Magnetic Systems for Four Channels of Neutrino Factory

Magnets

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Channel I

Initial Requirements

1 Channel length is equal to 50 m.
2 Br^2 = const = $B_0r_0^2$; B_0 = 1.25 T; r_0 = 0.3 m; $B_0r_0^2$ = 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.

The critical current density of NbTi:

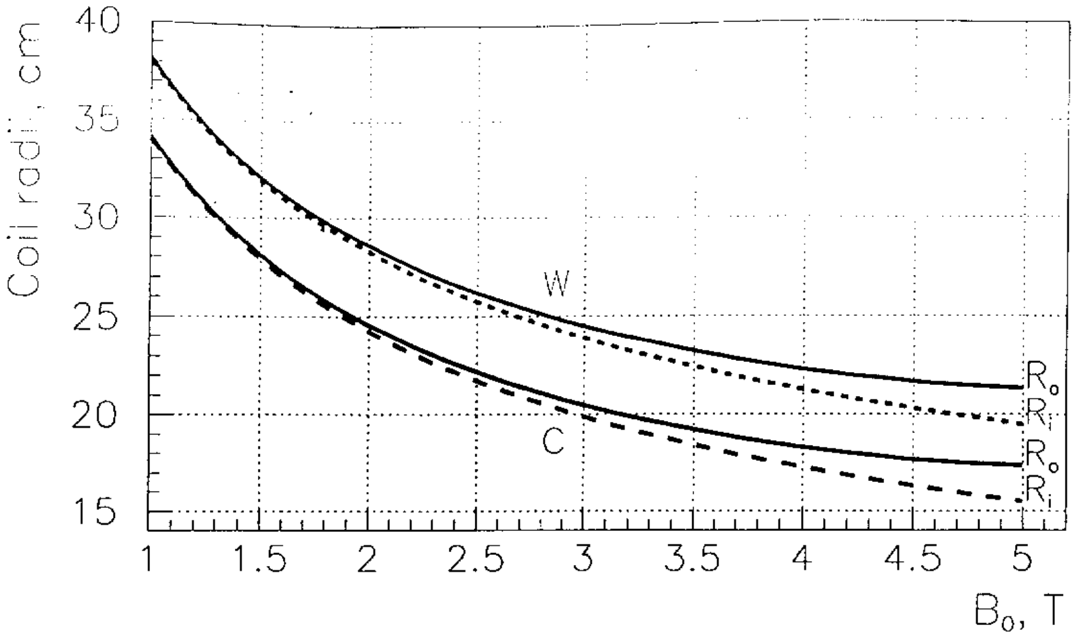
$$J_c(B,T) = J_0\left(1 - \frac{B-5}{5.5} - \frac{T-4.2}{3.2}\right)$$

