9. Solenoids for Decay, Phase Rotation, and Cooling Channels

9.1 Introduction

For the neutrino factory study several magnetic channels are required, all based on solenoids. Four channels have been specified technically [1] with the goal to investigate their technical feasibility, the critical items for an R&D program and finally the cost. In total, about 300 m of solenoids with different magnetic field strengths and bore sizes must be built in order to prepare the beam for injection into the muon accelerator of the Neutrino Factory. The combination of beam size and longitudinal magnetic field strength satisfies a simple condition for the first three channels that will be considered in this paper:

$$B \cdot r^2 = 0.1125 T \cdot m^2 \quad (1)$$

Here B is the longitudinal magnetic field, r is the radius of the inner bore (1/2 the aperture) and the product given in formula (1) keeps the acceptance constant. A trade off between stored energy which is proportional to B^2r^2 (= magnet cost) and the required acceptance given in equation (1) can be made. In our case the field on axis is 1.25 Tesla and the bore diameter 0.6 m.

Four channels will be described overall. The first channel is a 50 meter long drift channel, the second a 40 meter long drift channel which will not be used in our study but is of interest, if low frequency high gradient rf will be used within the decay channel. It would replace a part of channel 1 this case. The third channel is integrated into an induction linac with a length of 120 meters and the fourth channel is a cooling channel with a total length of 150 meter. This will be the most challenging one.

This chapter provides a preliminary layout of a magnetic system for each of the four channels. It helps to identify possible technical problems to work on during the R&D stage of the project. Also preliminary requirements on power supplies, cryogenic systems, and cooling systems are described

An inconsistency should be mentioned at this point. Because many things had to be specified at the beginning of the study, a number of parameters chosen for the magnetic channels do not necessarily fit the final solution described in other chapters. This inconsistency can not be removed in this report, because the presentation of a complete design is considered more useful. Instead of changing the design specifications after optimizing the beam dynamics the technical layout was finished on the basis of the specification provided at the beginning of the study. It should also be mentioned that the approach taken for solenoid design is more aggressive than what has been imposed as a limit when discussed in the cooling section in chapter 7. It will be part of the R&D program to study and test what the actual current density for a given field at the coil and the for the given force on the coil is going to be.

9.2 The Magnet Channels

9.2.1 The 50 m Long Drift Channel

The first channel has a length of 50 meters and can have either a cold bore or a warm bore. Cost trade offs for both solution have been made. The field interval can in principle be between 1.25 to 3 T and the field direction does not have to be changed within the channel. The radiation load from decay electrons and other particles is assumed to be negligible. Special care is necessary in the dump region (compare chapter 4) which will not be considered here. A preliminary study has shown that even if the magnet bore is getting smaller according to (1) the magnetic field has to increase, but magnet costs grow. This encourages us to choose a lower magnetic field in the channel. A reasonable compromise between magnetic field strength and bore size was achieved by choosing B = 1.25 T and R = 0.3 m for the first channel. The length of solenoids in the drift channel was chosen to be 4.7 m. A total of 10 magnets are used in the channel with 0.2-m gaps

Coil length, m	4.70
Bore diameter, m	0.6
Total ampere-turns, MA	4.69
Number of turns	780
Operating current, kA	6
$I_{nominal}/I_c$ ratio	0.3
Inductance, H	0.061
Cu/SC ratio	7:1
Coil inner radius, m	0.345
Cable length, km	1.7
Cryostat inner diameter, m	0.618
Cryostat outer diameter, m	0.935
Cryostat length, m	4.8
Cable mass, kg	370
Mass of magnet, ton	3.8
Stored energy, MJ	1.1

Table 1: Drift channel magnet parameters

between them. This leaves enough space for service ports that can also be used for installation of beam diagnostic equipment. The solenoid coil is placed in a cryostat that provides the required mechanical support to the coil structure and insures thermal insulation allowing the use of NbTi wire at 4.2 K. The required mechanical supports are different for magnets in the middle and at the ends of the magnet string. For example, the axial force on the magnet in the middle of the string is 170 kN. For the first and the last magnets in the string this force is 230 kN. Radial pressure developed at the coil location is about 0.6 MPa, and this makes the magnet design quite straightforward. The solenoid has a two-layer coil wound using NbTi cable. A stainless steel barrel is used to support the coil structure inside a stainless steel cryostat with a warm bore. Cable size is 12.0 x 2.1 mm^2, and the amount of copper used in the cable is defined by a Cu/SC ratio of 7:1. Dimensions of superconducting cable, quantity of copper for stabilization, and nominal-to-critical current ratio were determined taking into the account safe evacuation of energy stored in the magnet during a quench. The calculated temperature during a quench is less than 300 K and the maximal voltage does not exceed 1000 V. The cable in the coil is insulated using 0.1-mm kapton insulation. The coil is cooled by liquid helium flowing through copper piping soldered to copper shells and connected by collectors on the ends of the coil. A copper thermal shield cooled by liquid nitrogen is used to reduce heat leaks to the inner and outer surfaces of the superconducting coil. Super-insulation is installed between the coil and thermal shield and between the thermal shield and cryostat wall. Space inside the cryostat is pumped out to further improve thermal insulation. The main parameters of the solenoid magnet for the drift channel are listed in Table 1.

