Review of the progres in the 2D and 3D magnetic field simulation for the TESLA spectrometer magnets

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1.Estimation of the parameters for the ancillary magnets

Taking into account that the magnetic field requirements for the TESLA spectrometer ancillary magnets are not so extremely high as for main one, the calculations and it's design were assumed for three possible versions:

- the same magnet design in the transverse section (Fig.1) as for the spectrometer magnet, but in two times shorter in the length (1.5 m);
- more compact design in the transverse section (Fig.2) and with the length equal 1.5 m;
- more compact design in the transverse section (Fig.4) and the longitudinal direction.

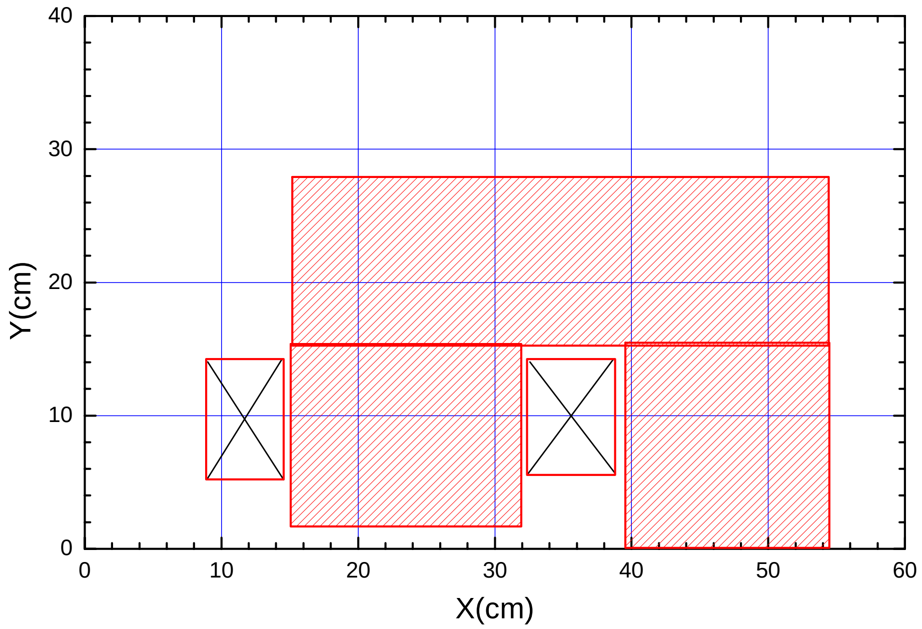

Fig.1. Cross-sectional view of of the TESLA spectrometer ancillary magnet (V.1)

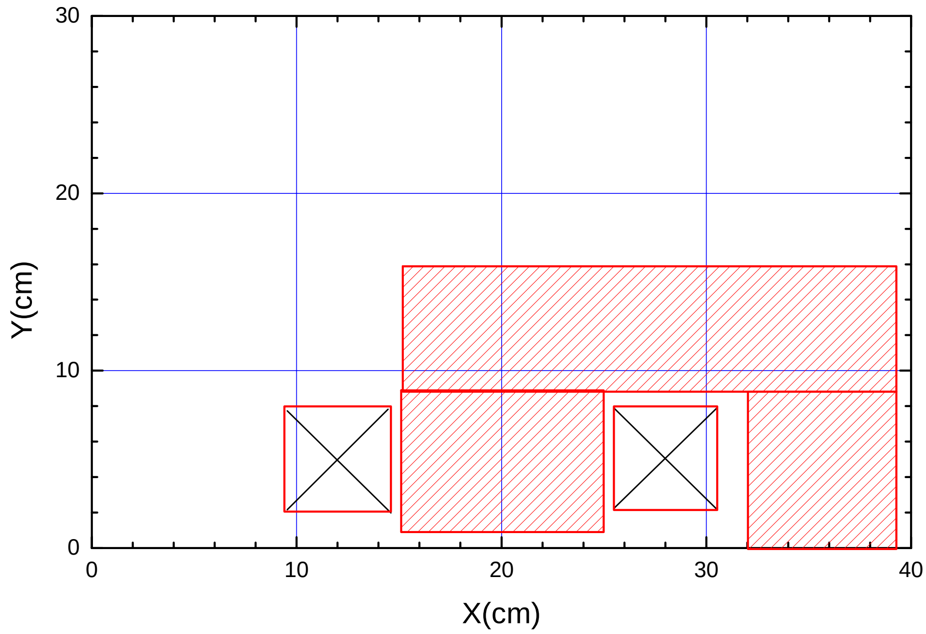

Fig.2. Cross-sectional view of of the TESLA spectrometer ancillary magnet (V.2)

For the version V.3 of the ancillary magnet the most compact design in the transverse and longitudinal direction was approached. Because of the magnet length decreasing the SR energy loss increases more then twice. The SR energy loss for the two ancillary magnets is equal to the one for the spectrometer magnet (Fig.3).

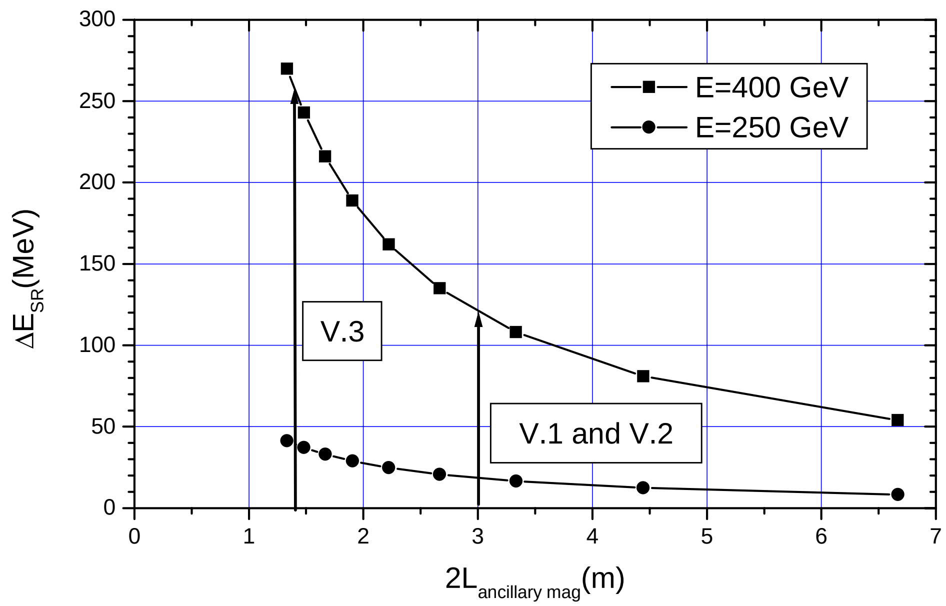

Fig.3. Energy loss due to synchrotron radiation in the two TESLA spectrometer ancillary magnets for the beam energy E=250 and 400 GeV

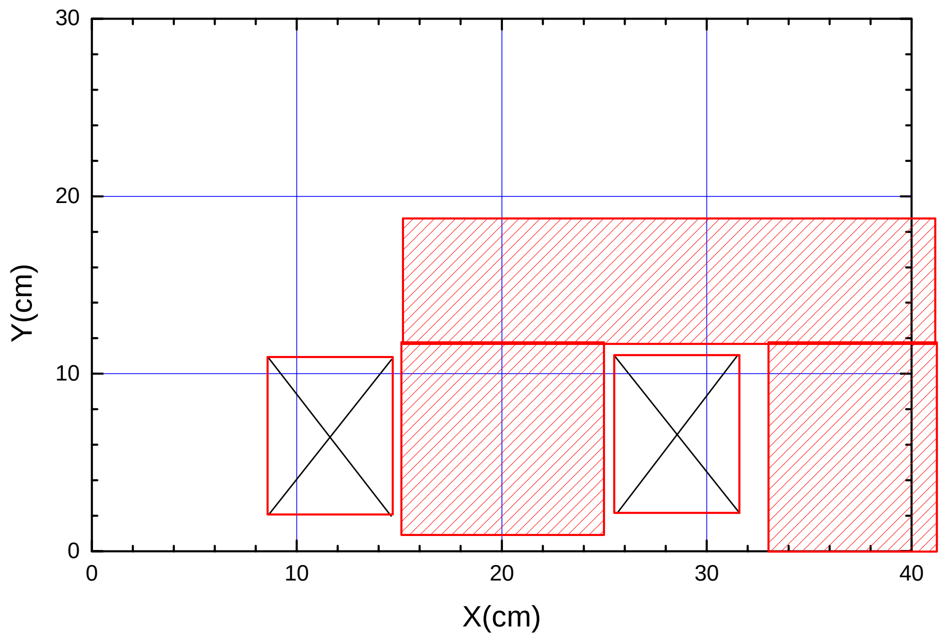

Fig.4. Cross-sectional view of of the TESLA spectrometer ancillary magnet (V.3)

The various versions for the ancillary magnet can be compared using the information on the magnets basic technical parameters from the Tab.1. The V.2 of the ancillary magnet has the minimal value for the magnet design optimization parameter (yoke weight)×(energy loss due to synchrotron radiation). So the preference should be given to this design version of the ancillary magnet.

