LBNL-45288
SCMAG-711

Induction Linac Superconducting Solenoids For the Neutrino Factory Phase Rotation System

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Introduction

An induction linac has been proposed for phase rotation of the muon produced by the decay of pions that have been produced from a fixed target. A solenoidal magnetic filed is used to capture and guide the pions produced at the target. Pion capture occurs in a 20 T field. This field is reduced adiabatically to a level between 1.25 T and 3.0 T. Before phase rotation can occur using an induction linac, the pions must decay to muons in a decay channel that is at least 50 meters long. As the pions decay to muon down the channel, the beam spreads. At the end of fifty meters, a distance of about 7 meters separates the slowest muons (at a momentum of 100 MeV/c) from the fastest muon (at a momentum of 300 MeV/c). If one increases the drift space for pion decay to 100 meters the muons will be spread along a distance of 12 to 14 meters in the channel. One hundred meters of induction linac should be able to bunch the muons to an average momentum of about 200 MeV/c, provided the induction linac acceleration gradient is of the order of 2MV per meter.

Figure 1 below shows the proposed induction linac channel for phase rotation of muons for the neutrino factory. The linac channel is down stream from 50 to 100 meters of muon decay channel. The induction linac channel consists of 40 one-meter long induction linac cells fit into 44 meters of channel. Then there is a drift space and mini-cooler that is 55 meters long. The mini-cooler section is ten meters long. The mini-cooler section consists ten meters of solenoid. One two-meter section contains a liquid hydrogen absorber. Another two-meter long section has a pair of solenoids for flux reversal. Forty-five meters of solenoidal drift channel follow the mini-cooler section. The final 60 one-meter long induction linac cells reside in the 66-meter long channel down stream from the drift section.

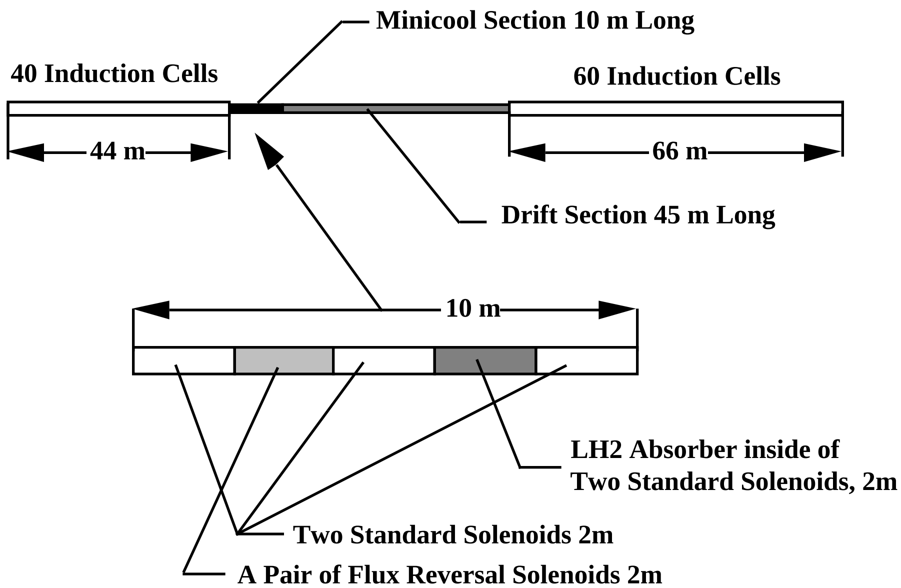

Figure 1. A schematic Representation of a Neutrino Factory Induction Linac Phase Rotation Channel

Phase Rotation and Drift Cells

Figures 2 and 3 on this page and the next page show the cell configurations for a typical one-meter long drift cell and a typical induction linac phase rotation cell. Both figures show the location of the superconducting magnet coil and cryostat within the cell. Figure 2 below shows a typical drift cell. This type of cell can be used 53 meters of the 55-meter long drift section between the induction-linac phase-rotation sections. The only section where the coil geometry shown below can not be applied in the 2-meter long section where the flux in the solenoidal channel is reversed. In this section, there are strong longitudinal forces that push the solenoid coils apart. There must be cold longitudinal support members to carry the forces generated by the flux reversal process.

Figure 3 on the next page shows a typical induction linac cell. The typical linac cell shows how the induction linac must be fit around the solenoid and why the solenoid must be made physically thin so that the Metglas, the voltage dividing structure and the insulator can be brought close to the region where the muons passes through the structure. Because, the metglass is an expensive component for the induction linac, reducing the superconducting magnet thickness and the inside radius of the solenoid cryostat is desirable. Every ten induction linac cells, there is a cell without the acceleration structure. This cell is used for vacuum pumping and beam diagnostics. Hence, 60 linac induction cells take 66 meters of length.

The periodicity of each cell is 1 meter. The gap between the superconducting coils at the ends of the magnet cryostat is 140 mm. There is an 80-mm gap between coils at the center of the solenoid as well. This gap allows the magnet cold mass support to be attached. This is also where the current leads, and cryogen supply to the magnet enters the cryostat. If it is desirable from a beam dynamics standpoint, one can increase the gap in the center of the solenoid to 140 mm, thus reducing the field periodic length from 1 meter to 0.5 meters. The solenoids shown in Figures 2 and 3 generate an average induction of 3 T on axis.

