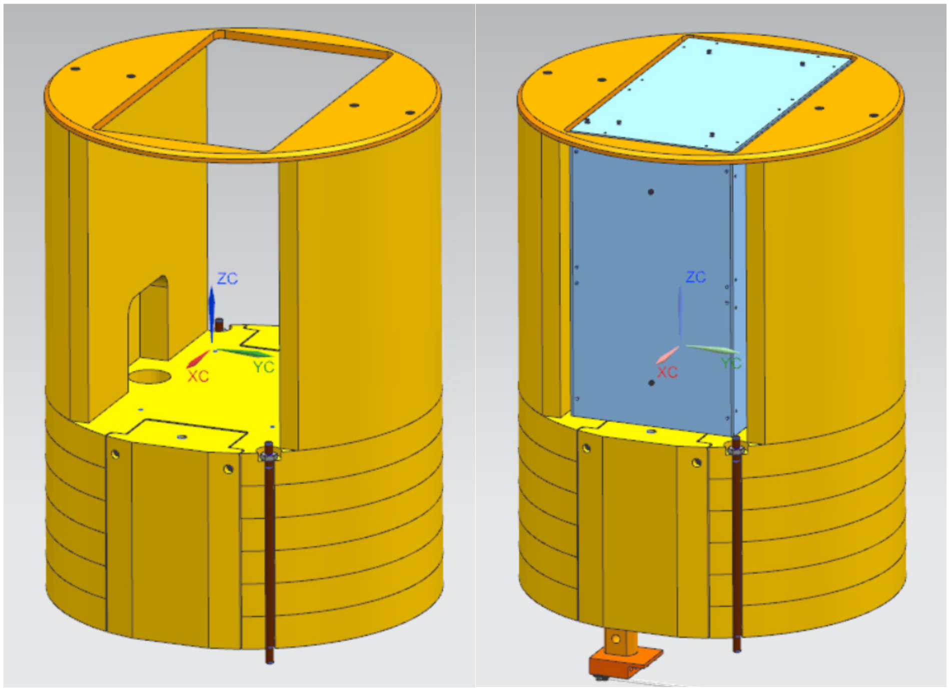


Figure 5.3.2: Copper shield surrounding the module support box

All this copper shielding will be at or near room temperature. As mentioned in Section 5.2, the coldfinger is equipped with standoffs to ensure thermal isolation between these regions. The thermal isolators on the support box (Section 5.1) limit the thermal coupling there. And the use of electropolished surfaces minimizes the thermal radiation transfer between neighboring parts.

The copper used for all this internal shielding is C101 OFHC.

6.0 VACUUM VESSEL

This chapter presents the design of the vacuum vessel that houses the Section 5 detector assembly and contains electrical and services feedthroughs that support the readout and operation of the detector. An overview of the layout is shown in Figure 6.0.1. The uppermost section contains the CCD module support box and is covered with a copper bell jar and additional external copper shielding. Underneath the internal copper portion of the vessel is a stainless-steel weldment which contains the electrical, cooling, and vacuum interfaces.

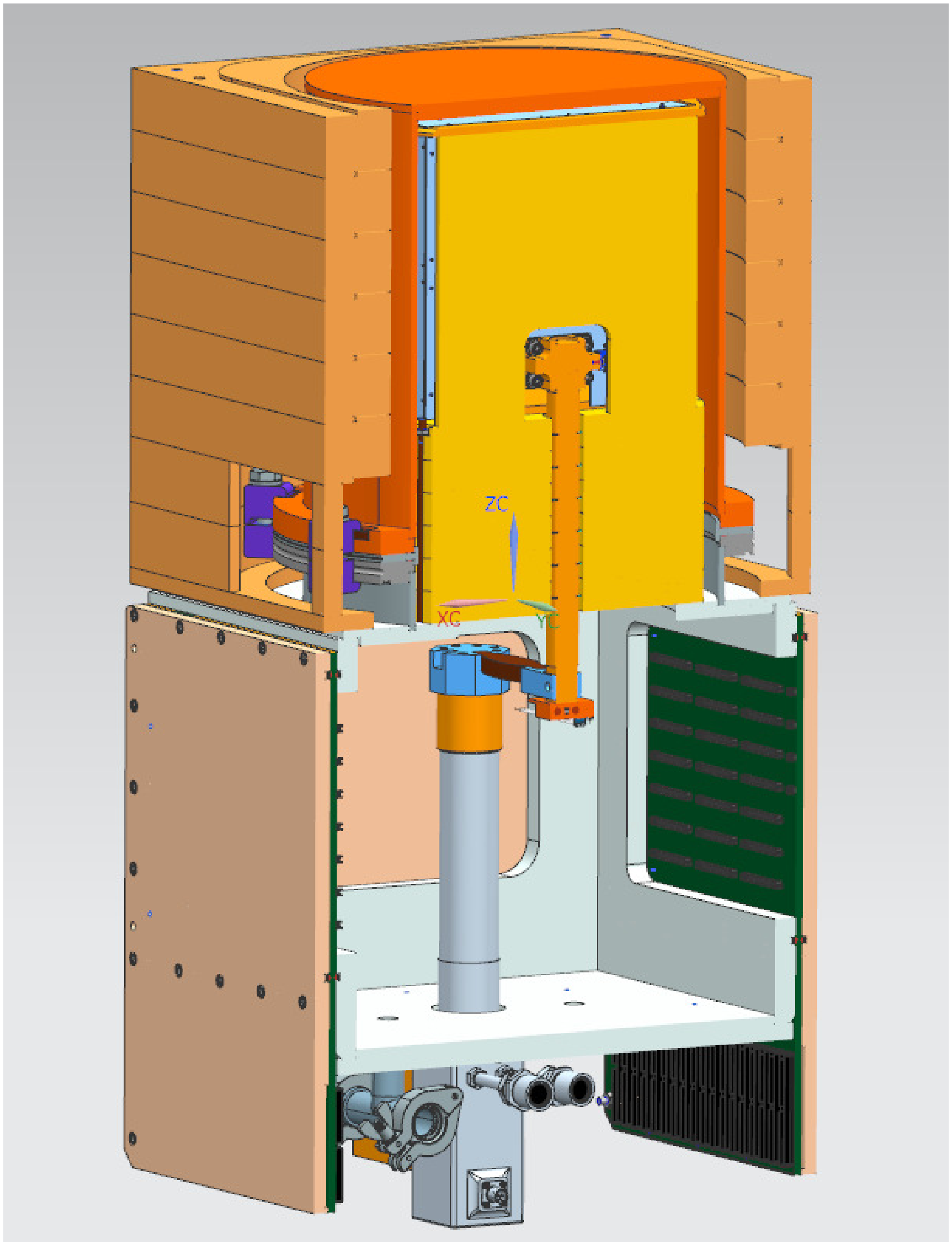


Figure 6.0.1: Overview of the vacuum vessel

6.1 Copper Bell Jar

In order to easily access the modules during supermodule installation or maintenance, the uppermost portion of the vacuum vessel was conceived of as a simple bell jar (Figure 6.1.1), fabricated from a copper weldment for radiopurity reasons. This bell jar is sealed using a standard NW320 O-ring assembly and modified vacuum flange claw clamps re-made with copper claw blocks. A finite element analysis of the bell jar with 19 psi of external pressure shows that the stress remains well below the 6 ksi allowable and that the deformation is small (Figure 6.1.2).

