A Thin Superconducting Solenoid for Use in a Phase Rotation Induction Linac*

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Abstract— **One of the proposals for delivering a cooled muon beam to a muon collider or a high intensity neutrino source uses an induction linac to phase rotate the muons that result from the decay of pions produced by a high intensity proton beam on a target. An induction linac with an acceleration gradient of 2MV per meter is proposed to produce bunches of muons that have a momentum of 200 MeV/c. The induction accelerator is assembled around the 3T superconducting solenoids needed to contain the muon beam. The superconducting solenoid must have a warm 100-mm gap at 1000-mm intervals down the phase rotation channel. The acceleration structure for the induction linac is around this gap. The superconducting solenoid will have an inside warm radius of 201 mm. The thickness of the superconducting magnet and its cryostat must be about 60 mm near the acceleration gap. An access region of 85 mm between induction linac sections is allowed for the superconducting coil cold mass supports, the electrical leads and the supply of cryogenic cooling. This report presents a design for a 3 T phase rotation induction linac superconducting magnet system, its cryostat, and its cooling system.**

I. INTRODUCTION

An induction linac has been proposed for phase rotation of the muons produced by the decay of pions that have been produced from a fixed target. A solenoidal magnetic field 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 about 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 muons down the channel, the beam spreads. At the end of the decay channel, 7 meters separates the low momentum muons (100 MeV/c) from the high momentum muons (300 MeV/c). 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.

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 [1]. The drift space is 45 meters long, and the mini-cooler section is 10 meters long. The mini-cooler section consists of a two-meter section contains a liquid hydrogen absorber, a two-meter long section has a pair of solenoids for flux reversal and six meters of drift space. The forty-five meters of solenoidal drift channel that follows the mini-cooler section can use the same solenoids as the induction linac. The final 60 one-meter long induction linac cells reside in the 66-meter long channel down stream from the drift section. The total length from the target to the end of the induction linac section is 215 meters.

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 phase-rotation channel in this report has solenoids that generate an average induction of 3.0 T on axis.

II. THE SUPERCONDUCTING SOLENOID

The requirements for the phase rotation linac solenoids are as follows: 1) the solenoid outside diameter should be minimized. This means that the magnetic induction in the channel should be maximized. The solenoid diameter and average induction do affect beam stability. 2) The radial thickness of the solenoid cryostat should also be minimized. This allows the linac acceleration structure to be brought closer to the axis of the machine. 3) The space between the induction linac cells must be minimized. This is the space where the cold mass support system, the electrical leads, and the cryogenic feed system are located.

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 also designed to be cooled indirectly using flowing two-phase helium in cooling tubes attached to the support structure. The 40 K helium used to cool the shield is carried in tubes attached to the shields. This further reduces the solenoid cryostat thickness at the ends.

Fig. 1 shows a cross-section of a superconducting solenoid 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 402 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). The cryostat end thickness is 60 mm. The end of the coil is 20mm from the end of the cryostat vacuum vessel. This space includes a 40 K shield and multi-layer insulation.

