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. Of course an accurate cost can be determined after final development of magnetic system and issue of working drawings.

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 **Channel length** is equal to 50 m.
2 The value of Br^2 is constant and is equal to $B_0r_0^2$, where B_0 = 1.25 T, r_0 = 30 cm, so $B_0r_0^2$ = 0.1125 T×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 **DT=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.

In order to eliminate general behaviors of magnetic characteristics we have made all calculations in the first channel in the range of field 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):

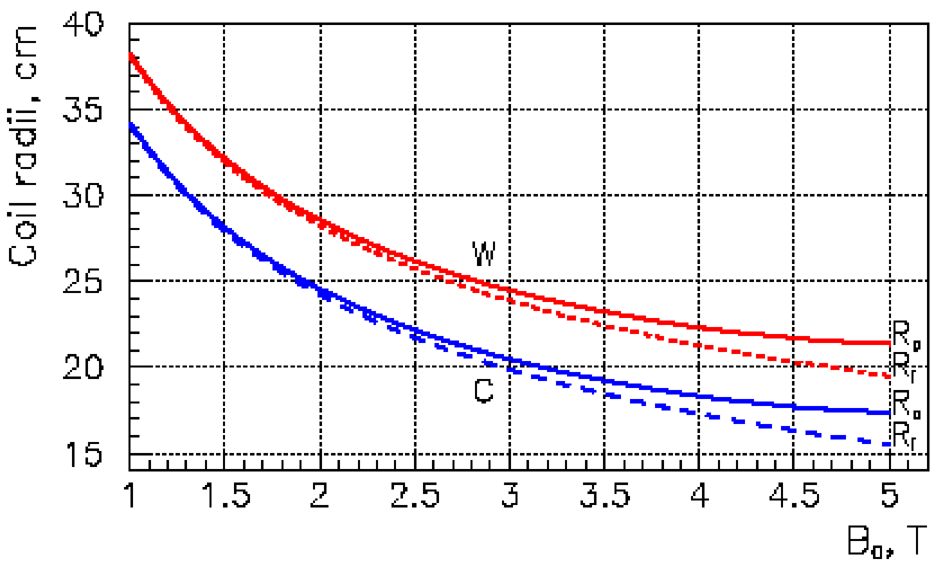

Fig.1. Dependences of inner R_i **(dotted lines) and outer R_o (solid lines) radii of coil versus magnetic field for cold (C) and warm (W) bores.**

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

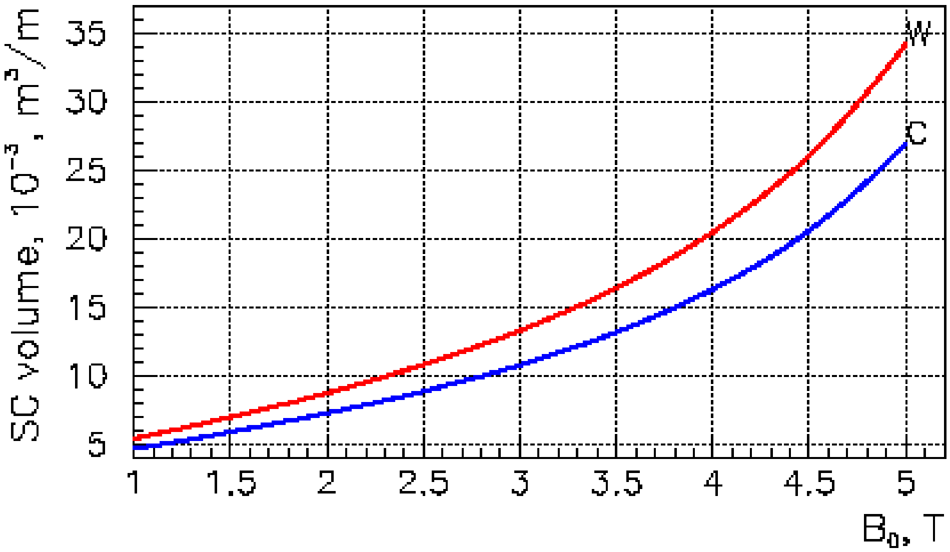

Fig.2. SC volume of coil against magnetic field per 1 m long magnet for warm (W) and cold (C) bores.

Stored energy behavior versus magnetic field is presented in Fig.3. Some nonlinearity is due to the coil thickness growth.

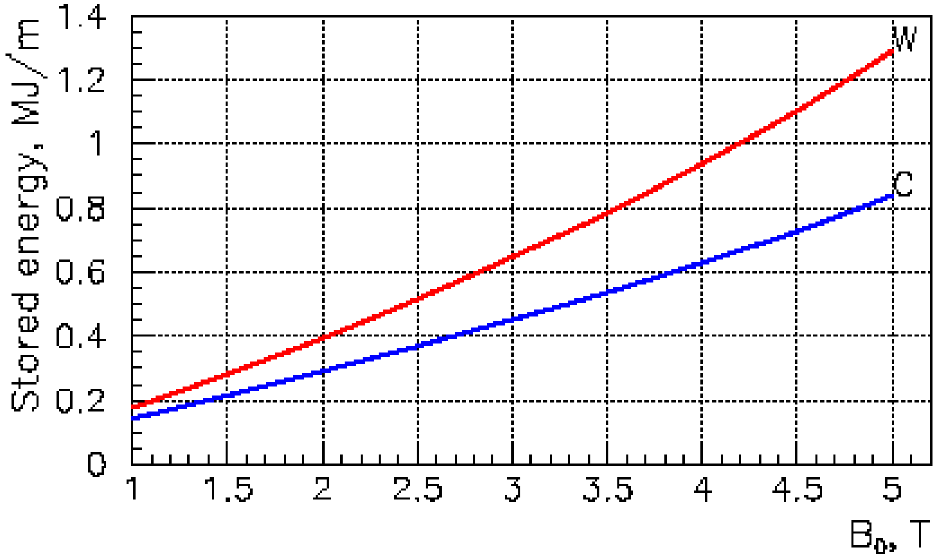

Fig.3. Stored energy against magnetic field per 1-m long magnet; W — warm bore, C — cold bore.

The radial pressure increases as $\mathbf{B}^2$ as it is shown on Fig.4 and it does not depend on radial dimensions of solenoid for long enough magnets.

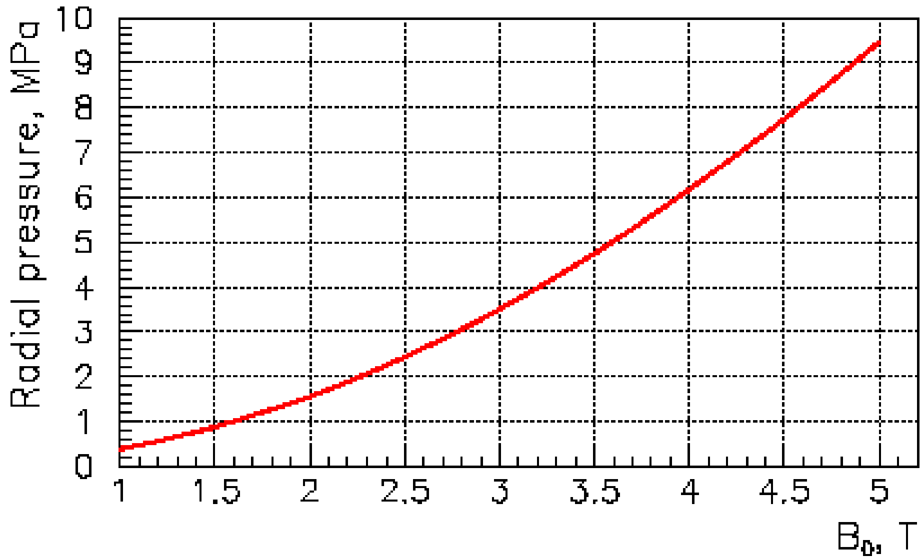

Fig.4. Radial pressure in solenoid against central magnetic field.