Table 1. Basic technical parameters of the TESLA spectrometer magnet and for the assumed versions of the ancillary magnet

	Spectrometer magnet	Ancillary magnet (V.1)	Ancillary magnet (V.2) (preferable)	Ancillary magnet (V.3)
Bending angle (mrad)	1	0.5	0.5	0.5
Magnetic field (min/max) (T)	0.05/0.44	0.05/0.44	0.05/0.44	0.107/0.95
Pole gap (mm)	35	35	20	20
Pole length (mm)	3000	1500	1500	700
Magnetic field integral (T•m)	0.15/1.33	0.075/0.665	0.075/0.665	0.075/0.665
Magnetic measurement error of the field integral (relative)	$(1\text{-}3)\times10^{-5}$	$(2\text{-}5)\times10^{-4}$	$(2\text{-}5)\times10^{-4}$	$(2\text{-}5)\times10^{-4}$
Energy loss due to synchrotron radiation (max) (MeV)	120	60	60	130.5
Yoke type	C	C	C	C
Yoke dimensions (mm)	395×560×3000	395×560×1500	240×320×1500	230×380×700
Yoke weight (t)	4.51	2.25	0.73	0.43
A*turns (1 coil) (max)	6335	6335	3600	9300
Number of turns (1 coil)	6*4=24	6*4=24	6*5=30	10*6=24
Conductor type	Cu, 12.5×12.5, ∅7.5	Cu, 12.5×12.5, ∅7.5	Cu, 8.5×8.5, ∅5.3	Cu, 8.5×8.5, ∅5.3
Conductor weight (t)	0.34	0.19	0.09	0.11
Coil current (max) (A)	264	264	120	155
Current density (max) (A/mm^2)	2.4	2.4	2.4	3.1
Coil voltage (max) (V)	13.3	8	8.5	12.3
Coils power dissipation (max) (kW)	3.5	2.1	1.0	1.9
Number of water cooling loops	6	6	6	10
Length of cooling loop (m)	56	32	33	23
Water input pressure (Bar)	6	6	6	6
Water input temperature (deg C)	30	30	30	30
Temperature rise (deg C)	1.4	0.6	0.7	0.7

2. 3D simulation of the ancillary magnet by the MAFIA code

For the 3D effects including into the ancillary magnet design the magnetic field calculations were realized by 3D electromagnetic simulation code MAFIA.
The mesh generation for the V.2 ancillary magnet 3D model was realized with 200000 meshpoints. Because of the magnet symmetry it was generated for the ¼ magnet part. The minimal value for the meshsize for this model was achieved about 1 - 2 cm. The exitation coils in the MAFIA code are defining by the filaments. The magnet coil was simulated by 12 filaments (2 vertical layers × 6 filaments). The filaments have the rectangular shape in the plane view. The 3D view of the model is presented in the Fig.5.

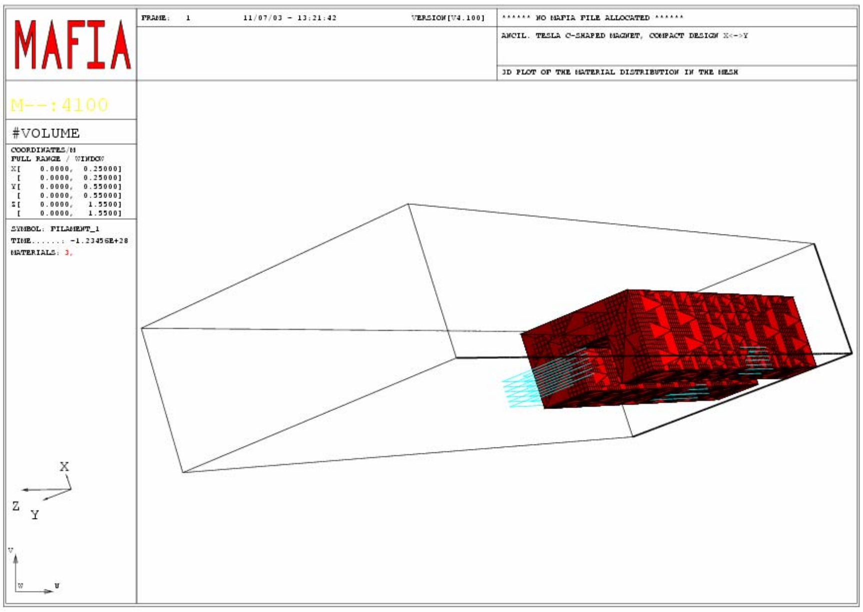

Fig.5. 3D view of the V.2 ancillary magnet model with iron yoke and filaments which represent the coil

Some MAFIA post processor views presenting the overall impression from the 3D picture for the ancillary magnet field are shown in the Fig.6 – 7 (maximal magnetic field B_{gap}=0.44 T).

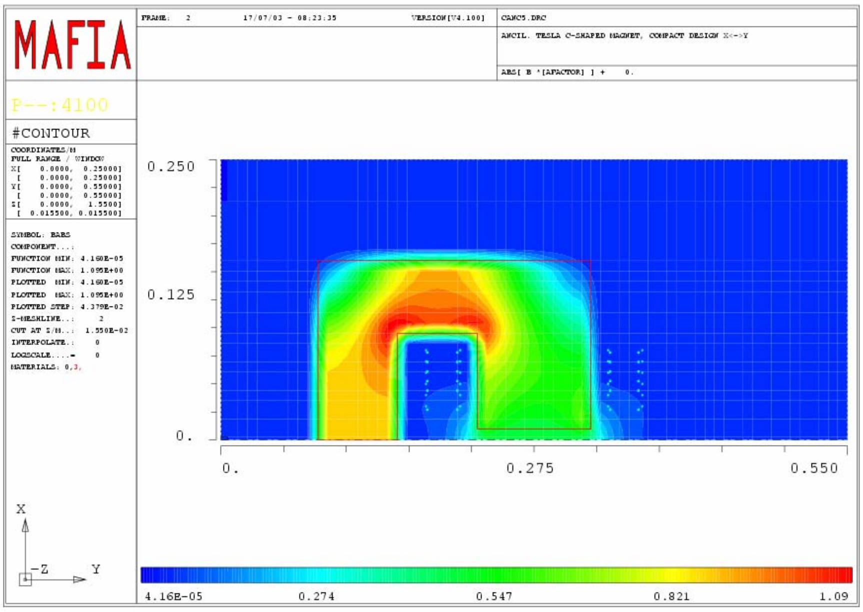

Fig.6. Magnetic field contour plot (middle cross-section, Z=0)

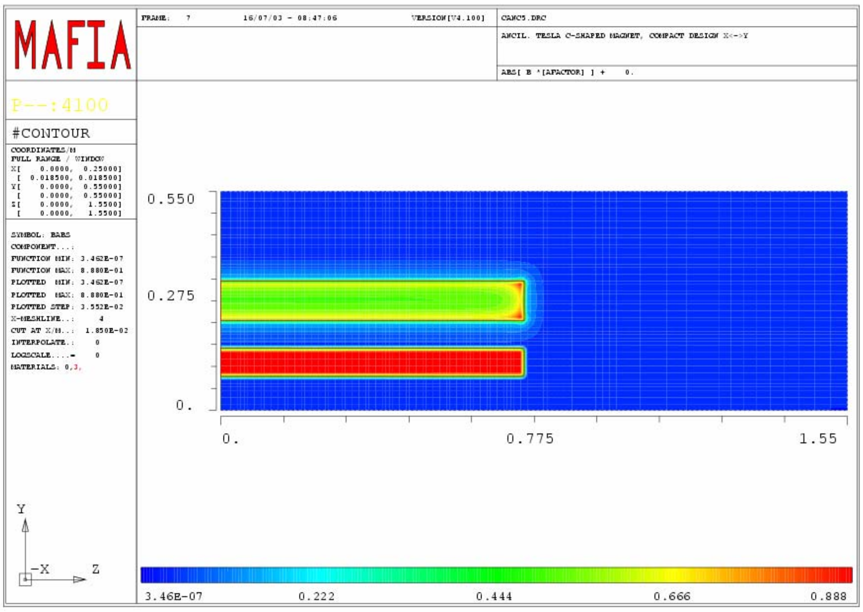

Fig.7. Magnetic field contour plot (horizontal cross-section, Y=1.85 cm)

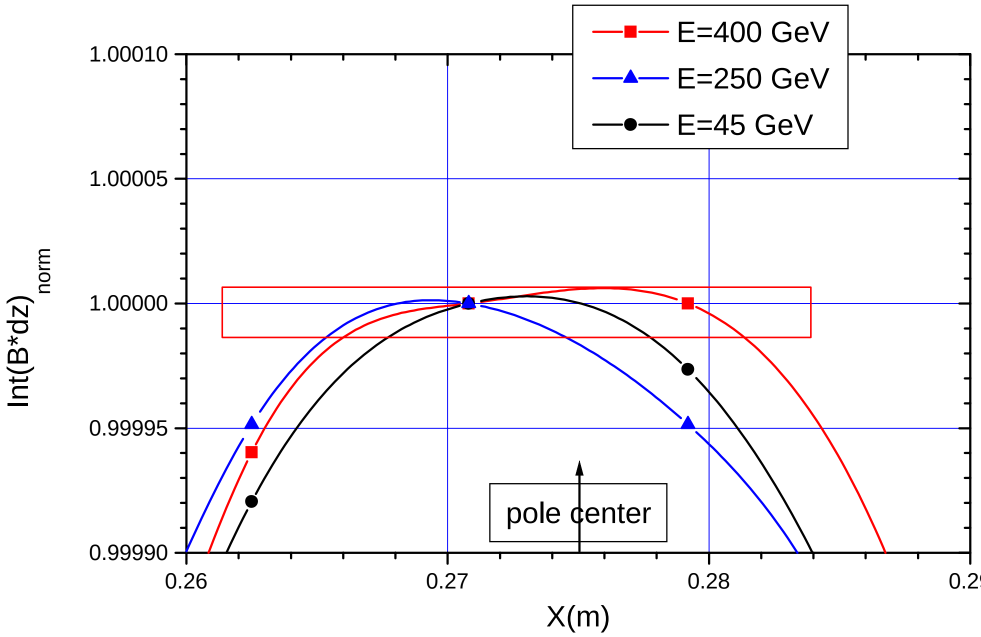

Fig.8. Longitudinal magnetic field integral (normalized)

Because of the 3D effects the uniformity region for the longitudinal magnetic field integral (Fig.8) is shifted on about 11 mm (from the one in the middle cross-section). This effect has to be taken into account in the magnet design. The width of the uniformity region is equal to 8 mm.