In the drift channel, all the magnets are connected in series using superconducting cable cooled by a pipe carrying liquid helium. It uses one 180 kW power supply, and it takes 200 seconds to reach the nominal current of 6 kA.

The protection system is shown schematically in Figure 1. When the quench detector sees an appearance of a normal zone in the coil, the dump resistor R_d is turned on by switch S_2 and the power supply is switched off by S_1. At that moment the stored energy of the string starts to dissipate in the dump resistor R_d. During extraction of energy out of the magnet, the maximum allowable voltage was 1000 V for R_d = 0.167 Ohm. A Simulation of a quench spreading through the coil was made for the case when the quench was provoked on the outer boundary of the inner layer of the coil. With a quench detector threshold of 1 V and a time delay of 100 ms, almost 97% of stored energy was dissipated outside the cryostat. The amount of energy dissipated in the coil was sufficient for adiabatic heating of the coil up to 180 K in the hottest area.

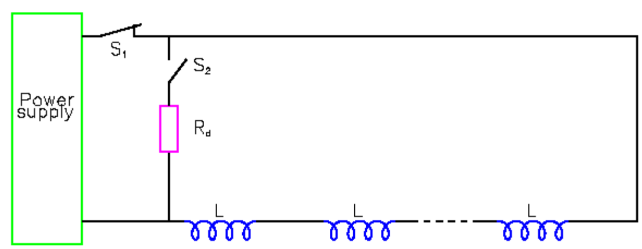

Figure 1. Quench protection scheme for the decay channel.

9.2.2 RF-based Phase Rotation Channel

The main idea of using RF cavities operating at low Frequency is, to have an early phase rotation stage that can simplify the requirements for the induction linac based phase rotation. The RF cavities are installed inside the magnets of this channel. The transverse dimensions of these cavities will determine the inner diameter of the magnets that generate the longitudinal magnetic field for beam transport. It is obvious that one must choose the magnets with the lowest field to reduce the channel cost. The RF frequency to be used in this channel is 30-60 MHz and the inner radius of the channel bore was chosen to be 0.7 m which will need very special cavity designs. The magnetic field in the channel is 1.25 T, and the field direction is the same for all solenoids in the channel. Length of a magnet in the channel must coincide with the length of the RF cavities. The cavities must be installed inside the magnet so feeding the cavities with RF power is possible. As the first approach, the magnet length was chosen to be about 1.8 m with 0.2 m gaps between the magnets, so in total 20 magnets are used in the channel. RF power dissipation in the channel is about 50 kW/meter, so an additional water-cooling system is required to reduce the power load on the inner wall of the magnet cryostat which will have to be a warm bore in this case. The cross-section of a magnet in the RF channel is significantly larger than a magnet cross-section in the drift or induction linac channel, and thus the axial magnetic forces are also higher, although

the radial pressure in the coil is at the same level of 0.6 MPa. For magnets in the middle of the magnet string, the axial force acting on the magnet end is about 550 kN. For the first and the last magnet in the channel, this force is about 900 kN. This force level requires strong support structures and a reliable protection system that can simultaneously and quickly remove all the energy stored in the magnets during a quench. The magnet design is similar to that of the drift and induction linac channel. The difference is that stronger banding is required to manage the higher longitudinal forces. Cable with 10.5 x 3.0 mm^2 cross-section made of NbTi wire is used for coil fabrication. The coil is cooled by liquid helium flowing through cooling pipes. A shell cooled by liquid nitrogen is used to lower heat leaks from the coil to cryostat walls, and superinsulation is used to further increase cryostat efficiency. The cryostat and coil support barrel are made of stainless steel. The inner space of the cryostat is pumped out.
The main parameters of a magnet in this channel are listed in Table 2.