J_0 = 2.5 kA/mm^2; B = 5 T, T = 4.2 K

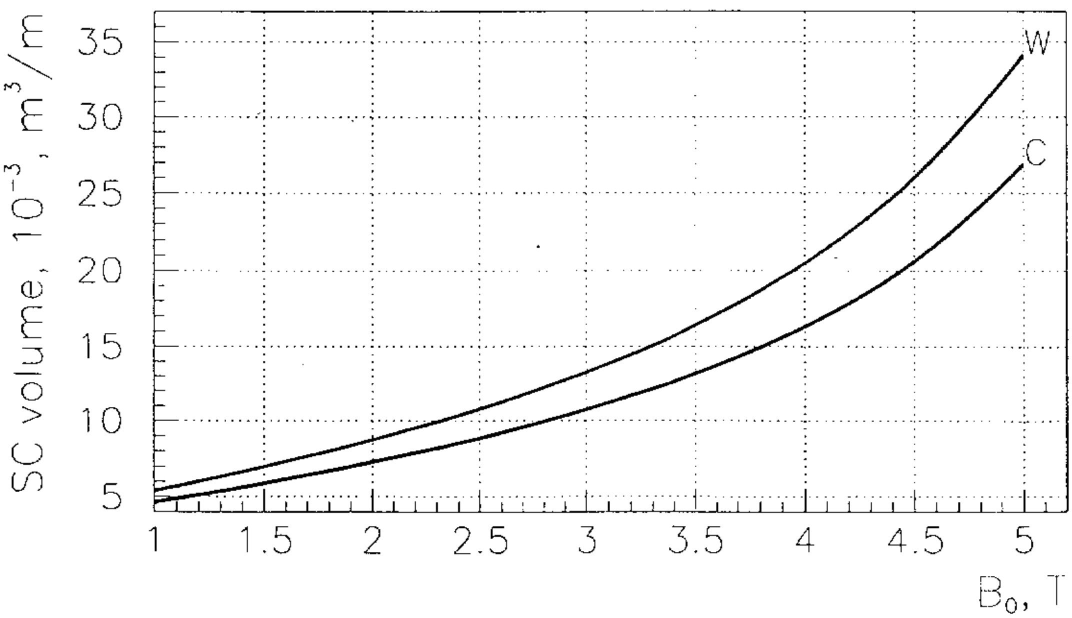
Cu:NbTi=0.6:0.4

J_{eng} = 1.0 kA/mm^2; B = 5 T, T = 4.2 K

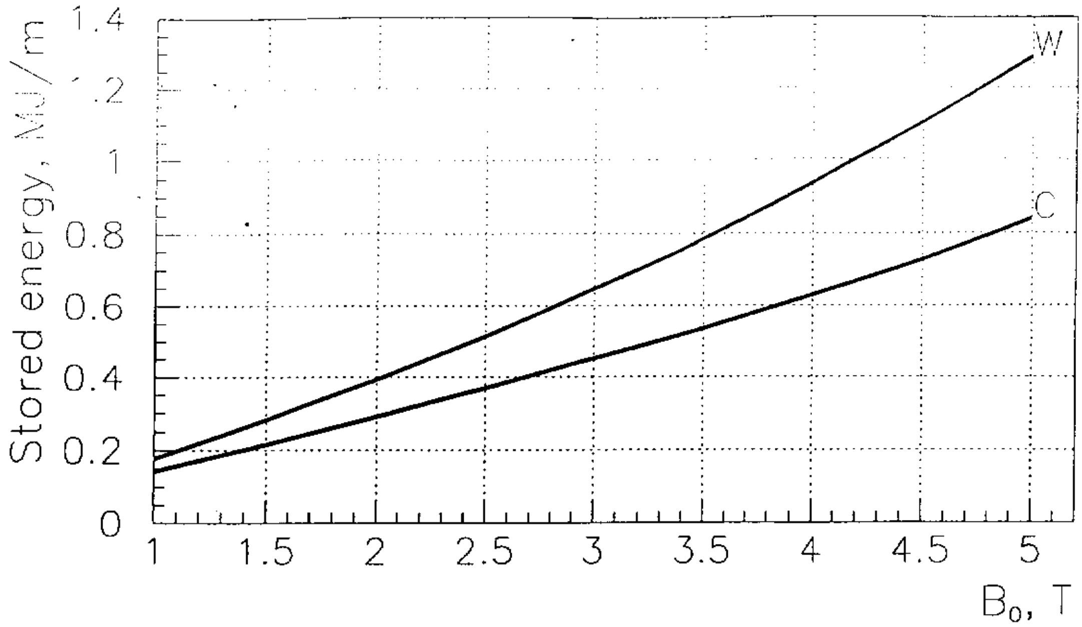
$(B-B_0)/B_0$ = 20%; ΔT = T-4.2 = 1 K



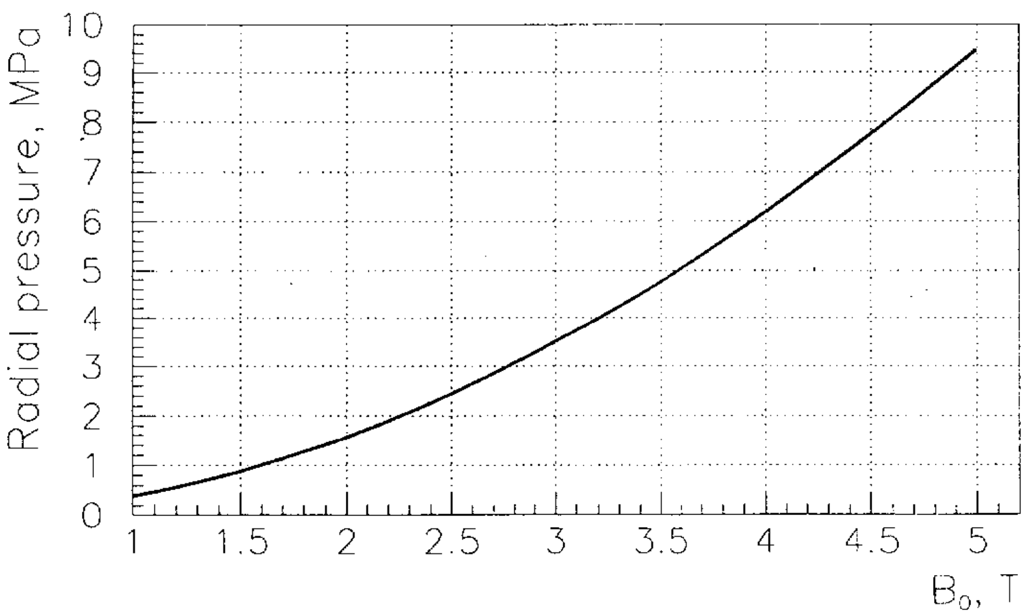
Dependences of inner R_i (dotted lines) and outer R_o (solid lines) radii of coil versus magnetic field for cold (C) and warm (W) bores.



Volume of superconductor of coil against magnetic field per 1 m long magnet.

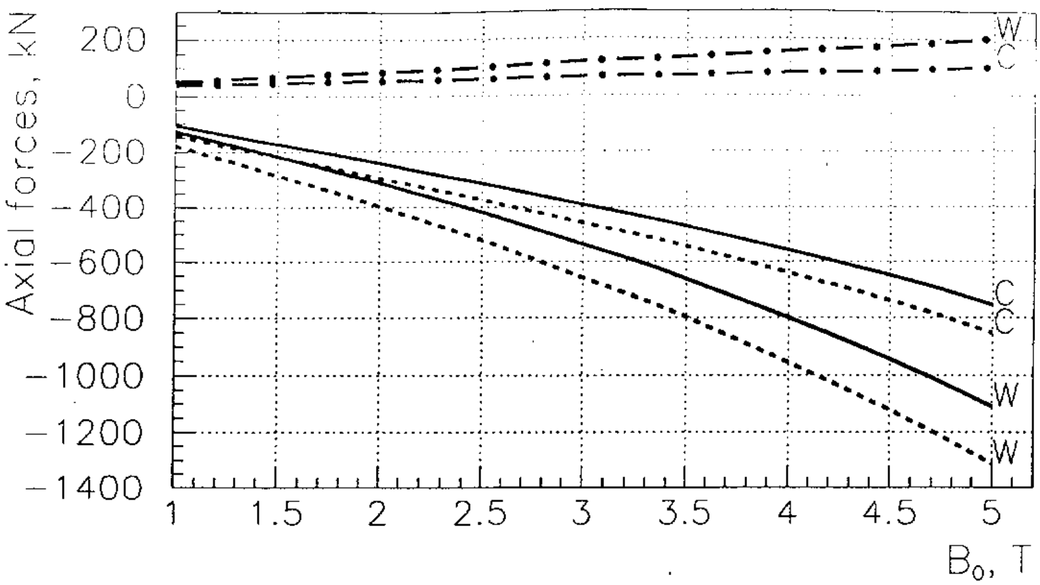


Stored energy against magnetic field per 1-m long magnet; W — warm bore, C — cold bore.



Radial pressure against central magnetic field in solenoid.

$$d[mm] = 0.323B^2 + 0.449B; \quad 1\ T \le B \le 5\ T;$$
$$Br^2 = const$$



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 Attractive forces between magnets.

M.A.Green et al. Superconducting Solenoids for the Muon Collider. MT-16, 1999, Ponte Vedra Beach, Fl, USA.

$$\text{Cost} = AR^{1.29}B^{1.4};\ Br^2 = \text{const};$$
$$\text{Cost} \sim B^{0.8}$$

Main parameters of magnet

Parameter	Unit	Magnitude	
Bore		Warm	Cold
Magnet coil length	m	4.7	4.7
Central field	T	1.25	1.25
Total turn-current	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

Main parameters for channel I

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

Magnetic forces

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

Channel II

Initial Requirements

1 Channel length is equal to 40 m.
2 Br^2 = const = $B_0 r_0^2$ = 0.1125 $T \times m^2$.
3 Warm bore.
4 Central field can be chosen in interval from 1.25 to 3 T.
5 Radiation load can be neglected.
6 RF cavities are inside channel.
7 Inner radius of RF cavities can be from 0.7 m to 1 m.

Main parameters of magnet

Parameter	Unit	Magnitude	
Bore radius	mm	700	1000
Magnet coil length	m	1.7	1.7
Central field	T	1.25	1.25
Total turn-current	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
Volume of superconductor	m^3	0.0063	0.0105

Main parameters for channel II

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

Magnetic forces

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

Channel III

Initial requirements

1 Channel length is equal to 100 m.
2 Br^2 = const = $B_0r_0^2$ = 0.1125 $T\times m^2$.
3 Warm bore.
4 Channel is inside LIA.
5 Radiation load can be neglected.
6 Magnet length is equal to 1 m.

