Magnetic Systems for Four Channels of Neutrino Factory

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Introduction

The goal of this note was to come out with a preliminary layout of a magnetic system for each of the four channels of Neutrino Factory [1] and make a preliminary cost estimate as a starting point to a more elaborated analysis. More precise estimate can be done after design of magnetic system is completed.

Further we will explore the channels in more details that will come out at the stage of a technical proposal. Some optimization was made at this early stage to choose a proper range of initial parameters to consider. The main parameter of optimization was the total cost of all the four channels that also included operation expenditures although reliability issues have also been taken into account.

For each channel initial requirements were stated, magnetic calculations were made to provide us with a reasonable range of a solenoid parameters to start optimization with, some optimization was done when it was possible, and cost estimate was made based on our experience, available material and labor costs.

At last this study allows one to reveal some problems, which require more detail research and development.

I Magnetic characteristics

1 Channel I

1.1 Initial Requirements

The initial requirements for the first channel are listed below:

1. **The length of the decay channel** is equal to 50 m.
2. The value of Br^2 is constant and is equal to $B_0 r_0^2$, where B_0 = 1.25 T, r_0 = 30 cm, so $B_0 r_0^2$ = 0.1125 $T\times m^2$, r is an inner radius of beam tube in the first channel.
3. **Bore** can be warm or cold.
4. **Central field** can be chosen in interval from 1.25 to 3 T.
5. **Radiation load** can be neglected.

1.2 Magnetic calculations

1.2.1 Main magnetic parameters

It is necessary to mention that the choice of a warm or a cold bore approach changes slightly coil dimensions. Cold bore requires the additional radial thickness of 5 mm for the coil reel. For warm bore additional 40 mm of radial thickness are required that includes the thickness of cryostat. One can find the other reasons for use of the warm bore, in particularly the channel can have beam diagnostic system, for which it can be necessary to have the warm bore.

The critical current density of NbTi has linear dependences versus magnetic field **B** and temperature **T:**

$$J_c(B,T) = J_0\left(1 - \frac{B-5}{5.5} - \frac{T-4.2}{3.2}\right).$$

Here J_0 is a critical current density of 2.5 kA/mm^2 at 5 T and 4.2 K. For choice of operating current density we have taken the temperature margin D**T=T-4.2=1 K** and field enhancement on the coil of 20 % against central field B_0. As a rule the superconducting wires have a cooper matrix with ratio **Cu/NbTi=0.6:0.4**, so the engineering current density at 5 T field and 4.2 K is 1 kA/mm^2.

For the solenoids of the first channel, all calculations were made in the magnetic field range from 1 T up to 5 T.

As it follows from **Br^2=const** condition, there is a trade-off between cross-sectional dimensions of solenoid and central field (Fig.1):

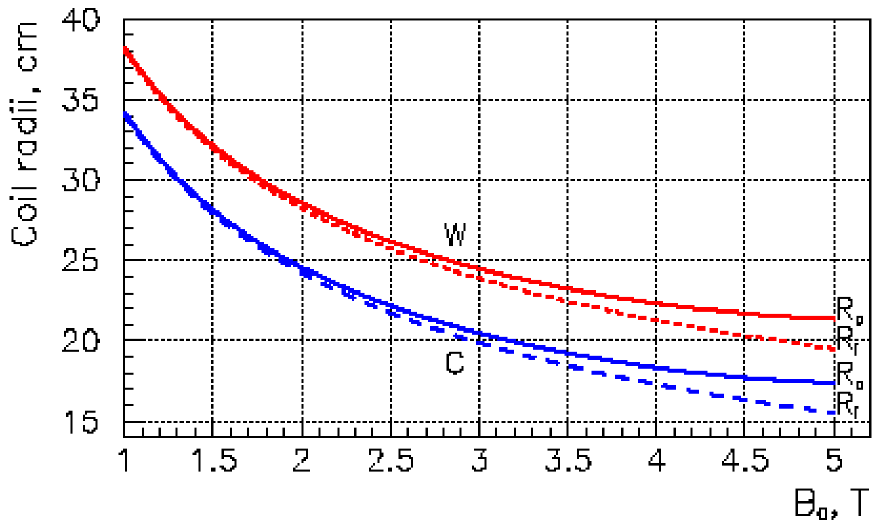

Fig.1. Dependences of inner R_i (dotted lines) and outer R_o (solid lines) radii of coil versus magnetic field for cold (C) and warm (W) bores.

One can see from this picture that coil thickness **w = R_o-R_i** increases with magnetic field. As a result the volume superconductor in the solenoid increases with magnetic field as it is shown in Fig.2.

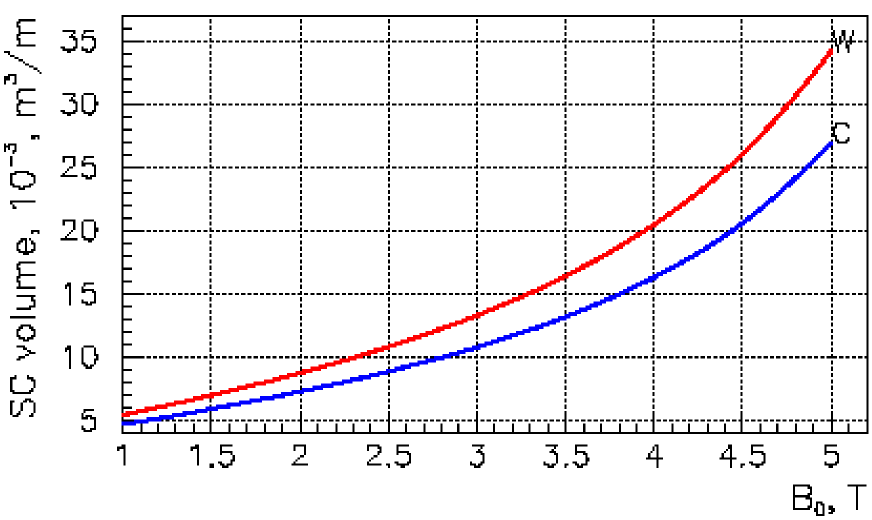

Fig.2. SC volume of coil against magnetic field per 1 m long magnet for warm (W) and cold (C) bores.

Energy stored in solenoid versus magnetic field is shown in Fig.3. Some nonlinearity is due to the coil thic kness growth.

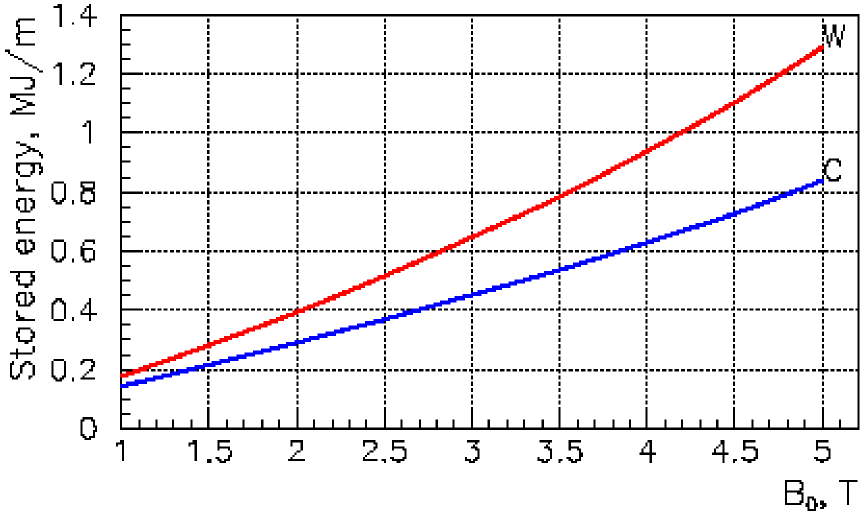

Fig.3. Stored energy per 1-m of solenoid length; W — warm bore, C — cold bore.

Radial pressure increases as B^2 as it is seen from Fig.4; it does not depend on radial dimension of solenoid for long enough magnets.

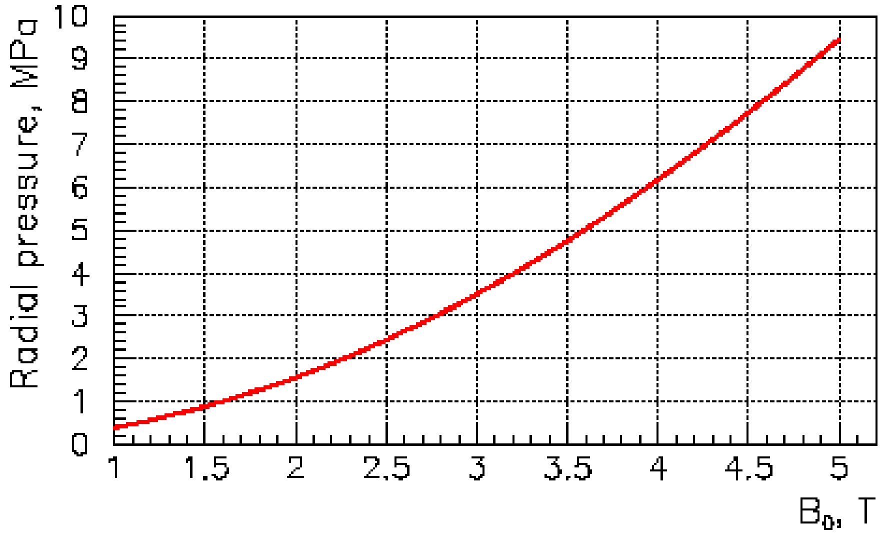

Fig.4. Radial pressure in solenoid against central magnetic field.