Central field, T	1.25
Bore diameter, m	1.4
Total current, MA	2
Total number of turns	320
Operating current, kA	6
$I_{nominal}/I_c$ ratio	0.3
Stored energy, MJ	2.0
Inductance, H	0.1
Cu/SC ratio	9:1
Magnet length, m	1.8
Magnet coil length, m	1.7
Coil inner radius, m	0.745
Cable length, km	1.5
Cryostat inner diameter, m	1.4
Cryostat outer diameter, m	1.82
Cryostat length, m	1.8
Cable mass, kg	410
Mass of magnet, ton	5.0

Table 2: RF channel magnet parameters

The quench protection scheme is very similar to that of the induction linac channels. Twenty magnets of the channel store 40 MJ of energy. The magnets in the channel are subdivided into two groups. The magnets in each group are connected in series with their own power supply. The scheme of one string is presented in Figure 2. A 180 kW power supply is used in each string to raise the current up to 6 kA during 10 minutes. One magnet in each string is equipped with protective heaters like in the induction linac channel. These heaters are necessary for synchronizing the extraction of energy from the strings. The resistance growth rate stimulated by the heater is higher than that in the original normal zone, and this reduces the difference in resistances of the two strings. The two strings will have similar time constants for current decay and thus reduces the imbalance of forces in the string. After quench detection, the power supply is switched off by S_1, the dump resistor R_d is turned on by S_2, and the heater is connected to the heater power supply by S_h. The stored energy of all strings is dissipated on the dump resistors which have resistance R_d = 0.167 Ohm. The maximum voltage does not exceed 1000 V.

9.2.3 The Induction Linac Based Phase Rotation Channel

The main difference between the drift channel (=nr 1) and the channel inside the induction linac is, that these magnets are placed inside the accelerating structure. This sets a strict limitation on the magnet length, that cannot be exceeded. Moreover, the gaps of the induction linac are formed by the surfaces of the two neighboring magnet cryostats. For this study, a 1-m long induction linac section length was chosen with a bore diameter of 0.6 m and a longitudinal magnetic field of 1.25 T. The total number of magnets in the channel is 100. The length of each magnet is 0.85 m, and the gap between cryostats is 0.15 m. The bore has to be warm and the magnetic field direction does not have to change along the linac. Table 3 shows the main parameters of a magnet in the induction linac channel. Another critical issue for this channel is that the fringe magnetic field outside the channel must be rather low because induction linac inductor performance gets worse if the field level is higher than a certain limit. Some optimization of coil shape is required to have this fringe field as low as possible. This optimization includes but is not limited to coil thickness variation along the coil length. Nevertheless, because of the voltage gaps, some level of fringe field will form a part of the inductor's working environment. The coil design is very similar to that in the first channel. The NbTi cable cross-section is 8.3 x 3.0 mm^2. The radial pressure at the coil location is about 0.6 MPa. Axial forces depend on the magnet location in the string. For a magnet in the middle of the channel,

Bore diameter, m	0.6
Total current, MA	1.0
Total number of turns	180
Operating current, kA	6
$I_{nominal}/I_c$ ratio	0.3
Inductance, H	0.01
Cu/SC ratio	7:1
Cable length, km	0.4
Coil length, m	0.75
Coil inner radius, m	0.345
Cryostat length, m	0.85
Cryostat outer diameter, m	0.89
Cryostat inner diameter, m	0.618
Cable mass, kg	86
Mass of magnet, ton	1.0
Stored energy, MJ	0.2

Table 3: induction linac channel magnet parameters

the axial compressive force is about 150 kN; for the magnets at the ends, it is about 200 kN. So precautions must be made to keep magnet displacements within an acceptable limit, especially during a quench when axial forces can appear in the middle of the string if the quench protection scheme does not work properly.

The total energy stored in the channel is 20 MJ. This energy is about twice as large than that for the drift channel. To make an efficient quench protection system, all magnets in the channel are subdivided into two groups. In each group, magnets are connected in series and powered by a 180 kW power supply. The quench protection concept is shown in Figure 2.

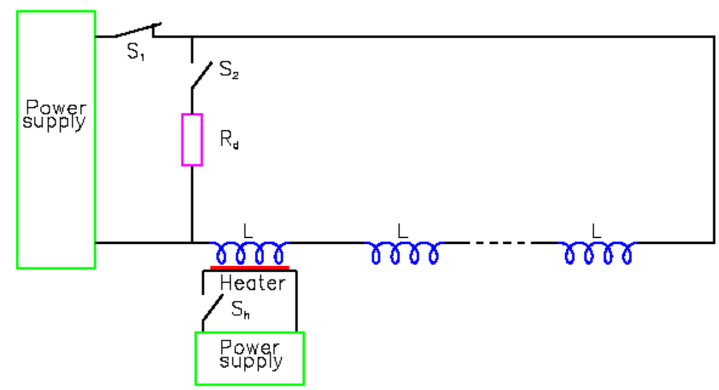

Figure 2: Quench protection scheme for the induction linac channel.

In each group of magnets there is only one magnet with protective heaters. After a quench is detected in each string, the power supply is switched off by S_1, the dump resistor R_d is turned on by switch S_2, and the heater is switched to heater power supply by S_h. Stored energy of both strings is dissipated in the dump resistors with resistance R_d = 0.167 Ohm. The maximum voltage does not exceed 1000 V. As a simulation of the quench process shows, the hot spot temperature does not exceed 200 K in the magnet where quench originates and 170 K in magnets with the heater-initiated quench.