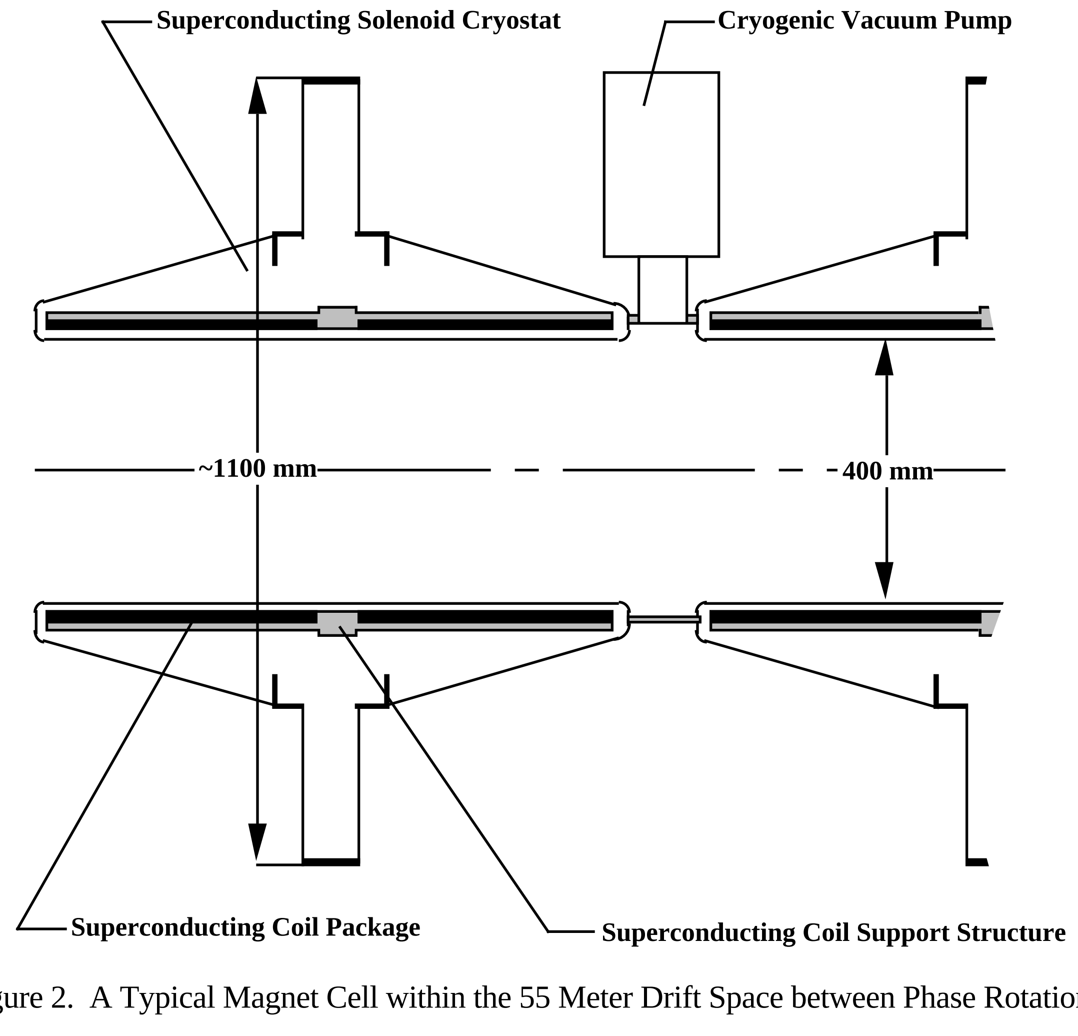

Figure 2. A Typical Magnet Cell within the 55 Meter Drift Space between Phase Rotation Sections

Figure 3 below shows a simplified schematic view of the induction linac structure. The magnet must fit between the acceleration cells the 2 MV of acceleration voltage across the gap between the two magnet cryostats. The acceleration gap between the magnet cryostats shown below is 100 mm. The ends of the superconducting coil must be as close to the ends of the acceleration gap as possible.

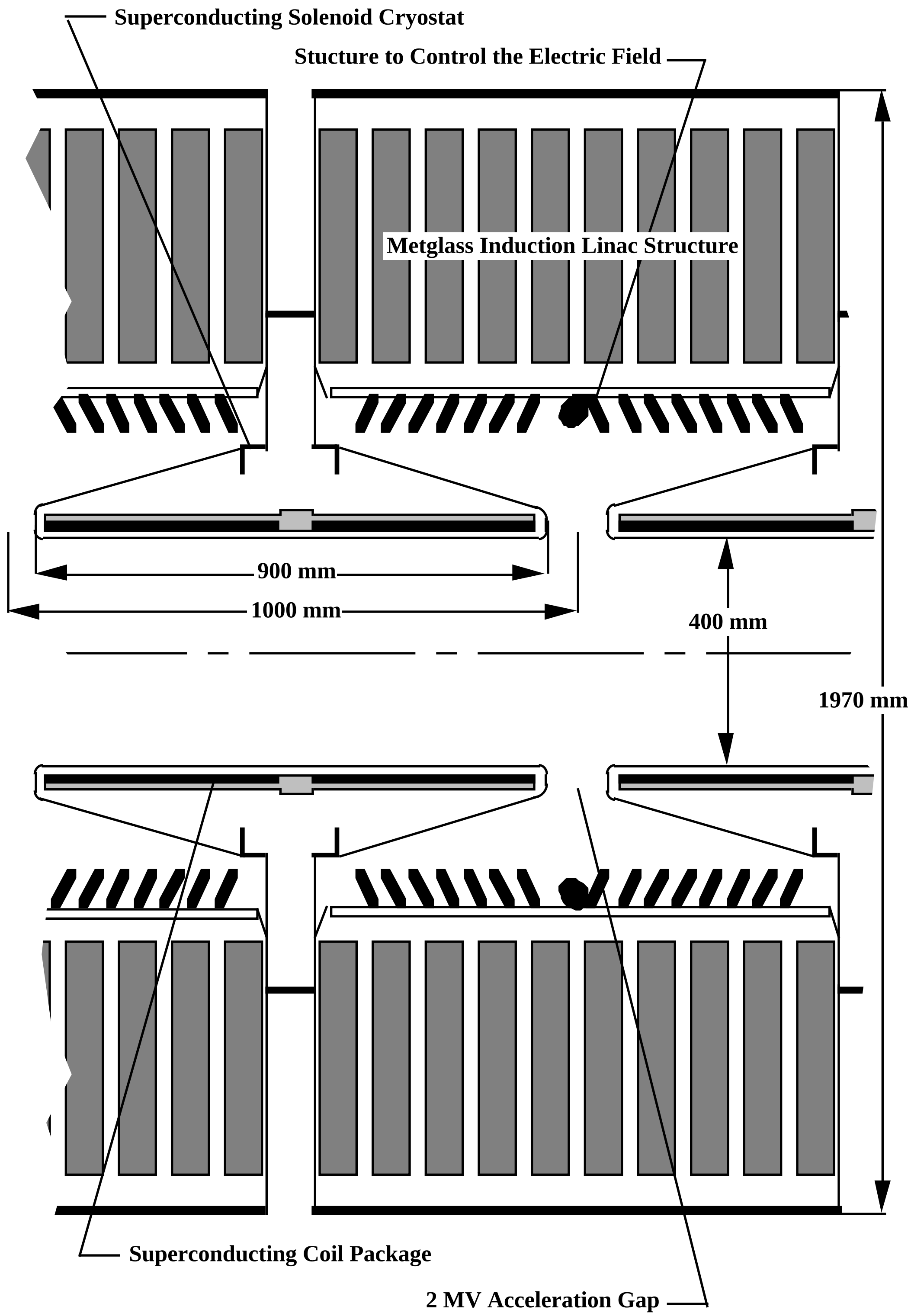

Figure 3. A One-meter Long typical Phase Rotation Linac Cell Showing the Location Of the Linac Structures with Respect to the Superconducting Solenoids

Phase Rotation Superconducting Solenoid Design Options

The requirements for the phase rotation linac solenoids are as follows: 1) the solenoid outside diameter should minimized. This means that the magnetic induction in the channel should be maximized. The magnitude guide magnetic field and the size of the phase rotation channel both affect the stability of the muon beam. If the channel induction is too high beam blow up will occur due to the periodic structure of the magnetic field[1]. Large diameter coils produce a smaller on axis field variation than do smaller diameter coils for a given gap between the superconducting coils. 2) The radial thickness of the solenoid cryostat should also be minimized. This allows the induction linac acceleration structure to be brought closer to the axis of the machine. As the magnetic field goes up, the thickness of the superconducting magnet that creates the field must also go up. The support structure that supports the superconducting coil goes up as the field on axis is increased. 3) The space between the induction linac cells must be minimized. This means that the space used for the cold mass support system, the electrical leads and the cryogen feed system must fit in this minimum space.

Several solenoid configurations were studied. The on axis average induction varied from 1.25 T to 3.75 T. The warm bore radius for the magnet varied from 300 mm (the 1.25 T case) down to 173 mm (the 3.75 T case). The coil and cryostat thickness ranged from 55 mm for the 1.25 T case to nearly 90 mm for the 3.75 T case. By winding the coils separately and shrink fitting them in the coil support structure, the cryostat thickness could be reduced. The multi-layer insulation thickness could also be reduced at the ends of the cryostat, further reducing the physical thickness of the cryostat in this region. The solenoid magnet was designed to be cooled indirectly using flowing two-phase helium in cooling tube attached to the support structure. The 40 K helium used to cool the shield is carried in tubes attached to the shields.

Figure 4 below shows a cross-section of a superconducting solenoid that is designed to generate an average induction of 3 T on the axis of the phase rotation linac. The inner bore of the solenoid cryostat is 400 mm. This allows a 200 MeV muon beam with a nominal diameter of 384 mm (at 3 T) to pass through the solenoid without loss (except from muon decay). Figure 5, at the top of the next page shows a cross-section at the 60-mm thick end of the magnet cryostat. The distance from the end of the superconducting coil to the outside end of the cryostat can be reduced to 20 mm. If an additional support clip is needed at the end of the coil, it can be accommodated in the space shown.