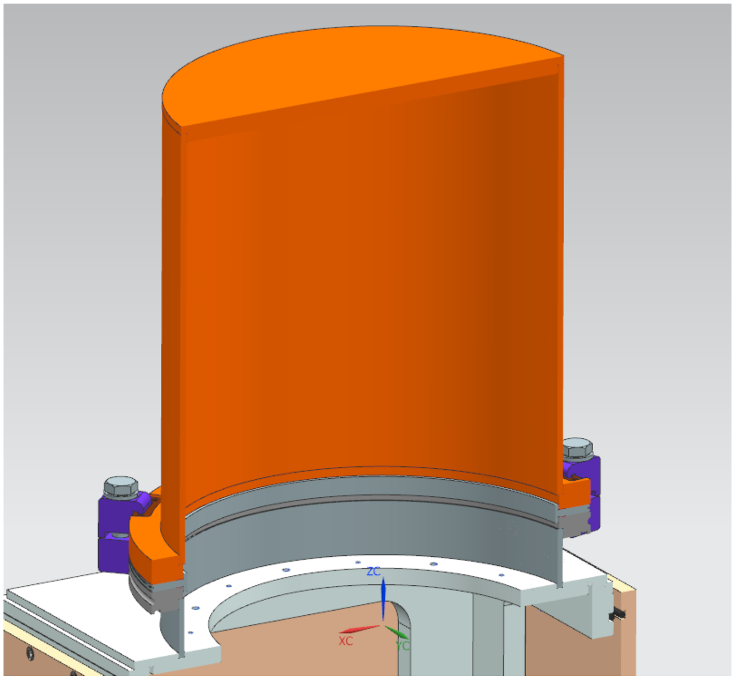


Figure 6.1.1: Overview of the vacuum vessel

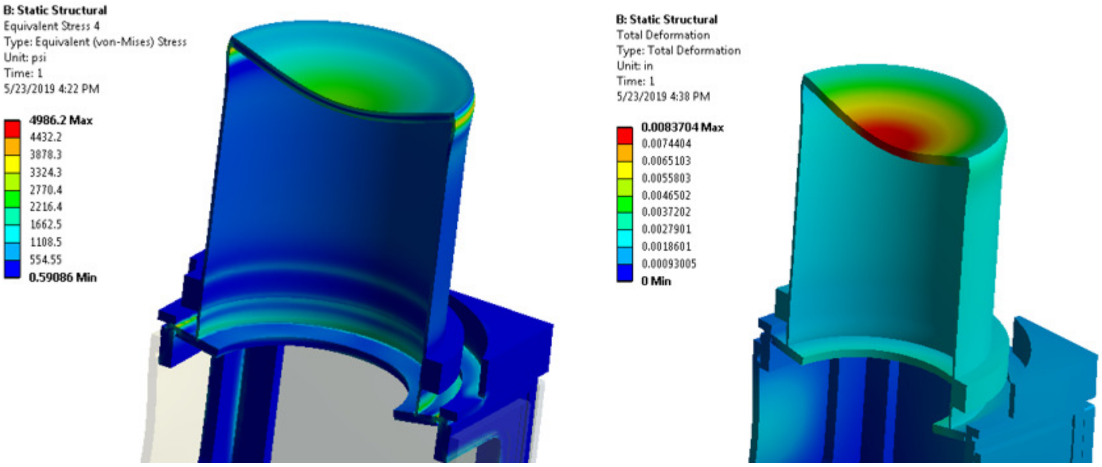


Figure 6.1.2: Deformation of bell jar with 19psi external pressure

The bell jar, at 60 pounds, is heavy enough to require assistance when opening the vessel. Therefore, a lifting bar, connected to threaded rods screwed into the vacuum flange, can be temporarily attached to the bell jar to provide a hoist ring pickup point, as shown in Figure 6.1.3. A lifting device like the SNOLAB RBK or equivalent is therefore necessary whenever opening or closing the vessel. But as described in Sections 5.3 and 6.6, this crane is also needed to aid handling of some copper shielding blocks that must be manipulated as part of this same process.

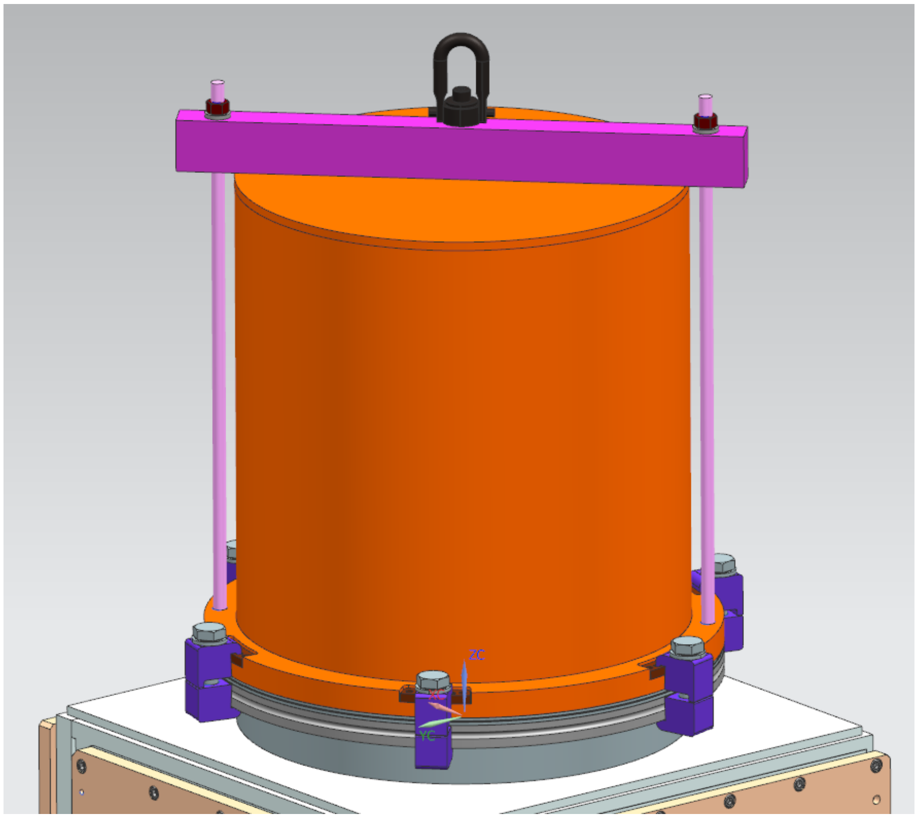


Figure 6.1.3: Overview of the vacuum vessel

6.2 Lower Weldment

The module support box and the internal shield sit on top of a stainless-steel weldment (Figure 6.2.1) that has accesses for electrical feedthroughs, cryocooler mounting, vacuum connections, and ports for hands-on access to internal electrical and cooling connections. At its top end, the vessel has an NW320 vacuum flange for connection to the copper bell jar previously described. This flange is welded to a tube stub slightly above the weldment box top plate, which has an internal ledge upon which the internal copper shield is supported. The middle portion of the top is open, however, and allows the module cables to be routed from the upper region of the vessel down into the lower volume.

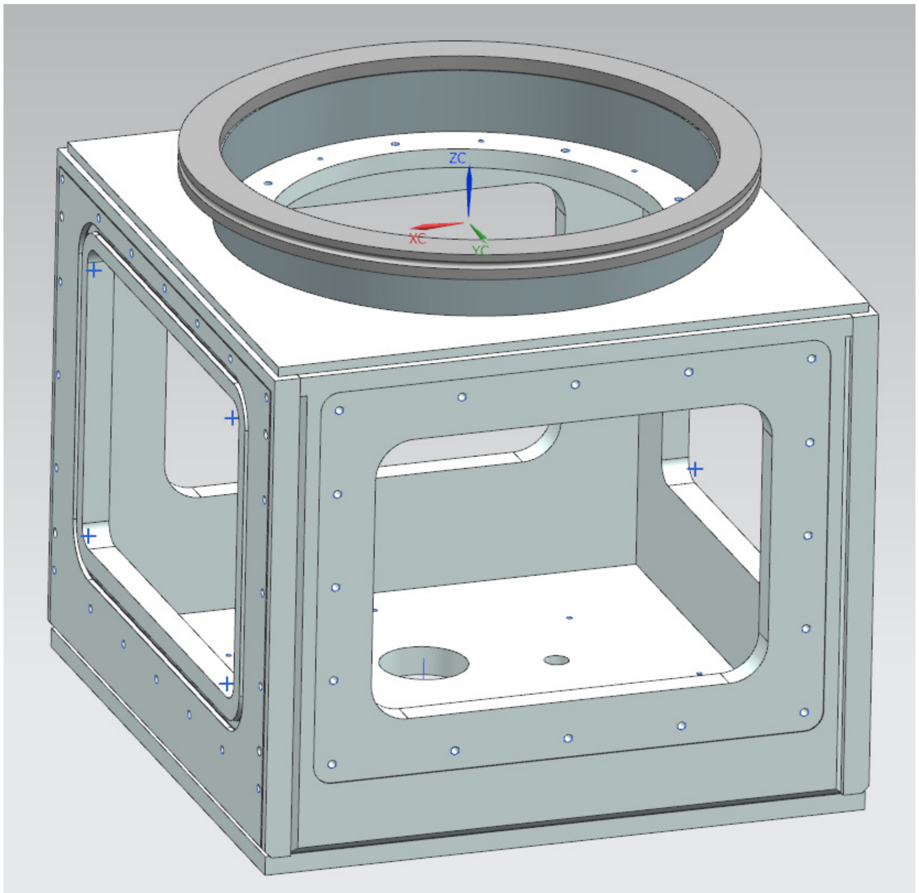


Figure 6.2.1: Lower vessel weldment

Two opposing sides of the vessel have openings in which the vacuum interface boards (VIBs) are mounted. These boards, discussed in Section 6.3 below, are partially inside and partially outside the vessel and therefore allows the feedthrough of electrical signals for the CCD modules and also the temperature control services.

The other two sides of the vessel have simple flange covers with O-ring seals. These ports are opened to allow access inside for cable connections and also access to the cryocooler cold strap connections. Handles can be temporarily attached to the cover plates, which weigh 21 pounds each, to simplify handling.

The bottom face of the vessel has several ports to allow mounting of the cryocooler and for two NW25 vacuum flanges. The under-vessel area is discussed in greater detail in Sections 6.3 through 6.5.