9.2.4 Cooling channel

The channel is used to reduce the beam emittance to an acceptable level using ionization cooling. RF cavities installed inside the channel compensate for energy loss during the cooling process. The cavity transverse dimensions of about 1.4 m will determine the solenoid diameters in the channel. The length of the cooling channel was assumed to be 100 m, which is different from the final result presented in the chapter 7. Strong magnetic fields, alternating along the channel length, provide a field configuration optimized for cooling efficiency. The bore of the magnets has to be warm and very frequent changes of the magnetic field direction on axis are necessary. Also much higher fields are required. Several schemes of this channel type were considered that differ in magnetic field amplitudes and field period length. One of the latest schemes makes use of a magnetic field that changes following a sine law with a period of 2.2 m and field amplitude B_m = 3.6 T. Another channel configuration was proposed with period 1.5 m and amplitude B_m = 3.4 T. And increasing the field amplitude to 5.5 T was also considered. In this chapter, we will discuss the magnetic system with longitudinal period 2.2 m and amplitude B_m = 3.6 T, again, chosen very early in the study. The longitudinal period determines the length of a magnet, which in this case has to be less than 1 m. The construction of these magnets is

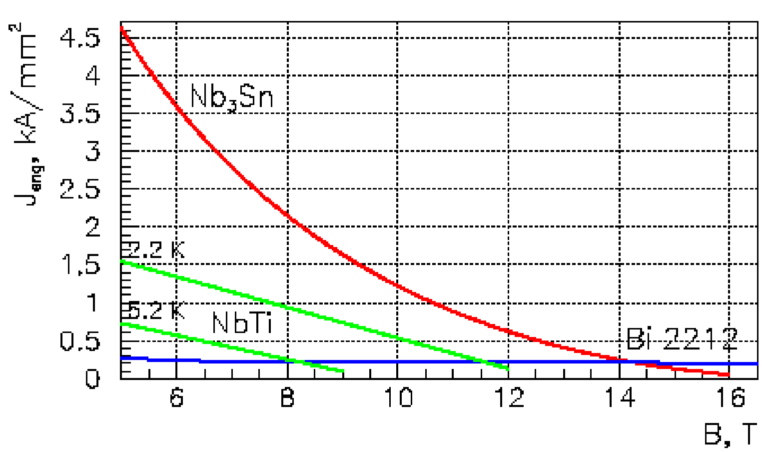

Figure 3: Engineering current densities for different superconducting materials.

challenging. First of all, the magnetic field is rather high compared with the drift and phase rotation channels. Also, alternation of field direction along the channel length results in large longitudinal forces. Combination of both of these factors has significant impacts on the magnet design.
Figure 3 shows the engineering current density (that is, the critical current divided by the coil cross-section) for different superconducting materials.

It can be seen that NbTi can not be used in magnetic fields higher than 9 T at 5.2 K. Using NbTi at 2.2 K allows one to extend the field range up to 12 T. Nb_3Sn can work in fields up to 15 T at 5.2 K and has superior magnetic properties compared to NbTi at 2.2 K. High temperature superconductors (HTS) like Bi-2212 can work at much higher field (up to 30 T) practically without any reduction in critical current density, but it will take some time until long enough pieces of HTS superconducting cable will be available commercially.

For magnetic fields alternating in direction, magnetic fluxes from neighboring solenoids add in the gap between the magnets, so in the coil the maximal field can be higher than on the magnet axis. Figure 4 shows the longitudinal distribution of the magnetic field in the cooling channel for the case where the coil thickness **w** = 50 mm, and the solenoid length L = 1 m. The sine-like line shows the magnetic field along the axis of solenoid; the other lines show the field components $\mathbf{B_r}$, $\mathbf{B_z}$ and the absolute value $\mathbf{B_t}$ on the inner surface of the coil. One can see that the component $\mathbf{B_r}$ gives the main contribution to the edge field. Here the magnetic field reaches almost 10 T. According to Figure 3, NbTi wire cannot be used in such a field, and it is necessary to use Nb_3Sn alloy. From the same chart, it is clear that the Nb_3Sn coil thickness must be more than 65 mm.