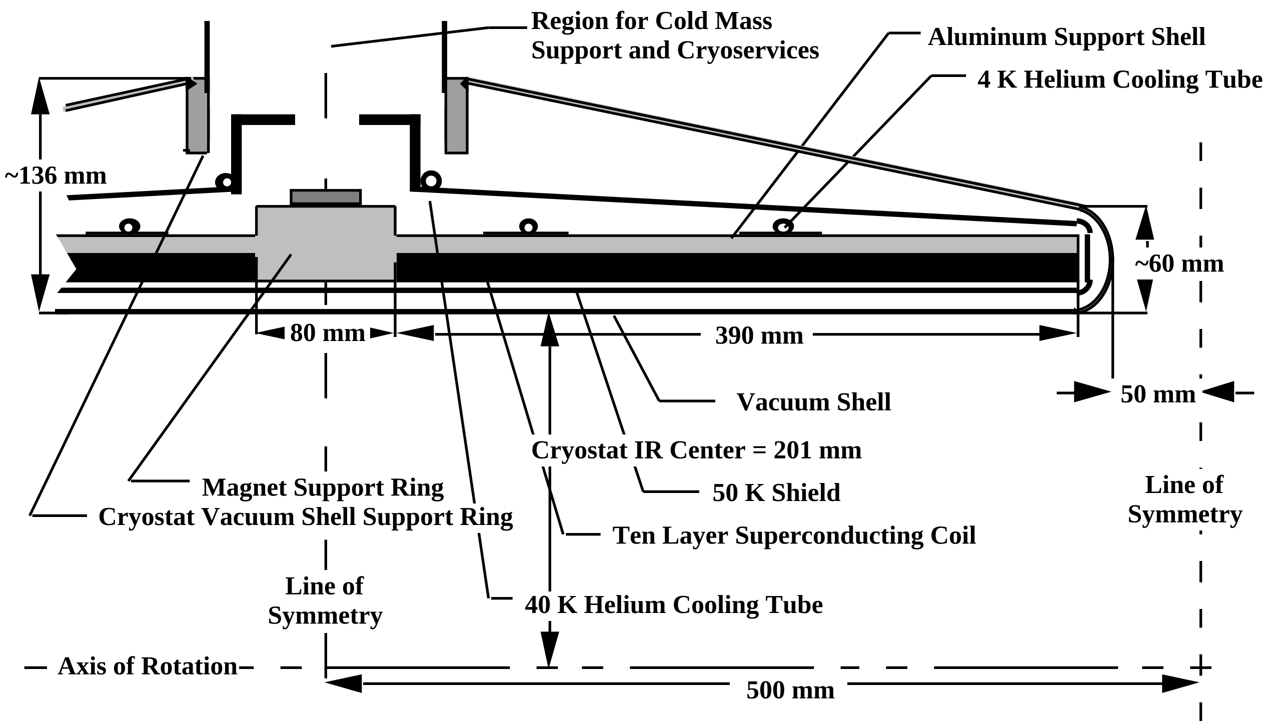

Figure 4. A cross-section of the Induction Linac Superconducting Coil and Cryostat

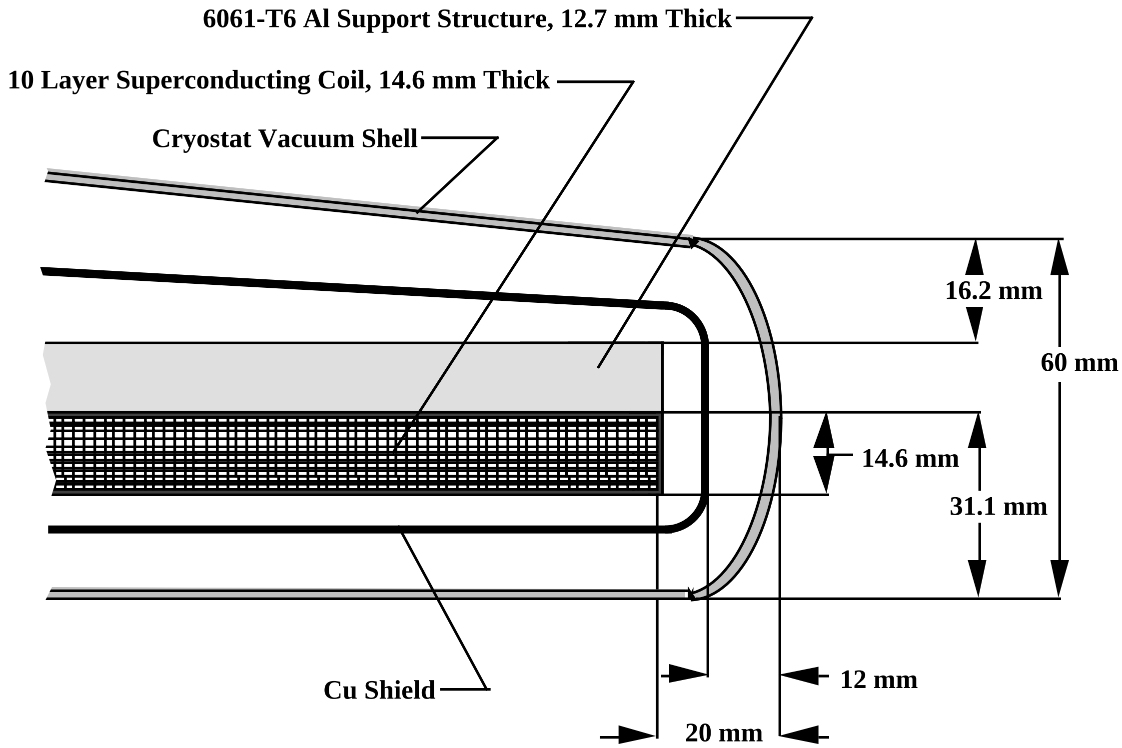

Figure 5. A Cross-section of the End Tip of the Induction Linac Solenoid

The proposed conductor for coil shown in Figure 5 above is a standard MRI magnet conductor that is 1 part Nb-Ti and 4 parts RRR=70 copper. This is the same conductor used for the RF solenoid[2]. This conductor has fifty-five 85-μm filaments twisted with a twist pitch of 12.7 mm. The bare matrix dimensions of the conductor are 0.955 mm by 1.65 mm. The insulation on the conductor is 0.025 mm thick. At an average design induction of 3.0 T on axis, the coil design current is about 521.3 A. The use the RF solenoid conductor results in a 10 layer coil that is 14.6 mm thick (including 2 mm of ground plane insulation). If the coil design current is reduced to 300 A, the coil package will have 12 layers and it will about 15.4 mm thick. The bare conductor dimensions would be 0.81 mm by 1.12 mm. A lower current magnet can be cooled using a 1.0 to 1.5 W Gifford McMahon cryocooler[3].