In order to help with lifting of the vessel, a lifting arm can be bolted to the top plate of the weldment (Figure 6.2.2). Attaching it there requires that all the internal shielding will be removed, which is a desired feature of any movement of the vessel. A description of the vessel transport and assembly sequence is described in Section 6.7.

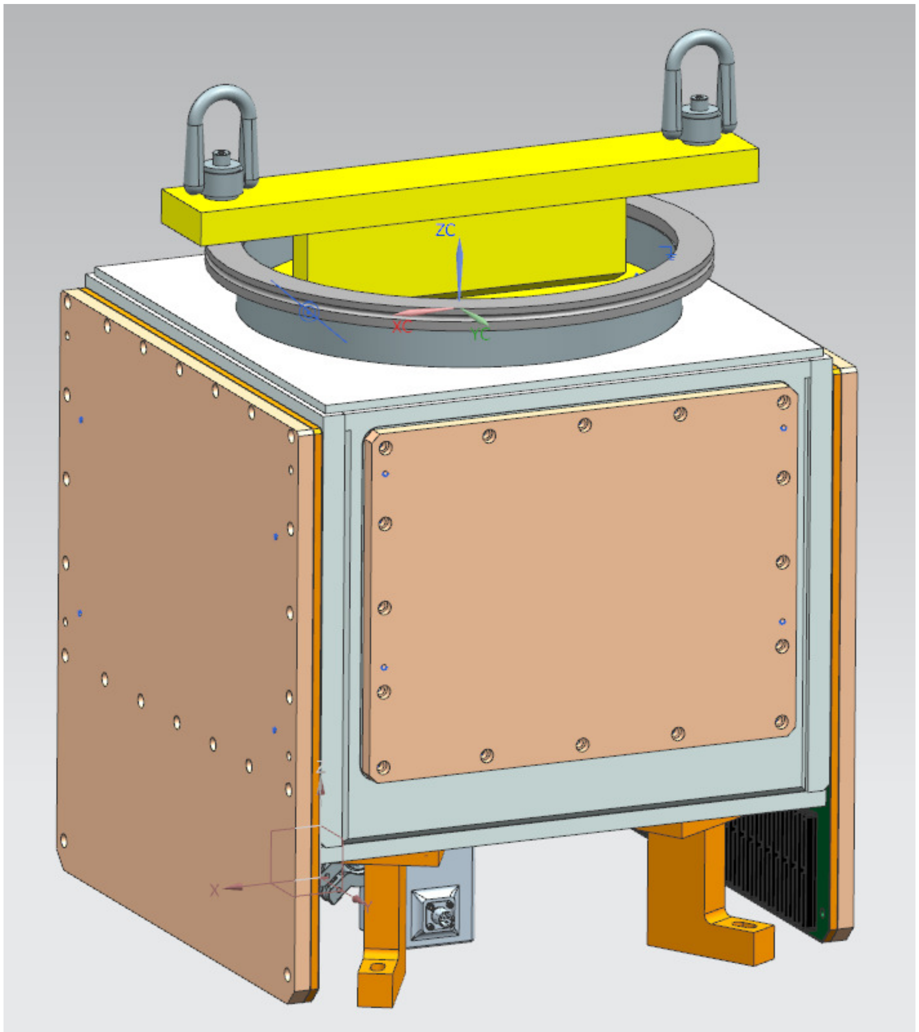


Figure 6.2.2: Lower vessel weldment with lifting fixture

6.3 Cryocooler

Cooling is provided by a Cryomech AL63 cryocooler mounted to the bottom face of the vessel (see Figure 6.0.1). The cooler's cold end is attached by copper braids to the coldfinger described in Section 5.2 above. The braid assembly (see Figure 6.0.1) has copper blocks at each end for attachment to the cryocooler and coldfinger hardware but uses a brazed-in braided section to allow a flexible connection scheme that can accommodate imperfect hardware alignment. A second flexible braided section is to be used to connect the cable interconnect support frame described in Section 6.4 below to the cryocooler.

The cryocooler head is taller than the vessel's support legs, thus making it the lowest point on the vessel assembly. The vessel's handling support stand and the lower plate of the external copper shield will have to be fabricated with a clearance cutout to ensure adequate room for this.

6.4 Vacuum Interface Board (VIB)

These boards are mounted on two opposing faces of the lower vessel weldment. They have connectors mounted in two regions: one area where the connectors will be mounted inside the vessel vacuum and also in a second area where the connectors will be exposed in the open volume underneath the vessel, as shown in Figures 6.4.1 and 6.4.2. Flat, exposed-solid-groundplane surfaces will be configured on each face of the vessel to allow the board to be sandwiched between the vessel and an external rectangular flange, with an accompanying O-ring seal on each face. A vent hole in the board will expose the trapped volume behind the board to the vessel vacuum. In addition to being metalized in the O-ring sealing areas, all edges of the board are also metalized in order to help prevent light leaks into the vessel.

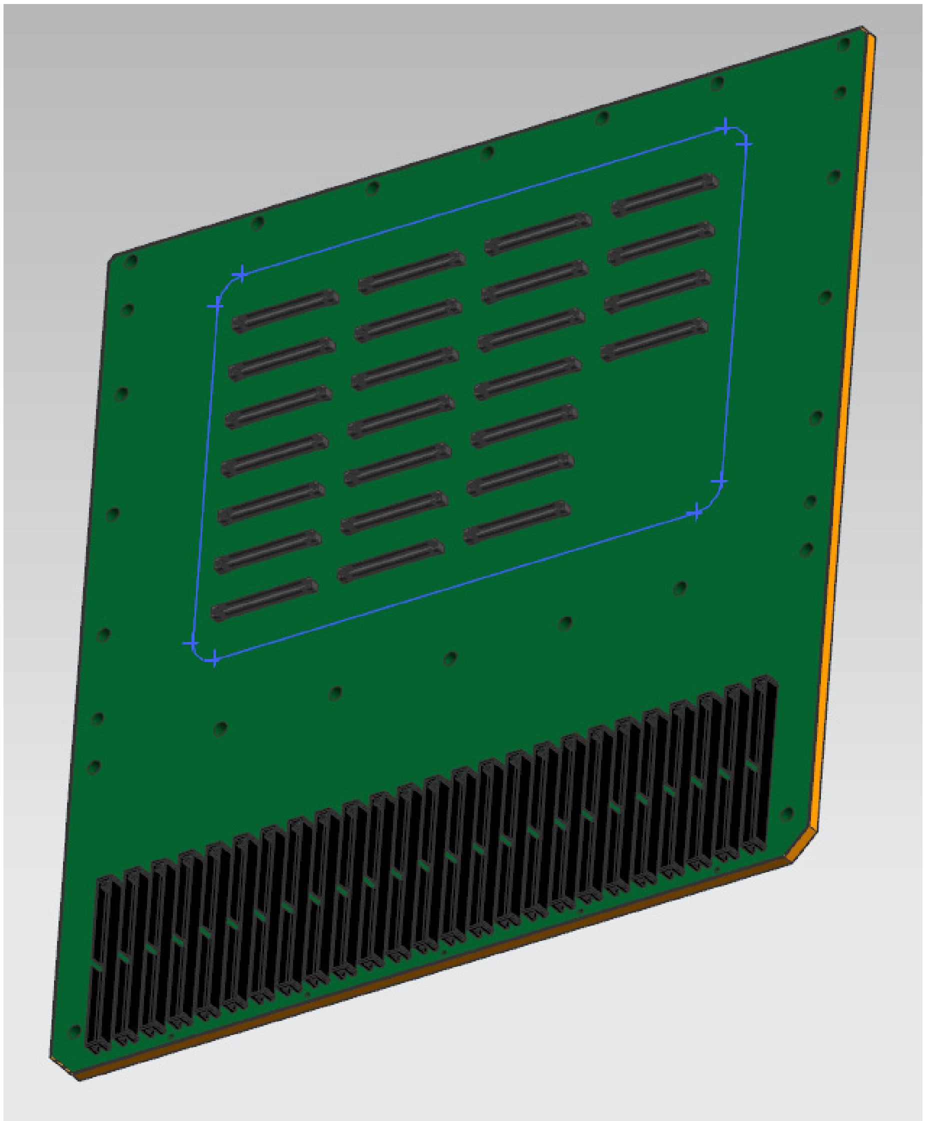


Figure 6.4.1: Vacuum interface board (VIB)

