

# Vertical Access Zero Boiloff Rampable Superconducting Magnet System with Horizontal Field for Semiconductor Crystal Growth

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**Abstract**—A magnet system has been designed and built to minimize convection mixing during the growth of 0.2m (8 inch) diameter semiconductor crystals. Due to the size requirements of the crystal growth furnace, the magnet has a room temperature vertical access bore of diameter 1.27 m and height 1.2 m. The cold bore of the magnet is diameter 1.4 m and height 0.8 m with a 280 liter liquid helium bath. The field is perpendicular to the cylindrical bore and is provided by two saddle shaped NbTi coils. The two coils, each with 1200 turns operating at 200 A, produce a 0.2 T horizontal field at the center of the bore. The series inductance is 0.3 H for a total stored energy of 6 kJ. High Tc (BISCO in silver tape) leads were used to allow the system to be operated without persistent current switches, for ease of ramping. A 100 W at 80 K, 5 W at 20 K shield GM cooler plus a 45 W at 50 K, 1.5 W at 4.2 K helium recondensing GM cooler were used to achieve zero boiloff. The measured shield temperatures in operation are 65 K and 17 K. Design considerations, including thermal staging of the silver tape / BISCO (HTC) current leads, lead quench protection circuit, low thermal conduction mechanical support structure and magnet construction, are discussed.

**Index Terms**—Closed-Cycle, Crystal growth, Current Leads, Horizontal field, Superconducting magnet, Zero Boiloff

## I. INTRODUCTION

THE semiconductor industry is continuously striving to improve the purity of silicon crystals and hence the yield of devices manufactured from these crystals. Single crystals are grown by pulling from a molten bath. The growth of high quality semiconductor crystals can be assisted by means of a magnetic field to reduce thermal convection eddy currents in the liquid semiconductor (silicon) melt[1],[2]. Commercial practice includes water cooled conventional magnets as well as superconducting magnets for this application. The cylindrical furnace is vertical but the required magnetic field is horizontal or cusp shaped posing special difficulties for the magnet designer. Passive magnetic shielding, typically iron shielding, is required around the magnet to minimize stray magnetic fields.

The push for higher quality and quantity and low cost in

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semiconductor manufacturing provides a driving force for the development of large magnets for this application. Closed cycle cryocoolers result in a zero boiloff system.[3]

In this paper we discuss the design, construction, and experimental testing of a zero boiloff transverse field superconducting crystal growth magnet. A novel design approach is used to carry the 200A current from 300K to 4K with minimum heat load.

## II. CRYOSTAT DESCRIPTION

A magnet cryostat has been designed to accommodate two NbTi racetrack superconducting coils (saddle coils). The cryostat is equipped with two closed-cycle G-M refrigerators: a large one (20 K, 5 W) for shield cooling and smaller one (4.2 K, 1.5 W) for helium reliquefing. HTC leads are incorporated so that there is constant connection to the magnet for ramping the field up and down.

The cryostat is also composed of the following items, shown in Fig.1 and Fig.2:

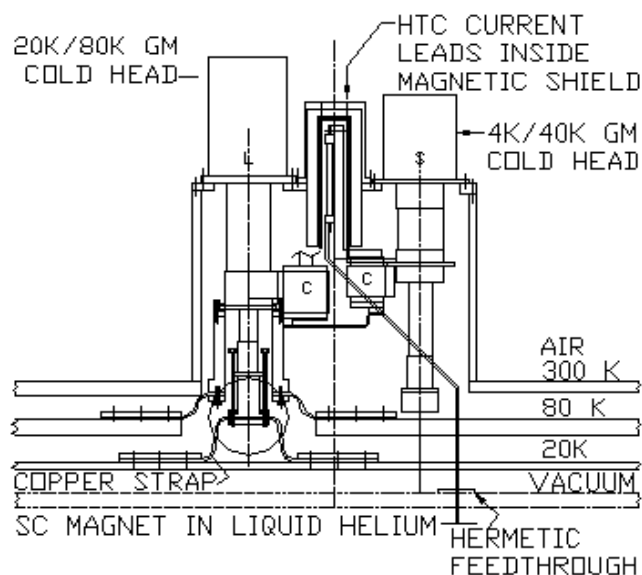


Fig. 1. Cryostat Cold Head Connections

### A. Vacuum Vessel

The stainless steel vacuum vessel is 1.2 m high by 1.67 m diameter with a 1.27 m warm bore. On top of the annular vessel is a box, 0.6 m x 0.35 m x 0.35 m high, which houses the current leads and the two cryocoolers. Access to the connections between these devices and the magnet and