It is proposed that the coils be wound and cast on a form that is removed after the coil is cured. The coils can be impregnated as a wet lay up or they can be wound dry and vacuum impregnated. After curing the coils are removed from the mold and machined at the ends and on the outer radial surface. After the coils are machined they can be shrunk fit into 6061 aluminum support structure that has been machined so that the coils closely fit with in it. When the magnet is cooled from 300 K to 4 K the aluminum support structure shrinks over the superconducting coil packages that have a lower total thermal contraction coefficient from 300 K to 4K (4.2×10^{-3} for the aluminum versus 3.2×10^{-3} for the superconductor copper and insulation in the superconducting coils). Since the longitudinal force on the coils push them toward the center of the magnet, a simple clip can be used to support the coils from the end inside of the aluminum support structure. Each coil has an even number of layer (10 12 or 14 depending on the size of the conductor used) so that the coil leads come out of the same end of the coil. It is proposed that the coil leads be fed through the support structure at the island between the two coils. This allows both pairs of leads to be interconnected to the leads that carry the current to and from the outside world. An alternative approach is the coil lead routing is to bring the leads out the gap end of the coil. The leads then have to brought to the center of the magnet on the outside of the aluminum support structure. In either case, it is recommended that the coil be covered with a layer of pure copper that is 1 mm thick. This layer of copper distributes any heat that may leak on to the coil package through holes in the 40 K-shield.

Table 1. Phase Rotation Solenoid Parameters

Magnet Physical Parameters	
Induction Linac Cell Length (mm)	1000.0
Magnet Cryostat Length (mm)	900.0
Magnet Coil Package Length (mm)	860.0
Number of Coils in the Coil Package	2
Length of Each Superconducting Coil (mm)	390.0
Inner Cryostat Radius (mm)	201.0
Superconducting Coil Inner Radius (mm)	224.3
Superconducting Coil Thickness (mm)	14.55
Support Structure Thickness (mm)	12.7
Magnet Cryostat Thickness at Ends (mm)	60.0
Magnet Cryostat Thickness at Center (mm)	136.0
Cold Mass per Magnet Cell (kg)	247.0
Overall Mass per Magnet Cell (kg)	292.0
Magnet Electrical Parameters	
Average Central Induction (T)	3.00
Peak Induction in the Windings (T)	~4.5
Number of Turns per Cell	4580
Magnet Design Current (A)	521.27
Magnet Design Operating Temperature (K)	4.4
Conductor Critical Current at Operating T (A)	~790
Magnet Stored Energy per Cell E (kJ)	618
Magnet Self Inductance per Cell (H)	4.55
Superconductor Matrix J ($A\ mm^{-2}$)	331
E J^2 Limit per Magnet Cell ($J\ A^2\ m^{-4}$)	6.76×10^{22}

Table 1 above presents the proposed design parameters for a phase rotation solenoid that uses a bare superconductor with the dimensions of 0.955 mm by 1.65 mm. The coil package is 860 mm long. It fits into a cryostat that has a maximum length of 900 mm. The magnet is designed to operate at a temperature of 4.4 K. At this temperature, the magnet design current is a little over 80 percent of the magnet short sample current along the load line. One can increase the magnet margin by increasing the number of layer from ten to twelve. A twelve layer coil that is 17.1 mm thick would have a design current of 434.4 A. The design current is less than 74 percent of the short sample current along the load line.

The primary mode of quench protection is quench back from the 6061 aluminum support structure that is inductively coupled to the superconducting coil circuit[4]. If needed, cold diodes and resistors can be put across the coils inside the cryostat. One must look at the magnet fault modes before deciding on the appropriate quench protection method for the phase rotation induction linac solenoids.

Cold Mass Support and Current Leads

The space available longitudinally for leads, cryogenic services and cold mass supports is about 85 mm at the center of the magnet. There is not enough room for a self centering support system that is similar to the support system used for the solenoid around the 805 MHz RF cavity experiment. The cold mass of phase-rotation solenoid (including the 40 K shield and lower lead assembly) is estimated to be about 250 kg. We propose that a pair 50 mm diameter oriented carbon fiber tubes (with a wall thickness of about 3 mm) be used to carry forces from the cold mass to 300 K. Vertical forces would be carried in tension and compression in the cylinder walls. Cross-wise forces, both longitudinal and radial would put the support cylinders into bending. The tubes, which would be about 600 mm long, would have to be clamped to the magnet support structure at the middle of the tube. A 40 K thermal intercept would be clamped to the carbon fiber tubes 150 mm from each end. Thermal contraction of the support mandrel would put the tubes in bending. Thermal contraction of the magnet support structure would have little effect on the tube along the axis of the cylinder. A high strength carbon fiber is proposed, to maximize the ultimate stress of the support cylinder to forces that put it in bending. Carbon fiber has a very low contraction coefficient in the direction of the fiber[5]. The support cylinders would see a small tensile load parallel to the axis of the cylinder due to thermal contraction of the cylinder when the magnet is cold. The primary problem with the proposed support system may be the spring constant of the support system in the longitudinal direction. The magnet coils are in unstable equilibrium in the longitudinal direction. If the magnet is displaced longitudinally, the force generated because of this displacement will be in the direction of the displacement. The support system, in the longitudinal direction, must have a spring constant that is greater than the force constant in that direction. It is the support system spring constant and the magnetic force constant that influences the thickness and the material selection for the cold mass supports. See Figure 6 below for a schematic representation of the cold mass support system.

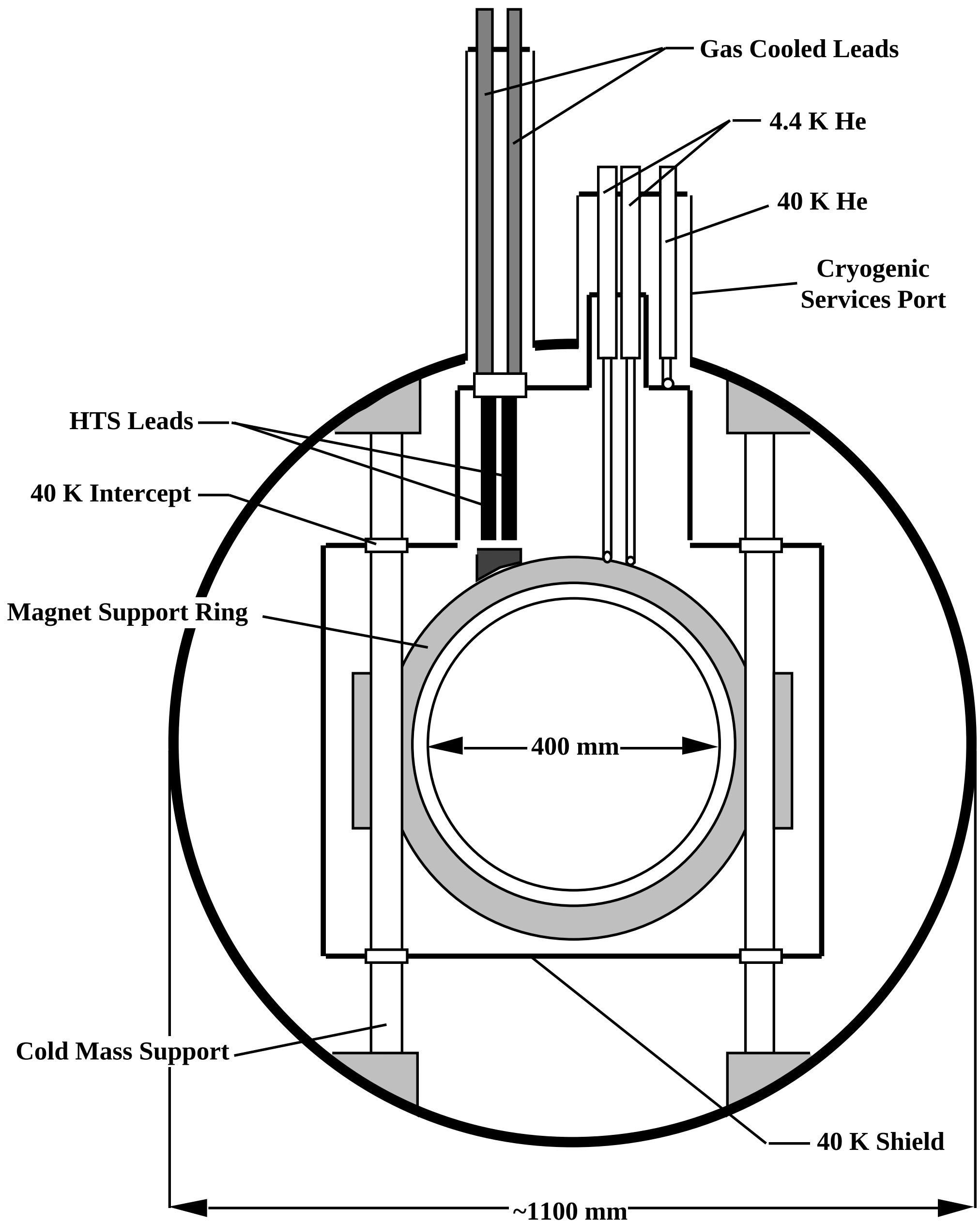

Figure 6. A Cross-section View Showing the Cold Mass Support Tubes,
The HTS and Gas Cooled Electrical Leads, and the 4 K and 40 K Cryogenic Services Port