Mechanical calculations show that solenoid coil at such radial pressure requires an outer bandage, which thickness **d** grows with field in the range of 1 T = B = 5 T as

$$d[cm] = 0.0323B^2 + 0.0449B$$

Axial force grows also proportionally to $\mathbf{B}^2$ as it is shown in Fig.5 for solenoid with the length of 4.7 m. Interacting forces between magnets are rather large and must be taken into account when one wants to design a proper magnet support.

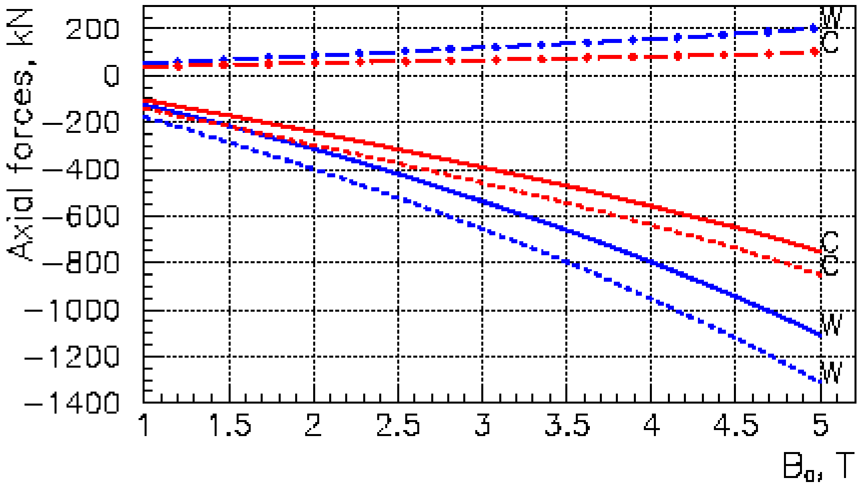

Fig.5. Axial forces versus central magnetic field for solenoids with cold (C) and warm (W) bores. Solid lines show forces acting on a magnet in the middle part of the channel; dotted lines present the forces in a single magnet; dash-dot lines show interacting forces for magnets in channel.

1.2.2 Choice of magnet type

One can see that magnet design is simpler for solenoid with lower field. The magnet with cold bore has some advantage here, but some additional equipment such as beam diagnostic system, vacuum pumps etc. must be introduced in the first channel that can require free access into the channel. The final choice between warm or cold bore can be made later, after the total channel system is developed.

A simple empirical formula can be found in [2] to estimate a 1-m magnet cost that is in an agreement with our independent estimate.

$$Cost = AR^{1.29}B^{1.4}\ .$$

Here A is a constant, R is the inner radius of coil, and B is magnetic field in the center. Using the relationship $\mathbf{Br^2 = const}$, one can get: $\mathbf{Cost \sim B^{0.8}}$. This formula is valid in the field range of 1 T ≤ B ≤ 5 T. So the cost of magnet with lower field is also cheaper.

1.2.3 Main parameters of magnet and channel

The main parameters of one solenoid magnet for the drift channel as it is proposed by this note are listed in the table below:

Parameter	**Unit**	**Value**	
Bore		Warm	Cold
Magnet coil length	m	4.7	4.7
Central field	T	1.25	1.25
Total ampere-turns	MA	4.686	4.684
Operating current	kA	6	6
Bore radius	mm	300	300
Coil thickness	mm	1.796	1.791
Inner radius	mm	345	305
Outer radius	mm	346.796	306.791
Stored energy	MJ	1.068	0.834
Volume of superconductor	m^3	0.00203	0.00180

The channel is arranged using these magnets in a way shown in the next table:

Parameter	**Unit**	**Value**
Length	m	50
Number of magnets		10
Gap between coils	m	0.3

Magnetic forces acting on a solenoid in a single magnet and a solenoid in a string of magnets are presented in the next table:

Bore	Warm	Cold
Radial pressure, MPA		
Single magnet	0.58	0.58
Magnet in string	0.61	0.61
Axial forces, kN		
Single magnet	-230	-180
Magnet in string	-170	-138
Attractive force	60	42

2. Channel II

2.1 Initial requirements

Channel II is to provide an initial emittance damping for the muon beam. There are an RF cavities installed in this channel, so dimensions of the RF cavities will determine the inner diameter of coil. One must choose the magnets with lower field to reduce the channel cost. Inner radius of channel bore is close to 1 m and probably can be reduced to 0.7 m. Some data for this magnet with bore diameters of 0.7 m and 1m are presented below. This channel will have a warm aperture.

2.2 Parameters of magnet and channel

The main parameters of magnets in the channel are listed in the table below:

Parameter	**Unit**	**Value**	
Bore radius	mm	700	1000
Magnet coil length	m	1.7	1.7
Central field	T	1.25	1.25
Total ampere-turns	MA	1.871	1.933
Coil thickness	mm	0.79	0.94
Inner radius	mm	745	1045
Outer radius	mm	745.79	1045.94
Stored energy	MJ	1.994	4.141
SC volume	m^3	0.0063	0.0105

Channel II arrangement can be understood from the next table:

Parameter	Unit	Value
Length	m	40
Number of magnets		20
Gap between coils	m	0.3

Magnetic forces acting on single magnet and solenoid in string are presented in the table:

Bore	**700 mm**	**1000 mm**
Radial pressure, MPA		
Single magnet	0.58	0.58
Magnet in string	0.61	0.61
Axial forces, kN		
Single magnet	-896	-1546
Magnet in string	-546	-856
Attractive force	350	690

3. Channel III

3.1 Initial requirements

Channel III is to perform a muon beam "phase rotation" procedure using linear induction accelerator (LIA). Solenoids must be installed inside the LIA to ensure particle transportation. The length of this channel is about 100 m. Parameters of the channel magnets are close to that of the first channel with warm bore. The magnet length is determined by LIA requirements and is about 1 m.

3.2 Main parameters of magnet

The next table shows what magnet for the channel can look like.

Parameter	**Unit**	**Magnitude**
Magnet coil length	m	0.9
Central field	T	1.25
Total ampere-turns	MA	1.0
Bore radius	mm	300
Coil thickness	mm	0.72
Inner radius	mm	345
Outer radius	mm	345.72
Stored energy	MJ	0.2
SC volume	m^3	0.0016

The total channel can be arranged as it is shown below:

Parameter	**Unit**	**Value**
Length	m	100
Number of magnets		100
Gap between coils	m	0.2

Radial and horizontal forces acting on magnets in the channel are shown in the table below:

Radial pressure, MPa	
Single magnet	0.58
Magnet in string	0.61
Axial forces, kN	
Single magnet	-144
Magnet in string	-208
Interacting force	64

4 Channel IV

4.1 Initial requirements

The channel is to reduce beam emittance to an acceptable level. Its cooling system uses RF cavities to compensate for the energy loss during the cooling. Cross-sectional dimension of the cavities of about 1.4 m will determine diameter of solenoids in the channel that was chosen equal to 1.49 m. The length of the cooling channel must be close to 100 m, and the channel will have a warm bore. The solenoids in the channel must provide high strength, longitudinally alternative magnetic field. There was also a proposal to have two sections in the channel IV. The amplitude of the magnetic field in the first section was suggested on the level of 3.6 T with possible increase it up to 5.5 T. Magnetic field oscillates along the channel with period of 2.2 m for this section. This value determines the length of a magnet, which has to be less than 1 m. The second section was considered with 1.5-m period and 3.4 T amplitude of magnetic field.

4.2 Magnetic calculations

4.2.1 Section I

Fig.6 shows engineering current density (that is the critical current divided by the total cross-sectional area including insulation and copper for stabilization) for different superconducting materials. It is possible to see that NbTi at temperature 5.2 K can be used in fields up to 9 T. Using NbTi at 2.2 K allows the maximal field up to 12 T. Nb_3Sn can work in fields up to 15 T at 5.2 K and has superior magnetic properties in comparison with NbTi at 2.2 K. High temperature superconductors (HTS) like Bi 2212 can work at much higher fields (up to 30 T) practically without any reduction of critical current density; it has an advantage in comparison with Nb_3Sn in fields greater than 14 T.

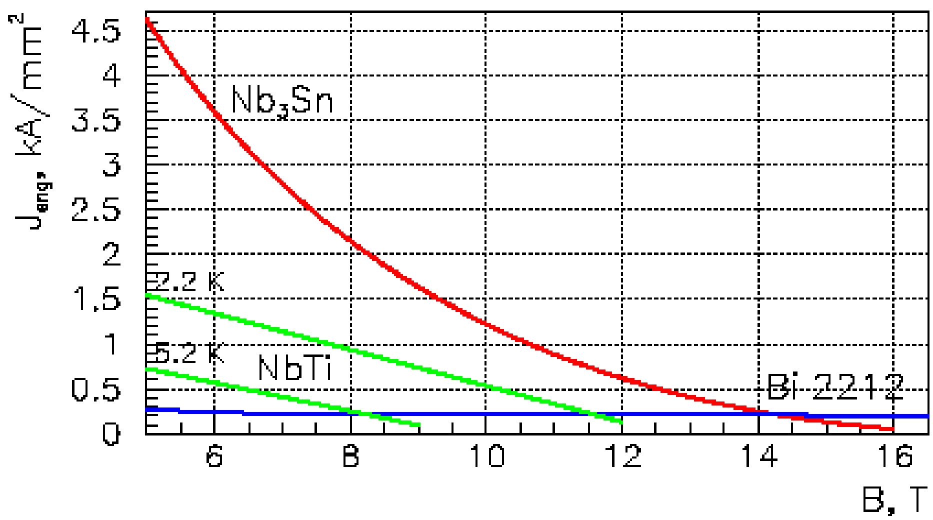

Fig.6. Engineering current density versus magnetic field for different superconducting materials.