Main parameters of magnet

Parameter	Unit	Magnitude
Magnet coil length	m	1.0
Central field	T	1.25
Total turn-current	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
Volume of superconductor	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

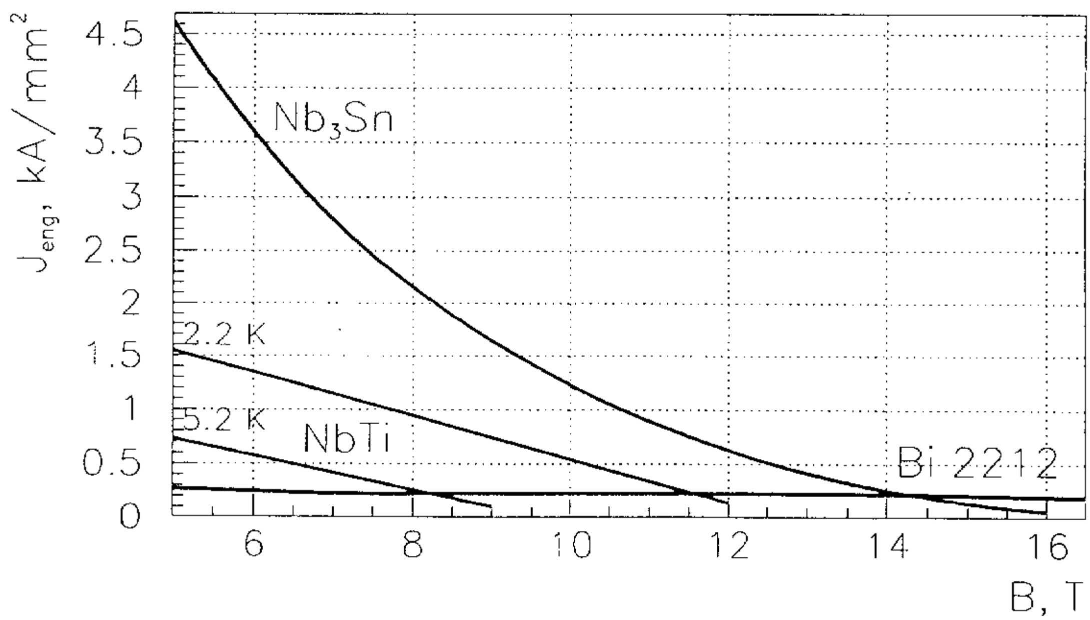
Radial pressure, MPa	
Single magnet	0.58
Magnet in string	0.61
Axial forces, kN	
Single magnet	-144
Magnet in string	-208
Attractive force	64

Channel IV

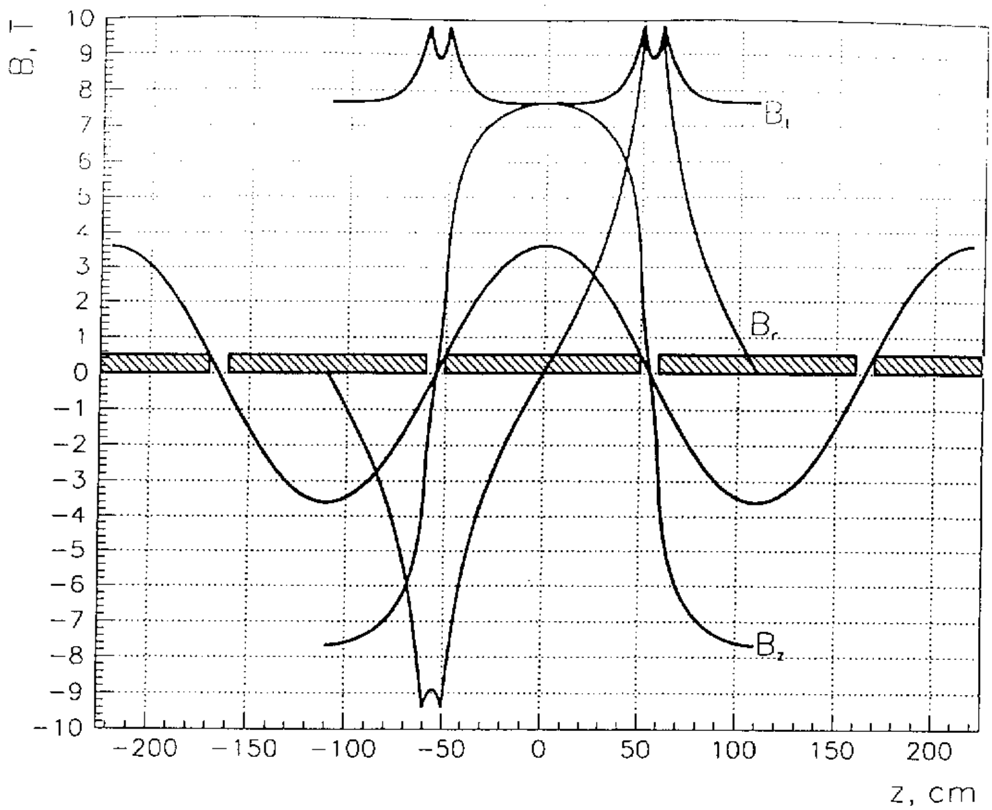
Initial requirements

1 Channel length is equal to 100 m.
2 Sinusoidal magnetic field.
3 Period of sinusoidal field 2.2 m.
4 Field amplitude B = 3.6 T → 5.5 T.
5 Warm bore.
6 RF cavities are inside channel.
7 Inner radius of RF cavities 0.7 m.
8 Radiation load can be neglected.
9 Period with 1.5 m and 3.4 T.