3. Simulation of the additional tolerance effects for the main magnet by 2D code

The magnetic field calculations were done for the spectrometer to provide some additional information for it which includes:

- the magnetic field influence of the design elements for connecting the magnet parts;
- the influence of the cavity defects in the magnet core;
- the influence of the magnet girder;
- the influence of the variation of the magnet steel chemical composition;
- the influence of the stainless steel vacuum chamber;
- and the possible position and geometry of the end field screens.

All effects mentioned above (except for the last) lead to the variation of the spectrometer magnet field in the longitudinal direction. The LEP experience shows this variation at the relative level 10^{-3} (Fig.1). Certainly this variation may be measured by NMR probe and the data used for the magnetic field integral evaluation. But it is evident that the more magnetic field variation amplitude, the accuracy of the field integral less. So the aim of those calculations was to provide the information on the magnetic field influence from the various reasons and on this base to estimate the reasonable magnet design requirements.

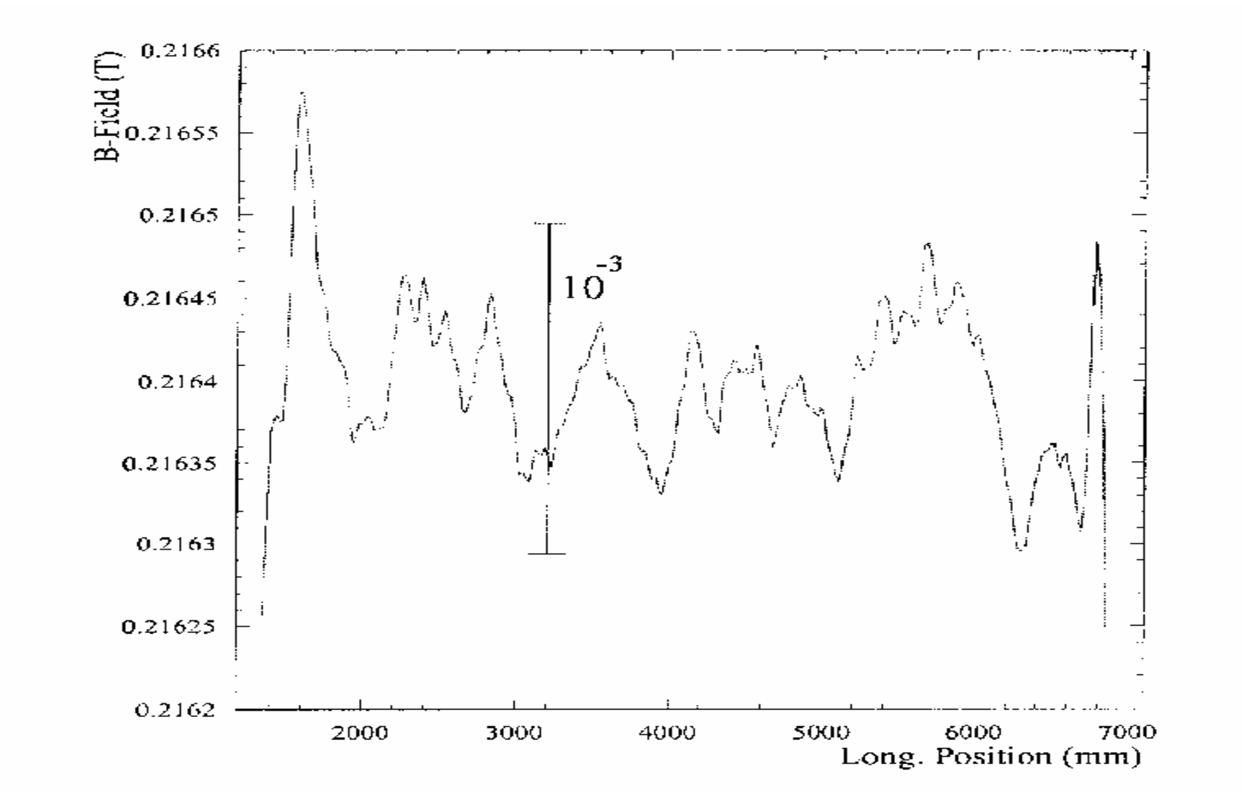

Fig.9. The longitudinal magnetic field structure for the LEP spectrometer magnet

One of the possible decision for the magnet parts (pole, horizontal and vertical yoke) join may be the use of the long bolts (Fig.10). The bolt (diameter 12 mm) influence arises from it head (H), from small gap (G=0.1 mm) and small cavity (C=∅10×5 mm). The magnetic field disturbance from the bolt (Fig.11 depends from it position in the magnet core (X_b).

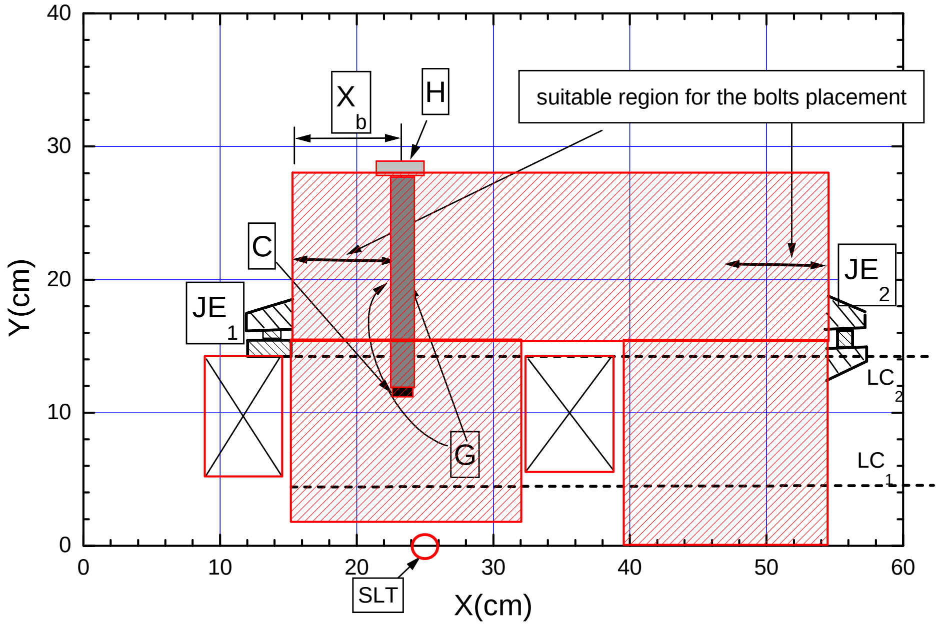

Fig.10. Magnet yoke with connecting bolt

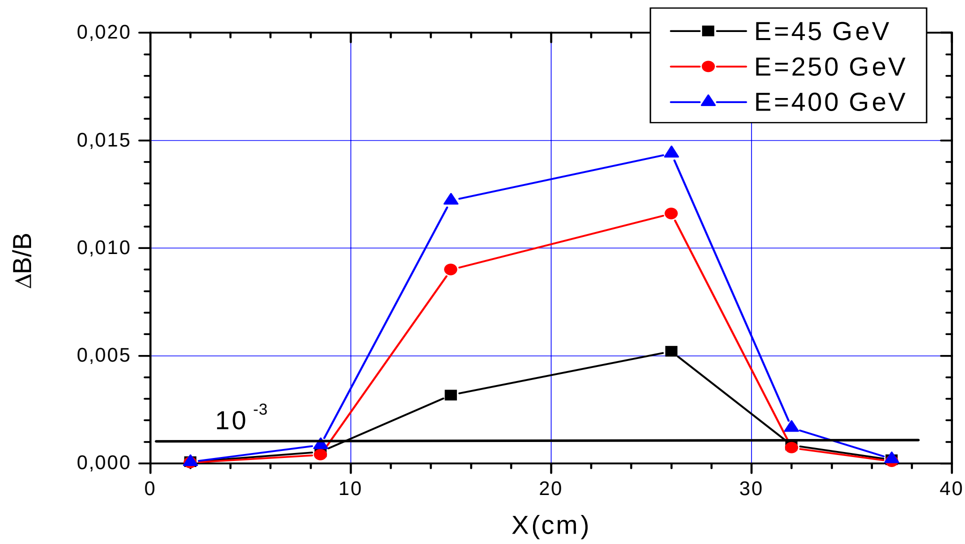

Fig.11. Magnetic field disturbance from the bolt

The relative bolts influence less then 10^{-3} exists in case of its placement inside the regions marked in the Fig.10 as "suitable".
At the magnet edges instead of bolts a special connecting elements (JE_1 and JE_2, Fig.10) may be used. The relative magnetic field calculation influence for the elements JE_1 and JE_2 is presented in the Fig.12

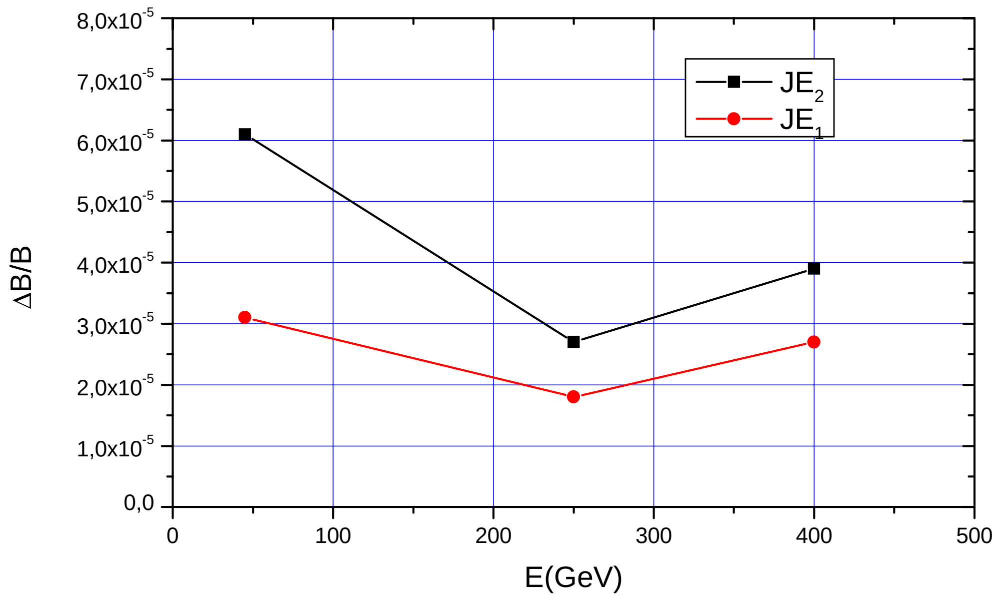

Fig.12. Magnetic field disturbance from the connecting elements JE_1 and JE_2

Cavity defects in the magnet core

During the magnet steel plates manufacturing the internal defects can appeared. It was studying the magnetic field influence for the magnet core defects like cavity with dimension 10×5 mm. The cavities are placed at two difference lines along the magnet core (LC_1 and LC_2 , Fig.10). The relative magnetic field disturbance depending from transverse cavity position is presented in the Fig.13 and 14.