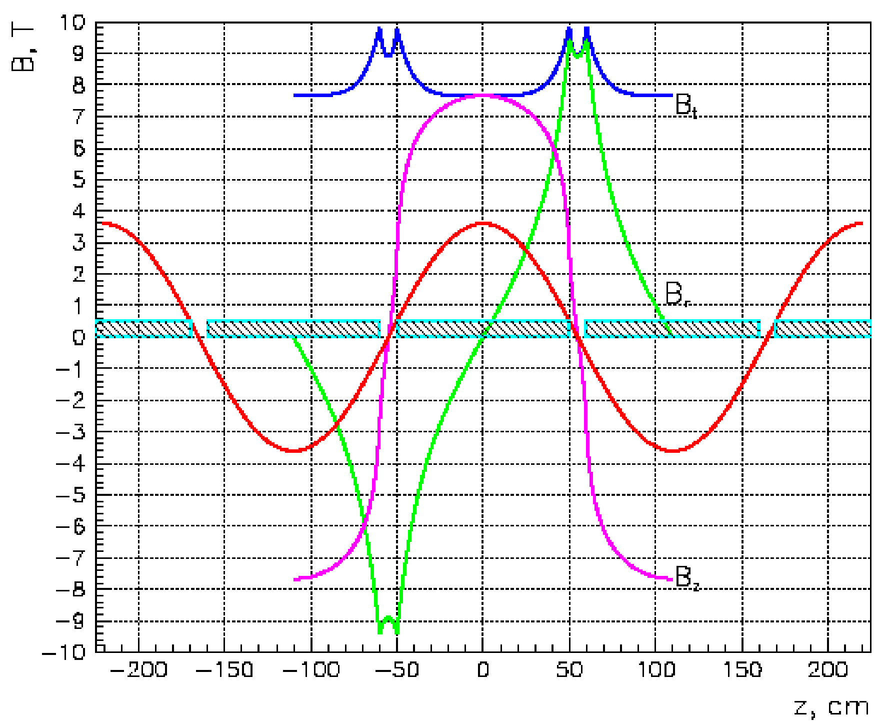

Figure 4: Magnetic field distribution in the cooling channel for solenoid length L = 1 m.

The choice of optimal coil length can reduce the magnetic field inside the magnet coil. Figure 5 shows how the maximal field in the coil depends on the solenoid length. The magnetic field near the edge of the coil (upper curve in Figure 5) is 9.2 T when the coil length is about 0.8 m. The magnetic field in the coil in the central area of the magnet (lower curve) is about 8.2 T with this coil length.

By increasing the coil thickness, it is possible to further reduce the field in the coil, as shown in Figure 6. Again, the upper curve here shows the magnetic field near the magnet edge and the lower curve shows the magnetic field in the coil in the center of the solenoid. It should be mentioned that the quantity of superconducting material does not necessary increase with coil thickness, because more copper can be added into superconducting wire to reduce the engineering current density. This addition can also be useful as a protective measure at a quench. The choice of coil thickness and wire and cable design must be finalized after the quench protection system is developed.

Figure 8 shows the longitudinal distribution of magnetic fields in a coil when with solenoid length L = 0.8 m and coil thickness w = 175 mm. One can see that the magnetic field in the coil now reaches only about 8.3 T, and the field does not change significantly along the length of the solenoid. It is also possible to see that the magnetic field near the edge of the solenoid is about 0.5 T higher than the field in the central part of the coil. An additional improvement of field distribution in the coil is possible if one uses a more elaborate optimization procedure.

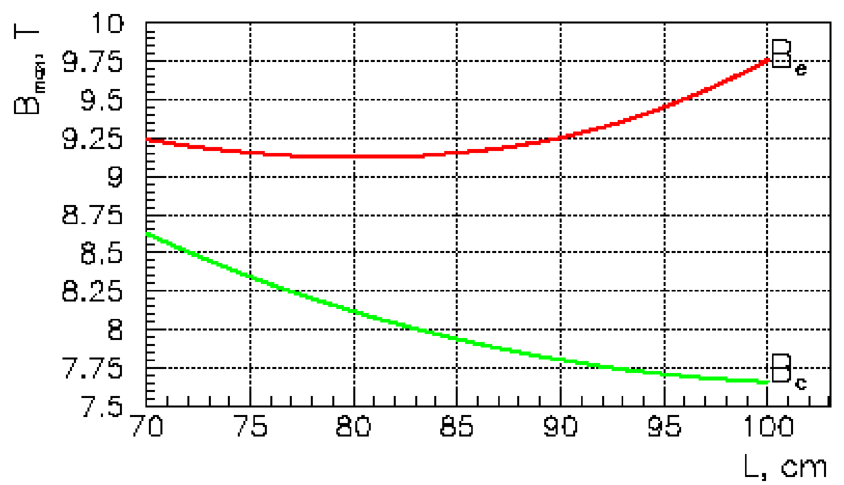

Figure 5: Maximal field in the coil versus solenoid length.