The 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

$$d = 0.0323B^2 + 0.0449B,$$

where d is in cm and B is in T. This formula takes into account the relationship **Br^2=const.**

Axial forces grow also as **B^2** as it is shown in Fig.5 for 4.7 m long magnet. The interacting forces between magnets are enough large and their magnitudes must be taken into account in design of magnet supports.

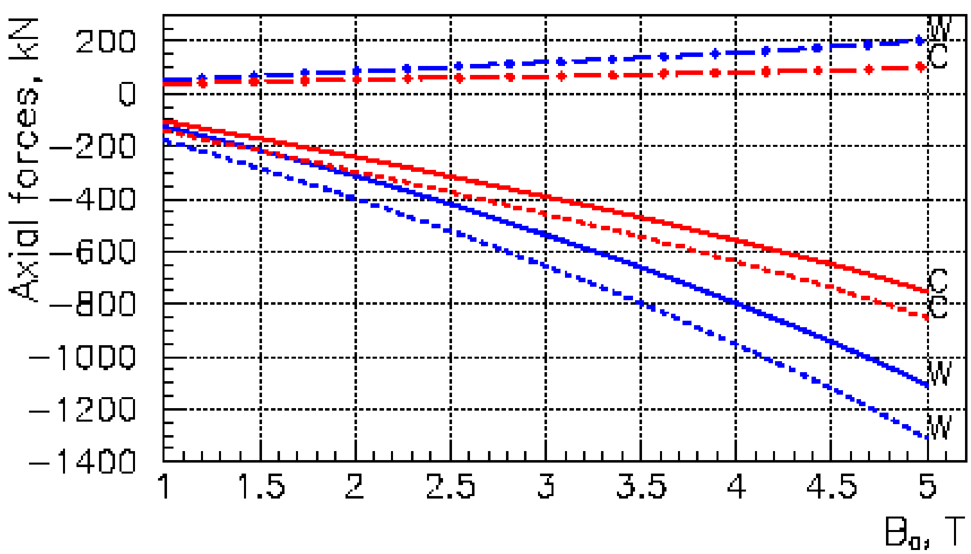

Fig.5. Dependences of axial forces versus central magnetic field for cold (C) and warm (W) bores. Solid lines show the forces acting on magnet in channel, dotted lines present the forces in the single magnet and dash-dot lines give the interacting forces between magnets.

1.2.2 Choice of magnet type

So one can see that the 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 a free access into the channel. So the final choice between warm or cold bore can be made after development of overall channel system.

The paper [2] gives a simple formula to estimate a 1 m long magnet cost that was in agreement with our calculations:

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

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

1.2.3 Main parameters of magnet and channel

The main parameters of magnet are listed 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 main parameters for channel I:

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

Magnetic forces acting on a solenoid of a single magnet and a solenoid in string are presented in the 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

The other magnetic systems will be considered only for magnet with warm bore as the magnet having more difficult magnetic parameters.

2. Channel II

2.1 Initial requirements

Channel II must provide initial emittance damping for the muon beam. It has RF cavities inside, so dimensions of RF cavity will determine the inner diameter of coil and one can 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 of 70 cm and 100 cm are presented below. This channel will have a warm aperture.

2.2 Parameters of magnet and channel

The main parameters of magnets are listed 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

The main parameters for channel II:

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

Further the other magnetic systems will be considered only for magnet with 1000 mm bore as the magnet having more difficult magnetic parameters.

3. Channel III

3.1 Initial requirements

The third Channel should be optimized together with LIA. The length of channel is about to 100 m. Probably the parameters of magnets will be similar the first Channel with warm bore. The magnet length will be determined by LIA requirements and most probably be about 1 m.

3.2 Main parameters of magnet

We have taken the magnets, which look like ones in the first Channel with warm bore and have the following magnetic parameters:

Parameter	Unit	Magnitude
Magnet coil length	m	1.0
Central field	T	1.25
Total ampere-turns	MA	1.08
Bore radius	mm	300
Coil thickness	mm	0.72
Inner radius	mm	345
Outer radius	mm	345.72
Stored energy	MJ	0.244
SC volume	m^3	0.0016

Main parameters for channel III:

Parameter	Unit	Value
Length	m	100
Number of magnets		83
Gap between magnets	m	0.2

Magnetic forces:

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 Fourth channel

4.1 Initial requirements

The channel length is equal to 100 m. It will have RF cavities inside solenoids; so cross-sectional dimensions of RF cavity will determine the diameter of solenoids and the channel will have a warm bore. As we mentioned in the second section, the diameter of bore could be in the region from 0.7 m to 1 m. The channel must have longitudinal alternative sinusoidal field. There is a proposal to divide the channel 4 by two sections. The amplitude of the magnetic field in the first section is equal to 3.6 T, and it is very desirable to increase it up to 5.5 T. The period of sinusoidal field is equal to 2.2 m. This value determines the magnet length, which has to be less then 1 m. The second section must have the 1.5 m long period and 3.4 T amplitude of field. The preliminary calculations has shown that the overall cross sectional dimensions of RF cavity could be equal to 140 cm, so we have chosen the inner radius of coil equal to 74.5 cm.

4.2 Magnetic calculations

4.2.1 Section I

The magnetic properties of various superconducting materials are presented in Fig.6. The engineering current density means the critical current divided by the total cross-sectional area, including insulation, cooper for stabilization and so on. This picture shows that NbTi at temperature 5.2 K can be used in fields up to 9 T. The decreasing of temperature to 2.2 K allows one to raise the maximal field up to 12 T. Nb_3Sn can work in fields up to 15 T at 5.2 K and it has superior magnetic properties when compared with NbTi at 2.2 K. The high temperature superconductor (HTS) like Bi 2212 can work the much higher fields (up to 30 T) practically without any fall in critical current density and it has an advantage in comparison with Nb_3Sn in fields greater then 14 T.

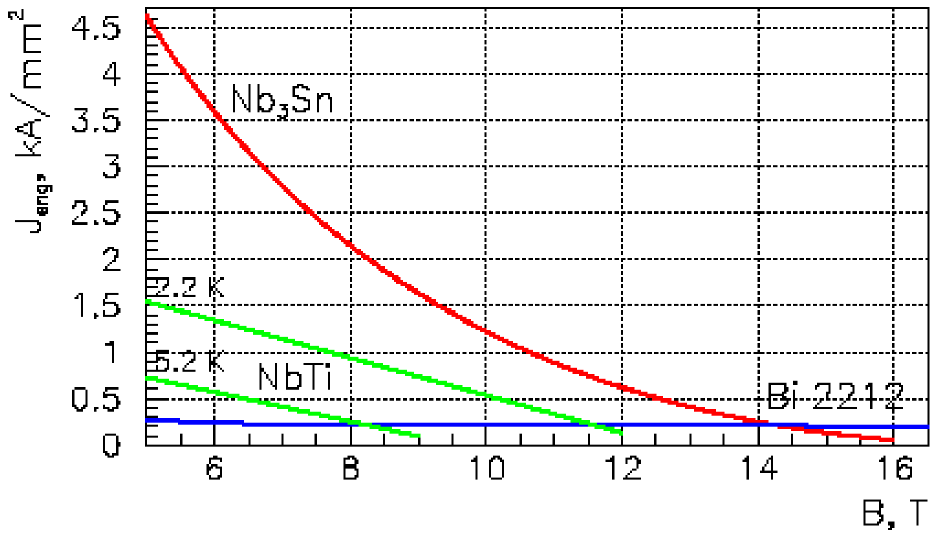

Fig.6. Dependences of engineering current density versus magnetic field for various superconducting materials.

It is clear that the magnetic fluxes from two the neighboring solenoids add in the gap between solenoids so the maximal field on the coil must be much higher the field on the axis. The longitudinal field distribution in channel with the magnetic parameters: period **T**=2.2 m, field amplitude $\mathbf{B_0}$=3.6 T and coil thickness **w**=50 mm is shown in Fig.7 for maximal length of solenoids L=100 cm. The sinusoidal line shows the field along solenoid axis, the other lines show the field components $\mathbf{B_r}$, $\mathbf{B_z}$ and the modulus **B** on the inner surface of 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 does not fit for such fields and it is necessary use Nb_3Sn. The coil thickness with Nb_3Sn is equal to 65 mm.