Magnet girder

The girder may be used for the spectrometer magnet mechanical support. The girder possible design is presented in the Fig.15. The girder steel plates serve as the additional magnet yoke. The magnetic field lines in case of using of the girder are presented in the Fig.16. The influence of the girder on the magnetic fields depending from the beam energy is shown in the Fig.17. This influence is a few of 10^{-4}.

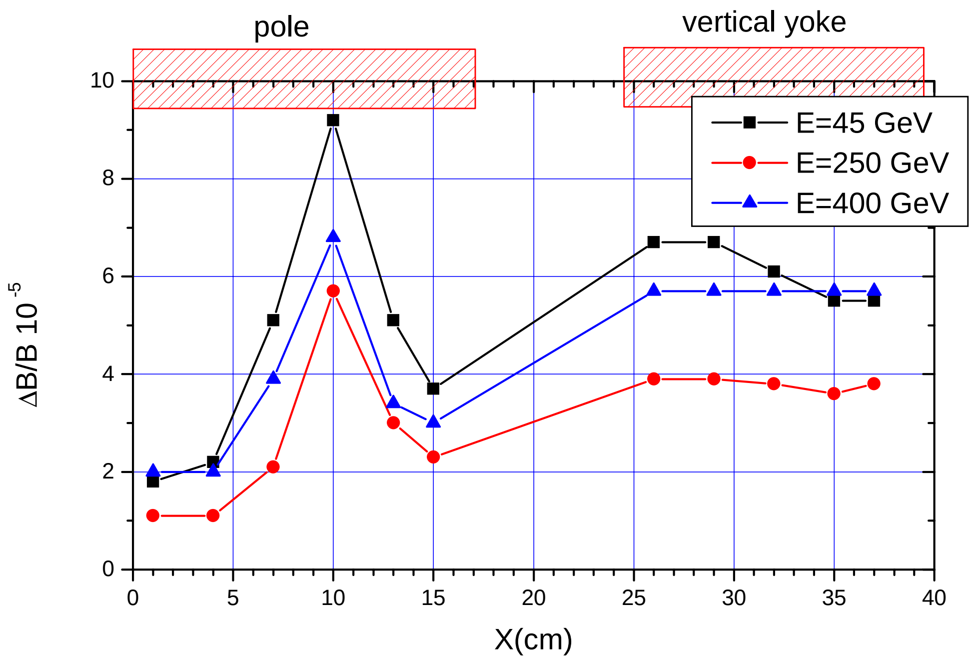

Fig.13. Magnetic field disturbance due to the cavity at the line LC_1

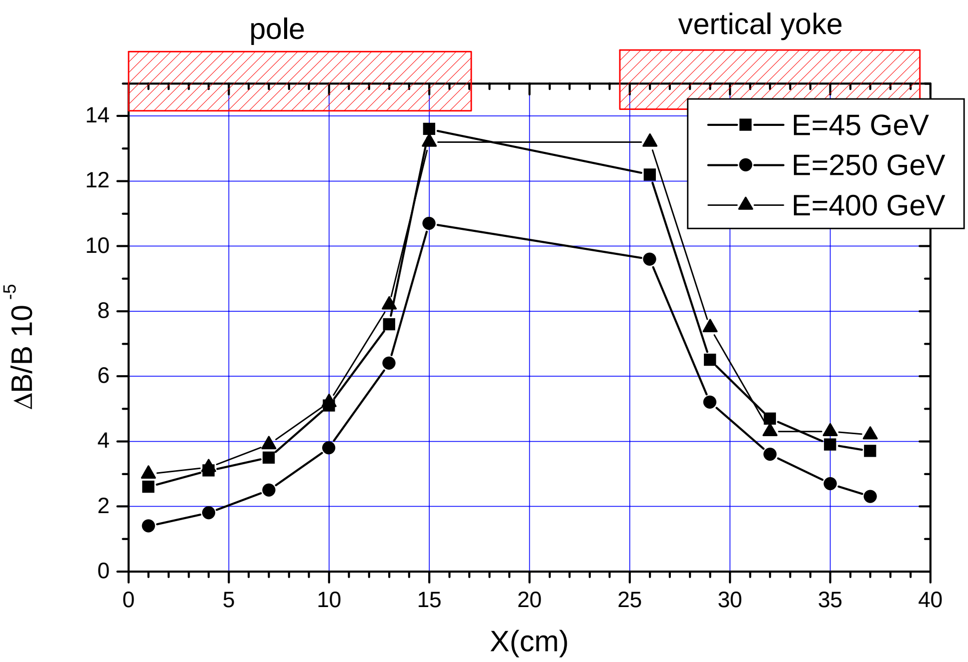

Fig.14. Magnetic field disturbance due to the cavity at the line LC_2

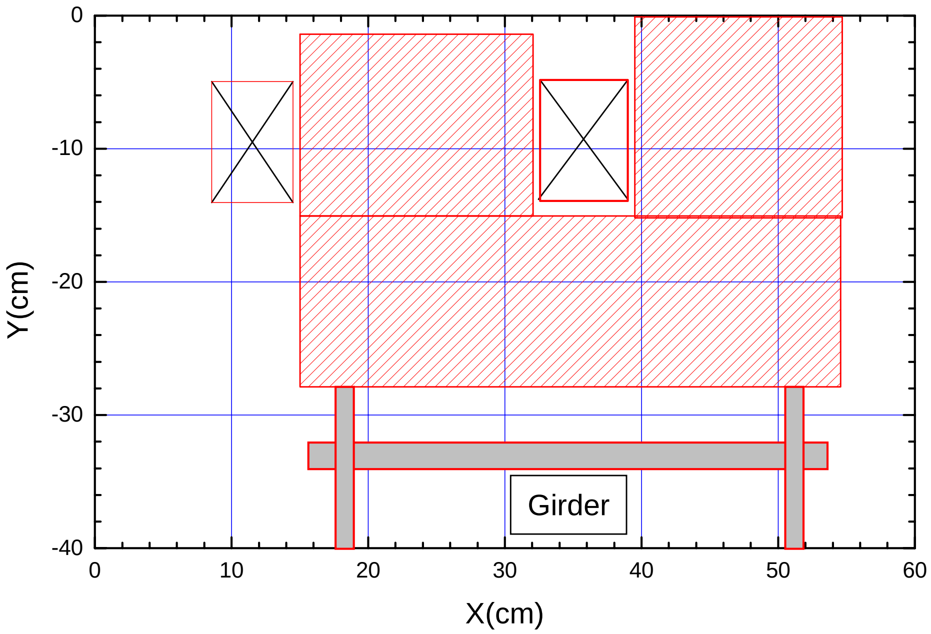

Fig.15. Spectrometer magnet with girder

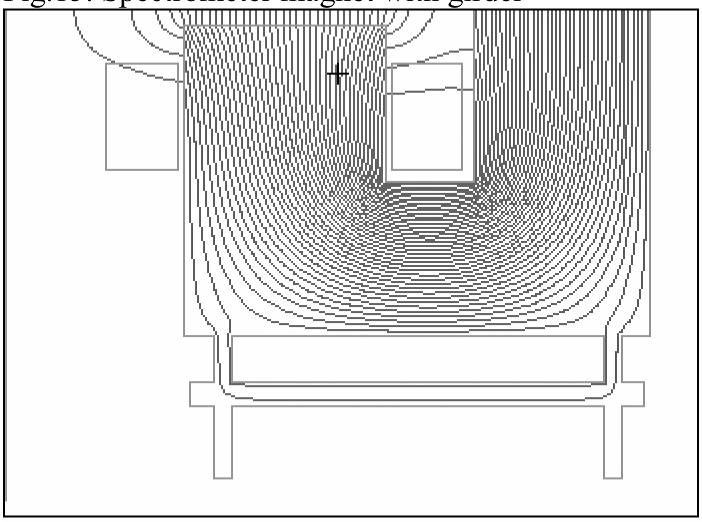

Fig.16. Field lines in the spectrometer magnet with girder

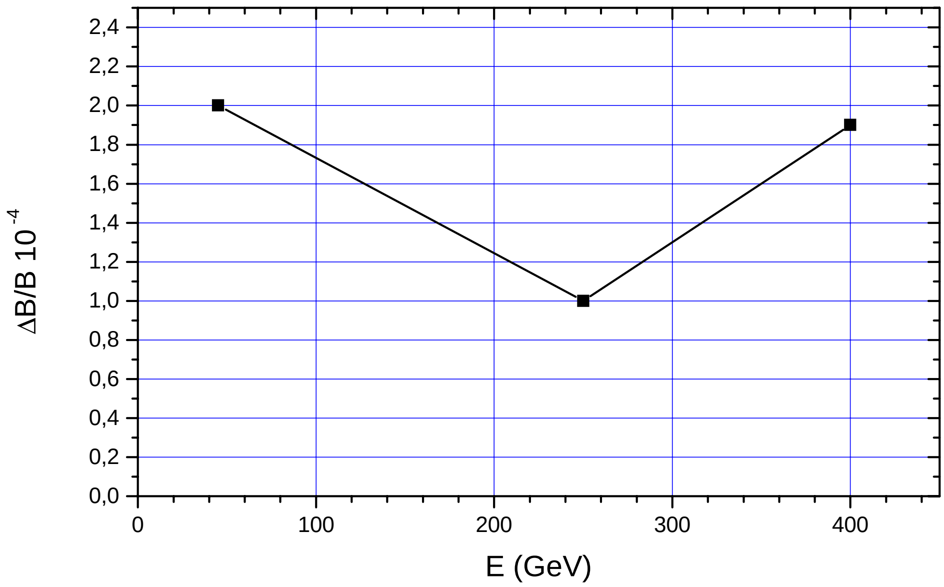

Fig.17. Relative magnetic field influence of the girder

Magnet steel chemical composition

A low carbon steel has normally to be used for building of the spectrometer magnets. The steel magnetic quality strongly depends from it chemical impurities composition. The effect is most serious for the carbon, cremnium and manganese. The average composition of the Russian low carbon steel type St-05 is in the Table 2.

Table 2. Chemical composition of steel St-05

Element	C	Si	Mn	P	S	Cr	Ni
Content %	0.06	0.03	0.4	0.035	0.04	0.1	0.25