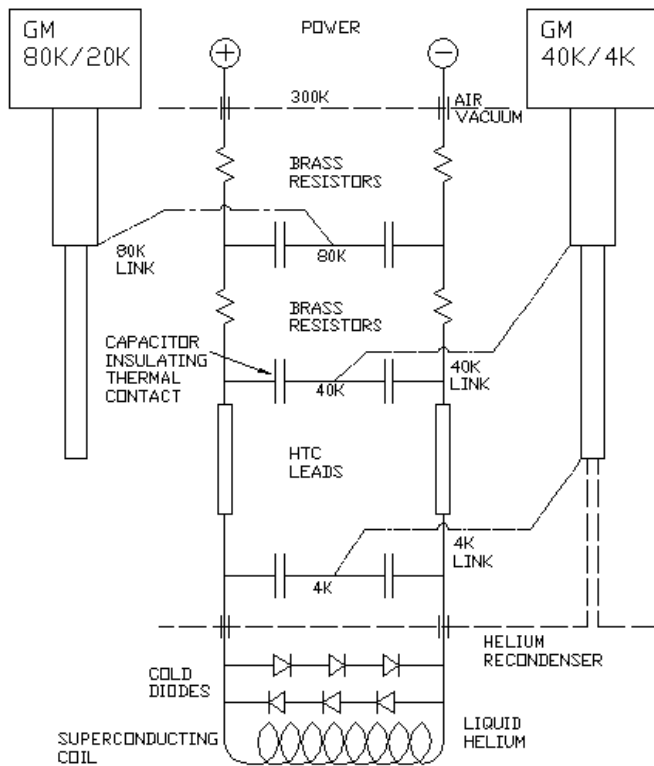


Fig. 2. 200A Current Lead Thermal Staging

shields is via removable cover ports on the sides of the box. On top of the cryostat vessel are three circular towers through the rectangular box which house the warm ends of the vertical hangers for the shields and the magnet vessel. A fourth tower is for access to the helium bath for initial cooling and filling and for the emergency vent.

### B. Shields

Since this is such a large area cryostat, the shields are arranged in two stages as shown in Fig. 3. The outer shield is 8 mm thick and the inner shield is 2 mm thick, both aluminum Al 1050. The top and bottom of each shield is closed by an aluminum plate, to which the cylindrical shields are screwed at 40 mm intervals.

The two shields are independently cooled by attachment to the first and second stage of a Leybold Coolpower 5/100 cryocooler. Multiple layers of thin copper straps, which accommodate the motion of the shields as they cool, connect the cryocooler and the shield top.

Only the outer shield uses superinsulation. The effective emissivity of this superinsulation is critical to correct operation [4]. Surfaces of the inner shields are covered with shiny aluminum foil (3M tape).

### C. Helium Vessel

The helium reservoir, which is covered with shiny aluminum foil tape, is all welded 304 stainless steel and has a helium volume of 280 liters. Initial cooling and filling of this vessel is via the service tower at the top of the vacuum vessel. The reservoir is connected via a stainless steel bellows to a small condensation vessel attached to the second stage of a

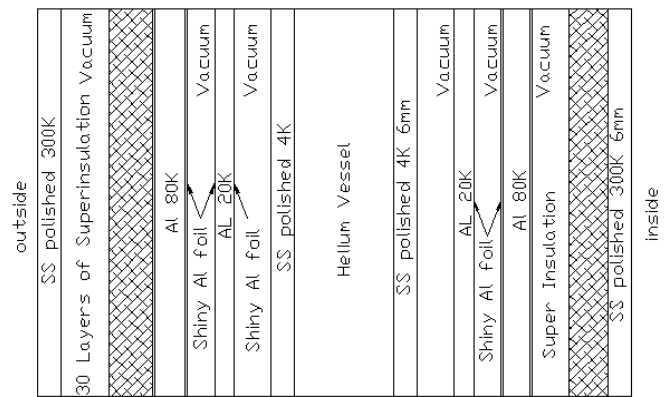


Fig. 3. 20K and 80K Shield Construction

Sumitomo RDK-415D cryocooler. This connection allows for the reliquefaction of helium evaporating in the reservoir.