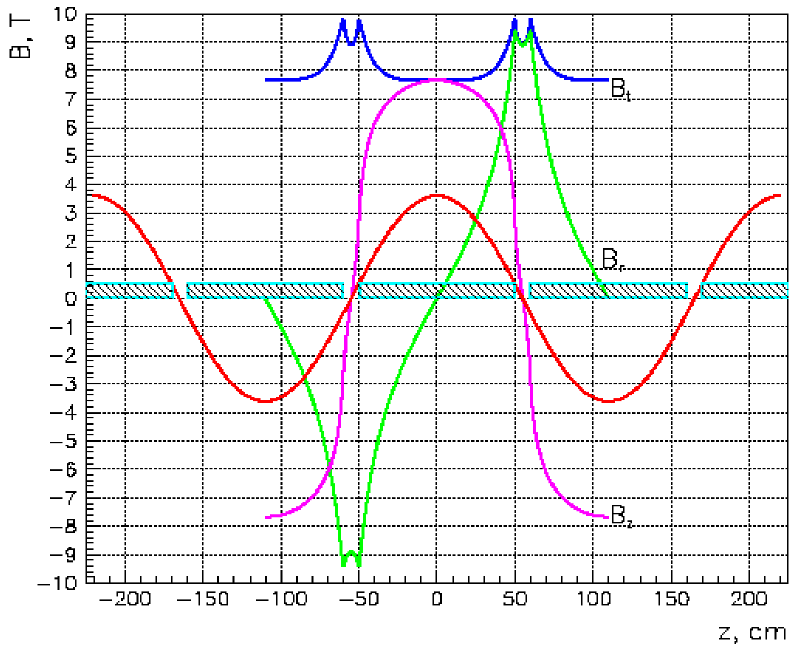

Fig.7. Distribution of magnetic field in the fourth channel at the maximal length of solenoids. Sinusoidal line shows field amplitude along longitudinal axis, the other lines show field components on the inner surface of solenoid.

The maximal field in solenoid can be made lower by choice of the optimal length of the coil. The dependence of the maximal field on 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 805 mm solenoid length. The lower curve presents the maximal field on the coil in the central cross section of magnet.

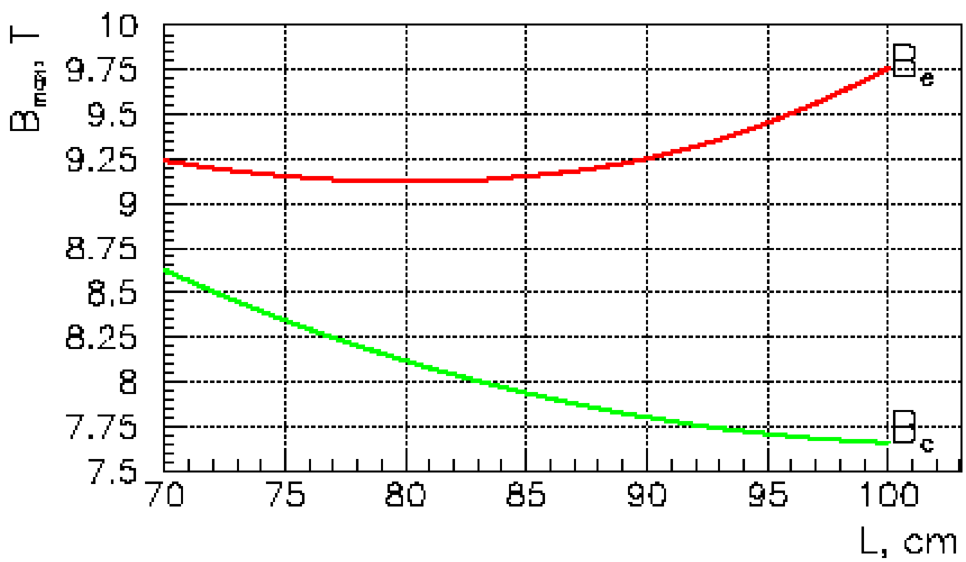

Fig.8. Dependence of the maximal field on the coil versus solenoid length. The low line shows the maximal field in the center of solenoid, the upper line presents the maximal field on the edge of solenoid.

Increasing the coil thickness, we can reduce the field enhancement on the coil as it is shown in Fig.9. The upper curve shows the maximal field in the edge of magnet and the lower curve shows the maximal field on the coil in the center of solenoid. In such a manner we try to match the maximal field along the inner surface of coil. Of course the quantity of superconducting material can be the same and the coil thickness can be increased by adding of cooper in the current currying element, what reduces the current density. This action can be also useful in the quench process, so final choice of coil thic k-ness and current currying element will be made after consideration of system protection. The reduction of the field enhancement allows one to increase the field amplitude. Growth of coil thickness increases slightly the stored energy in the magnet but decreases the axial pressure from the magnetic forces.

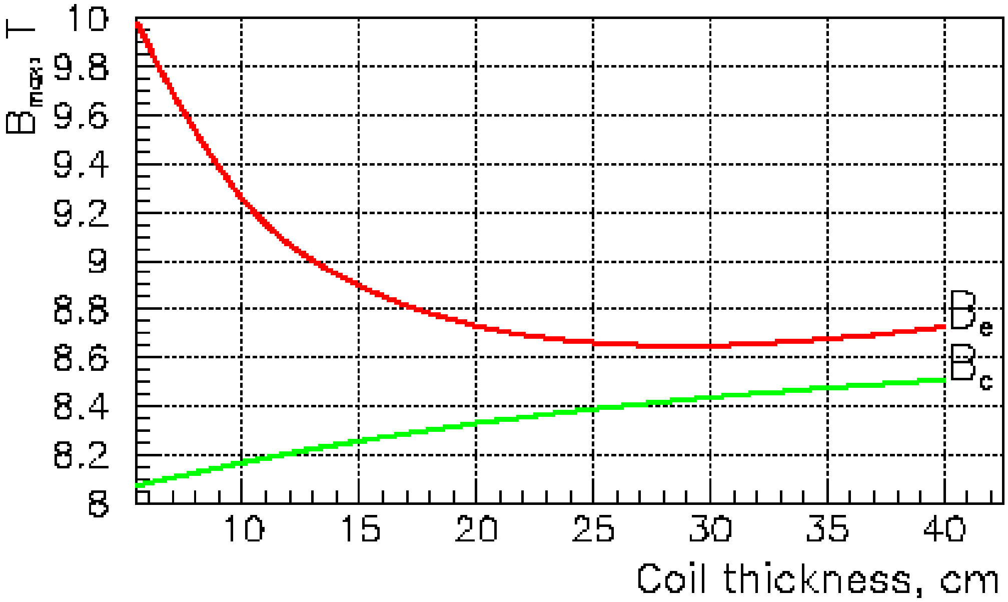

Fig.9. Dependences of the maximal field on the coil versus magnetic field in the center of solenoid (B_c) and on its edge (B_e).

The longitudinal field distribution on the coil for length of solenoid equal to 805 mm and 175 mm thickness is shown in Fig.10. One can see the maximal magnetic field is matched along whole length of coil. Note, that the ratio between coil thickness and magnet length is not quite optimal. It needs more detail calculations in order to find optimal relationship between length and thickness. But the differences between chosen and optimal values are not very large and they are enough for the first approximation.