For alternating magnetic field, magnetic fluxes from neighboring solenoids add in the gap between solenoids, so the maximal field in the coil must be higher than on the axis. Fig. 7 shows longitudinal distribution of magnetic field in the channel in the case when period **T**=2.2 m, field amplitude $\mathbf{B_0}$=3.6 T, coil thickness **w**=50 mm, and solenoid length L=1 m. Sinusoidal line shows the field along solenoid axis, the other lines show the field components $\mathbf{B_r}$, $\mathbf{B_z}$ and the absolute value **B** on the inner surface of the coil. One can see that the component B_r gives a main contribution in the edge field and its value is very large and reaches almost 10 T. According to Fig.6, NbTi can not be used in such fields, and it is necessary use Nb_3Sn. Nb_3Sn coil thickness must be about 65 mm to reach needed field value.

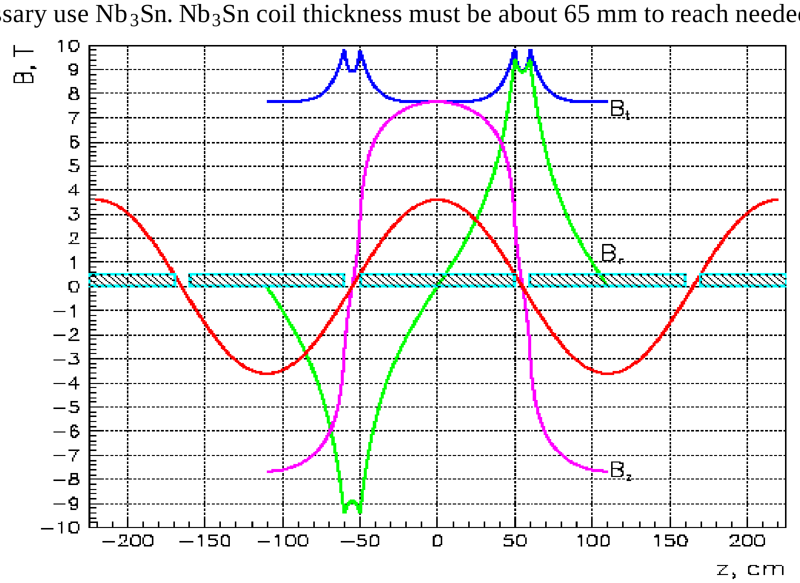

Fig.7. Magnetic field in the Channel IV for solenoid length L = 1 m.

The maximal field in solenoid can be made lower by optimizing the length of the coil. Maximal field in the coil versus solenoid length is shown in Fig.8. One can see the upper curve showing the maximal field on the edge of coil has a minimum, which is equal to 9.2 T at 0.805 m of solenoid length. The lower curve shows the maximal field in the coil in the central area of the magnet.

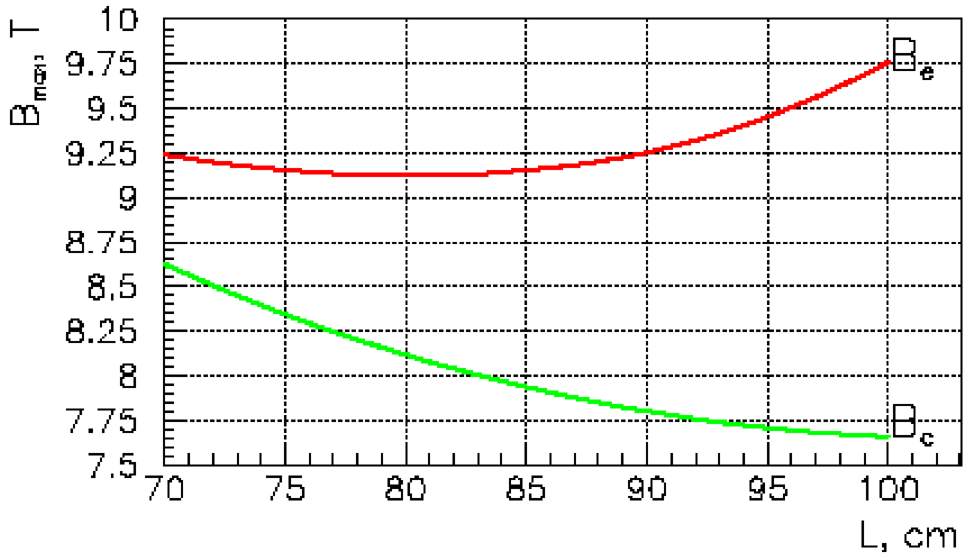

Fig.8. Maximal field in the coil versus solenoid length.

Increasing coil thickness, we can reduce field enhancement in the coil as it is shown in Fig.9. The upper curve shows the maximal field on the edge of the magnet and the lower curve shows maximal field in the coil in the center of the solenoid. Quantity of superconducting material does not increase significantly with coil thickness because more copper can be added into superconducting wire to reduce engineering current density. This can also be useful as a protection measure at quench, so the final choice of coil thickness and current currying element should be made after quench protection system is developed. The reduction of the magnetic field enhancement allows some increase in field amplitude. As coil thickness grows, the energy stored in magnet increases slightly, and axial pressure decreases.

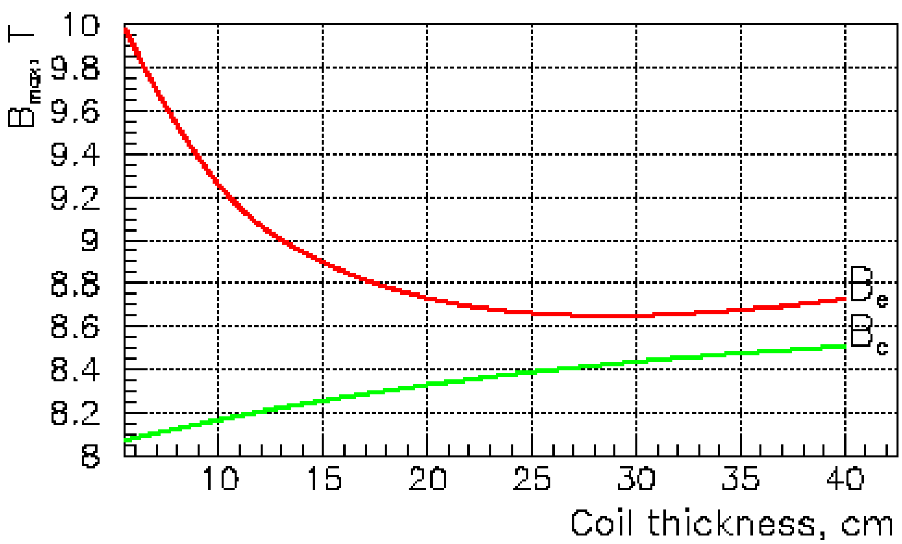

Fig.9. Maximal field versus magnetic field in the center (B_c) and on the edge (B_e) of solenoid

Fig.10 shows longitudinal distribution of magnetic field in the coil for the channel with solenoid length L = 0.805 m and coil thickness d = 175 mm. One can see that magnetic field in coil does not change significantly as it was for the 1-m solenoid length case. An additional improvement of field distribution in coil is possible after one uses more elaborate optimization procedure.

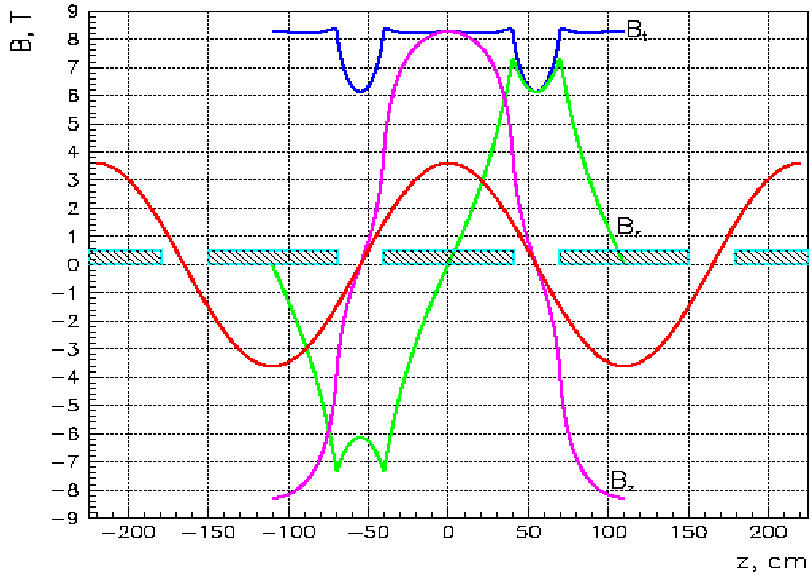

Fig.10. Longitudinal field distribution for optimal length of solenoid.

Radial distribution of magnetic field is shown in Fig. 11. The maximal value of magnetic field on the edge of solenoid is about 0.5 T higher than for the central part of the coil. One can see that the whole area of solenoid end face is found in high magnetic field.