### D. Magnet

The magnet consists of two racetrack coils, 1200 turns each, wrapped on the outside of a cylindrical aluminum mandrel. The coils have a series inductance of 0.3 H and operate at 200 A. They produce a field of 0.2 T, directed horizontally.

### E. Mechanical Supports

Each of the three suspended elements in the cryostat has three vertical hangers and twelve horizontal support rods.

The shields and the helium reservoir are supported vertically and horizontally by glass fiber reinforced plastic (FRP) G10 rods, all of similar construction (differing only in length). The support rods were made by threading (and epoxying) M10 stainless steel threaded rod 50 mm into opposite ends of a G10 tube, 20 mm OD x 6 mm ID. Three such assemblies were tested and had a breaking strength of 27 kN.

Each element (shield or reservoir) is supported by three vertical hangers arranged in the three support towers so that the warm end of the hanger is anchored at the next higher temperature; the 80 K shield hangs from the room temperature cryostat, the 20 K shield hangs from the 80 K shield, and the Helium reservoir hangs from the 20 K shield. The vertical support anchors are shown in Fig. 4.

Horizontal support is provided to each element at both top and bottom (Fig. 5), by three pairs of support rods (acting in tension against each other, so that no rod will go into compression). These rod pairs are separated by 120 degrees.

### F. Magnet Leads

The magnet leads from room temperature to the magnet at 4.2 K each consisted of four serial components shown in Fig. 2: a) a brass strap from room temperature to 80 K; b) a brass strap from 80 K to about 40 K; c) an HTC component to a temperature near 5 K; d) a NbTi/Cu wire leading to the bottom of the magnet.

The brass strap from room temperature to 80 K is located in vacuum and its cross sectional area to length ratio was optimized for the 80 K heat load at 200 A. The cold end of the

brass strap is thermally anchored to the first stage of the shield cryocooler through a “capacitor” electrically insulating thermal contact. The “capacitor” is a clamped stack of copper sheets, each insulated from the next by a layer of kapton tape, 0.025 mm thick. Every second sheet is connected in parallel to the current lead, and the other sheets are connected to the cryocooler. The copper sheets are 0.012 mm thick and the contact area is 5 cm x 5 cm.

The brass strap from 80 K to about 40 K is in vacuum and has its cold end thermally anchored to a capacitor contact attached to the first stage of the Sumitomo cryocooler. This stage has no other heat load and so is expected to operate at about 30 K. The cross sectional area to length ratio of the brass strap is optimized for carrying 200A from 80K to 30 K.

The HTC current leads that were initially chosen for this project had the advantage of very low thermal conductivity, a heat load of only about 28 mW per pair. We discovered later that they also had four disadvantages: a) high contact resistance of 0.9 to 6.5 microOhms at 400 A which results in heating at the 4 K end; b) the HTC leads are ceramic rods and, when they go normal, have a high resistance - this REQUIRES internal (COLD DIODE) protection on the magnet, as there is no other way to ensure magnet safety; c) the ends are soldered with low temperature Bismuth – Indium solder (60 C with a hot air gun); resoldering with tin-lead solder (up to 200C) must be done with the hot end DOWN, and may result in a change in the contact resistance; d) they are very fragile and susceptible to cracking. In testing four leads, three of them cracked during assembly or during cooldown. Probably, this was due to the assembly technique; i.e., not allowing sufficient flexibility for the current leads. They were replaced with flexible silver tape / BISCO leads in FRP tubes and these worked satisfactorily. The HTC leads operate in vacuum and a soft iron magnetic shield protects them from the high magnetic field of the superconducting magnet.

The NbTi / Cu wire attached to the cold end of each HTC lead passes from the vacuum space into the liquid helium filled magnet reservoir through a ceramic isolated copper tube hermetic feedthrough.