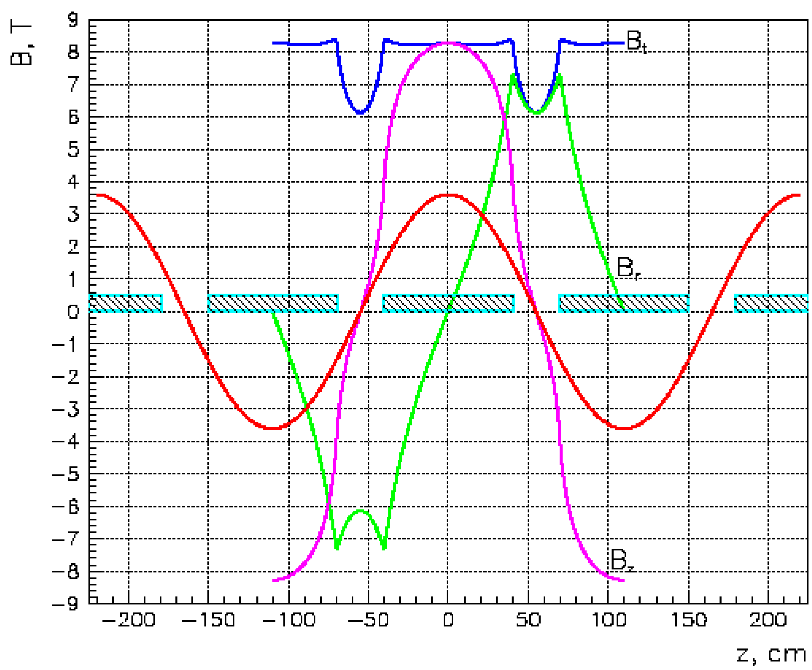

Fig.10. Longitudinal field distribution for optimal length of solenoid.

Radial distribution of field is shown in Fig.11. The maximal field on the edge of solenoid is 0.5 T greater than the central one. One can see that the whole area of solenoid end face is found under high field.

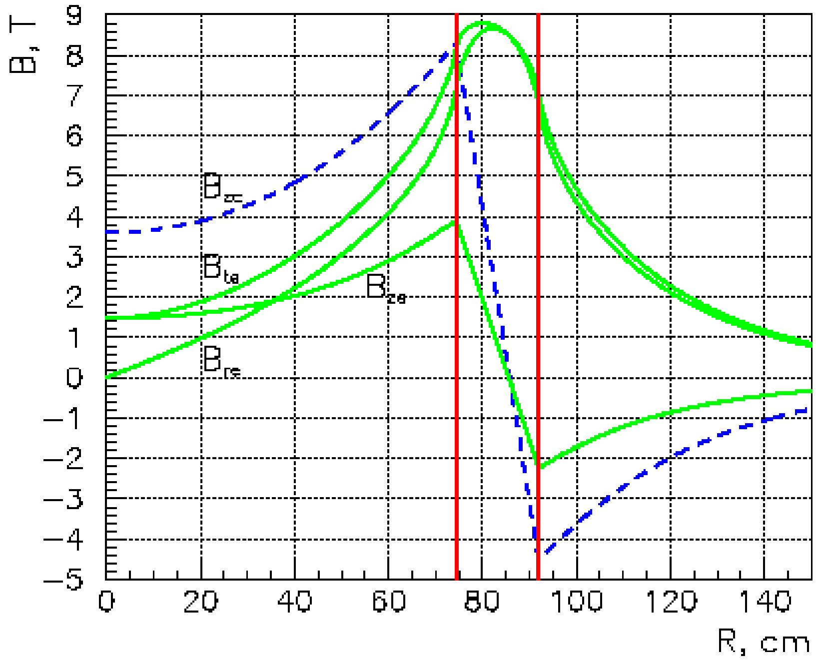

Fig.11. Radial distribution of field. Dotted line is the field in the center of solenoid, the other lines show end field components.

Fig.11 shows that field changes its sign behind coil and its maximal value reaches about 4.5 T. It factor has influence on the distribution of ponderomotive forces which is presented in Fig.12. The summary radial pressure on the outer surface of coil is 15.24 MPa and the axial pressure on the end face of coil is equal to –89.12 MPa. The field distribution creates a favorable radial force distribution. The 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 with enough firm partitions from stainless steel. Stored energy in one solenoid is equal to 48 MJ, so it is necessary also to pay attention to the protection system design. Note that the total current in the solenoid is equal to 9.64 MA.

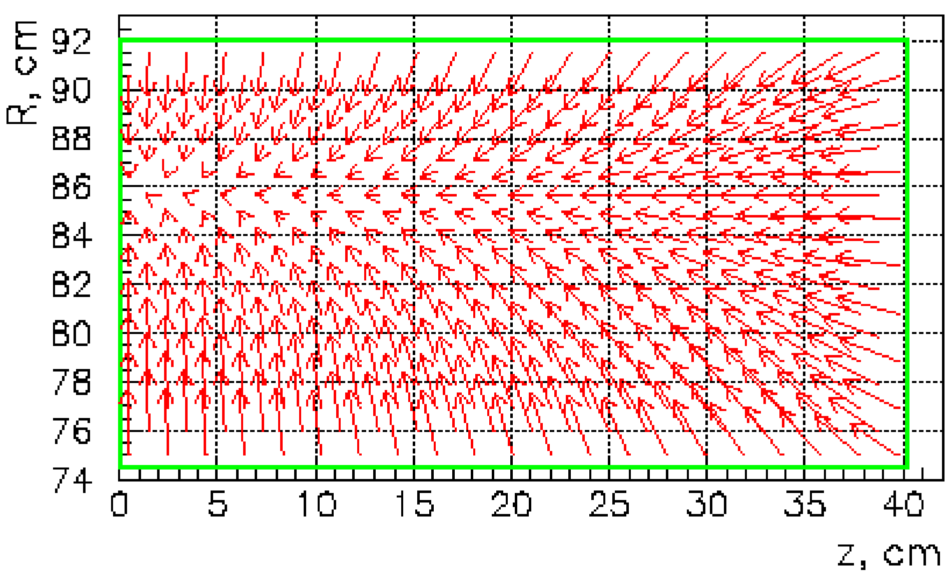

Fig.12. Distribution of ponderomotive forces in solenoid coil.

Fig.13 and Fig.14 show the radial and longitudinal field distribution for the single solenoid.

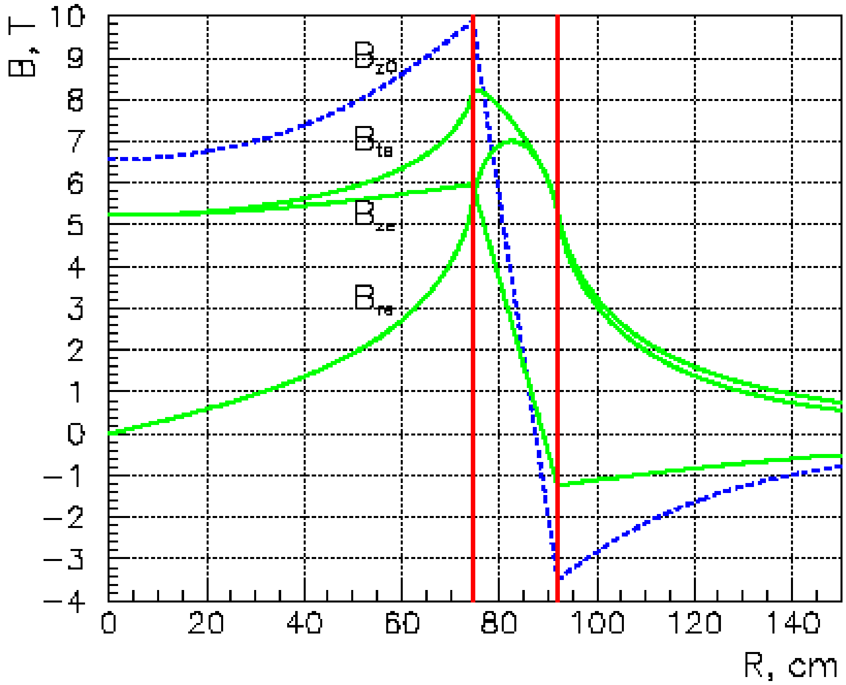

Fig.13. Radial field distribution for the single solenoid.