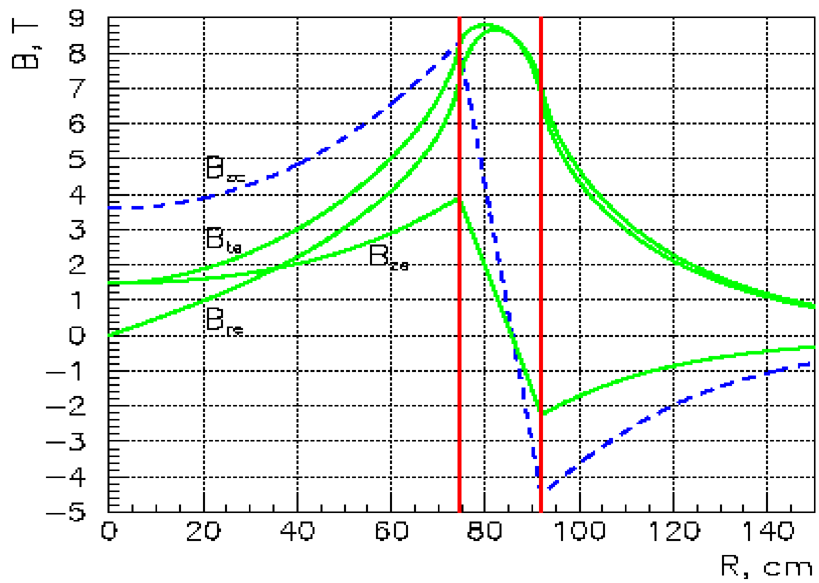

Fig. 11. Radial distribution of magnetic field. Dotted line is the field in the center plane of solenoid; the other lines show end field components.

Fig.11 shows that axial magnetic field changes its sign as one moves along the radius; its maximal value behind the coil is about 4.5 T. This results in the distribution of ponderomotive forces which is presented in Fig.12. The radial pressure on the outer surface of coil is about 15 MPa and the axial pressure on the end face of the coil is about –90 MPa**.** These values have been taken as magnetic forces, integrated over volume of the coil, and divided by area of outer surface of coil and of end face coil accordingly. It is an upper estimation of pressure. The friction between turns will decrease the pressure. It will depend on the stress in coil created by preloading during winding and by radial forces from a bandage. Using epoxy will further improve mechanical stability. Thorough mechanical calculations are need at the stage of engineering design study to finalize the magnet design. Coil geometry optimization as initial step will help to reduce maximal magnetic field in coil and improve the other magnetic and physical parameters.

The field distribution creates a favorable radial force distribution. Simple mechanical calculations show that the coil needs the outer radial the 6-mm stainless steel bandage or 10-mm aluminum one. The longitudinal forces are very large and it is probably useful to divide the solenoid coil by sections using strong stainless steel walls. Energy stored in one solenoid is about 48 MJ, so it is necessary also to pay attention to the protection system design. Total ampere-turns in the solenoid Iw = 9.64 MA.

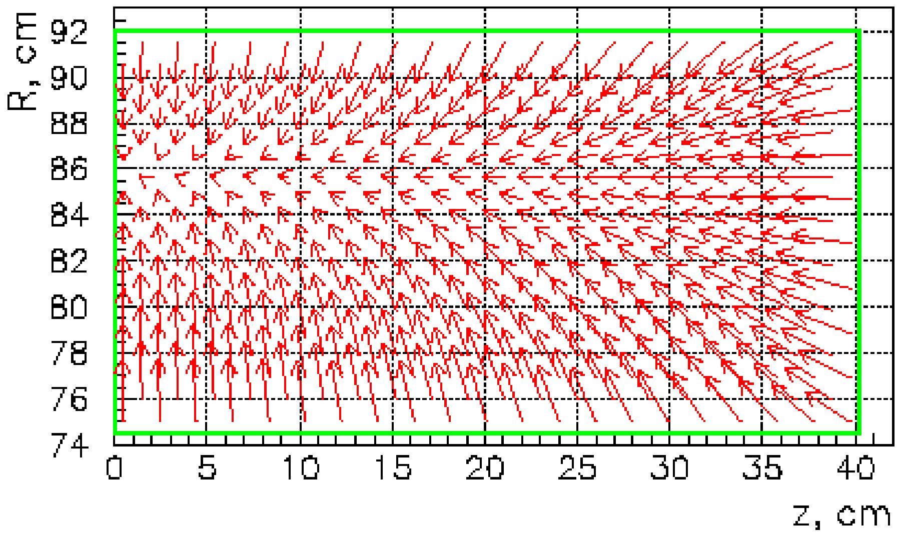

Fig.12. Distribution of ponderomotive forces in solenoid coil.

Oxygen-free high conductivity Copper, Soft, UNS C10200 [3] has the tensile yield strength about 65 MPa at room temperature. The superconducting cable contains 95 % copper, which defines its mechanical properties. So there is a possibility that high pressure that results from magnetic forces can result in cable degradation. However, **Oxygen-free high conductivity Copper, Hard, UNS C10200 [3]** has tensile yield strength of about 230 MPa at room temperature. The **Oxygen-free high conductivity Copper, H80 (40%) [3]** has the tensile yield strength is equal to about 345 MPa at room temperature. Electrical properties for all these sorts of copper are the same. At liquid helium temperature, yield strength is by factor of 1.3 larger [4]. So the tensile yield strength for **hard Copper, UNS C10200** will be about 300 MPa at the temperature of liquid helium, which looks quite satisfactory. Large inner radius of solenoid allows using "react and wind" technology that will help keeping copper in hard state. Fabrication of current carrying element that consists of Nb_3Sn superconductor and copper of different qualities and study of its mechanical properties are the subjects for R&D.

Using different coil thicknesses we have made calculations of magnet parameters with the goal in mind to decrease the average axial pressure below 60 MPa. Increasing the coil thickness from 175 mm to 350 mm gives pressure drop from 90 MPa to 55 MPa as it is shown in Fig.13.

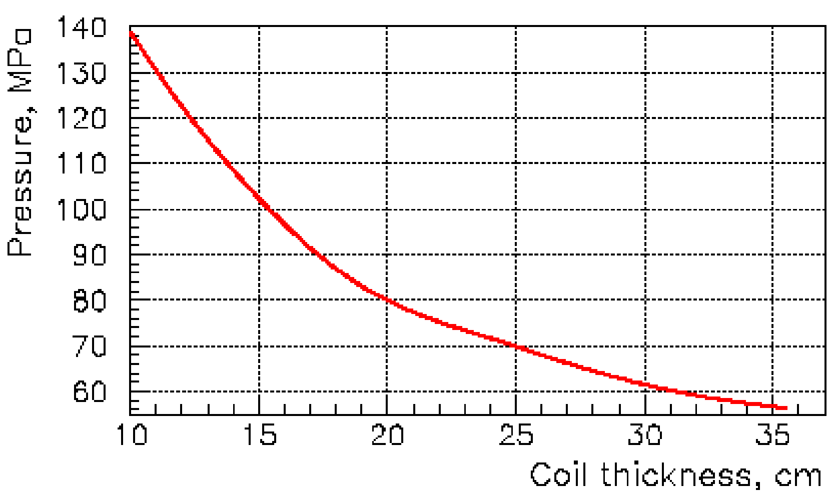

Fig.13. Dependence of axial pressure in solenoid versus the coil thickness.

. However stored energy (Fig.14) and total current in magnet (Fig.15) as well as the coil volume (Fig.16) grow nearly linear with the coil thickness. So superconducting material cost grows also almost linearly.

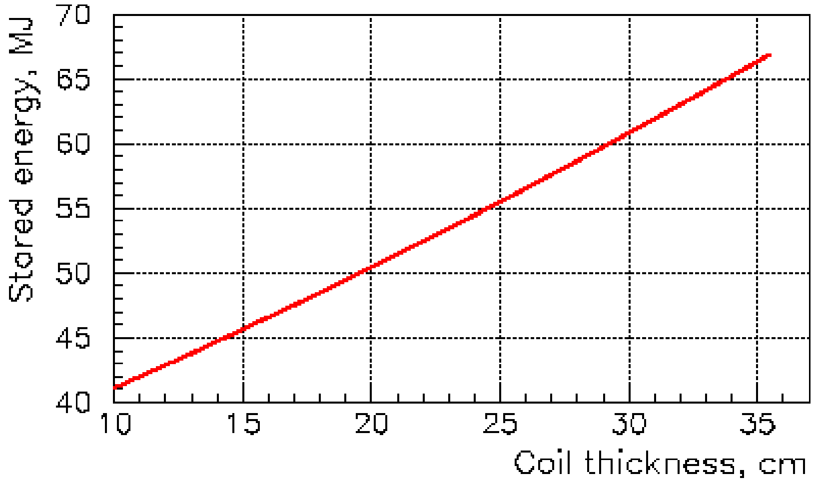

Fig.14. Stored energy in solenoid versus coil thickness.

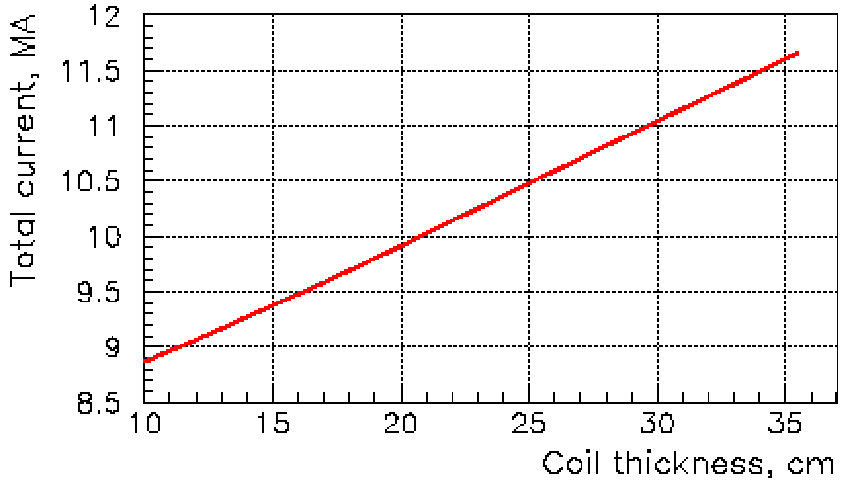

Fig.15. Total current in solenoid versus coil thickness.