The radial distribution of magnetic fields for this case is shown in Figure 7.For the case with L = 0.8 m and w = 175 mm, the calculated radial stress on the outer surface of the coil is about 15 MPa. This stress can be managed using strong banding. A simple mechanical analysis shows that to withstand the radial pressure, 6-mm stainless steel bands are required and does not seem to be a problem. Longitudinal stresses in the middle of the coil can be calculated given the magnetic field distribution and a detailed magnet design. Simple integration of forces along the length of the magnet gives an axial stress in the middle of the magnet of about 90 MPa**. T**he use of external bonding introduces friction between turns and layers which reduces this stress to some extent depending on the initial coil pre-loading, although a mechanical design involving stress management features and elaborate mechanical analysis must be performed to insure proper coil performance. Probably, it will be useful to subdivide the solenoid coil into several sections using strong stainless steel walls so that the stress in the coil does not exceed the yield stress of copper in the superconducting wire. Epoxy impregnation will also help to improve coil mechanical stability.

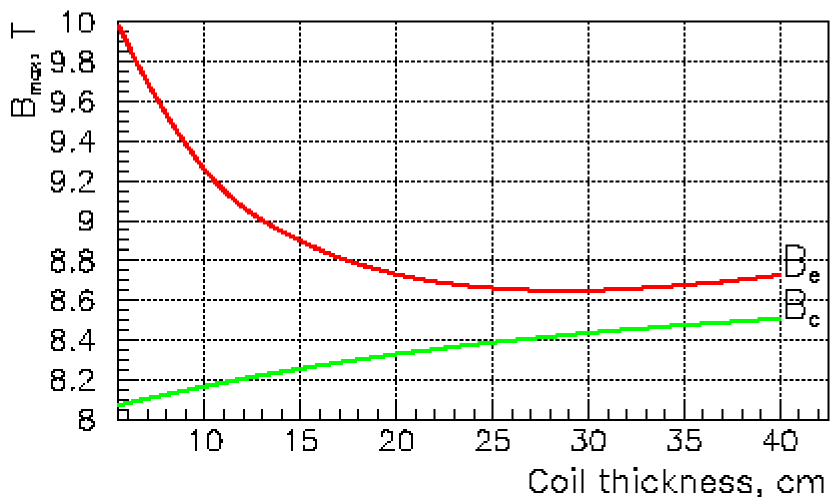

Figure 6: Maximal field in the center (B_c) and near the edge (B_e) of the solenoid versus coil thickness

It is worth noting that the tensile yield strength of oxygen-free high conductivity soft copper is about 65 MPa at room temperature [2], so one can expect wire critical current degradation at the expected stress level. On the other hand, oxygen-free high conductivity hard copper has a tensile yield strength of about 230 MPa at room temperature, and the tensile yield strength of especially hardened copper can reach 340 MPa [[2], [3]]. Using copper with this high yield strength can help to solve the solenoid design problems. The large inner radii of the solenoids allow the use of "react and wind" technology that will help to keep the copper wire in the "hard" state. Fabrication and study of a wire that consists of Nb_3Sn superconductor in a copper matrix are subjects for R&D. Another way of solving the problem of stress in the magnet coil is increasing the coil thickness. For example, if the coil thickness increases from 175 mm to 350 mm, the axial pressure drops from 90 MPa to 55 MPa. However, stored energy, total current in magnet, and coil volume (the amount of superconducting material and copper) grow when the coil thickness increases. Coil geometry optimization, as an initial step will help to reduce the maximal magnetic field in the coil and improve other magnetic and physical parameters. This work can be done more efficiently if the cavity geometry and beam envelope are defined.

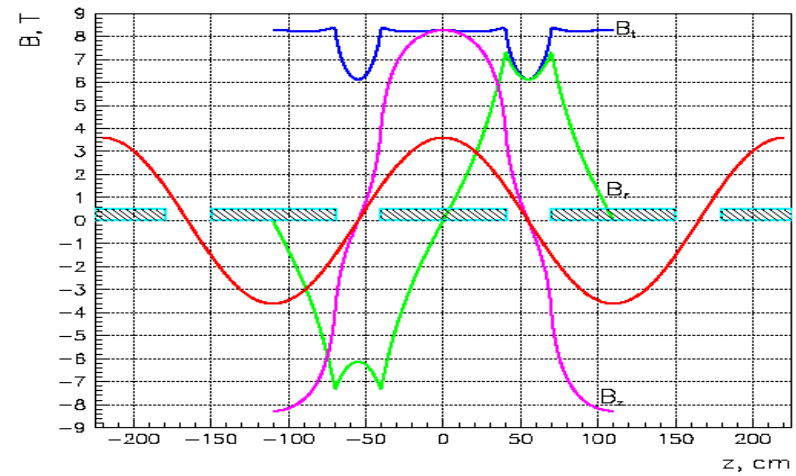

Figure 8: Magnetic field distribution for solenoid with L = 0.8 m and d = 175 mm

Significant repulsive forces between magnets in the channel can significantly complicate the channel design unless one takes special precautions. For magnets in the middle of the channel, the repulsive force can reach approximately 20 MN from each neighboring magnet. These forces are balanced for a magnet inside the channel, but the first and the last magnet must each have an adequate support to withstand the force. If one of the magnets inside the channel quenches, the balance of forces for neighboring magnets is broken, and this results in unacceptable longitudinal forces. This requires using rigid supports for each magnet in a channel, and this significantly complicates the mechanical design of the channel. To avoid this, it is possible to consider the removal of stored energy simultaneously from all magnets in the channel. For this purpose, a reliable and fast quench detection scheme is required. One possible solution can be a bridge-type quench detector. When the voltage on the resistive section of a coil exceeds a threshold value, the quench detector generates a signal to start protective actions.