For the spectrometer magnet the magnetic field variation depends from the variation of the chemical composition inside the single piece of the steel. For the calculation of magnetic field variation it was proposed that the value of chemical compound variation for the steel piece is equal to 10%. According to the publication [1] it was possible to calculate the variation of the magnetization curve for the steel St-05. This change is presented in the Fig.18. The results of the relative magnet field change for three magnet parts (pole, horizontal and vertical yoke) due to this chemical composition variation are presented in the Fig.19.

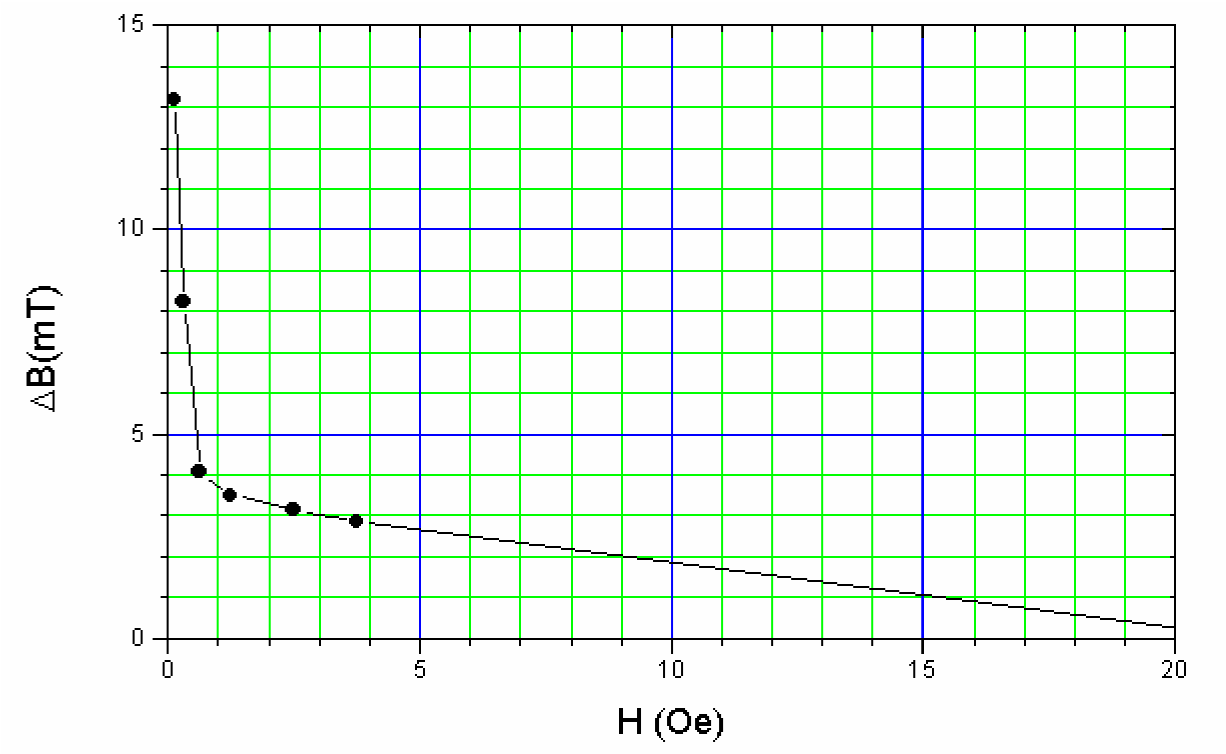

Fig.18. Change of the magnetization curve for the steel St-05 for the 10% change of it chemical composition

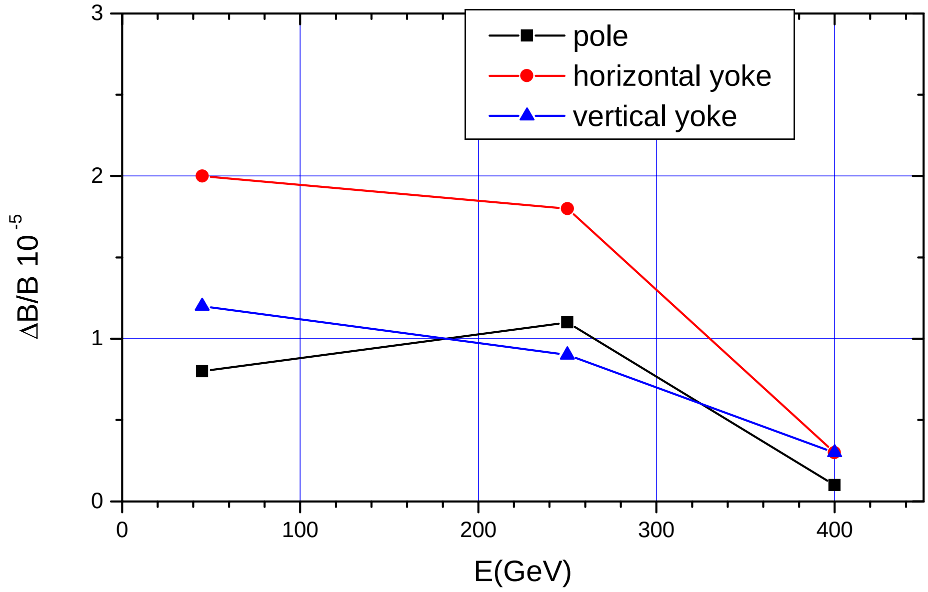

Fig.19. The spectrometer magnet magnetic field variation due to the 10% chemical composition variation for the steel St-05

Stainless steel vacuum chamber

According to the publication [2] the stainless steels have the usual value of the maximal relative permeability close to 1.01. The magnetization curve for the stainless steel type 304L was taken from publication [3]. It is shown in the Fig.20. The stainless steel tube of the diameter ∅20 mm with wall thick 2 and 1.5 mm was inserted in to the computer model (SLT, Fig.10). The results of computer simulation for the relative magnetic field change inside the stainless steel tube vacuum chamber are presented in the Fig.21.

