MUON TRANSPORT CHANNELS WITH LONGITUDINAL MAGNETIC FIELD

I.Bogdanov, S.Kozub, V.Pleskach, P.Shcherbakov, V.Sytnik, L.Tkachenko, V.Zubko
Institute for High Energy Physics (IHEP), Protvino, Moscow region, 142284 Russia
N.Holtkamp, I.Terechkine
Fermi National Accelerator Laboratory (Fermilab), P.O. Box 500, Batavia, Illinois 60510, USA

INTRODUCTION

The Neutrino Factory (NF) concept includes several channels that treat muon beam to allow its capture into the accelerating part of the complex [1]. There must be a "drift" channel where pions decay generating muons. In this channel a correlation develops between muon energy and its position (mass separation). Due to a very high beam emittance and energy spread after the target, a high magnetic field and large channel bore are required to have a satisfactory beam transport efficiency. There must be a "phase rotation" channel, where the correlation developed in the "drift" channel is used to reduce muon beam energy spread. Electrical field of low-frequency RF cavities or induction sections accelerates or decelerates different parts of the beam changing its energy distribution. Both RF and LIA channels require longitudinal magnetic fields similar to that in the drift channel. Because the action principle of the induction section is similar to that of a Linear Induction Accelerator (LIA), we will call the channel with the induction sections a LIA channel. After the "phase rotation" channels reduce the energy spread, an additional "cooling" channel is needed to reduce the beam emittance. The ionization-cooling scheme is not finalized yet, but it is developed to the extent that allows a preliminary analysis of the channel magnetic system. One of the approaches to the cooling system makes use of an alternating magnetic field of high strength. This report discusses main features of the magnetic systems for the decay, phase rotating, and cooling channels of the NF version developed at FNAL.

1 DRIFT CHANNEL

The length of the drift channel is 50 m. A preliminary study has shown that even if the magnet bore is getting smaller when the magnetic field increases (in accordance with the equation $Br^2 = 0.1125\ T{\cdot}m^2$), the cost of magnets in the channel grows. 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, so ten magnets are used in the channel with 0.2-m gaps between them. The solenoid coil is placed in a cryostat that provides needed mechanical support to the coil structure with thermal insulation allowing the use of NbTi wire at 4.2 K. 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 ~0.6 MPa, that makes the magnet design quite straightforward. The solenoid has a two-layer coil wound using NbTi cable. Dimensions of superconducting (SC) cable, quantity of copper for stabilization, and nominal-to-critical current ratio were determined taking into account safe evacuation of 11 MJ energy stored in the magnet.

The coil is cooled by liquid helium flowing through copper piping soldered to copper shells. A copper thermal shield cooled by liquid nitrogen is used to reduce heat leaks to the inner and outer surfaces of the SC coil. Space inside the cryostat is pumped out to further improve thermal insulation. All the magnets are connected in series. One 180-kW power supply is used to power the chain of the solenoids; it takes 200 seconds to reach the nominal current of 6 kA.

The quench protection system uses an external dump resistor to extract the stored energy. Simulation of quench spreading through the coil was made for the case when the quench was provoked on the outer boundary of the inner layer. With a quench detector threshold of 1 V and a time delay of 100 ms, ~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 point.

2 LIA-BASED PHASE ROTATION CHANNEL

The main difference between the drift channel and the LIA channel is that magnets in the LIA channel are placed inside the accelerating structure of the LIA. This puts a strict limitation on the magnet length that cannot exceed the length of the LIA section. Moreover, the LIA accelerating gap is formed by surfaces of the two neighboring magnet cryostats [2]. For this study, 1-m LIA section length was chosen with 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 coil design is very similar to that of the coil in the first channel. The radial pressure at the coil location is ~0.6 MPa. For a magnet in the middle of the channel, the axial compressive force is ~150 kN; for the magnets at the ends, it is ~200 kN. The total energy

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stored in the channel is 20 MJ. 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. There is only one magnet with protective heaters in each group. The maximum voltage does not exceed 1 kV. 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.