Since there is a solenoid magnet every meter down the phase rotation channels and the drift spaces between the phase rotation linac sections, leads must be brought out of each of these magnets. One has two choices: 1) All of the magnets or 20 to 25 meter long subsets can be hooked in series and run off of common power supply. Inter-connects between the solenoids can be either superconducting or conventional copper cable. 2) Each magnet can have its own set of leads to room temperature and its own power supply, so individual cells can be tuned. Conventional gas-cooled electrical leads can be used to carry current from room temperature to 4 K, when there are only a few of these leads. If each magnet must have its own set of leads, the leads between 4 K and 40 or 50 K must be made from high temperature superconductor (HTS). The leads from room temperature to the top of the HTS leads at 40 to 50 K should be gas-cooled, unless the solenoid is cooled using a cryocooler. The magnet shown in Table 1 has a design current of 521 A. This means that the HTS leads and the gas-cooled leads should be rated for a current slightly above the magnet design current. It is proposed that HTS leads be used between 4 K and the 40 K temperature of the shield. From the shield temperature on up, the leads should be gas cooled using 40 K shield gas brought from the refrigerator cold box. Using this scenario, the magnets to be operated with individual power supplies or several magnets can be operated off of a single power supply. Currently, the use of HTS leads on the magnet favors setting the magnet design current below 600 A. Improvement in HTS lead performance will allow one the design current to a higher value. The magnet described in this report can be built using today's technology.

If the phase rotation solenoid must operate off of a GM cryocooler instead of a conventional refrigerator with a J-T circuit and a 40 K gas source, the lead current should be set below 300 A. The heat load that determines the cryocooler design parameters is dominated by the conduction heat leak down the leads solid copper leads to the cryocooler first stage. At a current of 521 amperes, the total heat load into the cryocooler first stage approaches 60 watts. Over 50 watts of this heat load is from the copper leads between 300 K and the first stage temperature of the cryocooler. At a current of 300 A, the heat load into the first stage is under 40 watts. The heat conduction down the HTS leads is quite low (about 0.25 W). As a result, the heat load into the second stage can be kept below 0.5 W. A Gifford McMahon cryocooler used to cool a single solenoid magnet should have a refrigeration rating of 1.5 W at 4.4 K. This kind of cryocooler will produce about 40 W of refrigeration at 50 K[3]. As a result, the magnet temperature (the second stage temperature) can be as low as 3.5 K. If the magnet is operated in the persistent mode, the rated cryocooler refrigeration at 4.4 K can be below 1.0 W. The first stage of the cryocooler can warm up to 70 K while the magnet is being charged. Once the magnet is put in persistent mode, the first stage cryocooler temperature will drop down to about 50 K. The magnet temperature will be about 3.8 K while it is operating in persistent mode.

Cooling the Phase Rotation Solenoid and Its Shields Using a Conventional J-T Refrigerator

The induction linac superconducting solenoids are cooled by conduction from the 6061-aluminum support structure. The aluminum support structure will be cooled by two-phase helium flowing in tubes attached to the support structure. Two-phase helium cooling is commonly used to cool detector magnets and magnets that are used in experiments. The advantages of two-phase tubular cooling are as follows[6]: 1) There is very little helium inventory within the magnet. There is very little helium to be boiled in the event of a magnet quench. 2) The two-phase helium tubes have a high pressure rating (over 10 MPa). This means that the magnet cryostat is not a pressure vessel and there is not the potential safety hazard that a bath cryostat might have. 3) Two-phase helium cooling does not require a cold compressor or a helium pump to circulate the helium through the magnet cooling system. The pressure supplied by the refrigerator compressor is sufficient to circulate the helium through the magnet cooling tubes. 4) The helium in a two-phase helium cooling circuit decreases as along the flow circuit. In conventional supercritical helium flow circuits, the temperature rises along the flow circuit. Additional helium mass flow is needed in a supercritical flow circuit to limit this temperature rise. 5) The pressure drop along a two-phase helium flow circuit is generally lower than for a supercritical helium flow circuit. 6) If needed, cooling for leads and shields can be drawn from the two-phase helium flow circuit, but that is not proposed for the induction linac solenoids. The flow instability in a two-phase flow circuit talked about in the literature can be avoided if the flow circuit is properly designed. A large number of superconducting solenoid magnets have been cooled using forced flow two-phase helium in tubes.