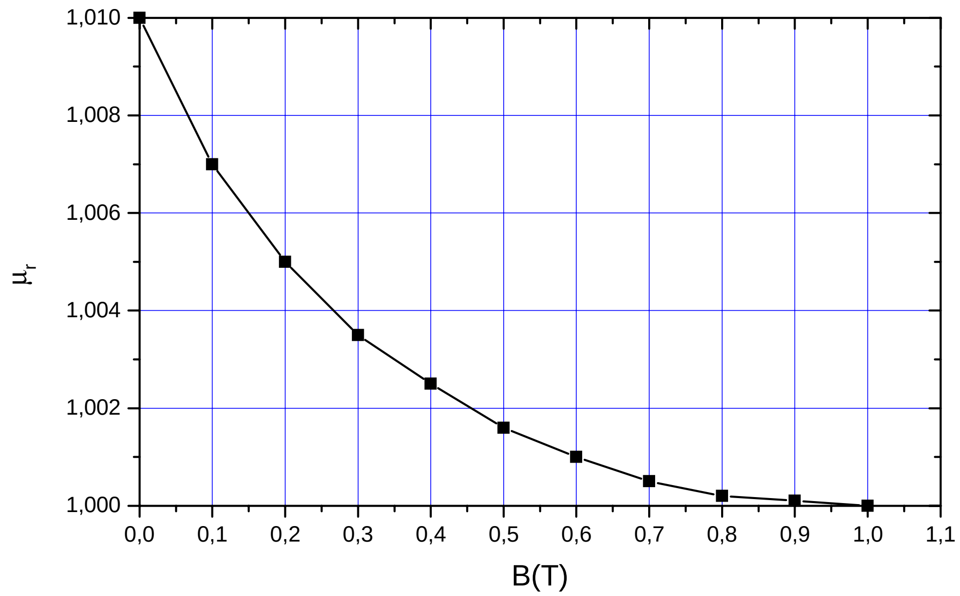

Fig.20. Magnetization curve for the stainless steel 304L

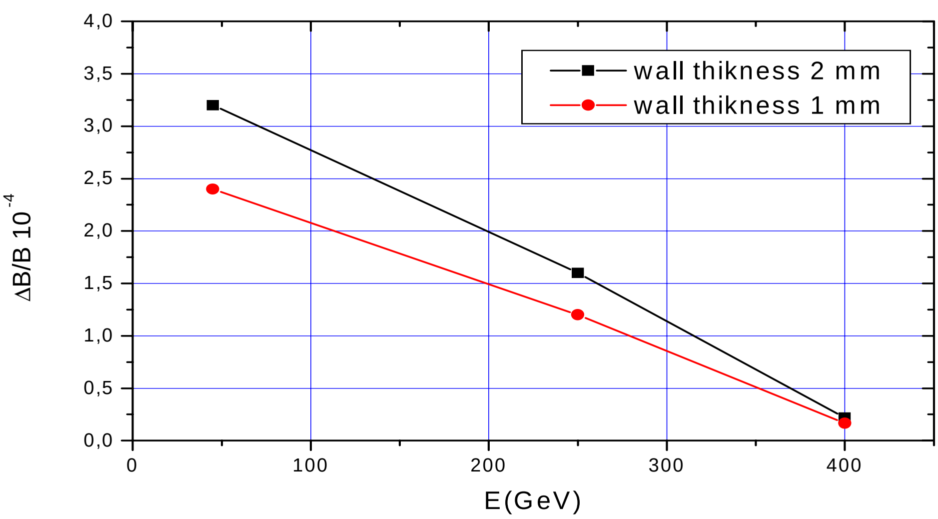

Fig.21. Magnetic field change inside stainless vacuum chamber

End field screens

The LEP spectrometer experience has shown that it is desirable to cut off the magnet field at the certain distance from the input/output pole edge. At the LEP spectrometer magnet the field cut off was achieved by using a shield of μ-metal wrapped around the vacuum pipe. The screens were placed at the distance from the magnet pole were the edge magnetic field falls to the value of 0.1 mT. For the calculation of the TESLA spectrometer magnet edge magnetic field we were used two computer models:

- 2D model for the longitudinal magnet section on the base of POISSON SUPERFISH code (the view of this model is in the Fig.22);
- 3D model on the base of RADIA code [4] (the view of this model is in the Fig.23).

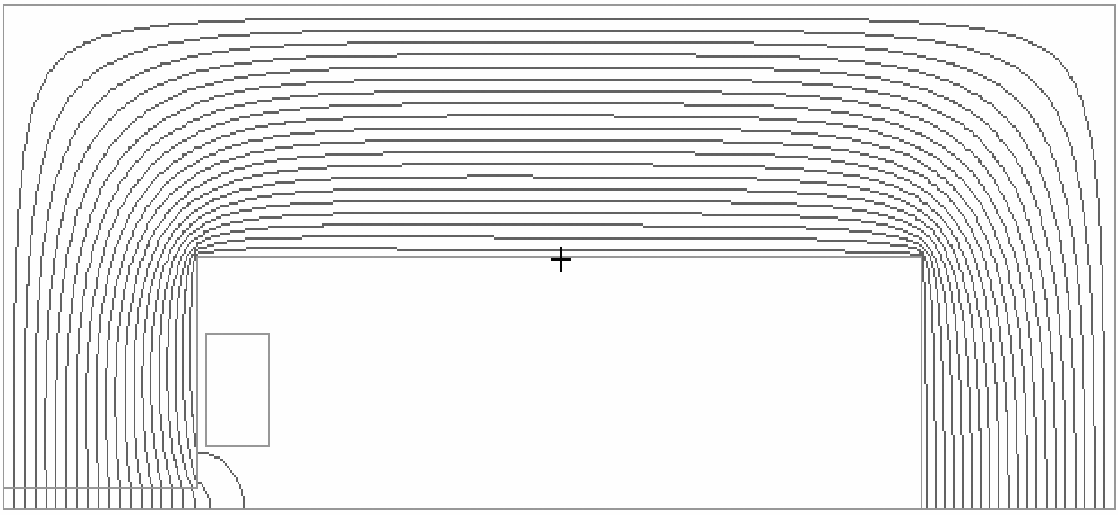

Fig.22. 2D model for the calculation of longitudinal magnetic field (SUPERFISH)

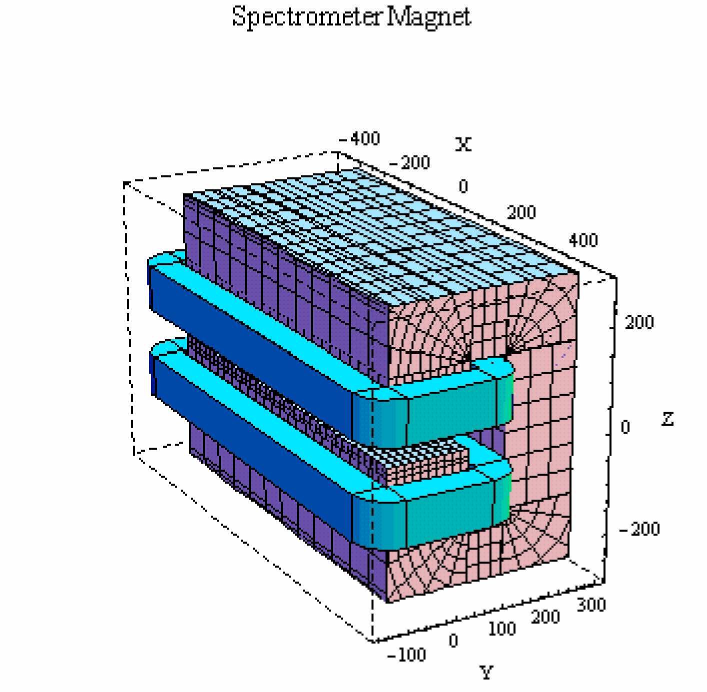

Fig.23. 3D model of the spectrometer magnet (RADIA)

The results of magnetic fields calculation by help of two models are shown in the Fig.24. The magnetic screen has to be placed at the distance from the pole edge equal to 280 – 330 mm.

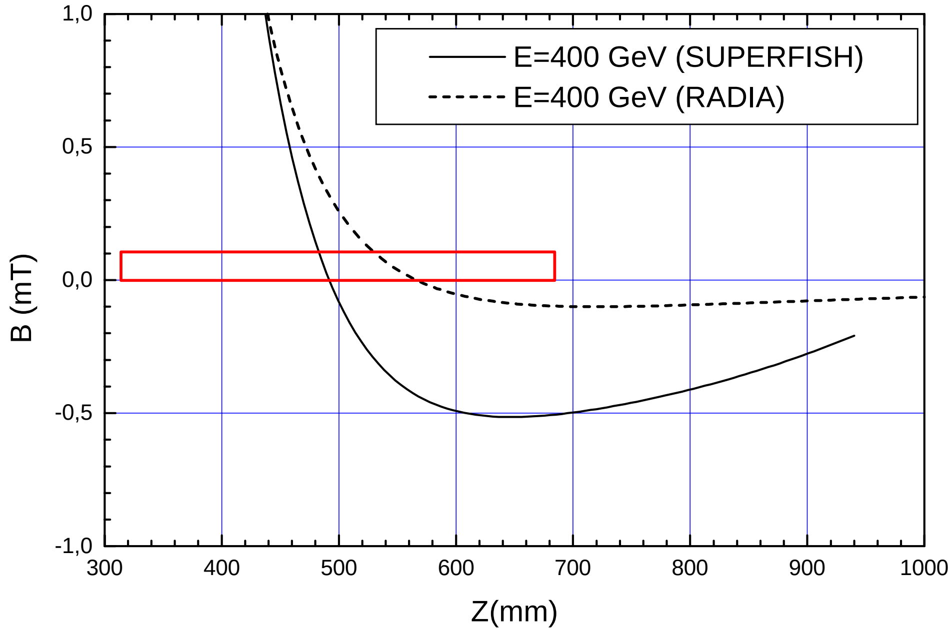

Fig.24. The spectrometer magnet edge magnetic field

A 2D model was used to estimate the shielding attenuation factor. The model is presented in the Fig.25.

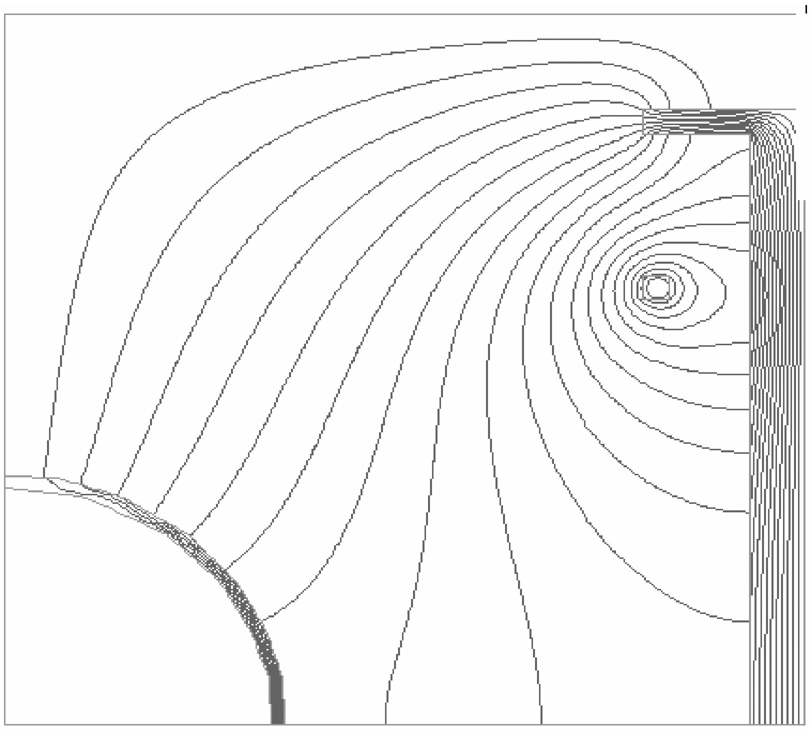

Fig.25. 2D model for the calculation of the field screen

The magnetic field in this model was generated by the current coil and effective iron yoke. The maximal value of the magnetic field was equal to 0.1 mT. For the field screen the permalloy metal type 50HXC (μ_{ini}=3000, μ_{max}=28000) 0.5 mm thickness was used. The permalloy tape is wrapped around the vacuum pipe. The magnetization curve for the permalloy is presented in the Fig.26. The attenuation factor for the field screen is shown in the Fig.27.