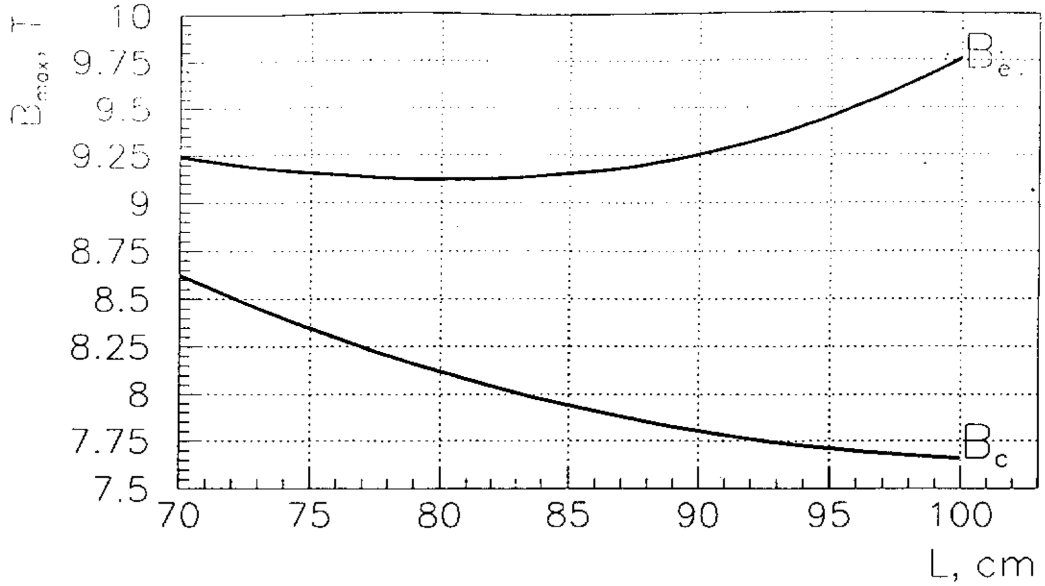
Magnetic properties of various materials



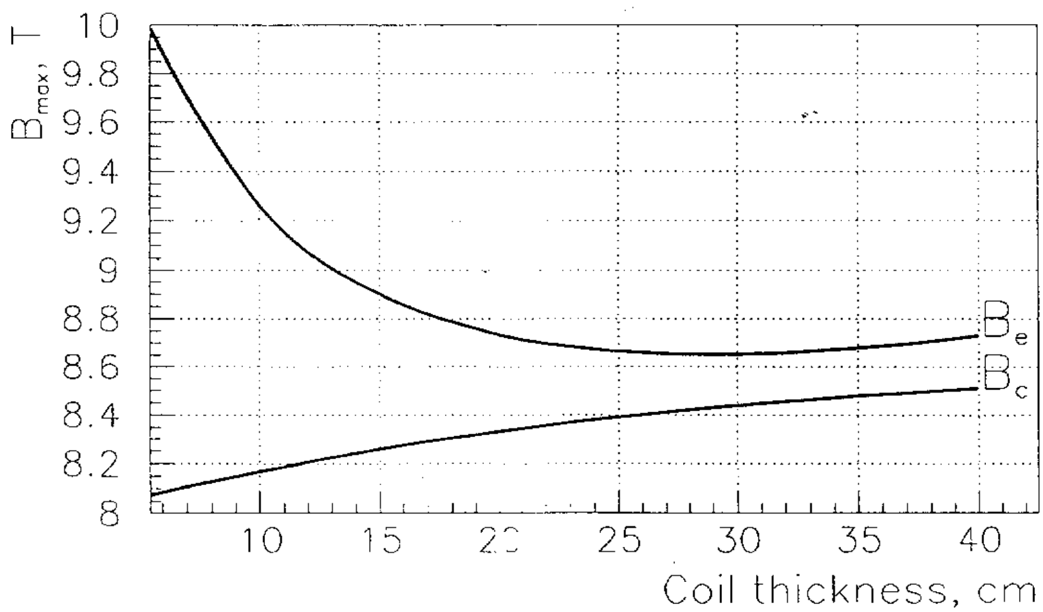
Dependences of engineering current density versus magnetic field for various superconducting materials.



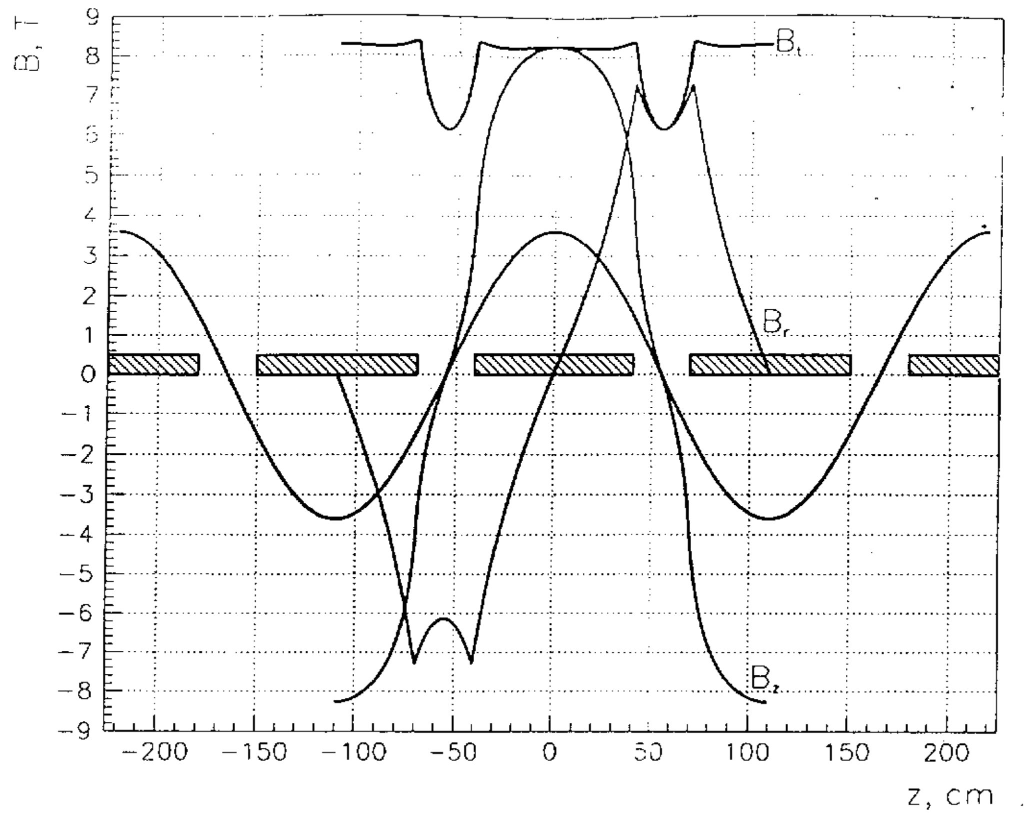
Distribution of magnetic field in the fourth channel at the maximal length of solenoids. Red line shows field amplitude along longitudinal axis, the other lines show field components on the inner surface of solenoid.