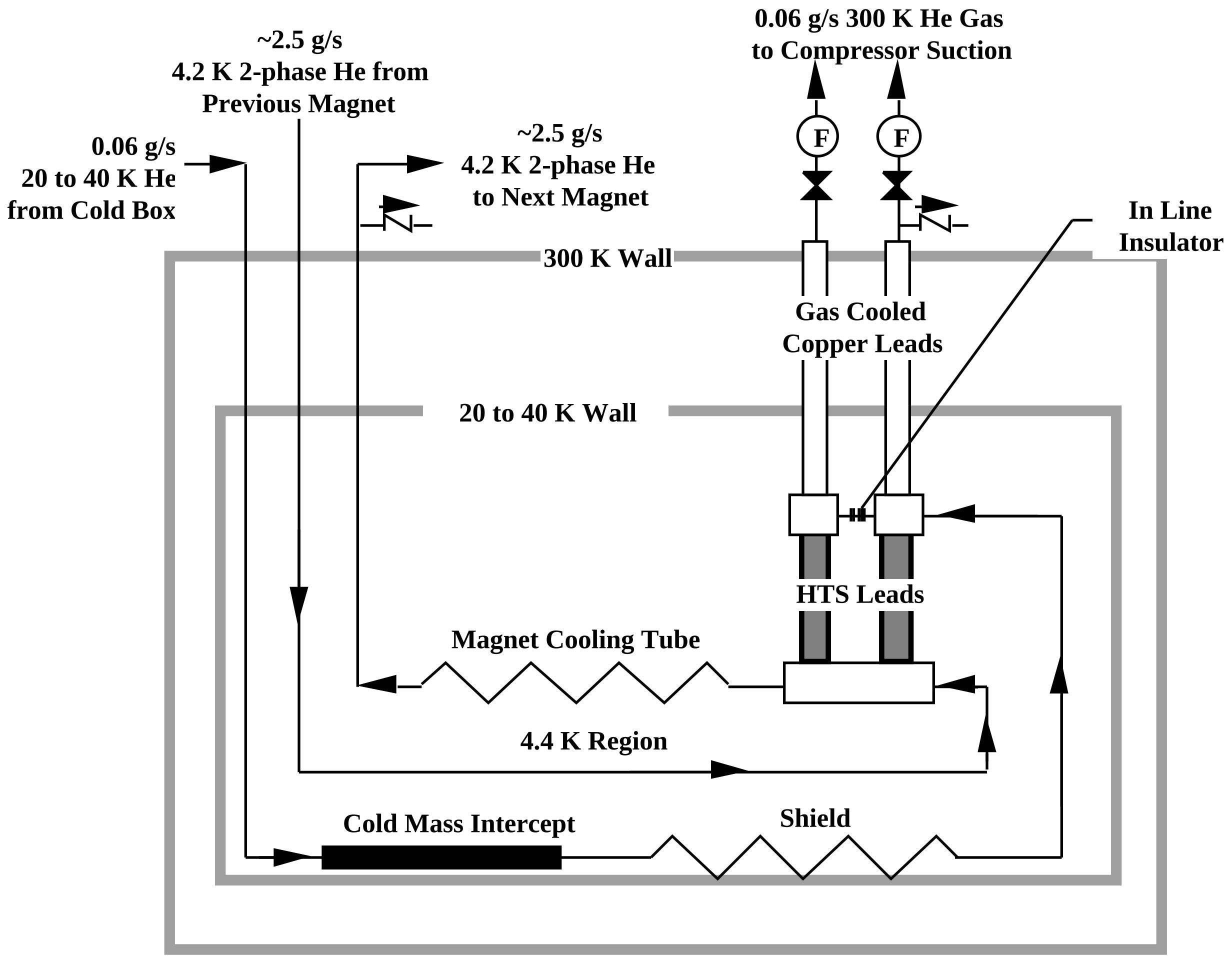

Figure 7. Cryogen Distribution within the Induction Linac Solenoid Cryostat

Figure 7 above show the proposed two-phase helium cooling system for the induction-linac phase rotation magnets. It is assumed that the magnet shown is one of twenty to twenty-five magnets that are cooled in series from the two-phase helium refrigerator and control dewar. If twenty to twenty-five magnets are cooled, the mass flow rate through the flow circuit should be about 2.5 grams per second. This two-phase helium flow can be carried by an aluminum tube with an outside diameter of 10 mm and a wall thickness of 1 mm. This tube would have a burst pressure above 35 MPa. The two-phase helium tube would be attached to the superconducting coil support structure, the base of the HTS leads and the attachment points of the cold mass supports. The heat that is added to the two-phase helium flow stream in each of the solenoid is expected to be about 0.5 W.

The shield gas comes from the refrigerator at a temperature of about 35 K. This gas enters the magnet cryostat through a single vacuum insulated tube. The helium flow in this tube is about 0.06 grams per second. The shield gas stream picks up heat from the cold mass supports and radiation on the shield. The expected heat load into this stream is about 4 watts. The 35 K helium stream temperature rises about 13 K as it flows to the base of the gas-cooled leads. It is proposed that the gas used to cool the shields and the cold mass support intercepts be used to cool the gas-cooled leads between about 48 K and room temperature. The gas exiting the room temperature end of the gas-cooled leads returns warm to the refrigerator compressor suction. The mass flow of 0.06 grams per second per magnet in the shield circuit is determined by the needs of the gas-cooled electrical leads. If the magnet current were 300 A, instead of 520 A, the gas flow in the shield and lead circuit would be about 0.035 grams per second. For this reason, one can make an argument for reducing the magnet current.

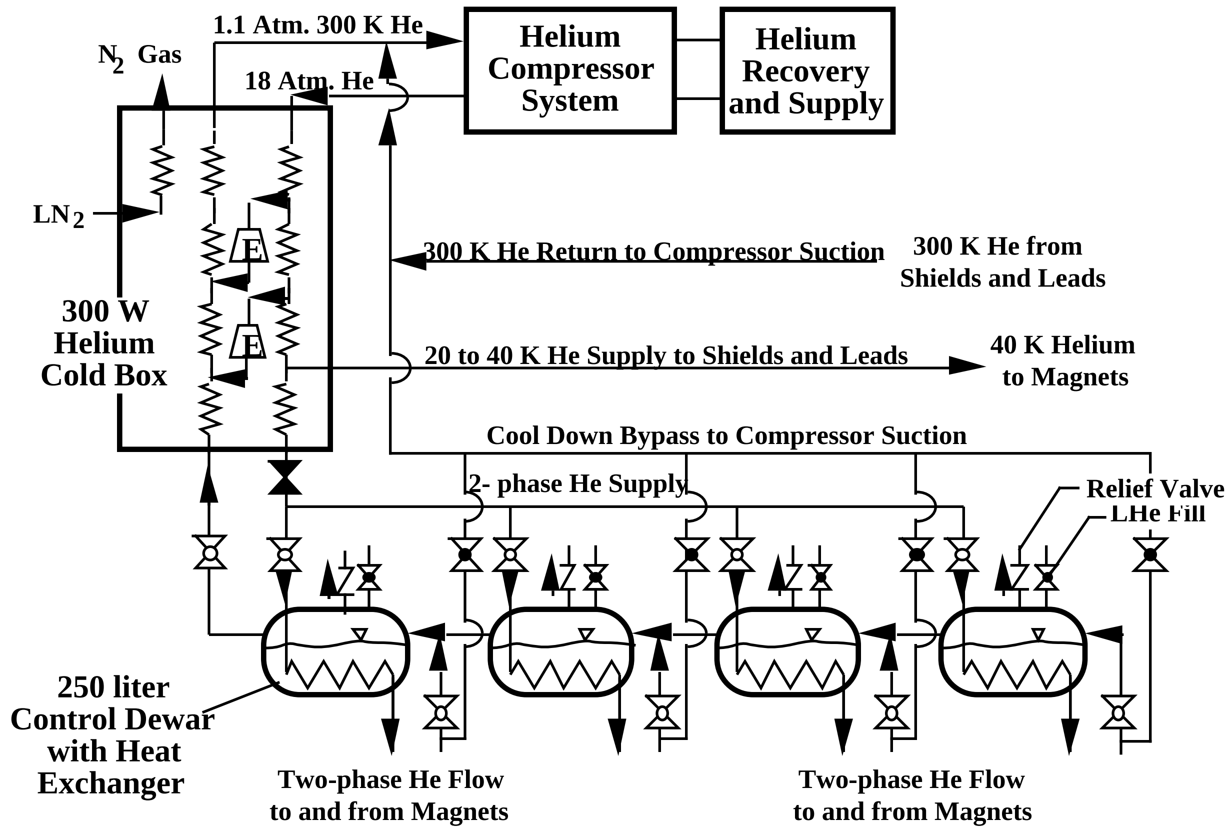

Figure 8. The Cryogenic Refrigeration Distribution System for the Phase Rotation Linac Solenoids

Figure 8 above shows a schematic of the refrigerator and helium flow system that delivers two-phase helium and 40 K helium gas to the magnets in the induction linac tunnel. The 650 W refrigerator shown in Figure 8 will cool one hundred solenoids that each have separate 520 A leads to room temperature. If the magnet lead current is reduced to 300 A, the 650 W helium refrigerator shown above would be sufficient to cool the entire 165 meter long string of solenoids that make up the phase rotation induction linac system.