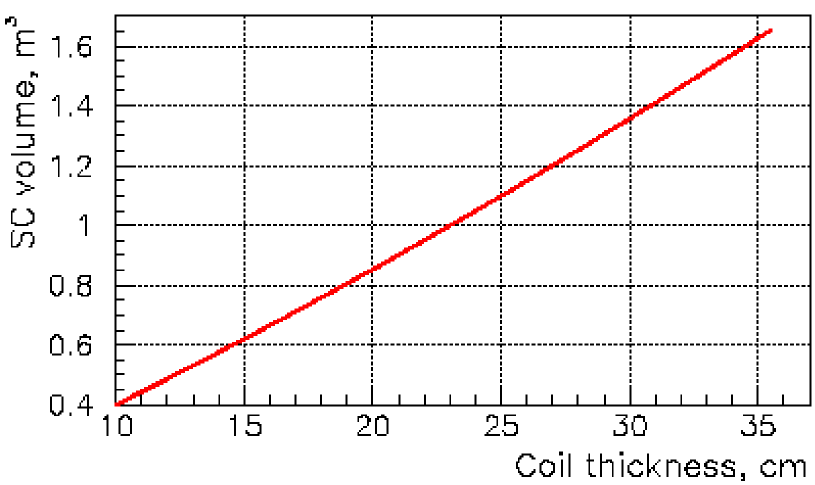

Fig.16. Volume of conductor in solenoid versus coil thickness.

Fig.17 and Fig.18 show the radial and longitudinal field distribution for the single solenoid with coil thickness of 175 mm.

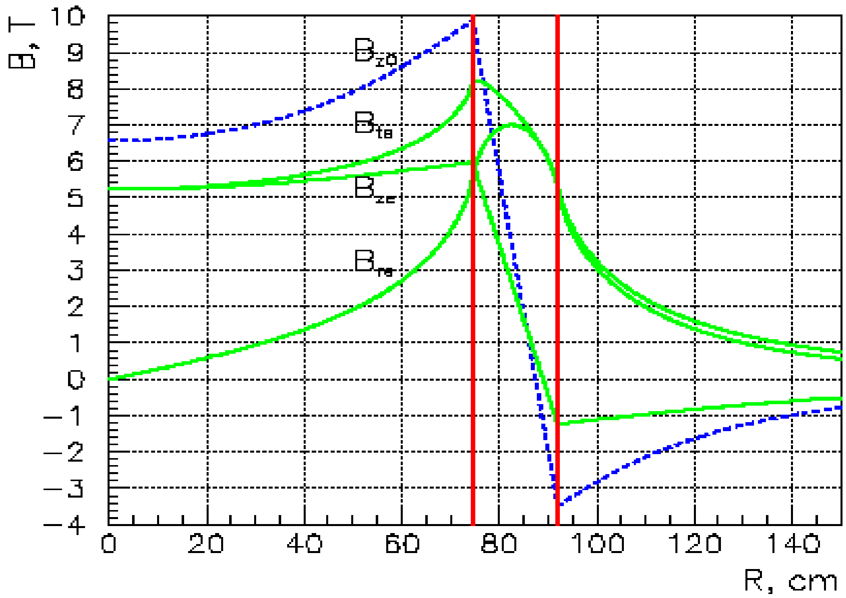

Fig.17. Radial field distribution for the single solenoid.

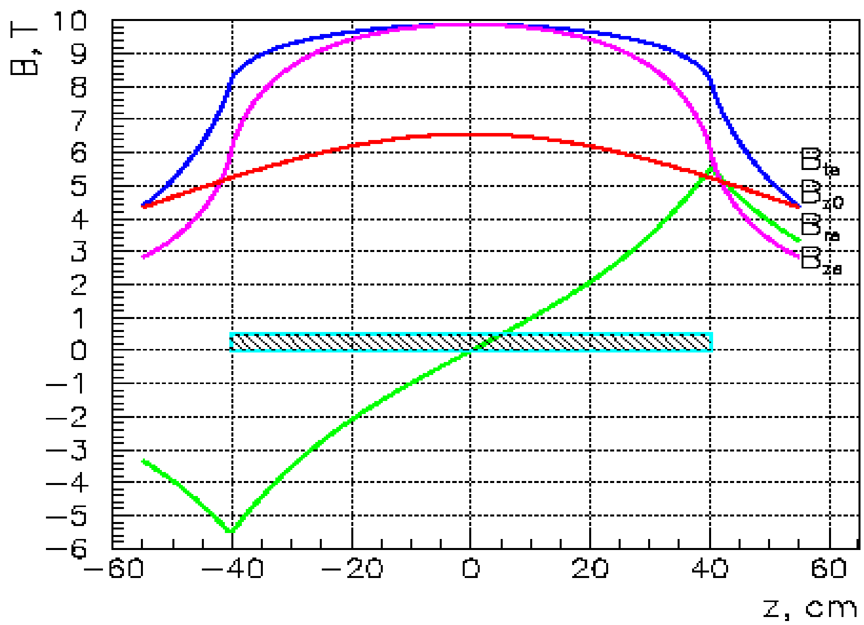

Fig.18. Longitudinal field distribution for the single solenoid.

This distribution will be for the first and the last magnets in the string of solenoids and also can occur in a solenoid when the neighboring solenoid quenches. Stainless steel bandage thickness needed in this case is about 50 mm.

If the amplitude of a magnetic field in the channel is 3.6 T, maximal field in coil is 8.8 T. The material properties of Nb_3Sn allow one to increase field amplitude up to 5.5 T. But because magnetic forces and stored energy grow as B^2, different approach to the magnet mechanical design and protection system must be considered. In particular, radial thickness of stainless steel bandage must be not less than 50 mm.

4.2.2 Section II

The second section of the Channel IV is even more difficult for implementation. Fig.19 shows the maximal field in the coil versus field period for alternating field with amplitude of 3.4 T. Lower curve presents field B_c in the center of the coil; upper curve shows the maximal value of field B_{max} on the edge of solenoid. The length of solenoid has been optimized for each value of period; the coil thickness was chosen to be 200 mm. The horizontal line shows the limit field for Nb_3Sn material, so the period must be larger than 1.65 m for Nb_3Sn coil. In principle, it is possible to talk about a reduction of field period by using HTS materials that can work in field up to 30 T at temperature of liquid helium, but it will require an extensive R&D before one can really start thinking about this option.

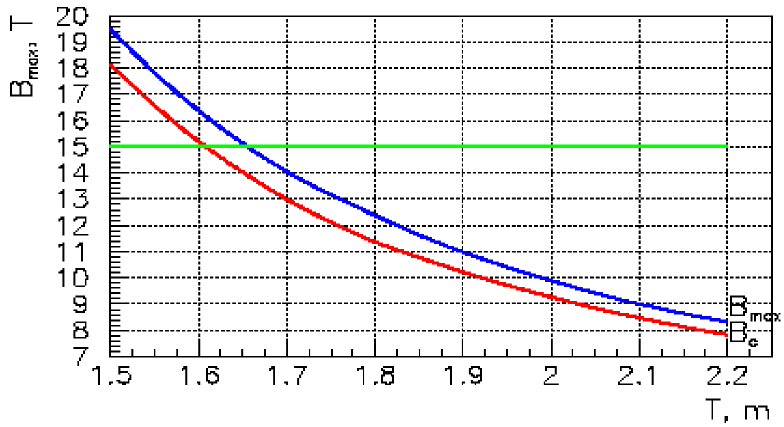

Fig.19. Maximal field on the coil versus field period. B_c is the field in coil in the center of magnet; B_{max} is the maximal field on the edge of coil. Horizontal line shows the limit value of field for Nb_3Sn material.

The best samples of HTS wire [5,6] with diameter 1.6 mm have the critical current of 900 A at 4.2 K. The critical current is 300 A at 28 T that corresponds to 800 A/mm^2 of current density in superconductor. The rectangular wire with the same cross section (1.12×1.12 mm^2) and in the same conditions can carry 360 A (current density of 1000 A/mm^2). The total current in solenoid with optimal length of 0.475 m 13.9 MA. This coil would have a thickness of 125 mm with 97 layers and 417 turns in each layer. Average length of each layer is 2 km, so the total length of HTS for one solenoid is about 200 km. Because ponderomotive forces are very high (60.25 MPa in radial direction and –425.40 MPa in axial direction), it is necessary to consider a careful stress management because the HTS material is very fragile. This issue needs more detail study as well as the choice of the protection system, which must ensure the evacuation of stored energy of 130 MJ per magnet. As an example Fig.20 shows the radial distribution of the magnetic field in this solenoid.