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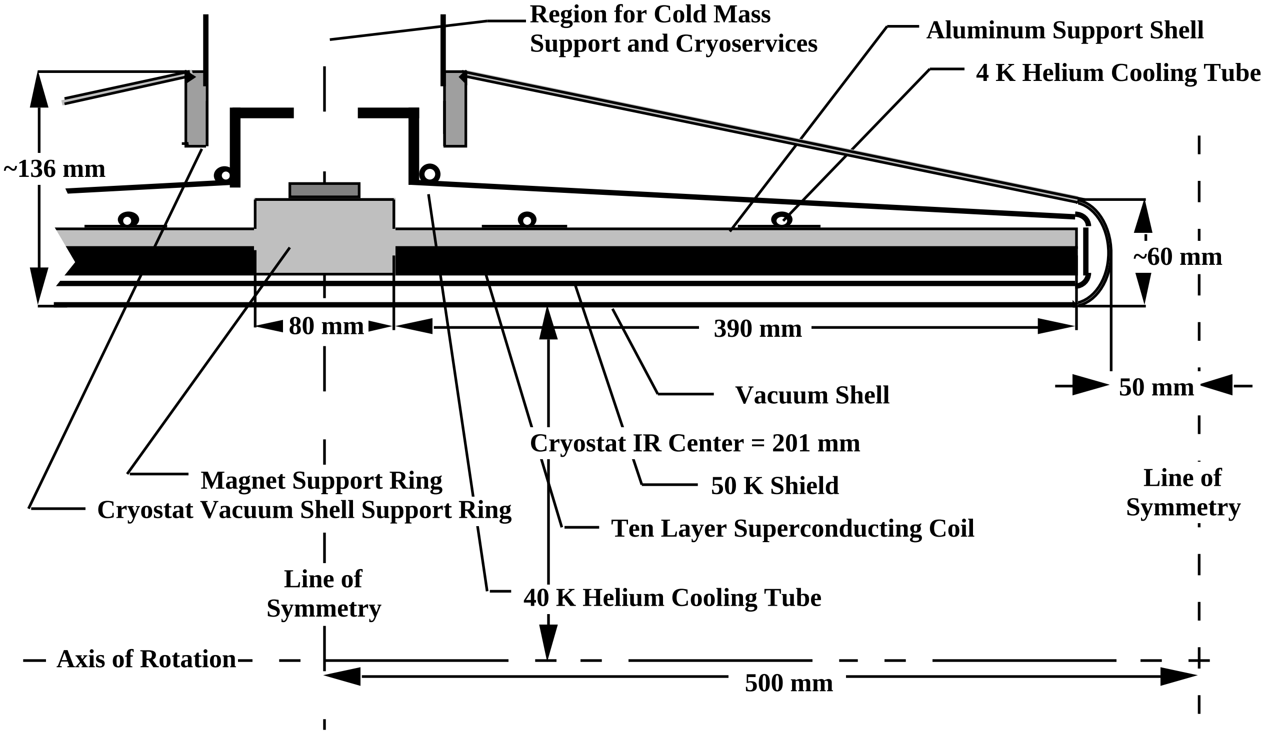

Figure 1. A Cross-section of the Induction Linac Superconducting Coil and Cryostat

TABLE I. INDUCTION LINAC SOLENOID PARAMETERS

Parameter	
Cell Length (mm)	1000
Cryostat Length (mm)	900
Number of Coils per Cell	2
S/C Coil Length (mm)	390
Cryostat Inner Radius (mm)	201.0
S/C Coil Inner Radius (mm)	224.3
S/C Coil Thickness (mm)	14.6
Support Structure Thickness (mm)	12.7
Cold Mass per Cell (kg)	247
Overall Mass per Cell (kg)	292
Average Induction on Axis (T)	3.0
Peak Induction in Windings (T)	~4.5
Number of Turns per Cell	4580
Magnet Design Current (T)	521.3
S/C Matrix Current Density (A mm^{-2})	331.0
Magnet Self Inductance (H)	4.55
Stored Energy at Design Current (kJ)	618
EJ^2 Limit for the Magnet (J A^2 m^{-4})	6.76×10^{22}

Note: All values of field, current density, stored Energy and quench parameters are at the design current for that mode.

Table I 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 [2]. The coil package is 860-mm long and it fits into a 900-mm long cryostat. The magnet is designed to operate at 4.4 K using two-phase helium flowing through tubes attached to the aluminum support structure. At this temperature, the magnet design current is a little over 80 percent of the magnet 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 [3,4]. 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. Since the magnet coils are continuously powered, quench protection diodes and resistors can be located in the power supply rack.

III. THE SOLENOID CRYOSTAT AND LEADS

The space available longitudinally for leads, cryogenic services, and cold mass supports is about 85 mm at the center of the magnet. The proposed cold-mass support system is a pair 600-mm long 50-mm diameter oriented carbon fiber [5] tubes, with a wall thickness of about 2-mm. 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 would be clamped to the magnet support structure at the middle of the tube. A 30 to 40 K thermal intercept would be clamped to the cold mass support tubes about 150 mm from each end.