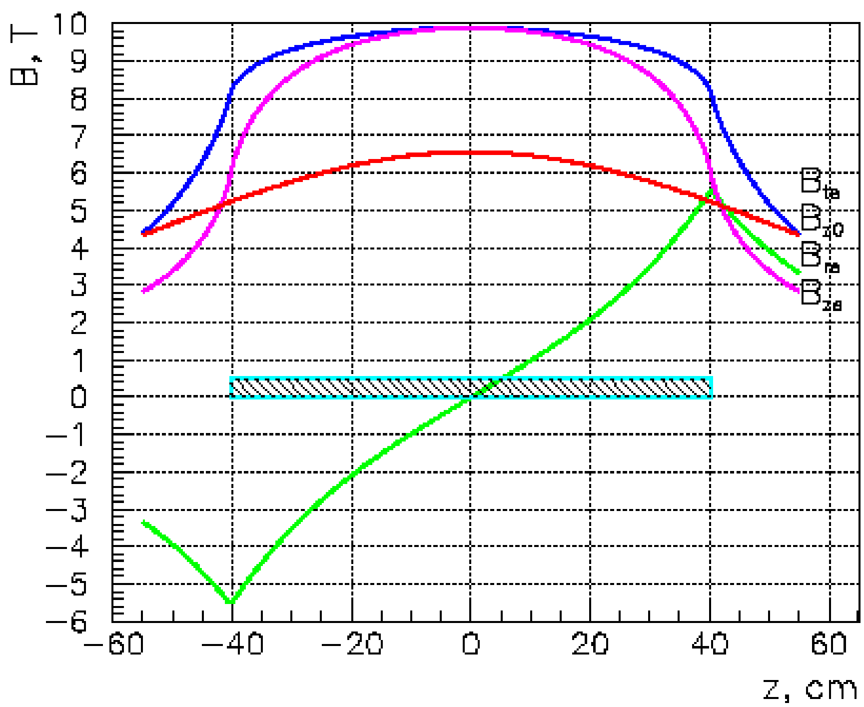

Fig.14. Longitudinal field distribution for the single solenoid.

This distribution will be for the first and the last magnets in the string of solenoids and also can occurs in the solenoid, when the neighboring solenoids can have a quench. It needs thicker bandage equal to 50 mm of stainless steel.

Maximal field on the coil in the solenoid placed into string is equal to 8.8 T if the central field is 3.6 T. The material properties of Nb_3Sn allow one to increase the field amplitude up to 5.5÷5.7 T.

But the magnetic forces and stored energy grow as $\mathbf{B}^2$ and in this case are 2.334 times higher. This results in the necessity to consider another mechanical design and different protection system. In particular the radial thickness of bandage from the stainless steel must be 50 mm.

4.2.2 Section II

The second section of the fourth channel is more difficult for implementation. **Fig.15** shows the maximal field on the coil versus period length of sinusoidal field with amplitude of 3.4 T. Low curve presents the field B_c on the coil in the center of magnet and upper curve shows the maximal value of field B_{max} on the edge of solenoid. The length of solenoid has been optimized for each period value and the coil thickness was constant and is equal to 20 cm. The horizontal line shows the limit field for Nb_3Sn material, so the lowest period is 165 cm with Nb_3Sn choice as current currying material. It is possible to reduce the field period by using HTS materials that can work in field up to 30 T at temperature of liquid helium.

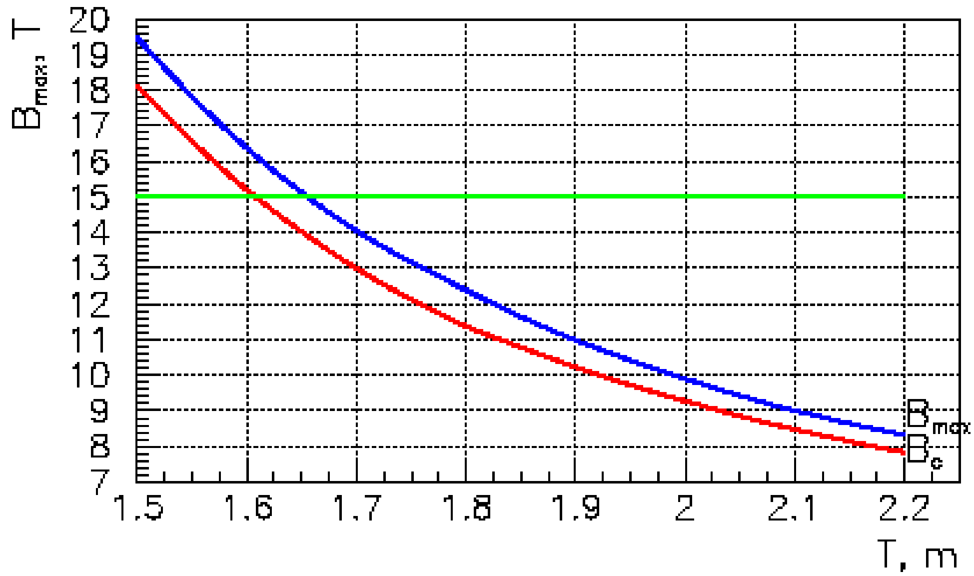

Fig.15. Dependence of maximal field on the coil versus period length of sinusoidal field. B_c is the field on coil in the center of magnet; B_{max} is the maximal field on the edge of coil. Horizontal line shows the limit value of field for Nb_3Sn material.

The best samples of HTS wire [3,4] of 1.6 mm diameter have the critical current of 900 A in own field and at 4.2 K. The critical current is 300 A in 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 has 360 A or 1000 A/mm^2. The total current in solenoid with 475 mm optimal length is equal to 13.9 MA and needs 125 mm coil thickness with 97 layers and 417 turns in each layer. Average length of each layer is equal to 2 km, so the total length of HTS for one solenoid is equal to 194 km. As the ponderomotive forces are very large and equal to 60.25 MPa of radial component and –425.40 MPa of axial component, so it is necessary to consider a careful stress management because the HTS material is very fragile. Probably the coil must have more sections, but the length of coil is too small in order to insert a great number of partitions. This question 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.16 shows the radial field distribution in this solenoid.

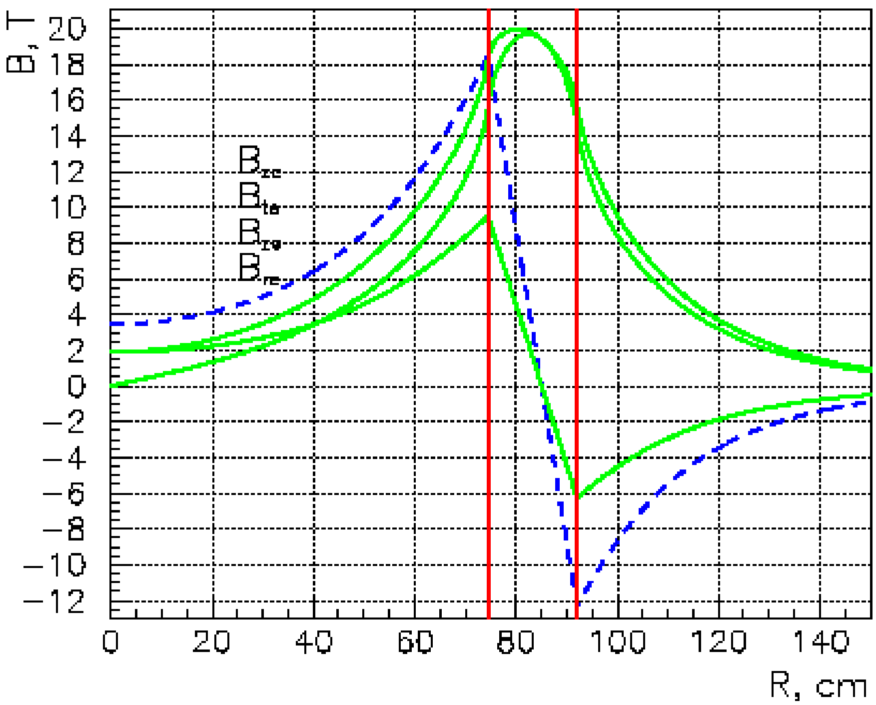

Fig.16. Radial field distribution in solenoid cell with magnetic field period of 1.5 m.