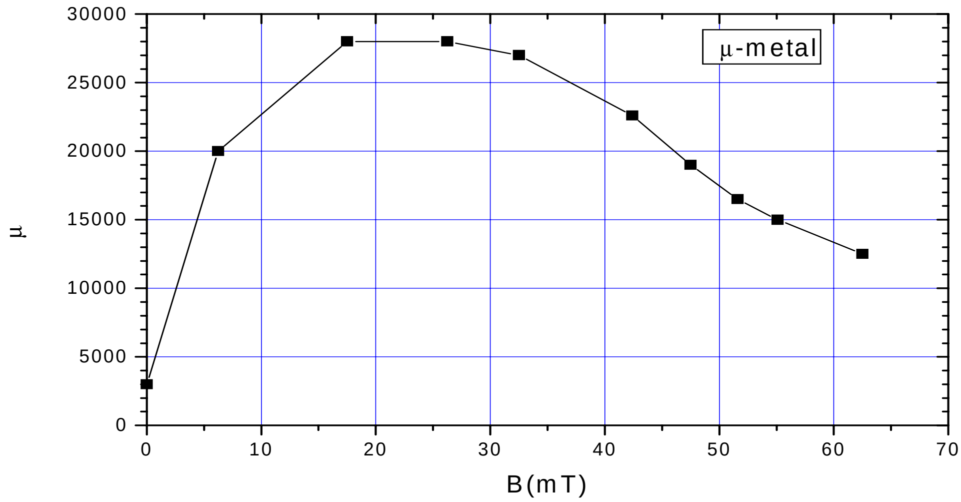

Fig.26. Magnetization curve for the 50HCX alloy

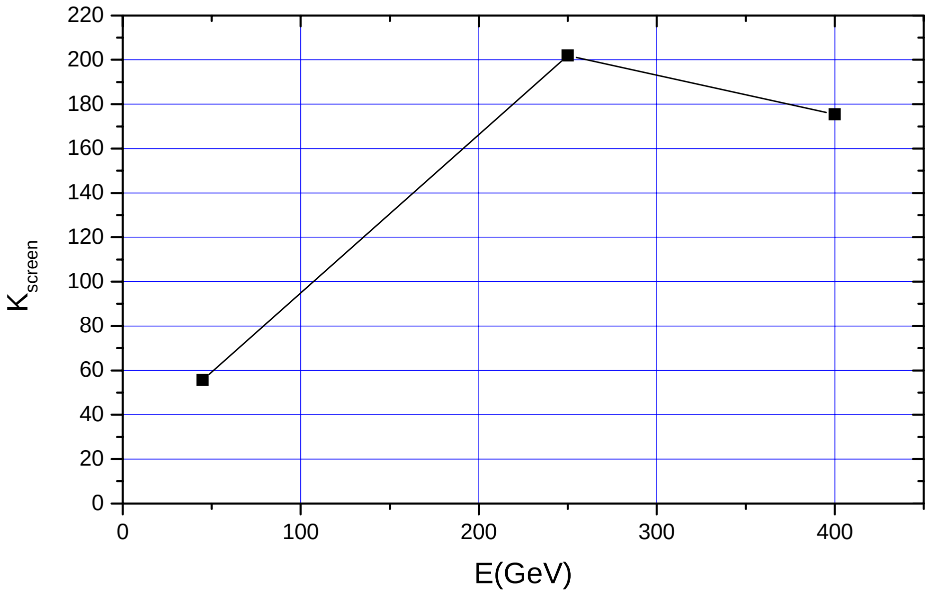

Fig.27. Attenuation factor for the field screen

Conclusions

1. The number of magnet yoke connecting elements has to be minimized. Their position has to be choose to provide relative magnetic field disturbance less then 10^{-3}.
2. The steel plates for the spectrometer magnet has to be tested by special defects detection methods for determination of the inside caverns.
3. The magnet girder has to be designed with minimal magnetic field distortion. The magnetic field measurements has to be provided for the magnet with the girder.
4. For the magnet manufacturing the low carbon steel use is preferable. The special attention should be given to a variation of the steel chemical composition, it has to be less then 10 %.
5. The wall thickness of the vacuum pipe has to be as small as possible. The stainless steel of the vacuum pipe has to have the minimal value of μ_r (preferable less then 1.005). The magnet test for the vacuum pipe has to be started as early as possible.
6. The position of the magnetic field screen has to be choose during the spectrometer magnet test.

4. **3D Magnetic field calculations for the main magnet by the MAFIA code**

For the 3D effects including into the procedure of the main spectrometer magnet design the magnetic field calculations were realized by 3D electromagnetic simulation code MAFIA.
The mesh generation for the main magnet 3D model was realized with 300000 meshpoints. Because of the magnet symmetry it was generated for the ¼ magnet part. The minimal value for the meshsize for this model was achieved about 1 - 2 cm. The exitation coils in the MAFIA code are defining by the filaments. The magnet coil was simulated by 12 filaments (2 vertical layers × 6 filaments). The filaments have the rectangular shape in the plane view. The 3D view of the model is presented in the Fig.28.

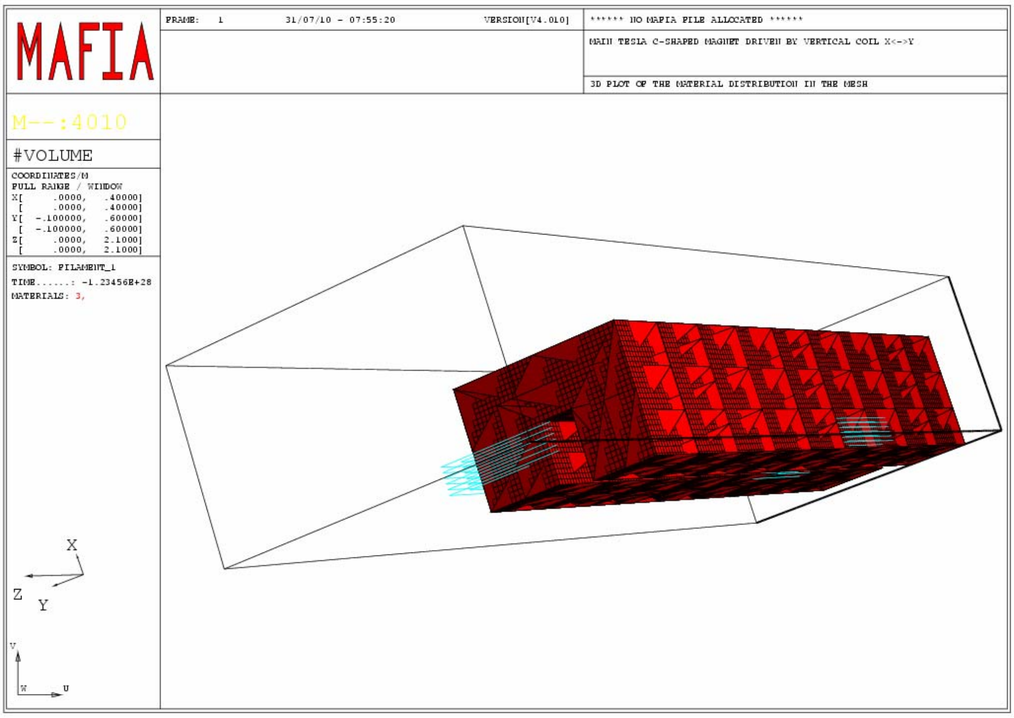

Fig.28. 3D view of the main spectrometer magnet model with iron yoke and filaments which represent the coil

The post processor views presenting the overall impression from the 3D picture for the main magnet field are shown in the Fig.29 – 30 (for the maximal magnetic field B_{gap}=0.44).

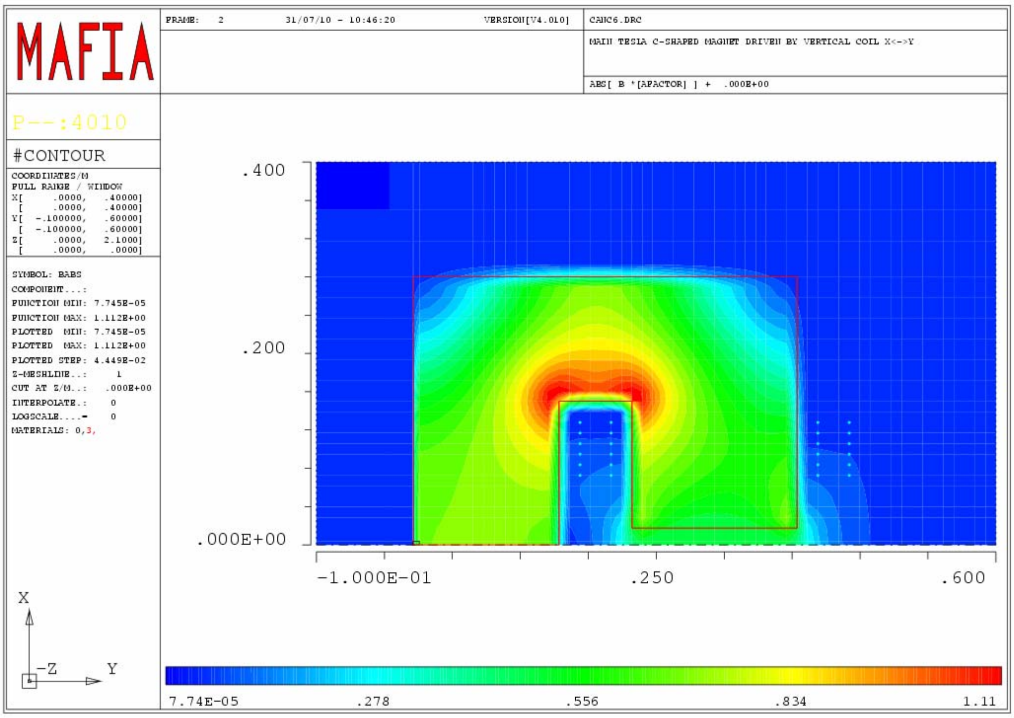

Fig.29. Magnetic field contour plot (middle cross-section, Z=0), (B=0.44 T)