3 RF-BASED PHASE ROTATION CHANNEL

One of the main ideas of using this 40-m channel is to have a preliminary phase rotation stage that can simplify requirements to the LIA-based system. RF cavities in this channel are installed inside the solenoids and their transverse dimensions determine the inner diameter of the magnets. Because the frequency used in this channel is 175 MHz, the 0.7-m inner radius of the channel bore was chosen to accommodate the cavities. The magnetic field in the channel is 1.25 T. Length of magnets in the channel must coincide with the length of the RF cavities. The cavities must be installed inside the magnet in a way that allows feeding of all the cavities by RF power. As the first approach, the 1.8-m magnet length was chosen with 0.2-m gaps between the magnets. Totally 20 magnets were used in the channel. RF power dissipation in the channel reaches ~50 kW/m, so an additional water-cooling system is required to reduce the power load on the inner wall of the magnet cryostat. The cross-section of a magnet in the RF channel is significantly larger than a magnet cross-section in the drift or LIA channels. This results in higher axial magnetic forces, 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 applied to the magnet end is ~550 kN. For the first and the last magnet in the channel, this force is ~900 kN. High level of the force requires strong support structures and a reliable protection system that in a case of quench can simultaneously and quickly removes all the energy stored in the magnets. The magnet design is similar to that of the drift and LIA channels. The difference is that stronger banding is required to manage the higher longitudinal forces. Twenty magnets of the channel store 40 MJ of energy. The magnets in the channel are subdivided into two groups, each fed by its own power supply. A 180 kW power supply is used in each string to raise the current up to 6 kA during 10 min. One magnet in each string is equipped with protective heaters like in the LIA channel. The heaters must be used to synchronize extraction of the energy from the strings. The resistance growth rate stimulated by the heaters is higher than that in the original normal zone that helps to reduce the difference in resistances of the two strings. This results in the similar time constants for current decay and reduces imbalance of forces in the string. The 40 MJ stored energy of all strings is dissipated on the 167-mOhm dump resistors. The maximum voltage does not exceed 1 kV.

4 COOLING CHANNEL

The channel is introduced 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 ~1.4 m will dictate the solenoid diameters in the channel. To provide a cooling, magnetic field must alternate along the length of the channel. One of the cooling schemes employs magnetic field with amplitude of 3.6 T and spatial period of 2.2 m. This determines the length of the magnet of less than 1 m.

High magnetic field alternating along the channel length results in large longitudinal forces. For alternating magnetic fields, magnetic fluxes from neighboring solenoids add in the gap between the magnets, so in the coil the maximal field is higher than on the magnet axis. Fig.1 shows the longitudinal distribution of the magnetic field of the cooling channel made of 1-m solenoids with coil thickness of 50-mm.

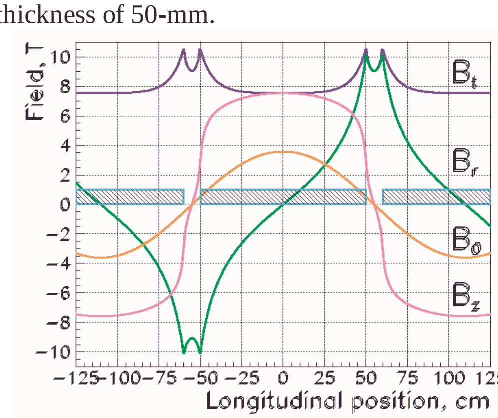

Fig.1. Magnetic field distribution in the cooling channel for solenoid length L=1 m.

The sine-like line shows the magnetic field $\mathbf{B_0}$ 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. The component $\mathbf{B_r}$ gives the main contribution to the edge field. Here the magnetic field exceeds 10 T. NbTi wire cannot be used in such a field, and it is necessary to use Nb_3Sn. Choosing optimal length and thickness of the coil can help to reduce the magnetic field inside the magnet. For example, when the coil length is 0.8 m, in the central area of the magnet magnetic field is ~8.2 T reaching ~9.2 T near the edge of the coil. By increasing the coil thickness, it is possible to further reduce the field in the coil. Fig.2 shows the longitudinal distribution of magnetic fields in a coil with 0.8-m solenoid length and 175 mm coil thickness. The magnetic field in the coil now reaches only 8.3 T, and the field does not change significantly along the length of the solenoid. The radial field distribution shows that the magnetic field near the edge of the solenoid is only 0.5 T higher than the field near the center of the coil.