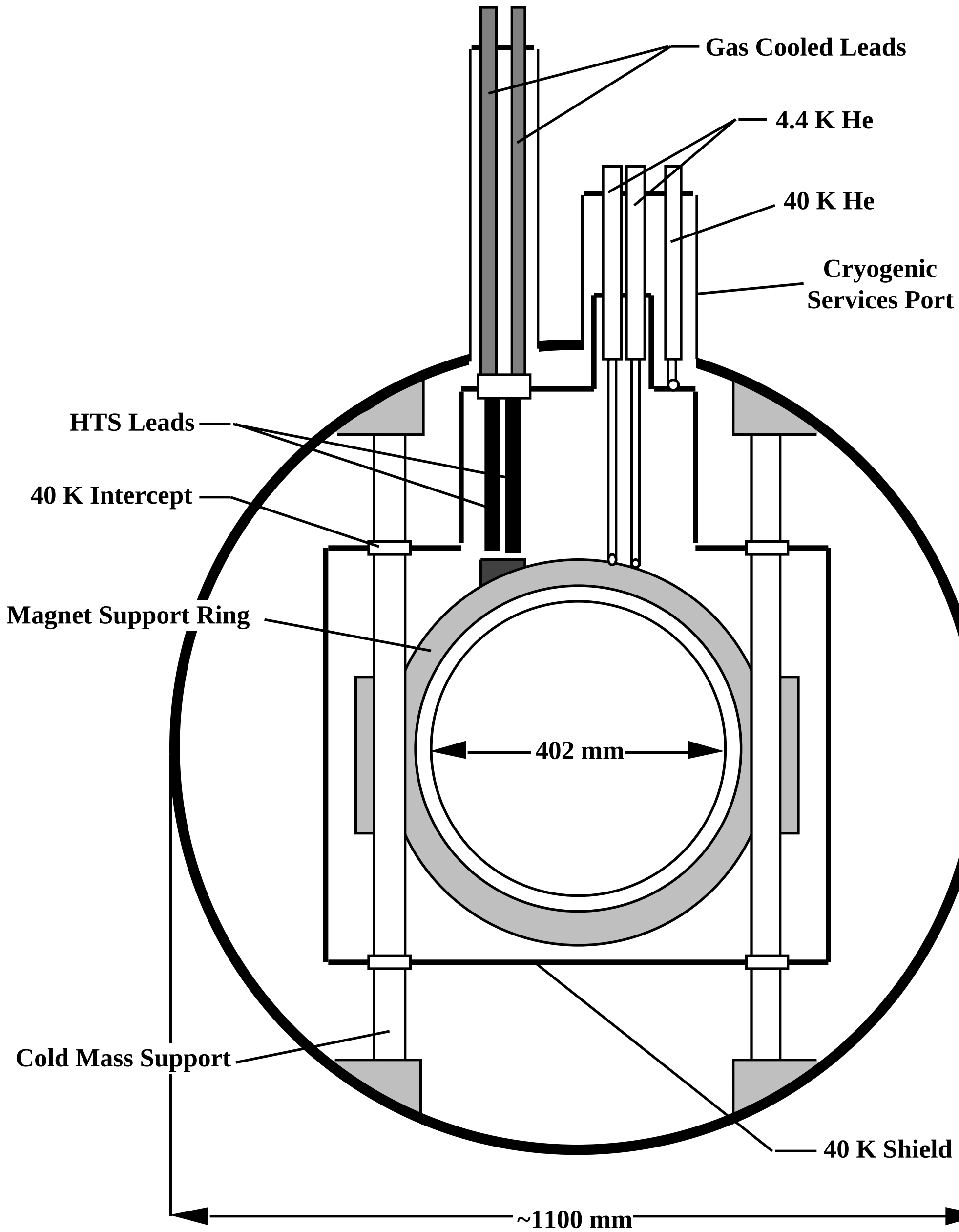

Figure 2. A Cross-section View Showing the Carbon Fiber Cold Mass Support Tubes, HTS between 40 K and 4 K, Gas Cooled Electrical Leads to 300 K, and the 4 K and 40 K Cryogenic Services Port

Fig. 2 shows a cross-section of the induction linac solenoid through the cold mass supports and the cryogenic services area. In Fig. 2 are a pair of high temperature superconductor (HTS) leads and a pair of gas-cooled electrical leads. The cryostat shields, the cold mass support intercepts and the gas-cooled electrical leads are cooled using 40 K helium gas from the high pressure side of the refrigerator heat exchanger near the second expansion engine.

The lower end of the gas-cooled leads and the upper end of the HTS leads will be at a temperature between 50 and 55 K. The gas pulled from the refrigerator, used to cool the shields and intercepts cools the gas-cooled leads and is returned to the refrigerator compressor intake at room temperature [6]. Using gas coming from the refrigerator at 35 to 40 K to cool the gas cooled leads means that this gas can not be used to cool the heat exchangers above the second expansion engine. If the gas were pulled from the refrigerator at 4.4 K, about 100 W of 4.4 K refrigeration would be lost for every gram per second of gas leaving the refrigerator at 4.4 K. (This is the equivalent of helium liquefaction.) If the gas is taken from the refrigerator at 35 K only about 13 W of refrigeration at 4.4 K is lost per gram per second of gas flow from the refrigerator. A pair of 521 A gas cooled leads will use about 0.06 g s^{-1} of helium gas or about 0.8 W of equivalent refrigeration at 4.4 K. Using HTS leads combined with using gas from the refrigerator at a higher temperature will reduce the amount of 4.4 K refrigeration needed to cool each induction linac solenoid by at least a factor of five.