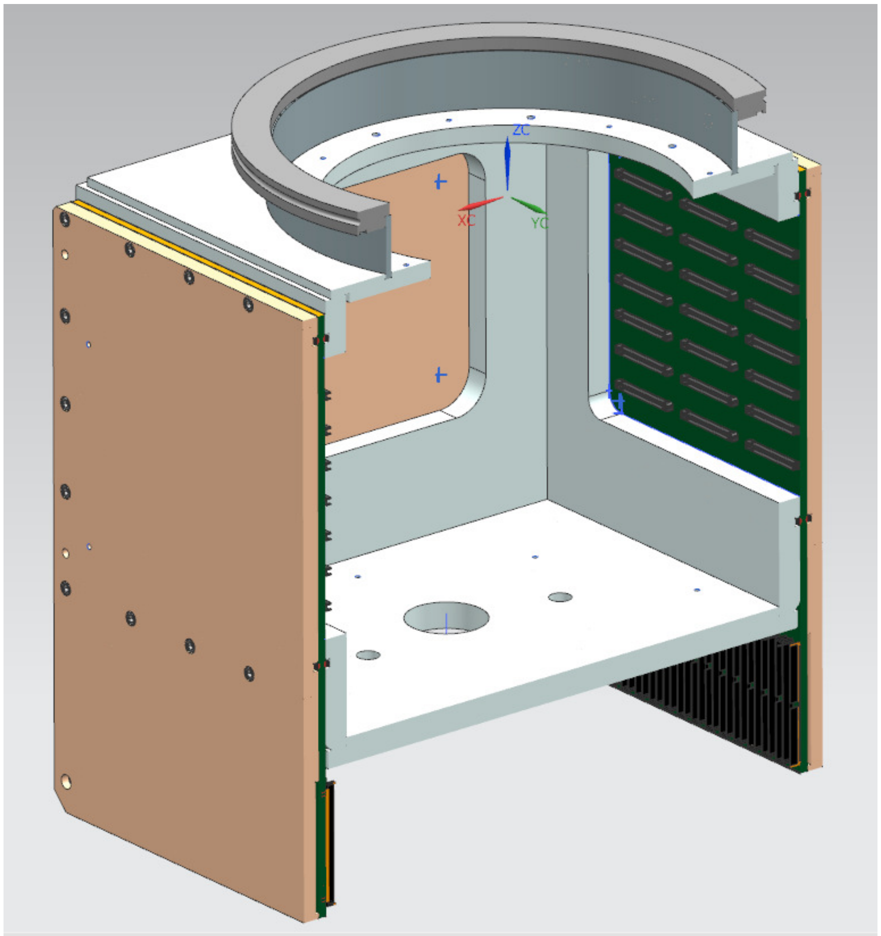


Figure 6.4.2: Vacuum interface board (VIB) shown mounted on the lower vessel weldment

The flex cables from the CCD modules do not plug directly into the VIBs but rather connect to the second-stage cables, and it is these cables that are plugged into these boards. The ends of the second-stage cables away from the VIBs generate a small amount of heat. An actively cooled framework is therefore required that will support the connected ends of each cable and provide cooling for the heat generated there. This frame will be suspended from the top plate of the lower vessel box weldment using low-thermal-conductivity mounts. Cooling will be provided via a copper strap to the cryocooler copper braid described in Section 6.3. An additional temperature controller assembly with RTD, heater, and thermal safety cut-off switch, as described in Section 5.2, will be used to control the temperature of the junction support frame to an acceptable level. Although the temperature here does not need to be kept at very low temperatures, the cryocooler is the only cooling source available and therefore the temperature to be maintained here will use a relatively restrictive thermal connection to the cryocooler, thus allowing the cable junction temperatures to be controlled.

6.5 Under-Vessel Interconnections

The 4.5 inch space underneath the vessel's bottom plate is used for connection of the electrical and mechanical services. An image showing this region can be seen in Figure 6.5.1. Three copper legs are used to support the vessel assembly and have slotted holes in them, intended to interface with threaded studs protruding up from the base floor plate of the copper shield. Nuts fastened to these studs once the vessel has been lowered into place will keep the vessel stable in its position. The cryocooler will have its service lines that have to be fastened in place and routed through the external shielding. The NW25 vacuum hose will also have to route through the shielding along with the cryocooler lines. A vacuum gauge is installed on the vacuum line as well and its cable will require routing along with these lines as well. An additional NW25 port is provided but is capped off. All of these services are to be routed through a channel that runs through the shield near the center of the face of the shield.

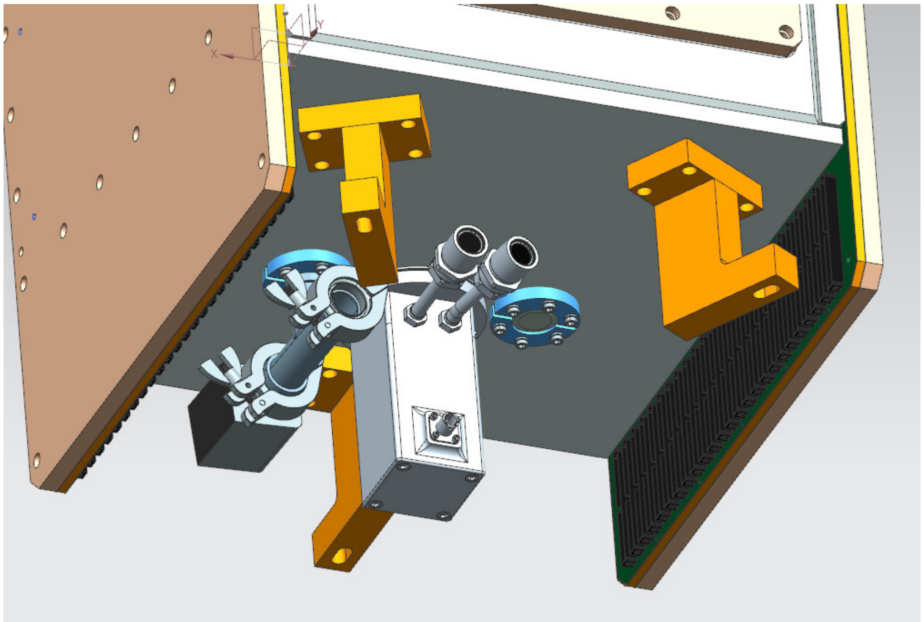


Figure 6.5.1: View of the region underneath the vessel

The cables from the VIBs, which will include both the CCD cables and the temperature control cables, will connect to the VIBs in this region as well. These cables will run in the same direction as the cryocooler and vacuum services, exiting the experiment in the same face of the shield but running in separate channels adjacent to the central services channel.

6.6 Additional External Copper Shielding

Since the copper bell jar described above is round and has a smaller diameter than the square size of the lower vessel weldment, it is possible to fill the available space with additional copper shielding. This shielding can be seen in the overall layout view in Figure 6.0.1 but is also shown in the exploded view in Figure 6.6.1.

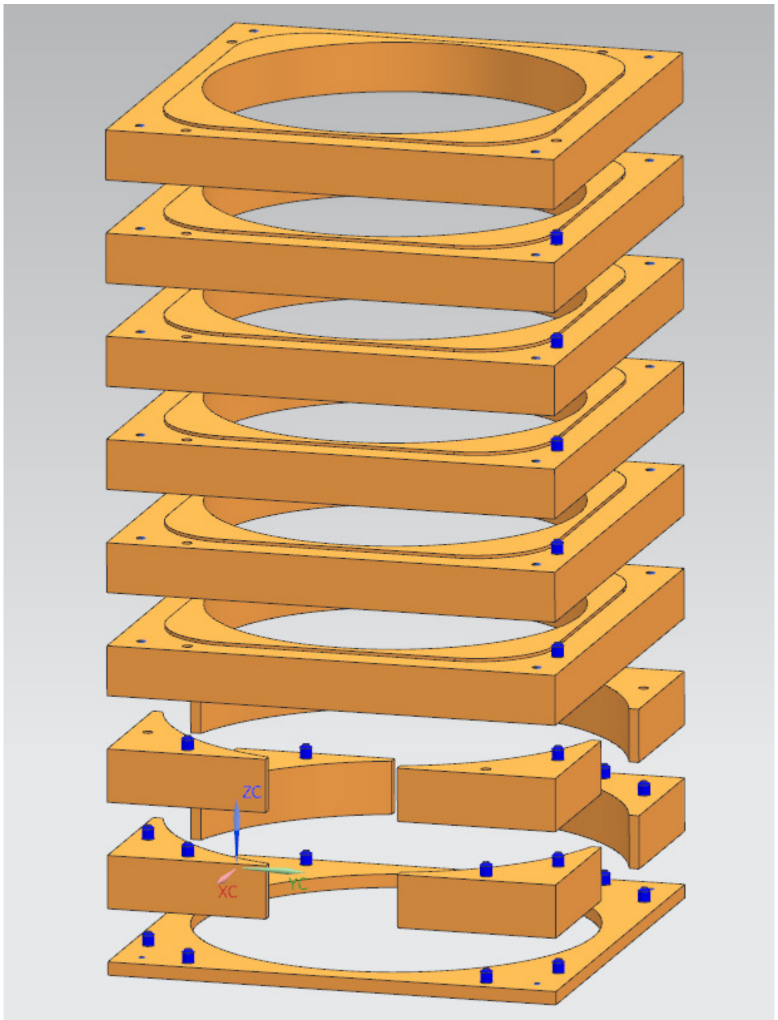


Figure 6.6.1: External copper shielding exploded view

The bottom-most ½-inch thick copper plate stays on the assembled vessel, but the rest of the 2-inch-thick pieces must be removed every time the vessel bell jar is to be opened. The bottom, triangular pieces that surround the bell jar's vacuum flanges are about 9 pound each and can be manipulated by hand. As shown, some loose-fitting plastic pins are used to guide together the parts during stacking. The upper 2-inch-thick plates have stepped surfaces top & bottom to prevent line-of-sight openings through the horizontal mating surfaces between adjacent plates, and these plates also utilize the plastic guide pins to aid assembly. Since these plates are approximately 80 pounds each they will need to use a lifting device (SNOLAB RBK or equivalent) when installing or removing them. Each plate is equipped with four Helicoil-lined threaded holes so a load-leveler with a sling at each end can be used for lifting without contacting the bell jar.