The flow system shown above assumes that 20 to 25 solenoids are cooled with two-phase helium in a series circuit. Each of these series circuits has a 250-liter control-dewar with a heat exchanger to sub-cool the two-phase helium entering the magnet flow circuit. The heat exchanger within the control-dewar is the key to making the two-phase flow operate in stable way. The pressure on the two-phase helium in the control-dewar is at the pressure of the low side of the refrigerator heat exchanger. This pressure and hence the temperature of the liquid helium is always lower than the temperature and pressure of the two-phase helium entering the heat exchanger from the refrigerator J-T valve. Since the pressure drop along the two-phase helium flow circuit is about 0.015 to 0.03 MPa (2.2 to 4.5 psig), the maximum temperature drop across the heat exchanger in the control-dewar is 0.1 to 0.2 K. The gas phase in the two-phase helium flowing from the J-T valve is condensed in the control-dewar heat exchanger. The helium flow stream leaving the control-dewar is pure liquid helium that is slightly sub-cooled. Because the control-dewar heat exchanger shifts the two-phase helium from the gas side of the two-phase dome to the liquid side of the two-phase dome, the pressure drop in the two-phase helium flow circuit is reduced a factor of three[7].

Once can use the helium refrigerators for magnet cool down. Flow from the J-T valve goes through the control dewar heat exchanger to the string of twenty or so superconducting magnets. Warm helium returning from the superconducting magnet string should bypass the control dewar and the refrigerator cold box and return to the compressor suction directly. The cooling for the magnets comes from the refrigerator liquid nitrogen pre-cooling and the output from the refrigerator expansion engines. The refrigerator is capable of cooling the string of magnets without any added liquid helium. However, liquid helium put in the control dewar when the string of magnet reaches 25 K will speed up the cool down.

In order to cool the magnet shields and the gas cooled leads from 40 K to room temperature, a separate 30 to 40 K helium flow circuit must be brought out from the refrigerator. The 40 K flow circuit is brought out from the high-pressure side of the refrigerator heat exchanger at some point below the temperature where the gas enters the second expansion engine. The gas withdrawn from the refrigerator to cool the magnet shields and leads is returned to the refrigerator at the compressor suction. During normal operation the 4.4 K refrigeration required is 0.5 W per solenoid plus a little over 90 W for heat leaks into the helium transfer lines and the control dewars. In addition, 9.9 grams per second of helium gas at 40 K is needed to cool the magnet leads and shields. The additional 9.9 grams per second of 40 K gas flow means that additional heater exchanger area is needed in the refrigerator to cool the extra gas flow. The need for additional gas flow is also reflected in larger compressors as well. The cooling required for 165 meters of magnet is equivalent to about 240 W of refrigeration at 4.4 K. One Fermilab satellite refrigerators can be used to cool 165 solenoids with 520 amp gas-cooled leads. If the magnet current is reduced to 300 A, the 165 magnets can be cooled using two Model 1400 refrigerators with wet expansion engines replacing the J-T valves. Connecting the magnets in groups of twenty, using superconducting interconnects, will further reduce the required refrigeration needed for magnet cooling. It is clear that refrigeration requirement are dominated by the magnet current and the number of gas-cooled leads, even when HTS leads are used between 4 K and 40 K.

The time needed to cool down the 165 meters of superconducting solenoids in the induction-linac phase-rotation channel is dependent on the size of the helium refrigerator doing the cooling. When every magnet has a pair of 520 amp-leads, the equivalent of 240 W of refrigeration available to cool down the magnets. It is estimated that the 45 metric tons of cold mass in the magnets and the transfer lines will take fifteen days to be cooled down using a 250 W refrigerator. If the lead current is reduced to 300 A and each magnet is separately powered, the equivalent refrigerator size is reduced to 200 W and the magnet system cool down time is increased to three weeks. If the number of gas cooled leads is reduced to the absolute minimum, the equivalent of about 150 W of refrigeration is still needed and the magnet system. As a result, the cool down time is extended to about four weeks.

Power Supply and Quench Protection

The induction linac solenoids are DC magnets. There is no real restriction on the time needed to charge the magnets from the accelerator operation standpoint. Theoretically the magnets could be operated in persistent mode, but it is likely that the operators of the induction linac may want to tune the machine as it carries muons. The rate at which the induction linac solenoids can be charged is limited by eddy current heating in the 6061-aluminum support structure for the solenoid superconducting coils. Charging the solenoid to full current in a half-hour (1800 seconds) will result in eddy current heating in the aluminum support structure of less than 0.05 W. The 1-mm thick copper layer around the coil will heat the coil more unless it is slit in the longitudinal direction and it is insulated from the support structure.

The voltage across the coil needed to charge a 520 A magnet in 1800 seconds is about 1.31 V. In order to overcome the voltage drops in the cables and the power supply diodes, a power supply for a single magnet should produce about 3 volts. A 2 kW (600 A and 3.3 V) power supply should be capable of charging a single phase-rotation solenoid magnet. If twenty magnets are hooked in series, the power supply should be rated at 600 A and 30 to 50 volts depending on whether superconducting or normal interconnects hook the phase-rotation solenoids together. If the magnet design current is reduced 300 A, a 1.4 kW (350 A and 4 volts) power supply is needed. For twenty magnets hooked in series, the voltage requirements for the power supply should be rated at 350 A and 40 to 60 V depending on the type of interconnects that used between the magnets.

The simplest and least expensive type of power supply is one that regulates the charging voltage as the magnet is being charged and the magnet current once the magnet has reached its desired current. It is not clear if the phase rotation solenoids require any more than that. In many accelerator applications, control of the voltage and current is required when the magnet is being discharges as well as when it is being charged. The most complex power supplies have full control of the voltage and current at both positive and negative currents in the magnets. It is probable that the simplest type of power supply can be employed for the phase-rotation solenoids. Figure 9 on the top of the next page shows the simplest power supply with a resistor to discharge the magnet. The quench protection system for the magnet shown in Figure 9 is a set of bypass cold diodes and resistors to balance the voltage in the circuit.

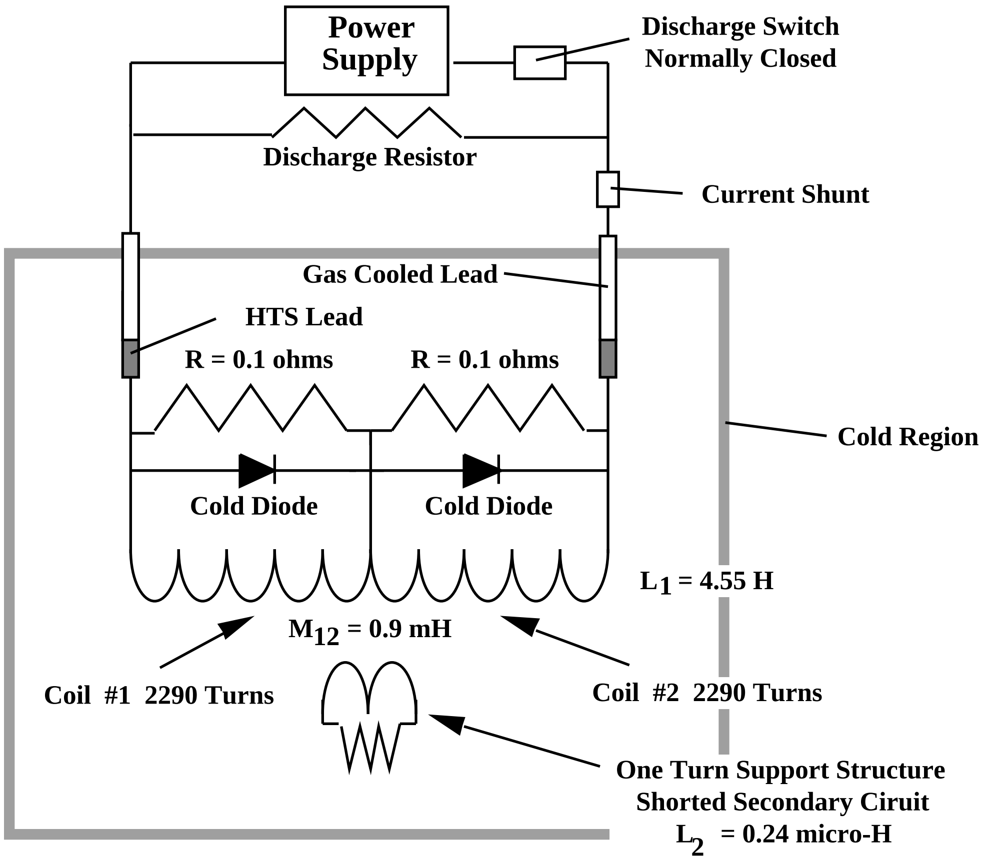

Figure 9. The Charging System and Quench Protection System for a Single Phase Rotation Solenoid