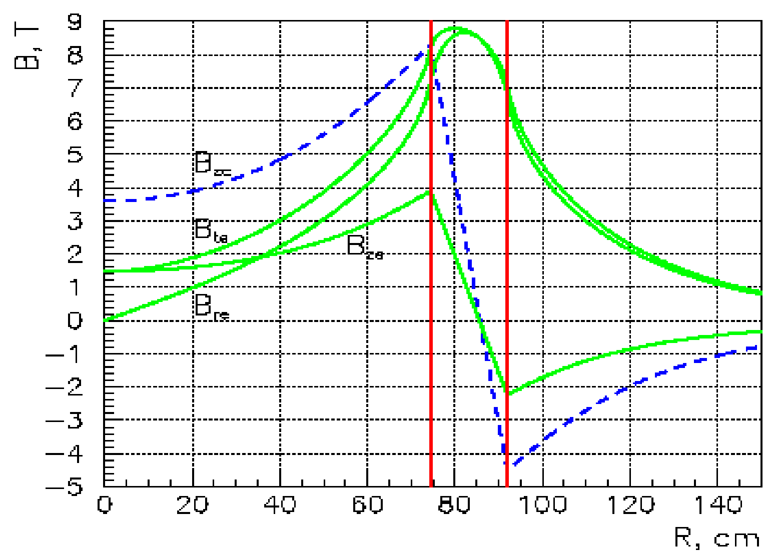

Figure 7: Radial distribution of magnetic field. Dotted line is the field in the center plane of solenoid; the other lines show end field components.

Central field, T	3.6
Bore diameter, m	1.4
Total current, MA	9.64
Total number of turns	1600
Inductance, H	2.55
Operating current, kA	6
$I_{nominal}/I_c$ ratio	0.5
Cu/SC ratio	35:1
Coil length, m	0.80
Cryostat inner diameter, m	1.4
Cryostat outer diameter, m	2.18
Cryostat length, m	1.0
Coil thickness, mm	175
Coil inner radius, m	0.745
Cable length, km	8.5
Cable mass, kg	3600
Mass of magnet, ton	8.0
Stored energy, MJ	48.0

Table 4: Parameters of a magnet in the cooling channel.

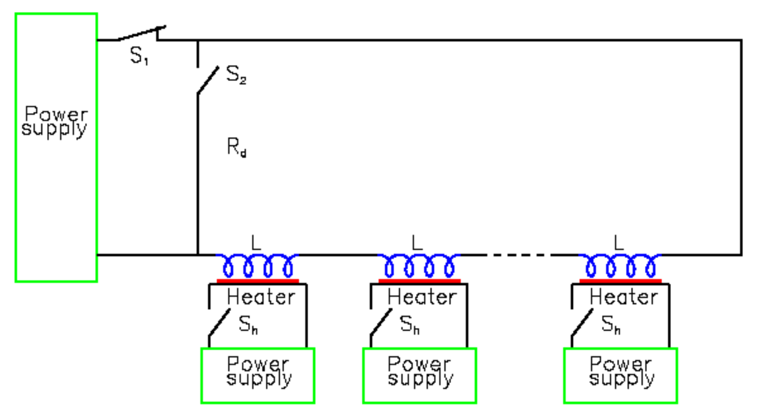

Figure 9: Quench protection sketch of magnets for the fourth channel.

There is a total of 90 magnets in the cooling channel. Each magnet is placed in its own cryostat. The cryostat inner diameter is 1.4 m and the outer diameter is 2.2 m. The gap between the neighboring cryostats is 10 cm. The magnet coil is wound using Nb_3Sn cable with a cross-section of 8.0 x 10.6 mm^2. For quench protection, the copper-to-superconductor ratio is 35:1 for this cable. The coil has 1600 turns in 16 layers. The total length of cable is 8.5 km, and its weight is about 3.6 ton, so several cable splices are to be done during winding. The main parameters of a magnet in the cooling channel are listed in Table 4.