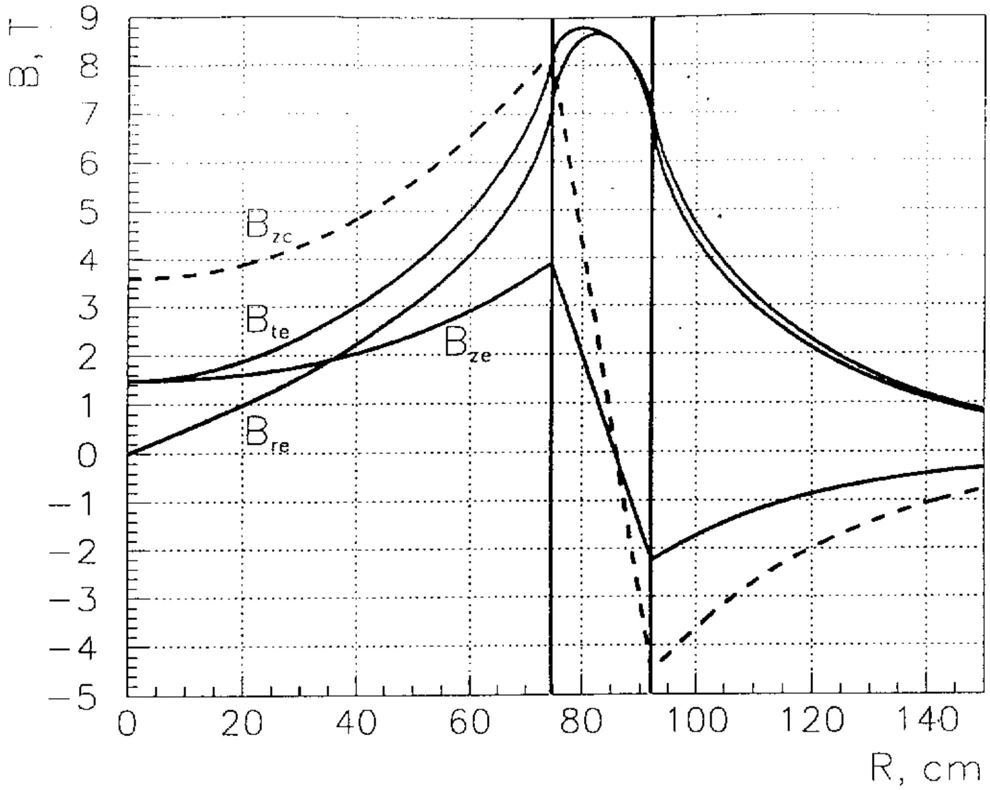
Dependence of the maximal field on the coil versus solenoid length. The low line shows the maximal field in the center of solenoid, the upper line presents the maximal field on the edge of solenoid.



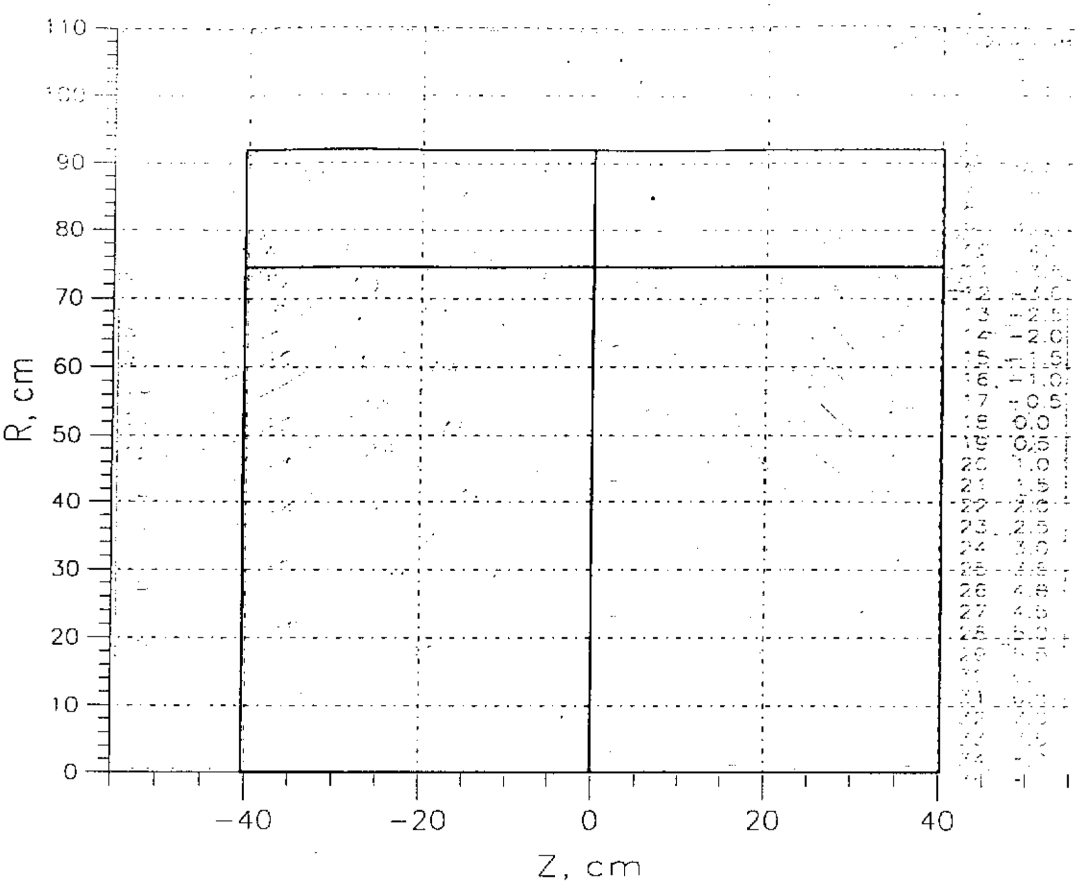
Dependences of the maximal field on the coil versus magnetic field both in the center of solenoid (B_c) and on its edge (B_e).