6.7 Detector Assembly Sequence

The outline below describes the basic steps involved in assembly of the detector and is included not as a detailed procedure but rather as a general description useful for understanding the sequence and planning details of the installation work.

1. Vessel prepared for mounting into shield as follows:
    a. Lower vessel weldment assembled with VIBs, cryocooler, and vacuum connectors
    b. Inner support frame for second-stage cable connections installed, with second-stage cables attached to VIBs
    c. Cryocooler hoses and vacuum hose installed
2. Shielding prepared for mounting of the vessel as follows:
    a. Lower plastic support assembled but water boxes removed
    b. Lead and copper shield floors installed but not sidewalls
3. Vessel lifting fixture used to lift vessel and mount it to the external copper shield floor plate, where it is fastened into place.
4. External electrical cables connected to VIBs
5. External services dressed in place
6. Inner copper shield and module support box installed
7. Cryocooler attached to support box coldfinger and second-stage cable junction support frame
8. Supermodules installed and cables connected to second-stage cables
9. Access ports sealed on lower weldment
10. Inner copper shield assembly completed
11. Bell jar installed and sealed
12. Vacuum applied, experiment cooled down, detector electrical functionality verified
13. Bell jar's external copper shield installed
14. SNOLAB copper & lead shield assembled
15. SNOLAB water box shields installed

7.0 Shielding Specification

Because the SENSEI experiment is focused *exclusively* on searching for dark matter through the electron recoil signal, the signal region for the experiment is restricted to a very narrow range of roughly one to ten electrons. In this very low energy band, the background requirements are significantly less demanding than those for other competing experiments that seek to also attain nuclear recoil sensitivity over a much wider recoil energy range. While there do not exist at this time reliable estimates of the radioactivity backgrounds in this eV infrared photon regime, experience in the DAMIC experiment suggests that a background rate of ~5 events/keV-kg-day in the range of 2-15 keV, comparable to the levels attained by DAMIC.

7.1 Shielding Geometry

The shield for SENSEI is based on the existing Polyethylene water tank system used by the PICO-2L experiment. The tanks plus a base of thick polyethylene slabs provide roughly 50 cm of polyethylene/water shielding to attenuate the neutron flux arising from the rock walls of the site. The PICO water shield provides an open usable cavity of roughly 36” square x 54” high, which is appropriate for housing the SENSEI apparatus plus the additional Pb and copper shielding necessary to attenuate the external gamma flux.

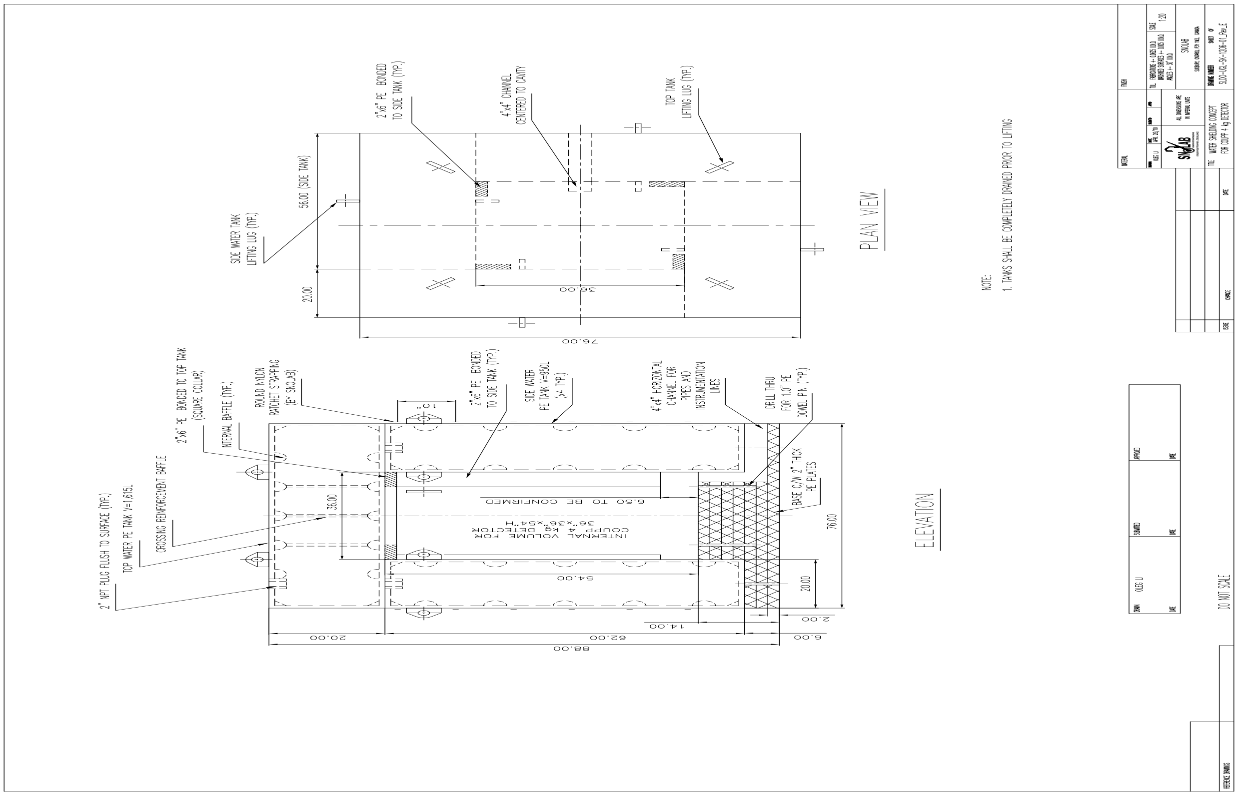
The primary gamma shielding for SENSEI will be provided by a 3” thick Pb casket that will be fabricated by Fonderie de Gentilly. The 3” wall thickness is sufficient to attenuate the external photons to a level below the level that will originate from the ~5 Bq/kg contamination level of the Pb material. To suppress the gamma flux originating in the Pb, an additional 2” of OFHC copper shielding will be used inside the Pb Casket. The Copper is assumed to be ~20 mBq/kg. Simulations indicate that the combination of 3 inches of 5 Bq/kg lead and 2 inches of 20 mBq/kg copper will be sufficient to attain the desired gamma rate in the SNOLAB rock environment.