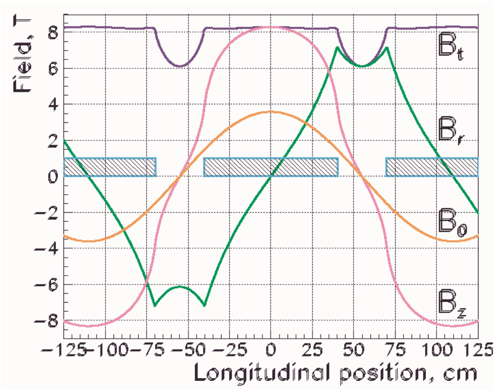

Fig.2. Magnetic field distribution for solenoid with L=0.8 m and d=175 mm.

For the last geometry the calculated radial stress on the outer surface of the coil is about 15 MPa. A simple mechanical analysis shows that to withstand this radial pressure, 6-mm stainless steel bands are required. Integrating forces along the length of the magnet, it is possible to find that axial stress in the middle of the magnet reaches 90 MPa**.** Using external bonding introduces friction between the turns and layers of the coil that reduces this stress to some extent depending on the initial coil pre-loading. Nevertheless, a thorough mechanical design involving stress management features and elaborate mechanical analysis must be performed to insure proper coil performance. Stress management can include the features like using an armored cable, sectioning the coil by strong walls, and epoxy impregnation. The large inner radius of the solenoids allows using “react and wind” technology that will help to keep the copper wire in the "hard" state. Fabrication and study of a SC Nb_3Sn wire in a copper matrix are subjects for R&D. Coil geometry optimization will help to reduce the maximal magnetic field in the coil and improve other magnetic and physical parameters. The quantity of SC material required for the coil does not necessary increase with its thickness, because more copper can be added into SC wire to reduce the engineering current density. Cu/SC ratio of 35:1 was accepted for the cable that is also useful as a quench protection measure.

Significant repulsive forces between magnets in the channel require taking special precautions. For each magnet in the middle of the channel, the repulsive force from each of the neighboring magnets can reach 20 MN. Although these forces are balanced for a magnet inside the channel, the first and the last magnet must have an adequate support to withstand the force. A dangerous situation can arise when force balance for the central magnets is lost during quench in one of the magnets. To avoid an excessive strengthening of the magnet support structure, it is possible to consider the removal of the stored energy simultaneously from all the magnets. For this purpose, a reliable and fast quench detection scheme is required like a bridge-type quench detector.

Ninety solenoids, each in its own cryostat, form the cooling channel. The inner diameter of the cryostats is 1.4 m and the outer diameter is 2.2 m with 10-mm gap between the neighboring cryostats. The total stored energy is 4.3 GJ, so development a reliable quench protection system for the channel is of crucial importance. Some protective precautions must be used like fast quench detection and fast removal of stored energy.

All the magnets in the channel are connected in series into one string. A 3-MW power supply is used that allows reaching the nominal current within 1 hour. There are no dump resistors in this scheme because it appears to be inefficient. All magnets are equipped with heaters that are fired simultaneously. The stored energy of each magnet is dissipated inside its cryostat, in the magnet coil. The maximum temperature reaches ~230 K in the magnet where the quench has originated; for other magnets, this temperature is below 190 K.

The essential feature of the channel is the long time required to cool down the magnets. In the protection scheme 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.

CONCLUSION

As part of 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 made with the goal of reducing its cost. Although design and implementation of every channel discussed above is a nonstandard technical task, one can expect to meet the most challenging problems working with the cooling channel. Both radial and axial ponderomotive forces in this channel are extremely large as well as the interacting forces acting on the first and the last magnets in the string. Because the mechanical behavior of a magnet in this channel is the main issue to study, thorough modeling of the system is a must in this case. Other objects of study are optimization of the quench protection system and analysis of stresses in coils during cooling down and warming up. Undoubtedly, modeling and prototyping of the channel magnets must accompany development of magnetic systems for the Neutrino Factory front end.

REFERENCES

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