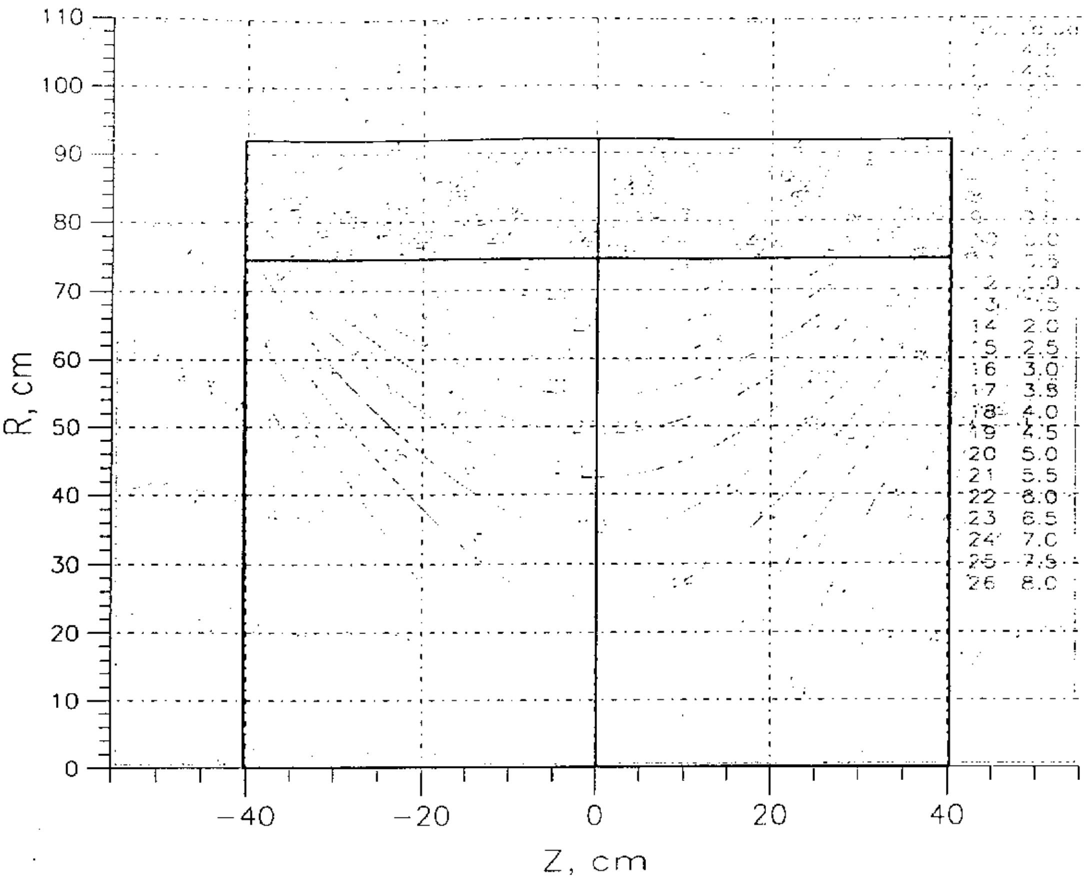
Longitudinal field distribution for optimal length of solenoid.



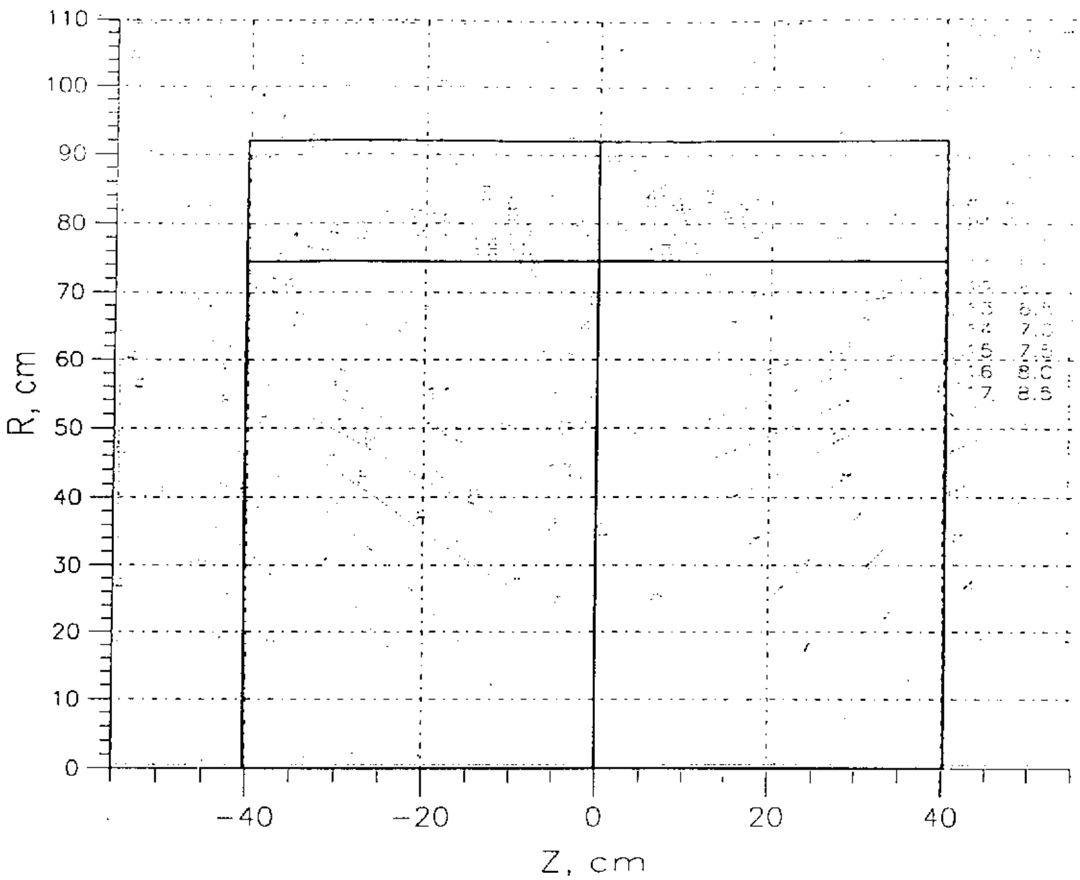
Radial distribution of field. Dotted line is the field in the center of solenoid, the other lines show end field components.



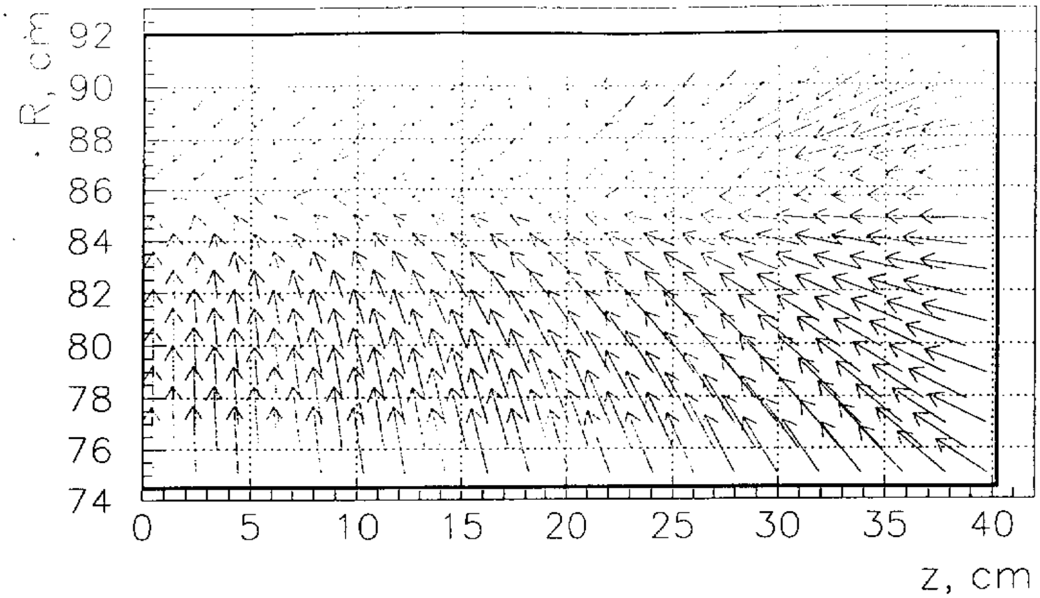
Map of the constant magnitudes of radial field component B_r.