The HTS leads are the largest heat load into the 4.4 K region. Cooling in this region is by conduction from the various heat sources to a cooling tube that carries two-phase helium at 4.3 to 4.4 K. The heat load into the shield circuit will cause a temperature rise in that circuit of about 14 K when the flow in that circuit is the 0.06 g s^{-1} that is required for the gas-cooled electrical leads. Gas entering the shield circuit at 35 K will enter the gas cooled leads at about 50 K. Table II shows the approximate heat loads at 4.4 K and 40 K. A diagram of the two-phase helium cooling system [7] and the 35 to 40 Kcooling system for the shields and leads is shown in Fig. 3.

TABLE II. INDUCTION LINAC SOLENOID HEAT LOADS

Source of Heat	Heat Flow (W) at 4.4 K	Heat Flow (W) at 40 K
Cold Mass Supports	0.07	1.56
Multi-layer Insulation	0.01	1.59
Helium Bayonet Tubes	0.02	1.23
Instrumentation Wires	0.01	----
550 A Leads	0.22	----
Total Heat Flow	0.33	4.38

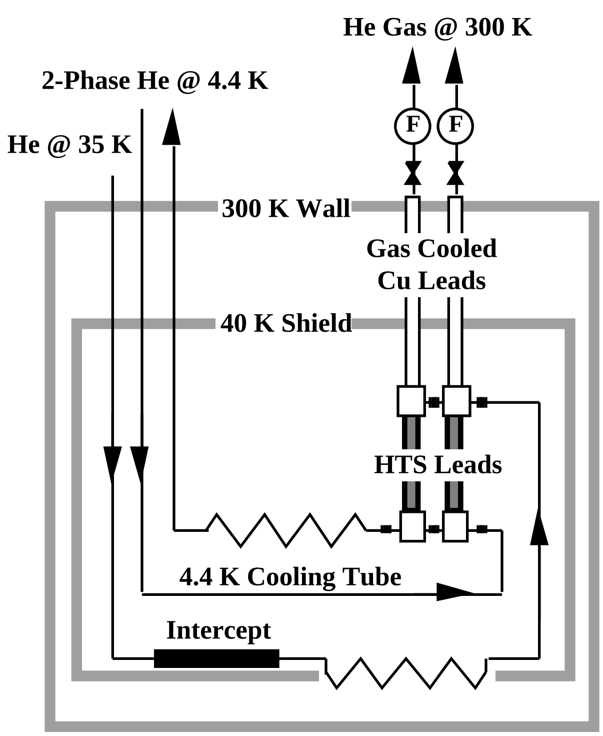

Figure 3. A Schematic Diagram of the Induction Linac Solenoid 4.4 K and 35 K Cooling Systems

A single induction linac test solenoid can also be cooled using a 1.5 W Gifford McMahon cryocooler [8]. When a cryocooler is used, solid copper leads replace the gas-cooled upper leads. The physical size of the HTS leads may have to be increased, because the upper end temperature approaches 70 K instead of 50 K. An alternative approach is to cool the copper leads to room temperature using liquid nitrogen. The leads between 80 K and 50 K would be fabricated using a relatively low thermal conductivity metal such as brass.

IV. CONCLUDING COMMENTS

A superconducting solenoid within an induction linac appears to be feasible. This solenoid can be made physically thin with access to the solenoid limited to an 85-mm long section at the center of the magnet. The solenoid must operate at a matrix current density of over 300 A mm^{-2}. This means that the primary quench protection mode is by quench back from the aluminum support structure located on the outside of the solenoid coils.

A 165-meter long string of induction linac solenoids can be cooled using two-phase helium in tubes mounted on the coil support structure. HTS leads must be used to reduce the refrigeration needed to cool the solenoids. The 40 K shields, cold mass support intercepts and the gas cooled leads can be cooled using a separate 35 K helium gas circuit from the refrigerator cold box. The gas flow from this circuit is returned to the compressor suction at 300 K. The cooling needed for 165 meters of solenoids is about 190 W plus the refrigeration needed to cool the helium transfer lines.

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