### G. Relief Valve and Venting

A pressure relief valve and a backup burst disk is included in the design to ensure safety. It is also essential to vent the gas OUTSIDE of the area where people are, as a dangerous quantity (about 200 cubic meters of gas) of helium gas could be released in one minute.

## III. ASSEMBLY

Figs. 6 and 7 show the top plate and shell assemblies. Due to the similarity between the top plate and the bottom plate, only one view is shown.

## IV. ZERO BOILOFF EXPERIMENTAL TEST

Three measurements were done per test, one with the 4K thermal strap connected to the 4 K cold head, and two with the strap not connected (one with no current and one with 200A).

## VERTICAL SUPPORT ANCHORS

(CUT-A-WAY VIEW SHOWING ATTACHMENTS)

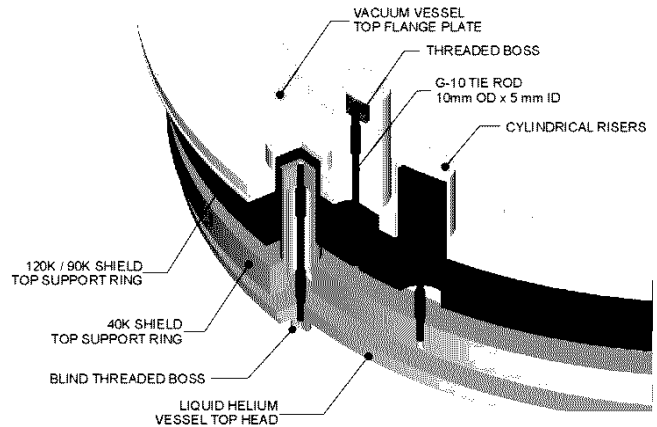


Fig. 4. Vertical Support Anchor Drawing

## LATERAL SUPPORT ANCHORS

(CUT-A-WAY VIEW SHOWING ATTACHMENTS)

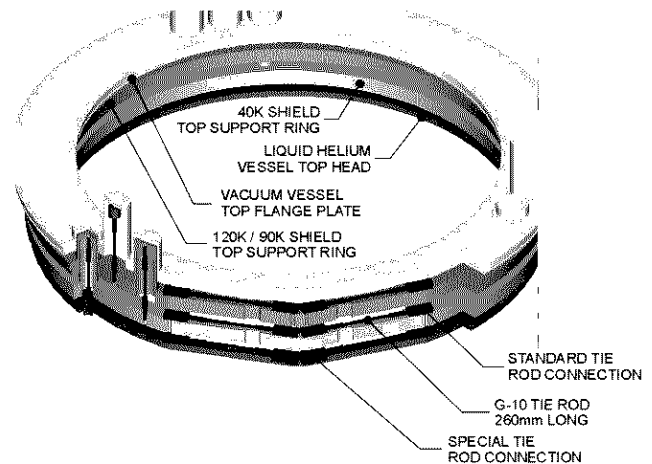


Fig. 5. Lateral Support Anchor Drawing

When the thermal strap was connected there was a net boiloff. With the thermal strap removed there was zero boiloff. The results of all three measurements are shown in Table I below.

### A. Discussion

1) *Heat Load from Current Leads at 4K:* With the thermal link installed, the hermetic power feedthrough to the liquid helium space was colder (6.6 K) than without the thermal link (8.4 K). Nevertheless, with the thermal link installed, the 4 K cold head was overloaded. This means that there was too much heat coming through the current leads. The published conductive heat load (per pair of leads) from American Superconductor ([www.amsuper.com](http://www.amsuper.com)) is 90 mW from 64 K to 4.2 K.

The observed difference in the heat load with the thermal link on and thermal link off was 830 mW\*. This suggests that some other form of heat load is associated with the 4 K thermal link.