4.3 Main parameters of magnet and channel

The main parameters of magnet are listed below:

Parameter	Unit	Magnitude	
Period	m	2.2	1.5
Magnet coil length	m	0.805	0.475
Central field	T	3.6	3.4
Maximal field on coil	T	8.8	19.5
Total ampere-turns	MA	9.64	13.9
Operating current	kA	6	6
Bore radius	mm	700	700
Coil thickness	mm	175	125
Inner radius	mm	745	745
Outer radius	mm	920	870
Stored energy	MJ	48	130
Volume of superconductor	m^3	0.0263	0.3012

The main parameters for channel IV:

Parameter	Unit	Value	
Section		I	II
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:

Section	I	II
Radial pressure, MPa		

Section	I	II
Single magnet	30.4	135.7
Magnet in string	15.2	60.3
Axial forces, MN		
Single magnet	-61.8	-264.8
Magnet in string	-79.9	-220.2
Interacting force	-18.1	-44.6

The other magnetic systems will be considered only for magnetic string with period of 2.2 m and field amplitude of 3.6 T as far as these magnets can be really realized without very large expenses on research and development.

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	1.1	1.0
Gap between cryostats	0.2	0.2	0.2	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	4.7	1.7	1.0	0.805
Bore radius, m	0.3	1.0	0.3	0.7
Total current, MA	4.69	1.93	1.08	9.64
Layer number	1	1	1	16
Total turn number	781	322	180	1608
Operating current, kA	6	6	6	6
Stored energy, MJ	1.1	4.1	0.24	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
$I_{nominal}/I_c$	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 one layer. 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 from conditions of safety evacuation of the stored energy out of magnet during quench process:

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

Operating current is equal to 6 kA, which corresponds 0.3 from the critical current at 1.25 T and 4.5 K. The ratio Cu/SC is equal to 7:1 in the first and the third channels and 9:1 in the second channel.

The superconducting coil in the fourth channel has 16 layers. Nb_3Sn has chosen as a current currying element for the channel IV with ratio Cu/SC 20:1 in superconducting cable.

The superconducting cable has kapton insulation of 0.1 mm thickness.

The coil is wound on stainless steel tube and is banded by copper shells and is cooled by liquid helium flowing through copper pipes. 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 is clamped with liquid helium pipe at transition from one to another magnets.

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

Superconducting coil and shield are hung up to a vacuum vessel in two cross-sections by two vertical suspensions and two horizontal tension members in each cross-section. This support system allows one to adjust the location of the coil both along horizontal and vertical directions. In the axial direction longitudinal members and anchor rigid on the vacuum vessel fix the cold mass.

The budget of heat leaks in the cryostat and heat load on cryogenic system 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

The second and the fourth channels have RF cavities in warm bore of superconducting solenoids. The cavities emit heat load of 50 kW per 1 m length to inside surface of the vacuum vessel.

The copper shield cooled by water is used to remove this heat load. The shield is 3 mm thickness and copper pipe of 25×1 mm is soldered on its outer surface with 100 mm pitch. In this case the temperature of shield in the middle point between neighboring turns of the pipe is 10°C higher than water temperature.

The each superconducting solenoid has the own shield. The shield of all magnets is supplied by water in parallel. The water flow rate is 1.5 kg/s, pressure loss is 0.6 MPa and heating of the flow is 16°C.

The total flow rate of water is 30 kg/s for the second channel and 135 kg/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) and it should threaten the integrity of the coils. Some protective precautions namely, fast quench detection and the removal of stored energy to the external dump resistor or/and the "smearing" of stored energy inside the magnets by heaters, must be used.

The main special feature of all the four channels are the following: all the solenoids are located very close to each other and their magnetic axes have the same directions. Therefore the large mutual influence of magnets exists. It can result in appearance of electrical signal in the neighboring magnets due to mutual inductance. But the most significant problem is the ponderomotive force between magnet coils in axial direction. This force is very large: attractive force is about 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 equilibrated inside the string of magnets, except the first and the last magnets. These magnets must have a very strong support. Therefore the protective schemes with energy evacuation from one or few magnets in the string are not useful because current removal from one or several magnets will result in unacceptable force generation. This forces us to use the rigid support for each magnet and that complicates the mechanical design of whole channel. With the aim to avoid this difficulty we assume that the stored energy under the quench must be removed from all magnets simultaneously and with the identical rate.

Because of the magnets in each channel are identical, it is possible to compare the voltage drops on magnets to one another for detection of the appearance of a normal zone. This is the simplest method of quench detection, although other techniques of compensation of coil inductive voltage are suitable too. For the first and the last magnets in strings of the second and the fourth channels quench detectors must differ from these in other channels. For example, these magnets can be equipped by bridge type of quench detector. When the voltage on the resistive section of coil exceeds given threshold, the quench detector system generates the signal to the protective actions.

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

1. Channel I

The stored energy in one solenoid placed in string of magnets is equal to 1.07 MJ. There are 10 solenoids in the channel. These magnets are connected in series and powered by one power supply. Thus the full energy stored in 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 about 200 sec.

The sketch of assumed protection method is shown in Fig.17. When quench detector detects the 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. Maximum voltage during the energy extraction was accepted from the point of view of insulation reliability and it is equal to 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. The time dependences of current, dump resistor and coil voltage, energy dissipated in coil and dump resistor, and hot spot temperature are shown in the picture.

It is clear from thesse curves that almost 97 percent of stored energy is dissipated outside of the cryostat. Amount of energy dissipated in coil is sufficient for adiabatic heating of the coil to 180 K in the hottest point.

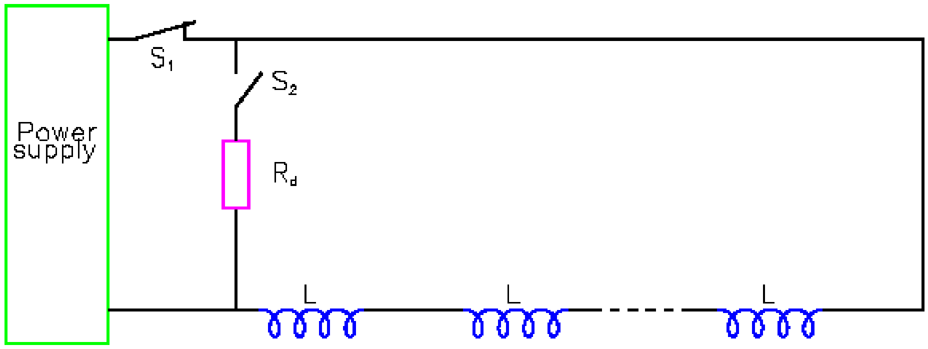

Fig.17. Quench protection sketch of magnets in the first channel.