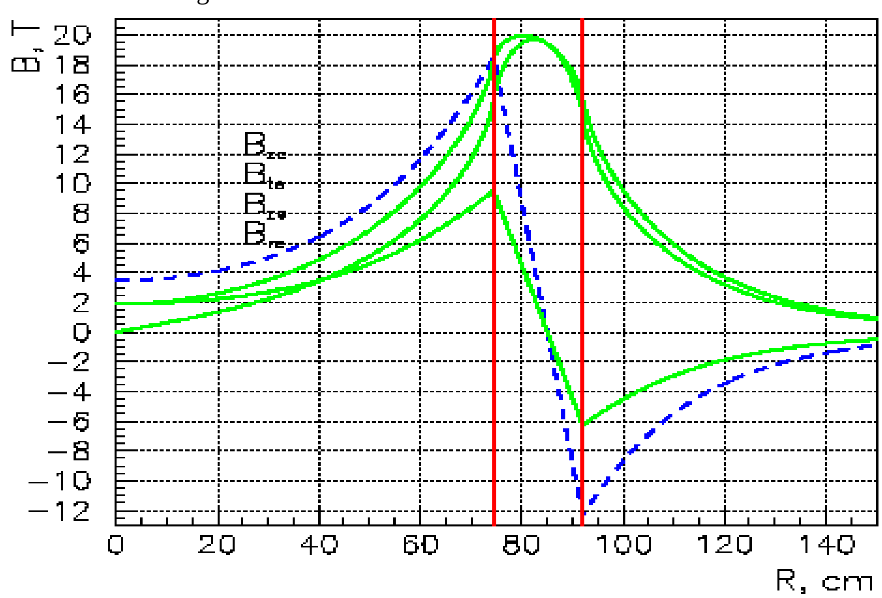

Fig.20. Radial field distribution in solenoid cell with magnetic field period of 1.5 m.

4.3 Main parameters of magnet and channel

The main parameters of magnet in the Channel IV are listed below:

Parameter	Unit	Value		
Magnet number		1	2	3
Period	m	2.2	2.2	1.5
Magnet coil length	m	0.805	0.805	0.475
Central field	T	3.6	3.6	3.4
Maximal field in coil	T	8.8	8.6	19.5
Total ampere-turns	MA	9.64	11.68	13.9
Bore radius	mm	700	700	700
Coil thickness	mm	175	350	125
Inner radius	mm	745	745	745
Outer radius	mm	920	1095	870
Stored energy	MJ	48	67	130
Volume of superconductor (without copper)	m^3	0.0263	0.0263	0.3012

The table below shows channel arrangement with magnets from the table above

Parameter	Unit	Value	
Magnet number		1,2	3
Length	m	50	50
Number of magnets		45	67
Gap between magnets	m	0.295	0.275

Magnetic forces acting on single magnet and solenoid in string are presented in the table:

Magnet number	1	2	3
Radial pressure, MPa			
Single magnet	30.4	36.3	135.7
Magnet in string	15.2	16.0	60.3
Axial pressure, MPa			
Single magnet	-68.9	-42.9	-425.8
Magnet in string	-89.1	-56.4	-354.0
Axial forces, MN			
Single magnet	-61.8	-86.6	-264.8
Magnet in string	-79.9	-114.6	-220.2
Interacting force	-18.1	-28.0	-44.6

II Magnet design

The basic technical parameters of the four channels of Neutrino Factory are presented below:

Channel	**I**	**II**	**III**	**IV**
Channel length, m	50	40	100	100
Central field, T	1.25	1.25	1.25	3.6
Bore diameter, m	0.6	2.0	0.6	1.4
Cryostat length, m	4.8	1.8	0.85	1.0
Gap between cryostats	0.2	0.2	0.15	0.1
Number of magnets	10	20	83	90
Total stored energy, MJ	11	82	20	4300

The main parameters of magnets for all the four channels are listed below:

Channel	**I**	**II**	**III**	**IV**
Central field, T	1.25	1.25	1.25	3.6
Coil length, m	4.70	1.70	0.75	0.80
Bore diameter, m	0.6	2.0	0.6	1.4
Total current, MA	4.69	1.93	1.08	9.64
Layer number	2	2	2	16
Total turn number	781	322	180	1608
Operating current, kA	6	6	6	6
Stored energy, MJ	1.1	4.1	0.2	48.0
Inductance, H	0.061	0.2	0.013	2.55
Radial pressure, MPa	0.61	0.61	0.61	15.2
Axial pressure, MPa	16	17	19	89
Cable dimensions, mm^2	6×4.2	5.3×6	6×4.2	7.8×6.2
Superconducting alloy	NbTi	NbTi	NbTi	Nb_3Sn
Cu/SC ratio	7:1	9:1	7:1	20:1
$I_{nominal}/I_c$ ratio	0.3	0.3	0.3	0.5
Cable length, km	1.7	2.1	0.4	8.5
Cable mass, kg	370	582	86	3600
Cryostat inner diameter, m	0.618	2.0	0.618	1.4
Cryostat outer diameter, m	0.935	2.42	0.885	2.18
Cryostat length, m	4.8	1.8	1.1	1.0
Mass of magnet, ton	3.8	8.4	1.2	8.0

Solenoid coil in the first three channels has two layers. NbTi superconductor in copper matrix is chosen as a current currying element. Dimensions of superconducting cable, quantity of copper for stabilization and ratio of nominal to critical currents were determined taking into the account safe evacuation of stored energy out of magnet during quench process:

1. The temperature of the hottest spot in the coil is less than 300° K.
2. Maximal voltage is not greater than 1000 V.

Operating current is 6 kA, that is 30% of the critical current at 1.25 T and 4.5 K. The ratio Cu/SC is 7:1 in the first and the third channels and 9:1 in the second channel.

Superconducting coil in the fourth channel has 16 layers. For this channel, Nb_3Sn was chosen as a current carrying element. Cu/SC ratio in superconducting cable is 20:1. The cable is insulated with 0.1-mm kapton insulation. The coil is wound on stainless steel tube, banded by copper shells, and cooled by liquid helium flowing through copper piping. The pipes are soldered to the copper shells and are connected by collectors on the ends of coil. Several layers of super-insulation cover the outer surface of shells. The superconducting cable in the transition area from one magnet to another is cooled by a pipe carrying liquid helium.

Copper thermal shield cooled by liquid nitrogen is used to reduce heat leaks to the inner and outer surfaces of a superconducting coil. The outer surface of the shield is covered with 40 layers of super-insulation.

Superconducting coil and shield are attached to a vacuum vessel using two vertical suspension devices and four horizontal tension devices. This support system allows one to adjust coil position both in horizontal and vertical direction. In the axial direction longitudinal members and anchor rigid on the vacuum vessel fix the cold mass.

The budget of heat leak in the cryostat and cryogenic system heat load are presented below:

Channel	**I**		**II**		**III**		**IV**	
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 mains power, kW	115	26	219	57	331	57	383	133

To remove power dissipated in RF cavities in the second and the fourth channels (50 kW per 1 m of the channel length), a copper shield cooled by water can be used. The shield must be at least 3 mm in thickness, and 25-mm in diameter copper water pipe soldered to the outer surface of the shield as a spiral with 100 mm pitch can keep the shield temperature at reasonably low level. Each superconducting solenoid has its own shield; all of the shields are connected in parallel. Water flow rate for each magnet is 1.5 liters/s, required pressure drop is 0.6 MPa. The total flow rate of water is 30 liters/s for the second channel and 135 liters/s for the fourth channel.

III Quench protection

Superconducting coils of all the four channels are not self-protected against transition to the resistive state (quench) that threatens the integrity of the coils. Some protective precautions must be used like fast quench detection and the removal of stored energy to the external dump resistor or/and "smearing" of stored energy inside the magnets using heaters.

For all the four channels, solenoids are located very close to each other, and their magnetic axes have the same directions. Therefore, there exists large mutual inductance that results in high voltage induced in a magnet if its neighbor has quenched. Significant ponderomotive force between magnets can be a problem if not to take special precautions. Attractive force can reach 60 kN in the first and the third channels, 690 kN in the second channel and repulsion force of approximately 18000 kN is in the fourth channel. These forces are balanced for a magnet inside a channel, except the first and the last magnets that must have a very strong support. In a case of a quench for a magnet inside a channel, the similar situation develops that results in an unacceptable longitudinal force for neighboring magnets. This requires using rigid support for each magnet in a channel that complicates channel mechanical design. To avoid, it is possible to consider a removal of stored energy simultaneously from all magnets in a channel. Because all magnets in each channel are identical, it is possible to compare magnet voltages for detection of normal zone appearance. Other techniques of quench detection can be used also. For the first and the last magnet of the second and the fourth channels quench detection scheme will is different. These magnets are to be equipped by a quench detector of bridge type. When the voltage on the resistive section of coil exceeds given threshold, the quench detector generates a signal to start protective actions.

Schemes of protection circuits, which take into account the peculiarities of each channel, are discussed below.

1. Channel I

Energy stored in one solenoid of the channel is 1.07 MJ. There are ten solenoids in the channel. The magnets are connected in series and powered by one power supply. Full energy stored in the channel is 10.7 MJ. The power supply with the output power of approximately 180 kW is sufficient to rise current up to 6 kA during 200 sec.

The protection method is shown schematically in Fig.21. When 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 power supply is switched off by S_1. At that moment the stored energy of the string starts to dissipate on the dump resistor. During extraction of energy out of a magnet, maximal allowable voltage was accepted at the level of 1000 V when R_d = 0.167 Ohm. Simulation of quench spread through the coil was made for the case when quench was provoked on the outer boundary of inner layer of the coil. The quench detector threshold was U_t = 1 V, time delay T_d = 100 ms and energy discharges on dump resistor R_d = 0.167 Ohm. The results are presented in Fig.21 that shows current, dump resistor and coil voltage, energy dissipated in coil and dump resistor, and hot spot temperature. Almost 97 percent of stored energy is dissipated outside cryostat. Amount of energy dissipated in coil is sufficient for adiabatic heating of the coil up to 180 K in the hottest area.