The total energy stored in the channel is 4.3 GJ, and this makes development of a quench protection system for the channel a first priority issue. As was mentioned earlier, some protective precautions must be used like fast quench detection and fast removal of stored energy from the channel into the external dump resistor and/or "smearing" of this energy inside the magnets using heaters. A protection circuit for the cooling channel that takes these special features into account is discussed below. The quench protection scheme is presented in Figure 9. All magnets in the channel are connected in series into one string. A 3 MW power supply is used that allows reaching the nominal current level within 1 hour. There is no dump resistor in this scheme because it appears to be inefficient for the cooling channel. All magnets are equipped with heaters that are fired by switches S_h simultaneously. The stored energy of each magnet is dissipated inside its cryostat, in the magnet coil. The maximum temperature reaches about 230 K in the magnet where the quench has originated; for other magnets, the maximum temperature is below 190 K. Quench process diagrams for the magnets of the channel are shown in Figure 10.

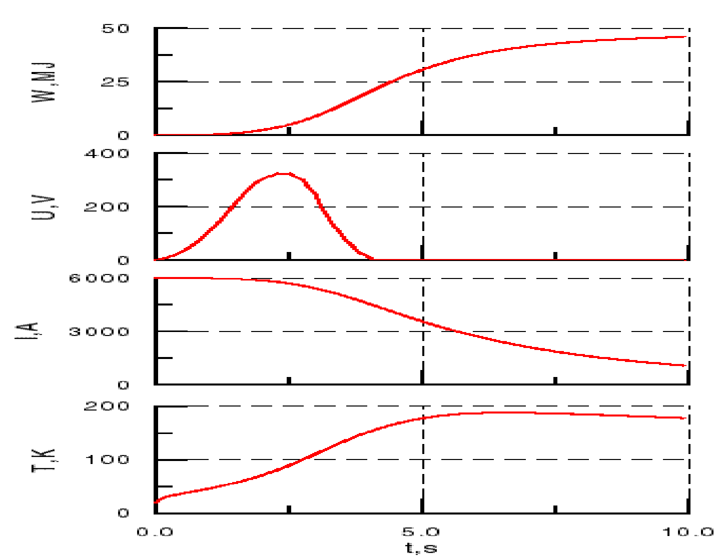

Figure 10. Quench process in magnets of the cooling channel.

9.3 Power supply and cryogenic system requirements

Table 5 summarizes the requirements on the power supply for each channel described above. Table 6 presents the calculated budget of heat leaks in the cryogenic system which can be considered as the initial requirements for the cryogenic plant providing cooling agent to the channels.

The essential feature of the channel is the long time required to cool down the magnets. In the protection scheme that was described it may take several days to reach 4.5 K after a quench. A more efficient protection scheme that dissipates energy out of the cryostats is a subject for R&D.

Channel	Drift	RF	I.L.	Cooling
Operating current, kA	6	6	6	6
Voltage, V	30	30	30	500
Power, kW	180	180	180	3000
Current stability	10^{-3}	10^{-3}	10^{-3}	10^{-3}
Total inductance of magnets, H	0.61	4.0	1.1	230
Ramp rate, A/s	30	10	30	1.7
Number of power supply	1	2	2	1
Energizing time, s	200	600	200	3600

Table 5: Power supply parameters for the NF front-end magnet channels.

Channel	Drift		RF + Drift		Induction Linac		Cooling	
Temperature	4.5	80	4.5	80	4.5	80	4.5	80
1. Cryostats:	52	650	86	1480	187	1370	300	3400
Radiations, W	30	550	52	1300	45	1120	100	2500
Supports, W	10	80	20	160	83	160	137	800
Voltage taps, W	10	20	10	20	42	90	45	100
Seals between coils, W	2		4		17		18	
2. Transfer line, W	1	20	2	20	10	200	10	200
3. 30% margin, W	17	230	32	500	63	430	90	1000
4. Total, W	70	900	120	2000	260	2000	400	4600
5.Current leads, l/h	21		41		41		21	
Required power, kW	115	26	219	57	331	57	383	133

Table 6: Budget of heat leak in the cryogenic system.

9.4 Conclusion

As part of this Fermilab Neutrino Factory study, a preliminary analysis has been made to realize the feasibility and complexity of the magnetic systems for the drift channel, phase rotation channel, and cooling channel. For each channel, a simple optimization was done with the goal of reducing its cost. It was impossible during this short study to identify and to address all the problems that can arise during magnet development and design. Some of these problems can be resolved in a normal way. Others need an additional research stage.

A preliminary cost estimate for the magnetic system construction and operational expenditures can be made based on the data obtained during this study. This cost estimate can be updated after the R&D program is completed at the time of a technical proposal. For each channel, it was shown that the major portion of the cost is the cost of the superconducting magnets. The cost of the drift channel makes up the bulk of the cost of the entire magnetic system. Technical difficulties anticipated in building the cooling channel indicate that the future R&D program must be devoted mainly to analyzing and modeling this channel.

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