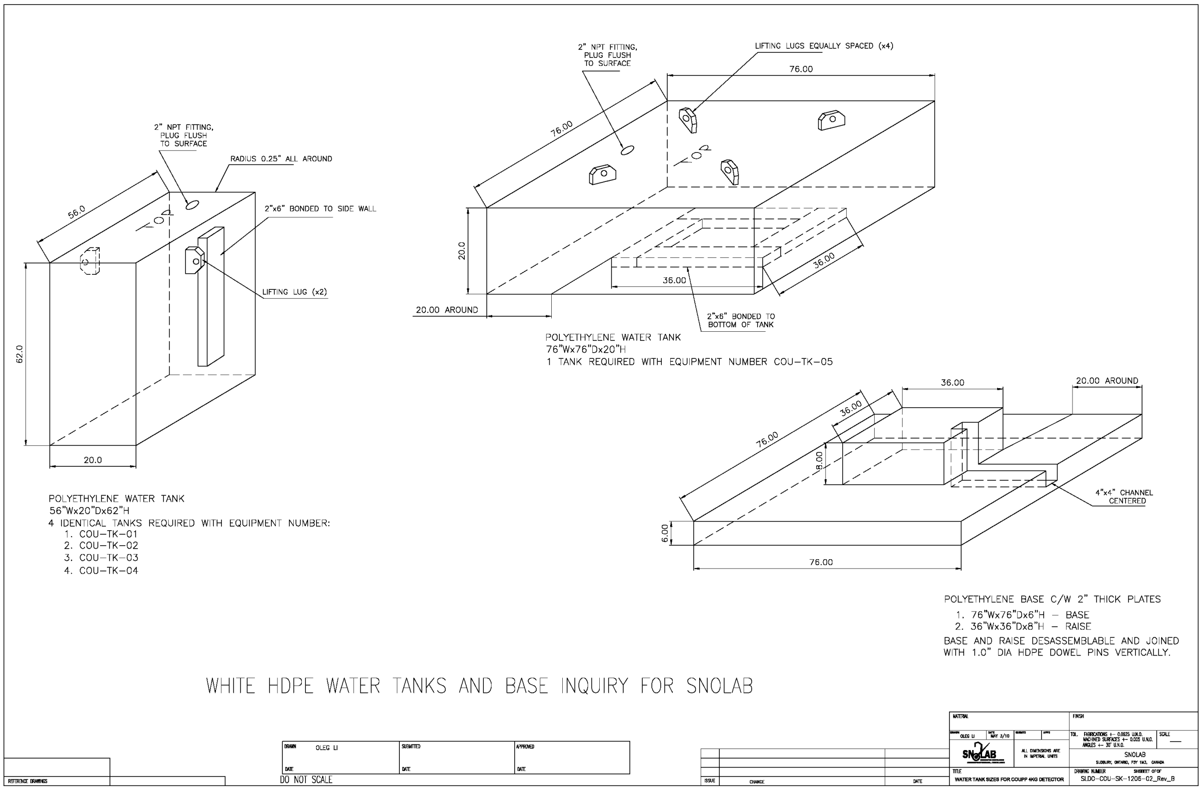
7.2 Shielding Simulation

This Section to be supplied by SNOLAB

7.3 Poly/Water Neutron Shielding

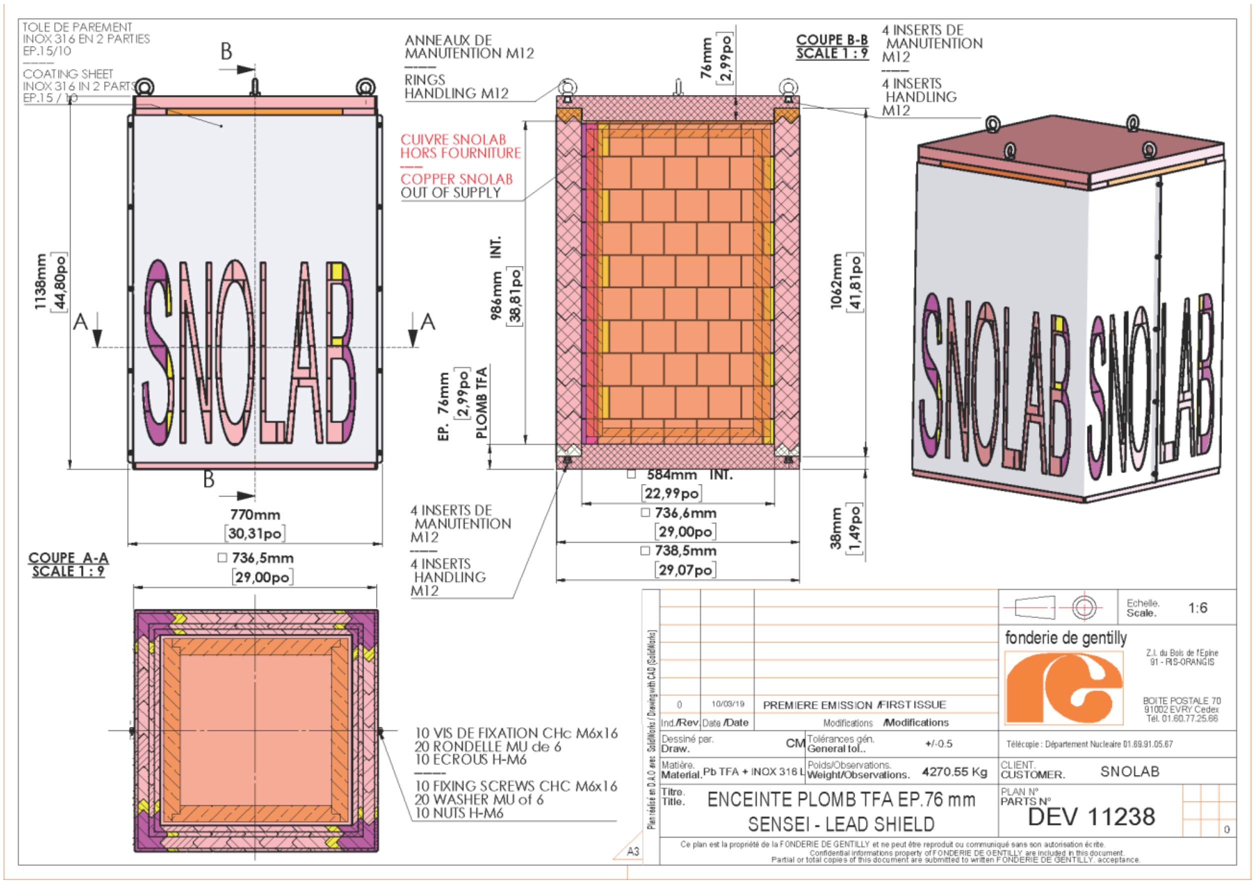
The Poly/Water neutron shielding was developed for the PICO-2L experiment and is already in place at the SENSEI site. The water tank system begins with a base of solid polyethylene slabs. Four water tanks form the vertical walls of the cavern providing 50 cm of shielding laterally. The top “lid” of the box rests on the side walls and provides 50 cm of shielding vertically. The boxes are provided with locking bars that allow them to be positioned easily into a closed structure that can be banded together for additional strength against seismic disturbance. The polyethylene boxes and the lid are provided with appropriate lifting lugs so that they can be easily handled and rigged into position. Drawings of the polyethylene shielding are shown below.


2" NPT PLUG FLUSH TO SURFACE (TYP.)
TOP WATER PE TANK V=1,615L
CROSSING REINFORCEMENT BAFFLE
2"x6" PE BONDED TO TOP TANK (SQUARE COLLAR)
INTERNAL BAFFLE (TYP.)
ROUND NYLON RATCHET STRAPPING (BY SNOLAB)
2"x6" PE BONDED TO SIDE TANK (TYP.)
SIDE WATER PE TANK V=950L (x4 TYP.)
4"x4" HORIZONTAL CHANNEL FOR PIPES AND INSTRUMENTATION LINES
DRILL THRU FOR 1.0" PE DOWEL PIN (TYP.)
BASE C/W 2" THICK PE PLATES
INTERNAL VOLUME FOR COUPP 4 kg DETECTOR 36"x36"x54"H
6.50 TO BE CONFIRMED
88.00
62.00
20.00
6.00
2.00
14.00
54.00
36.00
10"
76.00
ELEVATION
SIDE WATER TANK LIFTING LUG (TYP.)
2"x6" PE BONDED TO SIDE TANK (TYP.)
4"x4" CHANNEL CENTERED TO CAVITY
TOP TANK LIFTING LUG (TYP.)
56.00 (SIDE TANK)
20.00
36.00
76.00
PLAN VIEW
NOTE:
1. TANKS SHALL BE COMPLETELY DRAINED PRIOR TO LIFTING
DRAWN OLEG LI
SUBMITTED
APPROVED
DATE
DO NOT SCALE
REFERENCE DRAWINGS
ISSUE
CHANGE
DATE
MATERIAL
FINISH
DRAWN OLEG LI
DATE APR. 26/10
SUBM'D
APP'D
TOL. FABRICATIONS +- 0.0625 U.N.O.
MACHINED SURFACES +- 0.005 U.N.O.
ANGLES +- 30' U.N.O.
SCALE 1:20
ALL DIMENSIONS ARE IN IMPERIAL UNITS
SNOLAB
SUDBURY, ONTARIO, P3Y 1M3, CANADA
TITLE WATER SHIELDING CONCEPT FOR COUPP 4 kg DETECTOR
DRAWING NUMBER
SHEET OF
SLDO-UGL-SK-1206-01_Rev_E