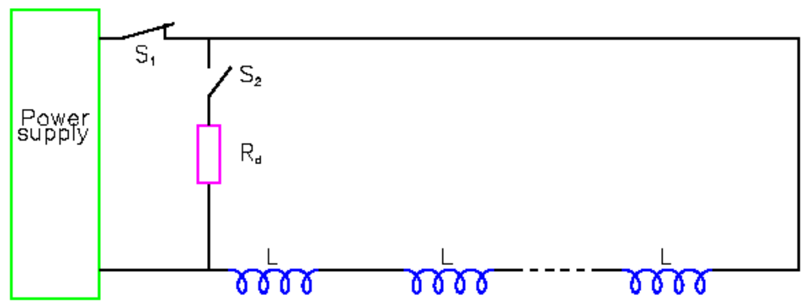

Fig.21. Quench protection sketch of magnets in the first channel.

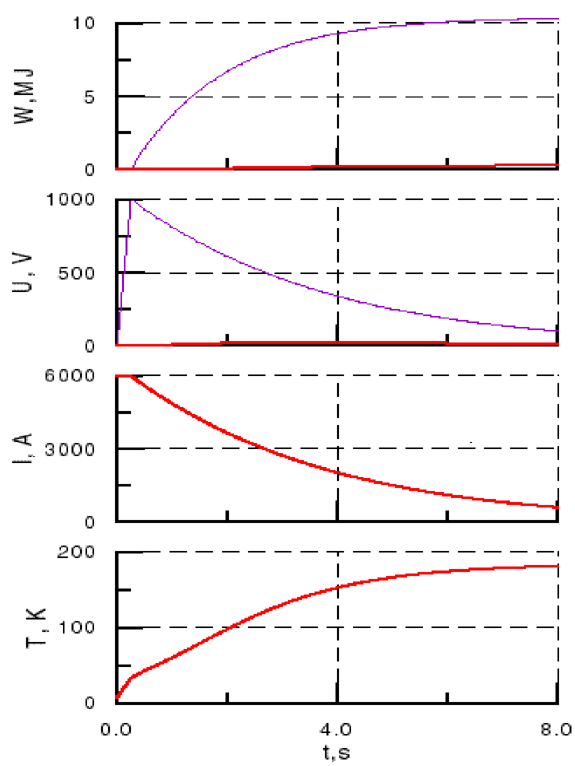

Fig.22. Quench process in magnets of the first channel. Thin lines correspond to dump resistor, thick lines are for superconducting coil.

2. Channel II.

Twenty magnets of the channel store 83 MJ of energy. All the magnets in the channel are subdivided in two groups. The magnets of each group are connected in series and form independent strings with their own power supplies. The scheme of one string is presented in Fig.23. Power supply with output power of 180 kW is sufficient to rise current in string of magnets up to 6 kA during 10 minutes.

The scheme is similar to that of the first channel with one exception. There are magnets equipped with protective heaters, one by one string. These heaters are necessary for synchronizing of energy extraction from the strings. Also, resistance growth rate stimulated by the heater is higher than that of the original normal zone; this will reduce a difference in string of resistances. Besides, the two strings will have close time constants of current decay that will reduce unbalance of forces in the string. After quench detection, power supply is switched off by S_1, dump resistor R_d is turned on by S_2, and heater is connected to heater power supply by S_h. Stored energy of all strings is dissipated on the dump resistors R_d = 0.167 Ohm. Maximum voltage does not exceed 1000 V.

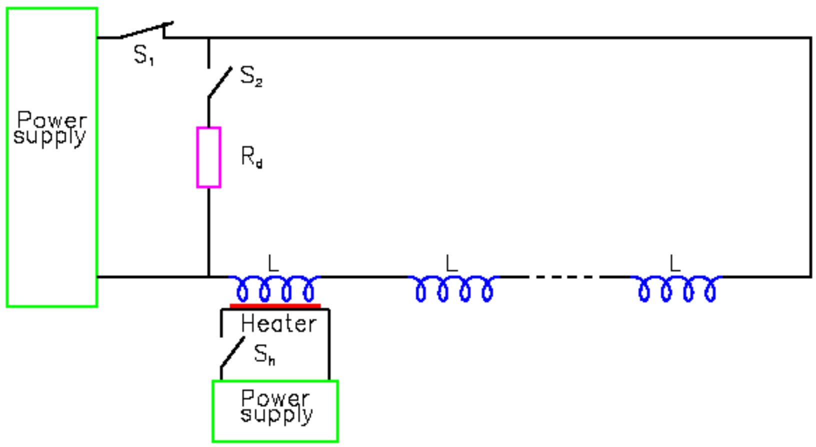

Fig.23. Sketch of quench protection in one string of second and third channels.

The results of simulation of quench process initiated by heater in the string of 10 magnets are presented in Fig.24. Maximum temperature in magnet with heater-initiated quench does not exceed of 210 K. The hot spot temperature in magnet with original quench is greater by 30 K and is equal to 240 K.

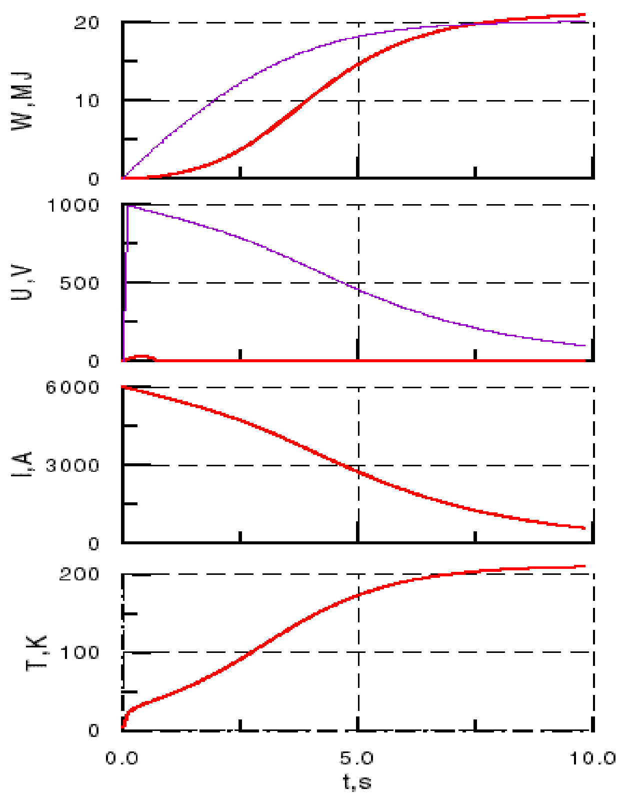

Fig.24. Quench process in magnets of the second channel. Thin lines correspond to dump resistor, thick lines are for superconducting coil.

3. Channel III.

There are 100 magnets in the channel with stored energy of about 0.2 MJ each. Total energy stored in the channel is 20 MJ. This energy is about twice as large than that for first channel. All the magnets in the channel will be subdivided in two groups. In each group magnets are connected in series and form two independent strings powered by 180 kW power supplies. Scheme of one of the string is presented in Fig.23. Quench protection concept is the same as for the second channel. Each string contains one magnet with protective heaters. After 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 heater is switched to heater power supply by S_h. Stored energy of both strings is dissipated on the dump resistors R_d = 0.167 Ohm. Maximum voltage does not exceed 1000 V.

The results of simulation of quench process are presented in Fig.25. In this case, hot spot temperature does not exceed 200 K in magnet where quench originated and 170 K in magnet with heater-initiated quench.

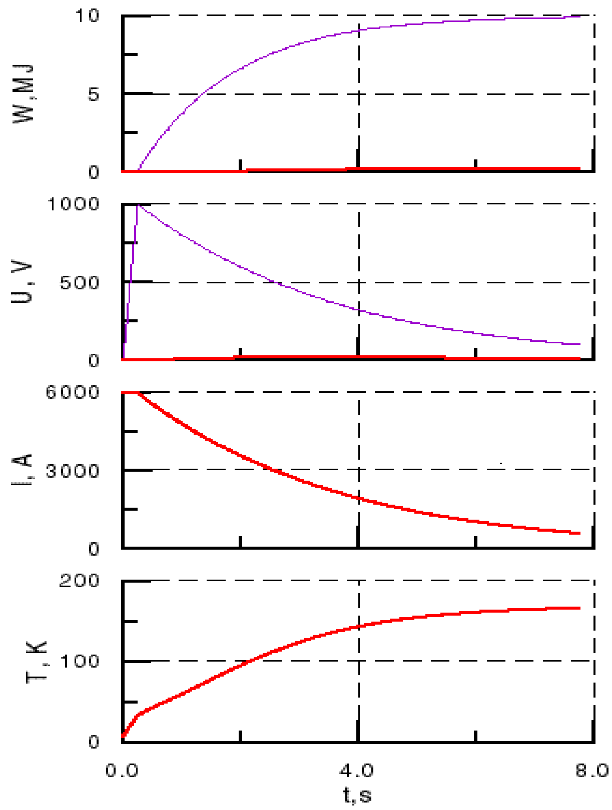

Fig.25. Quench process in magnets of the third channel. Thin lines correspond to dump resistor, thick lines are for superconducting coil.