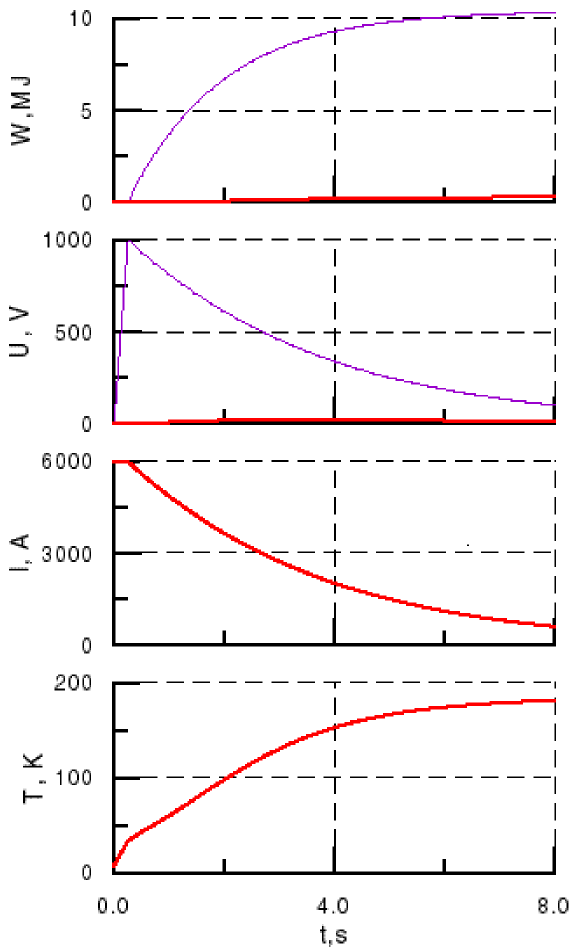

Fig.18. Quench process in magnets of the first channel. Thin lines correspond to dump resistor, thick lines are for superconducting coil.

2. II channel.

Twenty magnets of the channel store 83 MJ of energy. Previous estimation of quench process showed, that magnets are need in division on two groups. The magnets of each group are connected in series and they form two independent strings with their own power supplies. The scheme of one string is presented in Fig.19. The power supply with the output power of 180 kW is sufficient to rise current in string of magnets up to 6 kA during ten minutes. This scheme is almost the same as for the first channel with one exception. There are magnets equipped by protective heaters, one by one string. These heaters are necessary for synchronizing of energy extraction from the strings. Also the heater stimulates resistance greater than the resistance of original normal zone and it will diminish the difference of resistance of strings. Thus all strings will have the identical time constants of current dumping in order to exclude the unbalance 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 switch S_2, and heater is switched to heater power supply by S_h. Stored energy of all strings is dissipated on the dump resistors R_d = 0.167 Ohm in the same manner. Maximum voltage is equal to 1000 V.

The results of simulation of quench process initiated by heater in the string of 10 magnets are presented in Fig.20. 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.

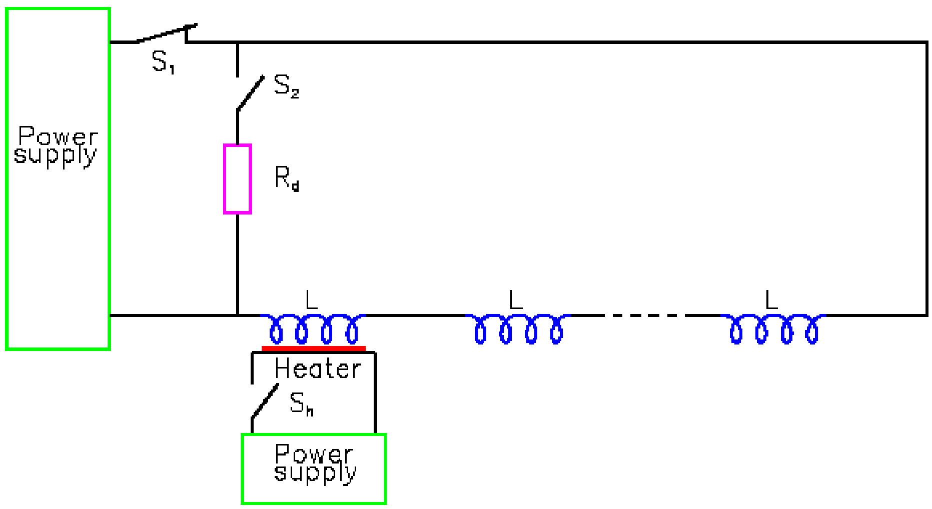

Fig.19. Sketch of quench protection in one string of second and third channels.

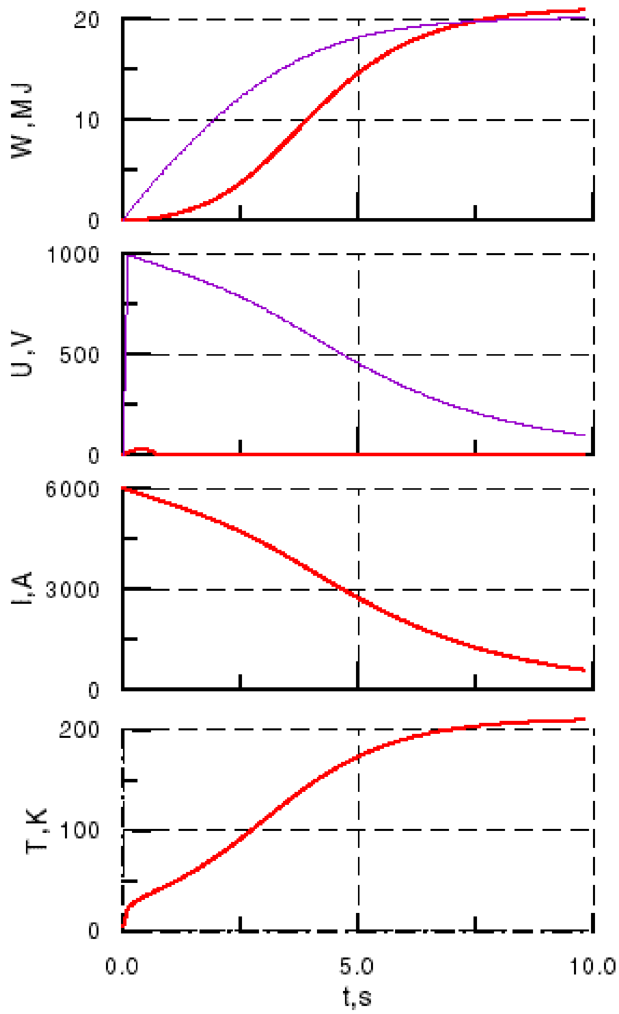

Fig.20. Quench process in magnets of the second channel. Thin lines correspond to dump resistor, thick lines are for superconducting coil.

3. III channel.

In the channel there are 83 magnets with the stored energy of 0.244 MJ each. Total energy stored in channel is 20.3 MJ. This energy is about twice more that for first channel, whereas the conductor in coil is the same. Therefore it supposes magnets will be divided on two groups of 41 and 42 magnets. In each group magnets are connected in series and form two independent strings with 180 kW power supplies. Scheme of one string is presented in Fig.23; the other one is the same.

The quench protection concept is the same as for the second channel. Each string contains one magnet with protective heaters too. After quench detection 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 in the same manner. Maximum voltage is equal to 1000 V.

The results of simulation of quench process in the string of magnets are presented in Fig.21. In this case the hot spot temperature does not exceed 200 K in magnet with original quench and 170 K in magnet with heater-initiated quench.

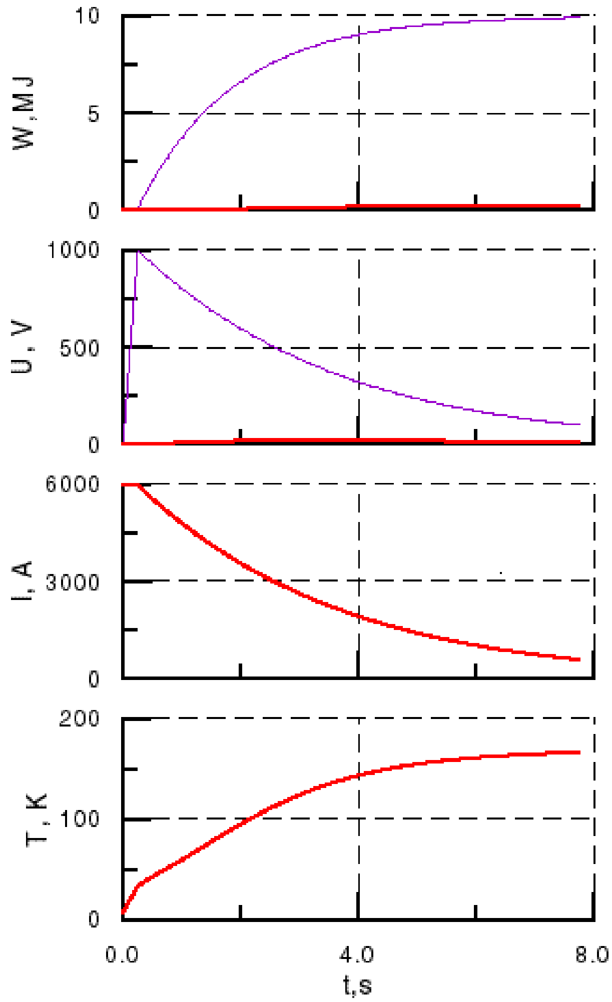

Fig.21. Quench process in magnets of the third channel. Thin lines correspond to dump resistor, thick lines are for superconducting coil.