Map of the constant magnitudes of longitudinal field component B_z.



Map of the constant magnitudes of field modulus B_t.



Distribution of ponderomotive forces in solenoid coil.

P_r = 15.24 MPa; **P_z = -89.12 MPa**

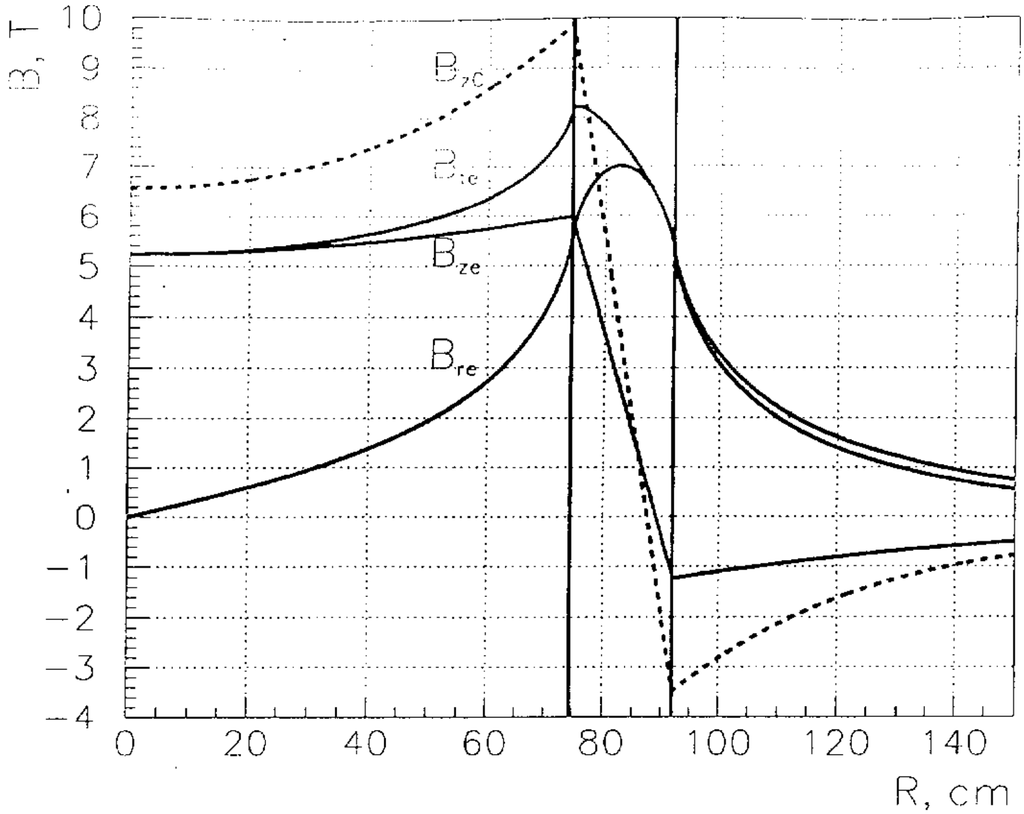
Bandage: 6 mm stainless steel or 10 mm Al

B = 3.6 T, B_{max} = 8.8 T;