4. Channel IV

All magnets of channel are connected in series into one string. Total stored energy is about 4400 MJ. Power supply must provide of 3.0 MW that will allow one to reach the nominal current within 1 hour. Quench protection scheme is presented in Fig.26. In this scheme, there is no dump resistor because it is inefficient for the channel IV. All magnets are equipped with heaters, that are fired by switches S_h simultaneously. Stored energy of each magnet is dissipated inside its cryostats, in the magnet coil.

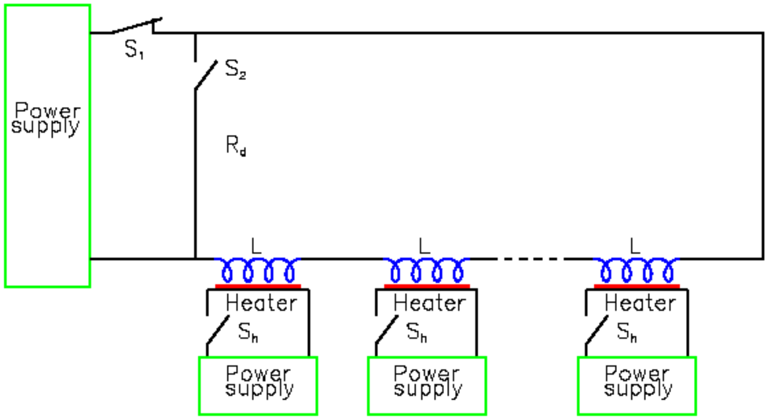

Fig.26. Quench protection sketch of magnets for the fourth channel.

Quench process diagrams for the magnets of the channel IV is shown in Fig.27. Maximum temperature reaches about 230 K in the magnet where quench has originated; for other magnets, maximum temperature in is below 190 K.

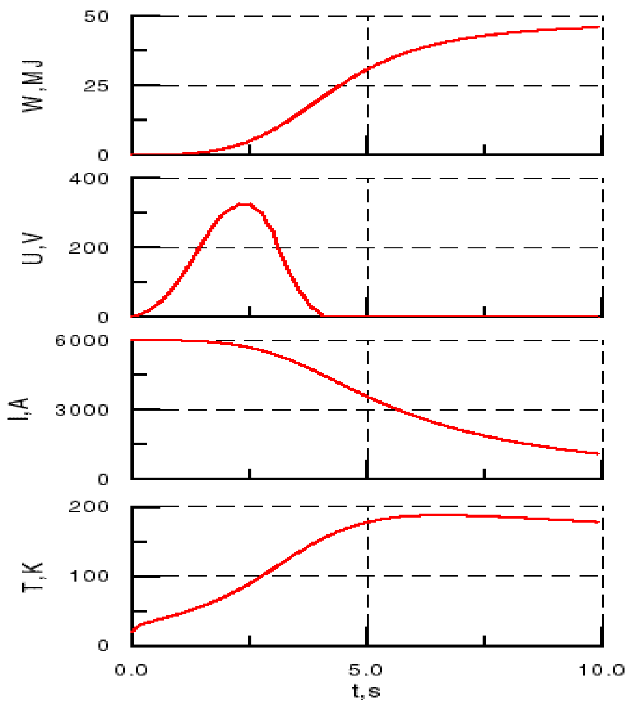

Fig.27. Quench process in magnets of the fourth channel.

5. Power supply

Main parameters of power supply for magnetic system for all channels are presented in the following table:

Channel	I	II	III	IV
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
Energizing time, s	200	600	200	3600
Number of power supply	1	2	2	1

Conclusion

As part of FNAL Neutrino Factory study, preliminary analysis has been made to realize magnetic system for decay channel, phase rotation channel, and cooling channels. For each channel, simple optimization was made with the goal to reduce the system cost. Design study was conducted to reveal problems that must be studied at R&D stage. Preliminary costs of the magnetic systems and operational expenditures have been estimated. This cost estimate can be updated after R&D program is completed at the stage of technical proposal. For each channel, it was shown that the major portion of the cost is the cost of superconducting magnets. Technical difficulties to build channel IV result in the situation when future R&D program must be devoted mainly to analyzing and modeling of this channel. Cost of the channel IV makes up the bulk of the cost of the entire magnetic systems.

The general cross-sectional and longitudinal views of the magnets for the all four channels have appended as conceptual drawings.

References

1. The μ^+ μ^- Collider Collaboration. "μ^+ μ^- Collider. A Feasibility Study." BNL-52503, July 1996.
2. M.A.Green et al. Superconducting Solenoids for the Muon Collider. MT-16, 1999, Ponte Vedra Beach, Fl, USA.
3. http:/www.matweb.com/SpecificMaterial.com/
4. Handbook on physical and technical basis of cryogenic. Editor by M.P.Malkov. Moscow, Energoatomizdat, 1985, p.234.
5. N.Okada. HTS High Field Magnets. MT-16, 1999, Ponte Vedra Beach, Fl, USA.
6. K.Marken, J.Parell and S.Hong. BSCCO-2212 Conductors for High Field Magnets. MT-16, 1999, Ponte Vedra Beach, Fl, USA.

Appendix

Estimated cost

The estimated cost has been made on a basis of our experience in fabricating similar super-conducting systems. The table below shows material cost (in USA dollars) that was taken as a base for the cost estimation of magnets and channel magnetic systems:

Materials	Unit	Cost, $
NbTi conductor	kg	120
Nb_3Sn conductor	kg	220
Copper	kg	6
Stainless steel	kg	10
Aluminum	kg	10
Labor	hour	25

The size of batch has influence on the fabrication cost that was also taken into consideration under cost determination.

Fabrication costs of magnet and its components for all four channels are presented below in k$:

Channel	I	II	III	IV
Materials	50	105	20	80
Superconducting cable	45	70	10	760
Labor	60	110	40	120
Cryogenic test	10	15	10	40
Total	165	300	80	1000

The overall cost of all magnetic and auxiliary systems for the all four channels are estimated in table below in M$:

Channel	I	II	III	IV
Fabrication cost of magnets	1.65	6.0	6.64	90.0
R&D, drawings, fabrication of prototype, tooling	0.5	0.8	1.5	4.0
Power supply	0.03	0.06	0.06	0.15
Quench protection system	0.02	0.05	0.05	0.12
Total	2.2	6.9	8.3	93.3
Power consumption of cryogenics during 10^8 s (5 years)	0.24	0.38	0.54	0.71
including at 4.5 K	0.20	0.30	0.46	0.53
including at 80.0 K	0.04	0.08	0.08	0.18

Altogether total cost of magnetic system production for all four channels is M$ 112 and power consumption of cryogenics during 10^8 s (5 years) is M$ 1.9.

It follows to note that in the case of decision making of solenoid production with increased coil thickness to 350 mm in the cooling channel, the fabrication cost of magnets will be M$ 180. Also it should increase the cost for R&D, drawings, fabrication of prototype and tooling to M$ 5. So the total cost of magnetic system production for all four channels will be M$ 203.

There is a prognosis [5,6] that the cost of HTS will be reduced by 6 times, from 300 k$/kA×m to 50 k$/kA×m at 77 K in own field. The cost of HTS at 27 K in external field of 1 T will be 25 k$/kA×m. One can suppose that the cost of HTS at 4.2 K in the external fields of 20÷30 T will be the same and equal to 25 k$/kA×m. So the cost of HTS for one magnet in the section II of channel IV can content of M$ 1.8. The most optimistic conductor can have higher the critical current density that can reduce the cost of HTS coil by half.

Problems for R&D

We did not have a goal to study in details all problems that can arise inevitably during development, engineering and designing of all the channels. Some of them can be solved in a normal way. Others need additional research stage.

1. Channel I

Channel I has no problem. One can start to develop and design working drawings.

2. Channel II

Forces acting on the first and last magnets in the string are very large. It requires more careful design of supports in order to maintain mechanical stability of magnets in string and keep heat load through these supports on an acceptable level.

3. Channel III

Channel III consists of many short magnets with small gaps between them. These gaps complicate electrical and cryogenic systems of the channel. Magnetic system leads can interfere with LIA pulsed power system feeders. This will require careful design study of the LIA section including magnetic system.

4. Channel IV

Channel IV creates a lot of design problems. Even using 2.2-m period with magnetic field amplitude of 3.6 T results in very large field in coil, stored energy and ponderomotive forces. First of all, it is necessary to make geometrical optimization of magnet coil with the goal to reduce magnetic field in the coil. It is possible, for example, to study coil, having layers with different current densities and different lengths. Another objects of study are quench protection system, mechanical strength of solenoid, stress in coil during cooling down and warming up of the channel. Both radial and axial ponderomotive forces are very large as well as the interacting forces acting on the first and the last magnets in the string. Undoubtedly the development of the magnetic system must be accompanied by modeling of solenoid prototypes. More detailed study is needed if one wants to answer the questions like:

- is it possible to increase magnetic field?,
- is it possible to increase coil inner radius?,
- is it possible to make period shorter?

5. R&D program suggestions for year 2000

1. Geometry optimization for the cooling channel: optimization of different magnet parameters with the goal of increasing field amplitude, shortening field period, increasing coil inner radius.
2. Mechanical calculations of the magnet coil mechanical stability.
3. Development of Nb_3Ti cable for magnets of the channel IV; development of coil fabrication technology.
4. Development and optimization of a cooling scheme for each channel with the goal to reduce time for for cooling down and warming up and helium consumption.
5. Design of special supports for superconducting coil for the second and the fourth channels.