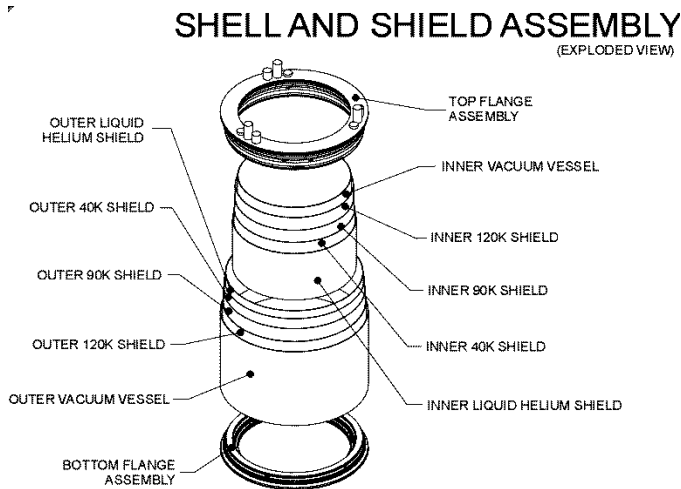


Fig. 6. Shell and Shield Assembly

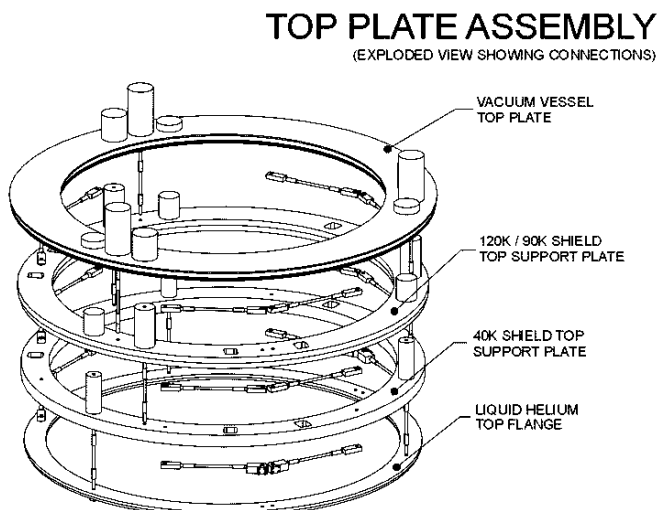


Fig. 7. Top Plate Assembly

2) *Joule Heating with Current Applied:* The theoretical optimum resistances of the leads (optimized for 200 A continuous operation) is 230 microOhms from 300 K to 80 K and 78 microOhms from 80 K to 40 K (1 side).

With the balance of the leads superconducting, this results in a total series resistance of 616 microOhms. This does not include contact resistances, which add up to about 100 microOhms. Thus the expected measured value of the total series resistance (when superconducting) is 700 microOhms. The actual measured resistance was 500 microOhms. This means that there is too much brass in the current leads; this could be reduced.

The values of the cold head temperatures, when combined with the manufacturer's data, allows estimation of the heat load on each stage of the cold heads. The manufacturer's data has a substantial scatter, so this must be taken as indicative rather than accurate. Note that most of the Joule heating load is deposited on the 40 K stage, rather than on the 80 K stage. This suggests that there is inadequate thermal link through the 80 K "capacitor" contact.

3) *Helium Recondensing:* There is an issue with the large temperature difference between the 4 K cold head (3.6 K) and

the helium bath (4.2 K). If this difference is real, it results in substantial lowering of the cold head cooling capacity from 1.5 W to 0.65 W.

4) *Conclusion of Tests:* The novel current lead "capacitor" thermal anchors work well. Overall, the experimental work shows excellent results. We accomplished our goal of achieving zero boiloff at 200 A current.

TABLE I  
EXPERIMENTAL RESULTS

Description (n.m. not measured)	Units	With 4K link	Without 4K Link	Difference due to 4K Link	Without 4K Link
Magnet current	A	0	0	0	200
Shield at 80K	K	60	64.8	4.8	65.8
Cold head at 80K (L)	K	45	45.5	0.5	47.8
Estimated heat load on 80K Shield at 20K	W	35	35	0	40
Cold head at 20K (L)	K	16	17	1	17
Estimated heat load on 20K Cold head at 40K (S)	W	3	3	0	3
Power feed on top of He vessel	K	25	28.8	3.8	36.5
Cold Head at 4K (S)	K	6.6	8.4	1.8	8.65
Estimated heat load on 4K	W	5	10	5	25
Net heat load on liquid He bath	W	6.6	-0.33	0.83*	-0.18
Liquid Helium Boiloff rate	L/hr	0.6	0	-0.6	0

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