2" NPT FITTING, PLUG FLUSH TO SURFACE
RADIUS 0.25" ALL AROUND
2"x6" BONDED TO SIDE WALL
LIFTING LUG (x2)
56.0
62.0
20.0
TOP
POLYETHYLENE WATER TANK
56"Wx20"Dx62"H
4 IDENTICAL TANKS REQUIRED WITH EQUIPMENT NUMBER:
1. COU-TK-01
2. COU-TK-02
3. COU-TK-03
4. COU-TK-04
2" NPT FITTING, PLUG FLUSH TO SURFACE
LIFTING LUGS EQUALLY SPACED (x4)
76.00
76.00
20.0
36.00
36.00
20.00 AROUND
2"x6" BONDED TO BOTTOM OF TANK
TOP
POLYETHYLENE WATER TANK
76"Wx76"Dx20"H
1 TANK REQUIRED WITH EQUIPMENT NUMBER COU-TK-05
36.00
20.00 AROUND
36.00
76.00
8.00
4"x4" CHANNEL CENTERED
6.00
76.00
POLYETHYLENE BASE C/W 2" THICK PLATES
1. 76"Wx76"Dx6"H - BASE
2. 36"Wx36"Dx8"H - RAISE
BASE AND RAISE DESASSEMBLABLE AND JOINED WITH 1.0" DIA HDPE DOWEL PINS VERTICALLY.
WHITE HDPE WATER TANKS AND BASE INQUIRY FOR SNOLAB
REFERENCE DRAWINGS
DRAWN OLEG LI
SUBMITTED
APPROVED
DATE
DO NOT SCALE
ISSUE
CHANGE
DATE
MATERIAL
FINISH
OLEG LI
MAY 3/10
TOL. FABRICATIONS +- 0.0625 U.N.O.
MACHINED SURFACES +- 0.005 U.N.O.
ANGLES +- 30' U.N.O.
SCALE
ALL DIMENSIONS ARE IN IMPERIAL UNITS
SNOLAB
SUDBURY, ONTARIO, P3Y 1M3, CANADA
TITLE
WATER TANK SIZES FOR COUPP 4KG DETECTOR
DRAWING NUMBER
SHEET OF
SLDO-COU-SK-1206-02_Rev_B

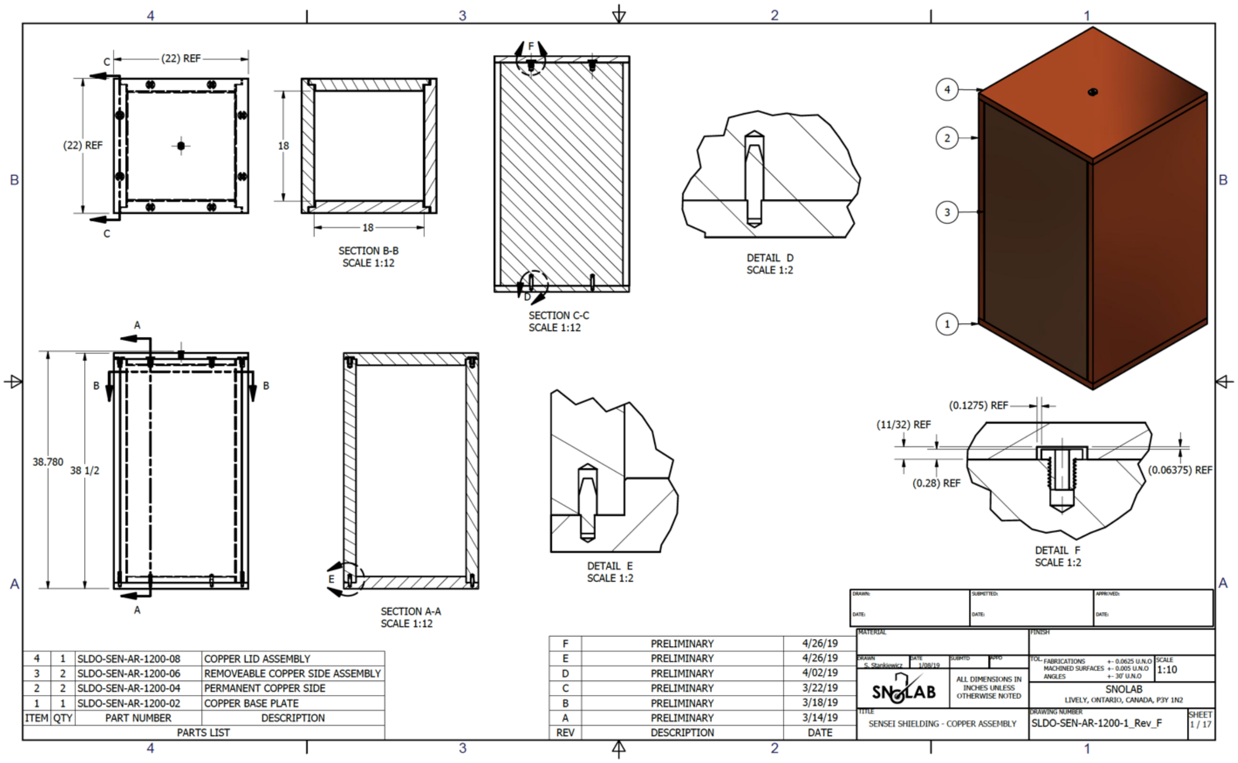
7.4 **Pb Gamma Shielding**

The primary gamma shielding for SENSEI is provided by a casket of Pb bricks fabricated by Fonderie de Gentilly. This vendor has been in the business of providing ultra-low background Pb shielding boxes for counting applications and has consistently provided low-background Pb <5Bq/kg. These Pb bricks have been fabricated and are in hand underground at SNOLAB.



7.5 Copper Gamma Shielding

Because the effectiveness of the Pb shielding is limited to its own internal contamination level, it is necessary to provide and additional 2” of copper shielding to attenuate the photons arising from the inner annulus of the Pb Shielding. The copper shielding parts will be fabricated form Copper 110 manufactured by Arubis Metals in Pori Finland. The materials will be procured through Thyssenkrupp.



ITEM	QTY	PART NUMBER	DESCRIPTION
4	1	SLDO-SEN-AR-1200-08	COPPER LID ASSEMBLY
3	2	SLDO-SEN-AR-1200-06	REMOVEABLE COPPER SIDE ASSEMBLY
2	2	SLDO-SEN-AR-1200-04	PERMANENT COPPER SIDE
1	1	SLDO-SEN-AR-1200-02	COPPER BASE PLATE

PARTS LIST

REV	DESCRIPTION	DATE
F	PRELIMINARY	4/26/19
E	PRELIMINARY	4/26/19
D	PRELIMINARY	4/02/19
C	PRELIMINARY	3/22/19
B	PRELIMINARY	3/18/19
A	PRELIMINARY	3/14/19

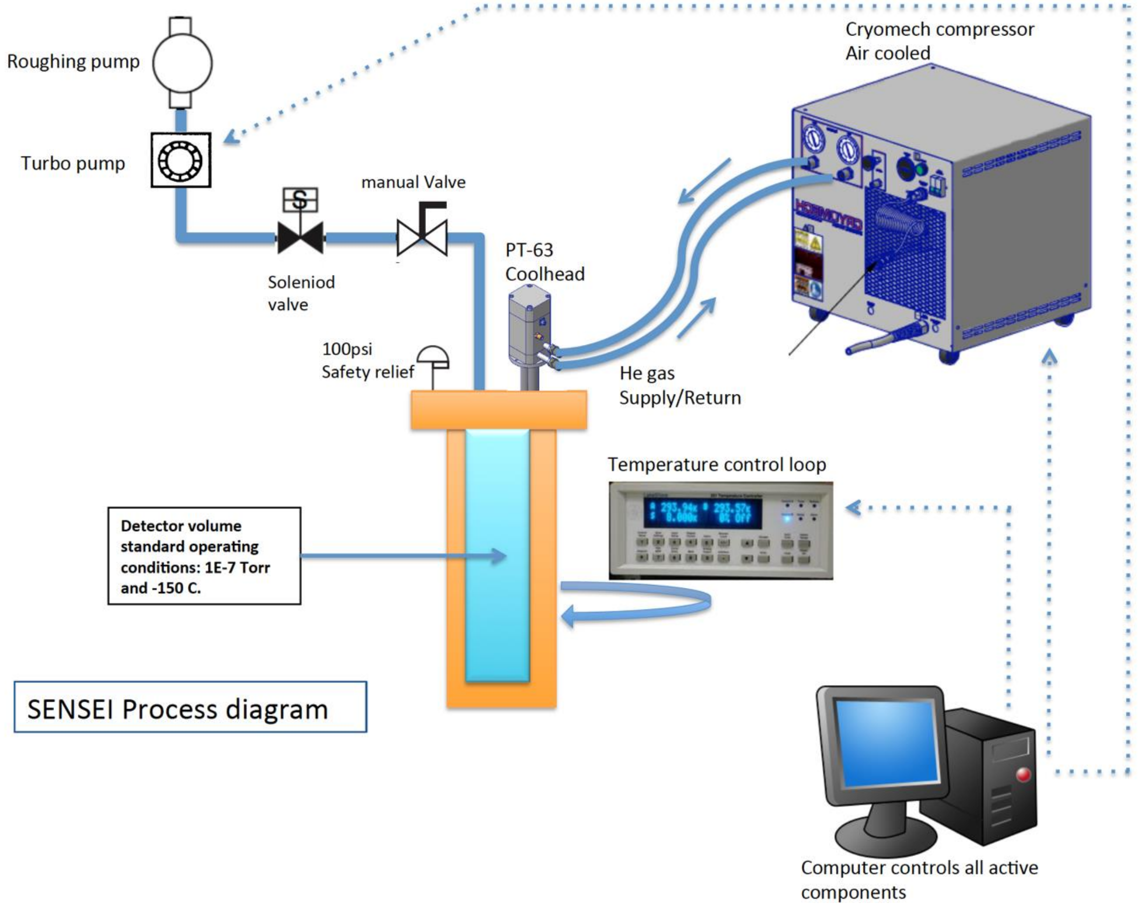
DRAWN: DATE:
SUBMITTED: DATE:
APPROVED: DATE:
MATERIAL
FINISH
DRAWN S. Stankiewicz
DATE 1/08/19
SUBMTD
APPD
ALL DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED
TOL. FABRICATIONS +- 0.0625 U.N.O
MACHINED SURFACES +- 0.005 U.N.O
ANGLES +- 30' U.N.O
SCALE 1:10
SNOLAB
LIVELY, ONTARIO, CANADA, P3Y 1N2
TITLE SENSEI SHIELDING - COPPER ASSEMBLY
DRAWING NUMBER SLDO-SEN-AR-1200-1_Rev_F
SHEET 1 / 17