The magnet charging system shown above has a dump resistor across the power supply and the magnet. To discharge the magnet the dump switch is opened allowing the magnet to discharge with a time constant of 1200 seconds. Diodes in series with the dump resistor can prevent current from flowing in the resistor as the magnet is being charged. If the magnet design current is 521.3 A, the resistance of the dump resistor would be 3.8 m-ohms. If the magnet current is reduced to 300 A, the magnet self inductance goes up to 13.78 H and the dump resistor resistance goes up to 11.5 m-ohm. The dump resistor shown in Figure 9 is only used for discharging the magnet under normal operating conditions.

A single phase-rotation solenoid is completely self-protected, while quenching, because a current change in the magnet coil induces a current in the aluminum support structure, which is inductively coupled to the superconducting coil. This induced current in the aluminum support structure heats the magnet and causes both superconducting coils to become normal. This phenomena is called quench back. The cold diodes shown in Figure 9 allow the current in a quenching coil to be by-passed, thus reducing the hot spot temperature of that coil. Further study is needed to see whether the use cold diodes are worth the extra trouble and expense.

Quench protection of a string of solenoids in series is different than for a single solenoid. Inducing all of the magnets in the string to become normal, when one magnet quenches can protect a string of solenoids. One can be done using heaters on the magnets or one can cause the magnets to go normal through quench back. In both cases, the quench protection system is triggered by comparing the voltage drops across the coils in the string. The dump resistor shown in Figure 9 could be replaced by a varistor resistor that has a voltage drop of 500 V at the magnet design current[8]. Since the aluminum support structure is closely coupled (~85 percent) to the superconducting coils, the varistor will drive most of the coil current into the aluminum support structure, thus driving all of the coils in the string normal through quench back. Figure 10 on the next page illustrates this type of quench protection system

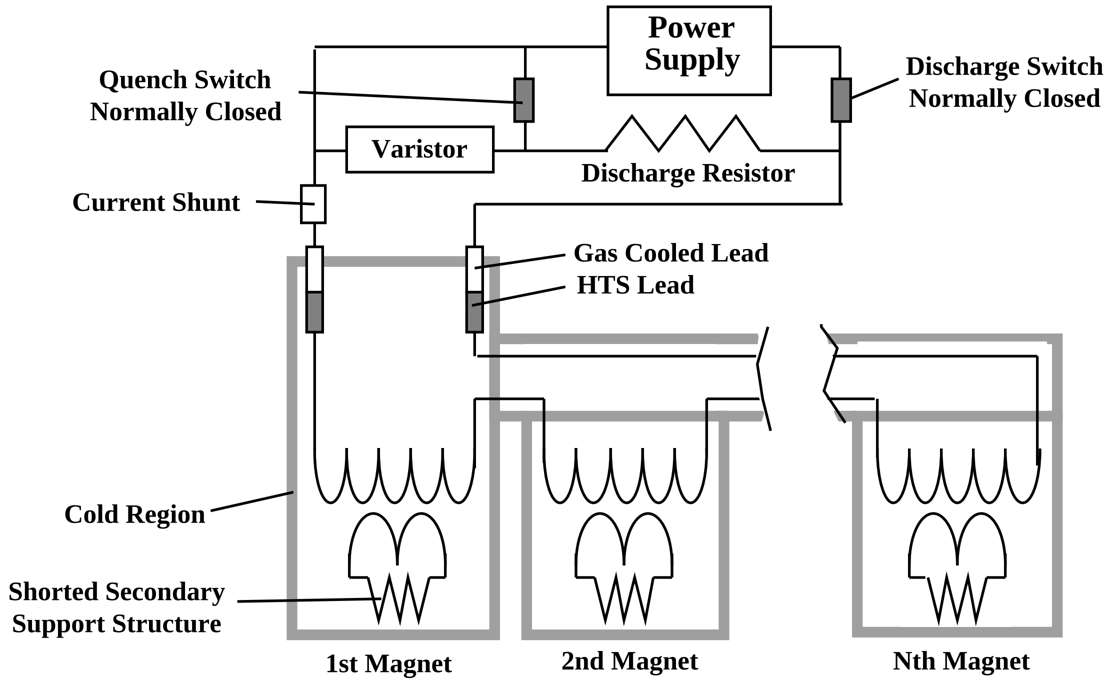

Figure 10. The Charging System and Quench Protection System for Several Solenoids
Note: The Varistor Forces Current into the Inductively Coupled Support Structure

Magnet System Cost

The cost of a single magnet was estimated using a cost algorithm based on stored energy and a cost algorithm based on the mass of the coil and cryostat[9]. The estimated cost of a single solenoid based on stored energy is 290k$ and the estimated cost based on the magnet mass is 280k$. Table 2 below presents a breakdown of the cost of a system of 165 meters of solenoids used for the induction-linac phase-rotation system shown in Figure 1. The magnet cost estimate includes: the superconducting solenoids and their cryostat, the refrigerator, the cryogenic distribution system, and the magnet charging system. The costs given in Table 2 are based on 521-ampere magnets each with its own power supply. Designing the magnets to operate at lower current and running several magnets in series will reduce the cost somewhat. It should be noted that the magnet system cost is dominated by the superconducting solenoids.

Table 2. The Cost of Various Components for Induction Linac Channel Magnets

Magnet System Component	Cost (M$)
155 Meters of Standard Solenoids @ 140 k$ per meter	21.7
Ten Meters of Special Solenoids @ 250 k$ per meter	2.5
Cryogenic Refrigerators, one @250 W	0.9
Cryogenic Distribution System	0.6
165 Standard 600 A, 4 V Power Supplies	0.7
Power Distribution System and Dump Resistors	0.4
Control System for the Magnets and the Refrigerators	0.7
TOTAL MAGNET SYSTEM COST	27.5

Concluding Comments

It appears that one can build physically thin 3 T solenoids that can be housed within an induction-linac. The solenoid design concept developed for the phase-rotation solenoids can be applied to solenoids that can be housed within 70 MHz RF cavities for RF phase-rotation. It also appears that the design presented in this report can also be applied to magnets that part of 200 MHz RF cavities that are part of the muon cooling sections of the neutrino experiment. While the magnets studied in this report appear to be feasible using state of the art superconductors and cooling techniques, considerable engineering will be needed to develop a reliable magnet that can be replicated for the phase rotation channel.

Acknowledgements

The author wishes to thank S. S. Yu for his input in determining what were important parameters for the induction linac solenoids. Discussions with D. L. Vanecek and R. E. LaFever helped cement the magnet design. Their design work was important because it showed that the magnet can be made to fit within a realistic induction linac acceleration structure. This work was performed at the Lawrence Berkeley National Laboratory with the support of Fermilab and the Office of Science, United States Department of Energy under contract number DE-AC03-76SF00098

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LBNL-45288
SCMAG-711

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March 2000

* This work was performed the Lawrence Berkeley National Laboratory with the support of Fermilab and the Office of Science, United States Department of Energy under contract number DE-AC03-76SF00098