4. IV channel.

All magnets of channel are connected in series into one string. Total stored energy is about 4368 MJ. Power supply must provide of 3.0 MW that will allow one to reach the nominal current within one hour. Protective scheme is presented in Fig.22. In comparison with the schemes considered above the dump resistor is absent due to inefficiency. All magnets are supplied by heaters, which are fired by switches S_h simultaneously. Stored energy of all magnets is dissipated inside the cryostats in magnet coils.

Quench process in magnets of the fourth channel in the case when heater provoked quench is presented in Fig.23. Maximum temperature of hot spot of original quench reaches about 230 K, where as maximum temperature in other magnets is 190 K.

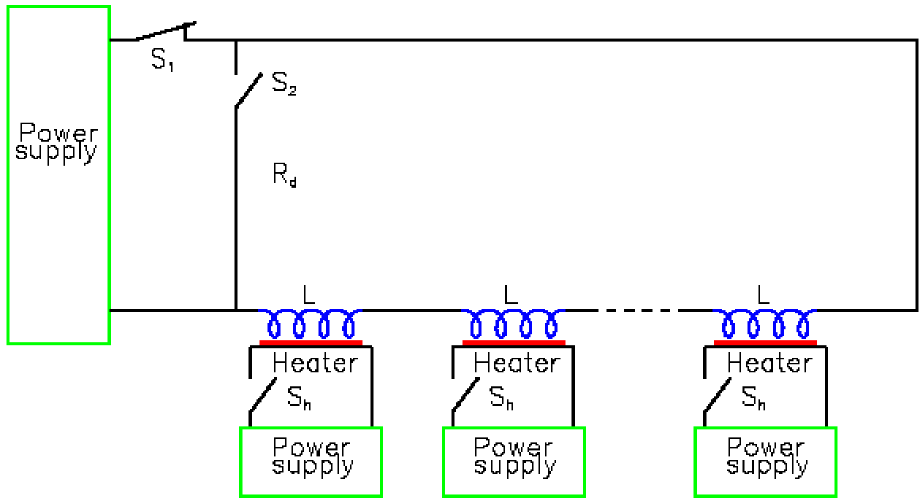

Fig.22. Quench protection sketch of magnets for the fourth channel.

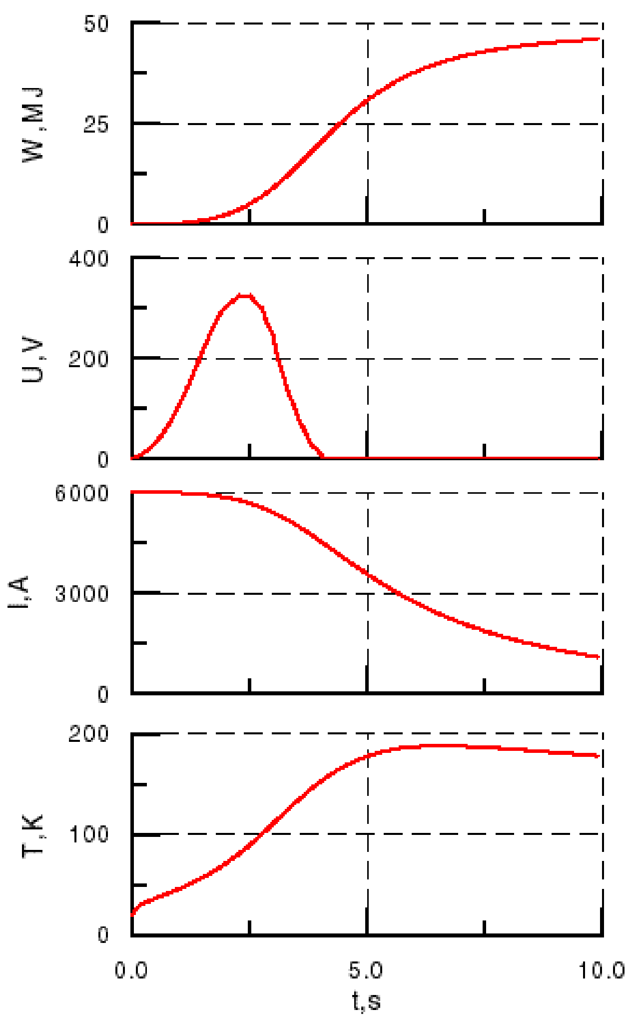

Fig.23. Quench process in magnets of the fourth channel.

5. Power supply

Main parameters of power supply for magnetic system over 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

Preliminary choice of the magnetic system geometries for four channels of Neutrino Factory has been made. Some magnetic parameters were optimized and were defined their optimal values. The preliminary costs of the magnetic systems have been estimated together with operation expenditure. The final costs will define more exactly after detail study and development of the working drawings. It was shown the major portion in cost of each channel constitutes the cost of SC magnets. The cost of the fourth channel makes up the bulk of the cost for all magnetic systems in overall.

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. N.Okada. HTS High Field Magnets. MT-16, 1999, Ponte Vedra Beach, Fl, USA.
4. K.Marken, J.Parell and S.Hong. BSCCO-2212 Conductors for High Field Magnets. MT-16, 1999, Ponte Vedra Beach, Fl, USA.

Appendix

Problems for R&D

Of course we did not pose the object to consider in detail all problems arising inevitably during development, engineering and designing of all channels. Some of them can be solved in the normal way. The other ones need additional research and development.

1 Channel I

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

2 Channel II

Channel II has one problem. The magnetic attractive forces acting on the first and last magnets in the string are very large. It needs more careful consideration in design of supports in order to maintain mechanical stability of magnets in string and to save an acceptable balance of heat loads over these supports.

3 Channel III

Channel III consists of many number of short magnets with enough short gaps between them. Small gaps create troubles in connection of magnets on electric joint and cryogenic. Besides LIA is placed outwardly of channel and it can also have own connections, which can make difficult in access of free space outside of cryostat.

4 Channel IV

Channel IV consists of great number of problems. Even the period of 2.2 m with sinusoidal field amplitude of 3.6 T has an enough large field on coil surface, large stored energy and large ponderomotive forces. One can try to optimize the geometry of magnet in aim of field enhancement reducing on coil. This object requires study of dependences and relationships the various geometric parameters. First of all it is necessary to consider the coil, having layers with variable current densities and variable lengths. There are many questions in development of quench protection system, mechanical strength of solenoid, cool down and warm up of superconducting solenoids. 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 detail studies are needed for consideration of the questions like: the increase of field amplitude, growing of coil inner radius, the shortening of the sinusoidal field period etc.

5 R&D Schedule

1. Geometry optimization for IV channel. Study of dependences and relationships of geometric parameters influencing on the magnetic field characteristics in order to increase the field amplitude, to short the field period and to raise the coil inner radius.
2. Conceptual design of cryogenic system for all four channels:
    - calculations and choice of cooling circuit;
    - calculations of cool down and warm up time;
    - requirements to cryogenic plant.
3. Overall drawings of the first and last magnets of all four channels:
    - special axial supports of superconducting coil;

- 6 kA current leads.

4. Developments of joint units between superconducting solenoids in channel III.