7.6 Cable and Resource Penetrations

Both the Pb and Copper shields will be procured as closed rectangular prisms of material with no penetrations. Once the final penetration specifications are determined, the ports for cables and services will be machined at SNOLAB. As of this writing, there is a detailed mechanical mockup of the cable services routing, but we are not yet ready to finalize the specifications for the ports to be cut into the copper and the Pb.

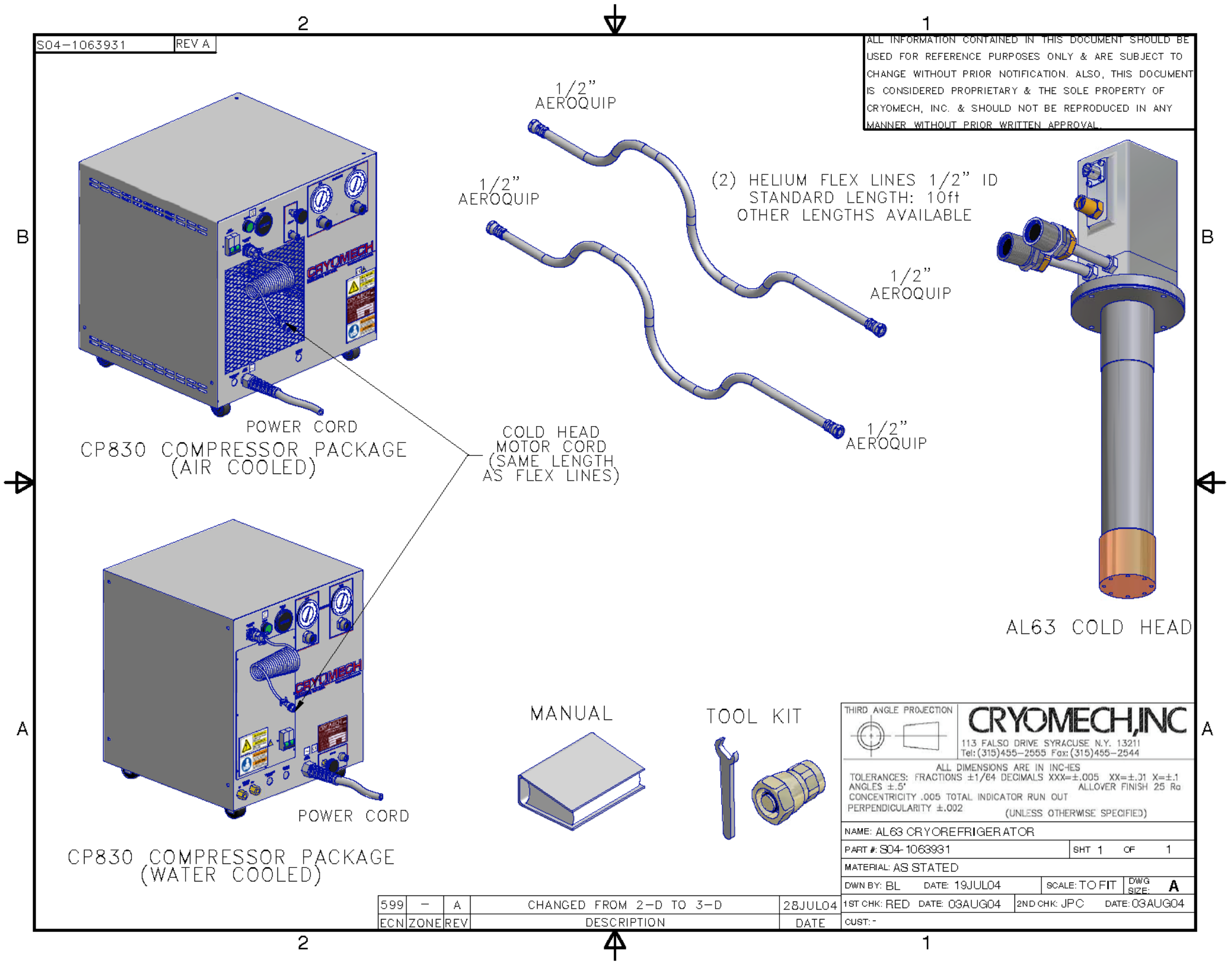
<u>8.0 External Services</u> [This is a Preliminary Specification]

The SENSEI experimental infrastructure is minimal, as shown on the P&ID below. A Cryomech CP830 air cooled compressor will provide cold helium flow to a Cryomech AL63 Cold head which provides the cooling to the detector array. NOTE: this is actually the DAMIC P&ID reflecting the equipment choices for DAMIC. A new P&ID will be prepared for SENSEI once we freeze the specifications of the actual chiller that we will deploy. The vacuum chamber will be equipped with a Pfeiffer Hi-Cube turbo pumping station (I believe this includes a roughing pump with the Turbo pump as a package.) Again these details will be clarified in the final SENSEI P&ID.



8.1 Cryo-Refrigeration System

The manufacturers specification drawing for the CRYOMECH AL63 System is included below. A full description of the cooling system will include a commercial temperature controller and a dedicated computer to provide an appropriate feedback control loop and monitoring.



8.2 Vacuum Pump

The vacuum pump will in all likelihood be the Pfeifer Hi-Cube Turbo Pumping Station noted in the advertising page below. Again, this is a preliminary specification.

Betriebsanleitung • Operating Instructions

Translation of the Original Operating Instructions

HiCUBE

Turbo pumping station

HiCube 80 Eco

PT 0263 BE/B (0907)

PFEIFFER VACUUM

8.3 Relay Rack, Power, UPS, and Monitoring Requirements

The two relay racks already in place from PICO-2L are likely to be completely adequate for the SENSEI Deployment. The detector will be readout using Fermilab LTA electronics boards. Each sensor will be provided with its own separate LTA board. Each LTA Board will receives its signals from the sensor through a multi-conductor ribbon cable, and is provided with a power connection and an ethernet connection for communication and data flow. We have chosen NOT to develop an electronics crate solution for the LTA boards (i.e. there will not be a backplane to provide power distribution.) Power will be supplied to each board with a power cable, and power cables will be serviced from a distribution panel not yet designed. The Power distribution panel will be driven by an appropriate power supply (again not yet specified) and will provide appropriate fusing for each individual power cable. The overall system will likely arrange the LTA boards in a simple open support rack, likely with 12 LTA boards occupying roughly 6-8u of rack space. We have not yet specified the cooling necessary for the system, but the open geometry will lend itself to the inclusion of appropriate fans. The engineering of this system will of course include an analysis of the heat management and if necessary would include an interlock to require fan operation (or a temperature limit) as a trip condition for the power supplies. The LTA system would occupy roughly ½ of one relay rack.

The balance of the rack space would be used for readout control computers. We do not yet have a specification of the computers that will be required. Specification details that are needed are:

1) DAQ Computers: number and specification of the computers, from which would derive the power and possible air-flow requirements for the DAQ computer rack.

2) DAQ data bandwidth specification: This will allow us to provide a final firm statement of the internet bandwidth required for the experiment.

3) Important Note: The initial SENSEI Deployment will only provide DAQ for 4-8 LTA Cards, representing a small fraction of the total DAQ and bandwidth requirements. We are one year away from needing to resolve the DAQ, power, and computing issues for the full 48 LTA board system.

4) The PICO-2L Racks are already equipped with a remotely controlled power distribution system and some level of UPS backup. This will certainly be suitable as is for the initial SENSEI 1 (or two) super-module deployment. We have not yet determined the UPS requirements for the full deployment.