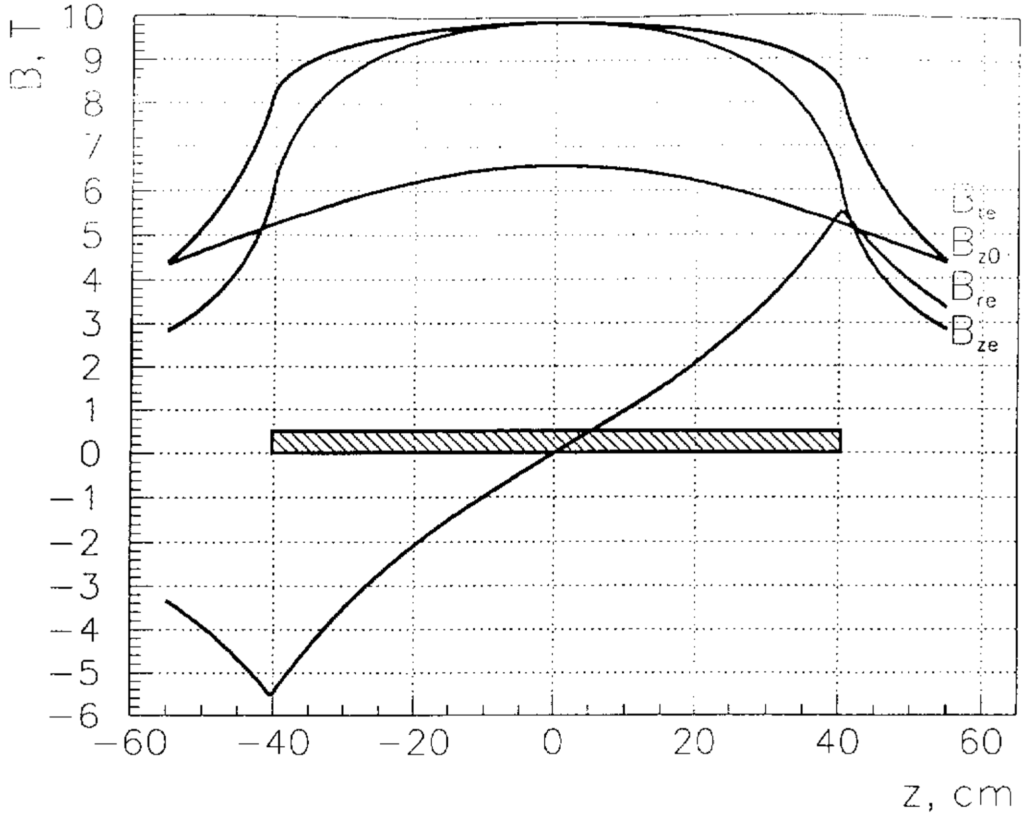
B = 5.5÷5.7 T, B_{max} = 13.4÷14.0 T

Force ↑ B^2; Energy ↑ B^2 ~ 2.5

Bandage: 50 mm stainless steel

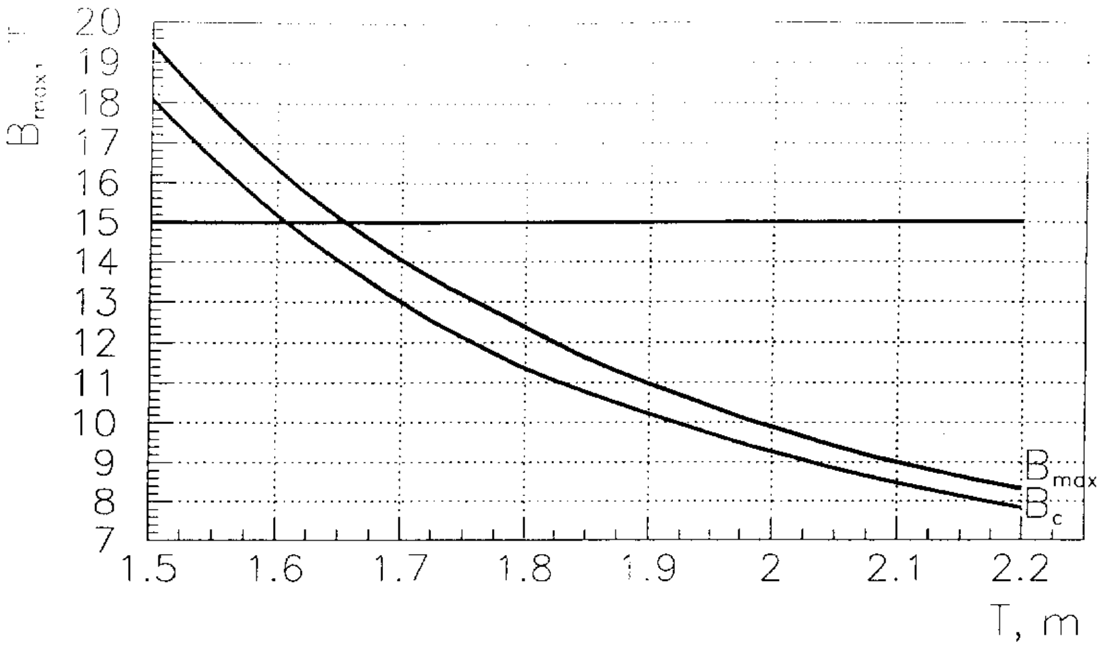


Radial field distribution for the single solenoid.



Longitudinal field distribution for the single solenoid.

Bandage: 50 mm stainless steel



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.

HTS

N.Okada. HTS High Field Magnets. MT-16, 1999, Ponte Vedra Beach, Fl, USA.

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

$\varnothing$1.6 mm, I_c = 900 A in own field and 4.2 K

I_c = 300 A in 28 T and 4.2 K

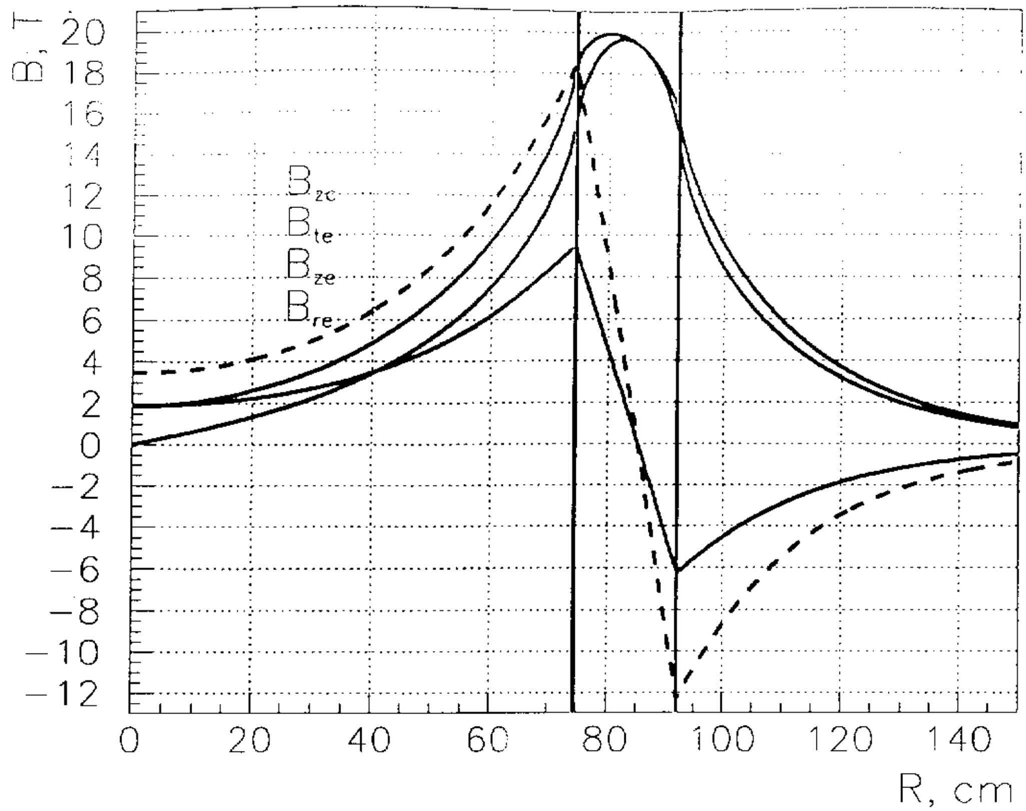
$\square$1.12×1.12 mm^2, I_c = 360 A

I_{total} = 13.9 MA, w = 12.5 mm, L = 475 mm

N = 97×417

L_{HTS} = 97×2 km = 196 km

P_r = 60.25 MPa; P_z = -425.40 MPa



Radial field distribution in solenoid cell with magnetic field period of 1.5 T.

Main parameters of magnet:

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 turn-current	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	0.026	0.301

Main parameters for channel IV:

Parameter	Unit	Value	
Part		I	II
Length	m	50	50
Number of magnets		45	67
Gap between magnets	m	0.295	0.275

Magnetic forces:

Part	I	II
Radial pressure, MPa		
Part	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
Repulsiive force	-18.1	-44.6

Conclusion

1. Geometry optimization of solenoid in channel IV:
   - **reduction of field enhancement in coil;**
   - **increase of field amplitude;**
   - **enlargement of coil inner radius;**
   - **shortening of sinusoidal field period.**
2. **Mechanical calculations:**
   - **first and last magnets in strings; supports;**
   - **radial and axial forces in channel IV; bandage; division on sections.**