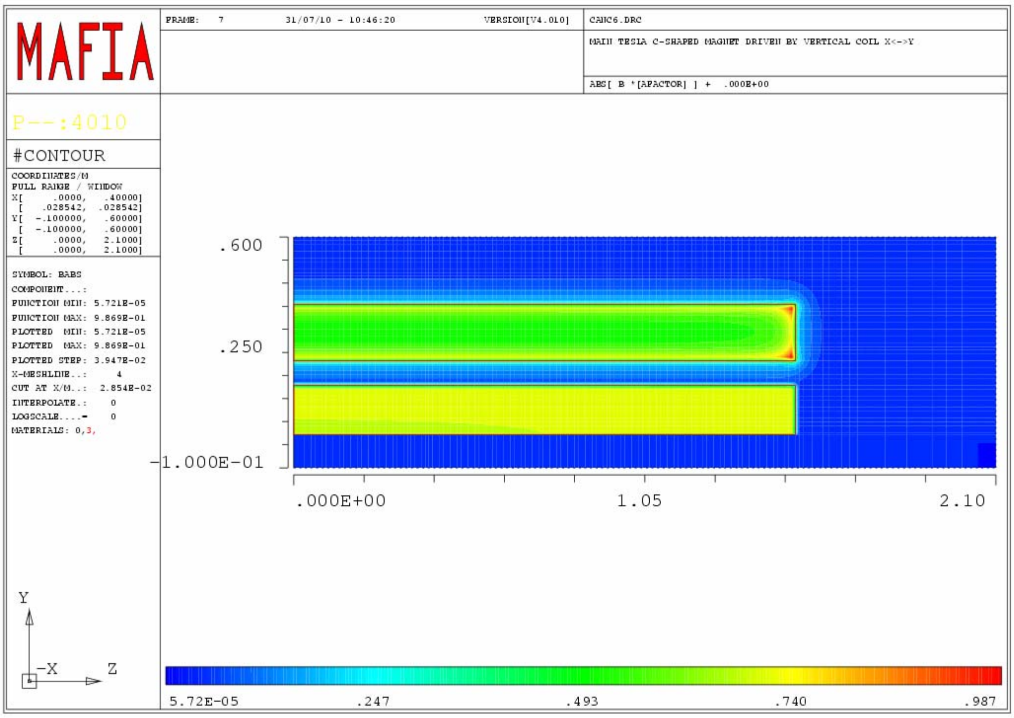

Fig.30. Magnetic field contour plot (horizontal cross-section, Y=2.8 cm) (B=0.44 T)

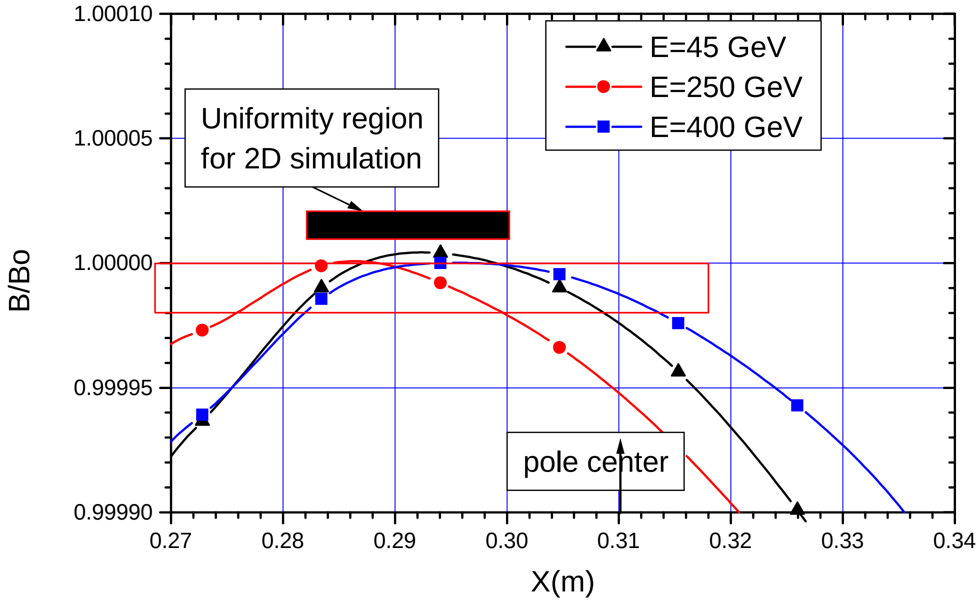

Fig.31. Normalized magnetic field in the middle cross-section of the main magnet

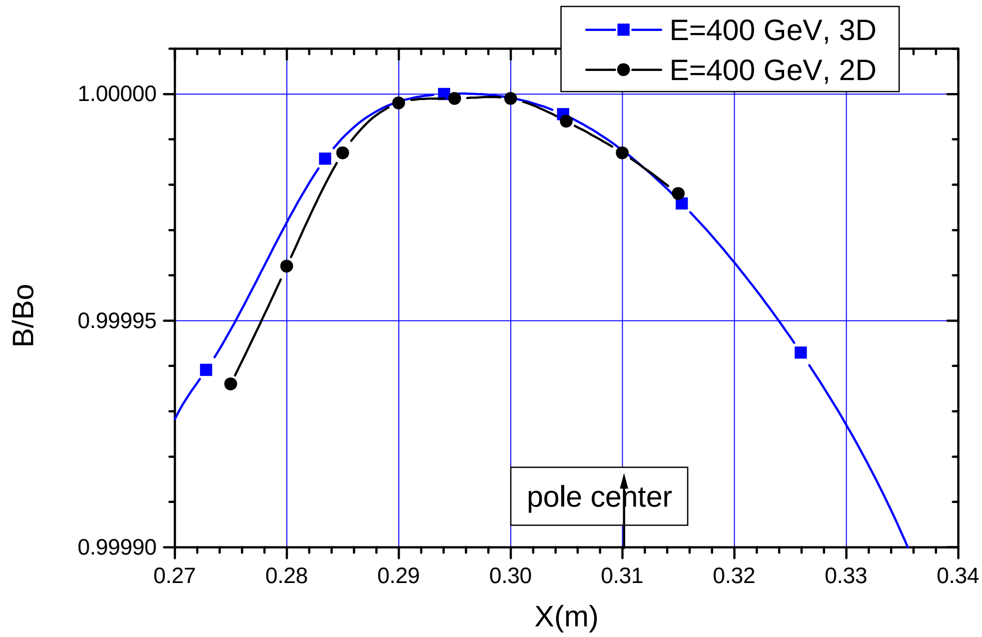

Fig.32. Normalized magnetic field in the middle cross-section of the main magnet for 2D and 3D models (B=0.44 T)

In the Fig.32 the normalized magnetic field for the middle magnet transverse cross-section is presented. The 3D magnetic field simulation shows that the field distribution is very closed to the 2D one (Fig.32). It means that only for the magnet length of 3 m the 2D simulation (it assumes that in the longitudinal direction the magnet is infinitely long) is closed to the reality. The magnetic field influence of the 3D effects is possible to see from the Fig.33.

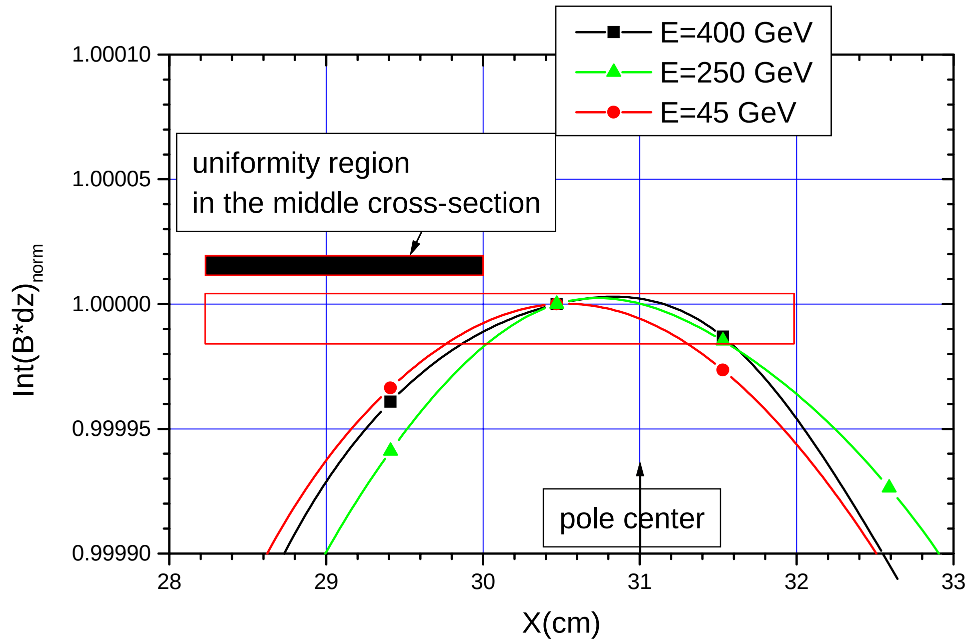

Fig.33. Longitudinal magnetic field integral (normalized)

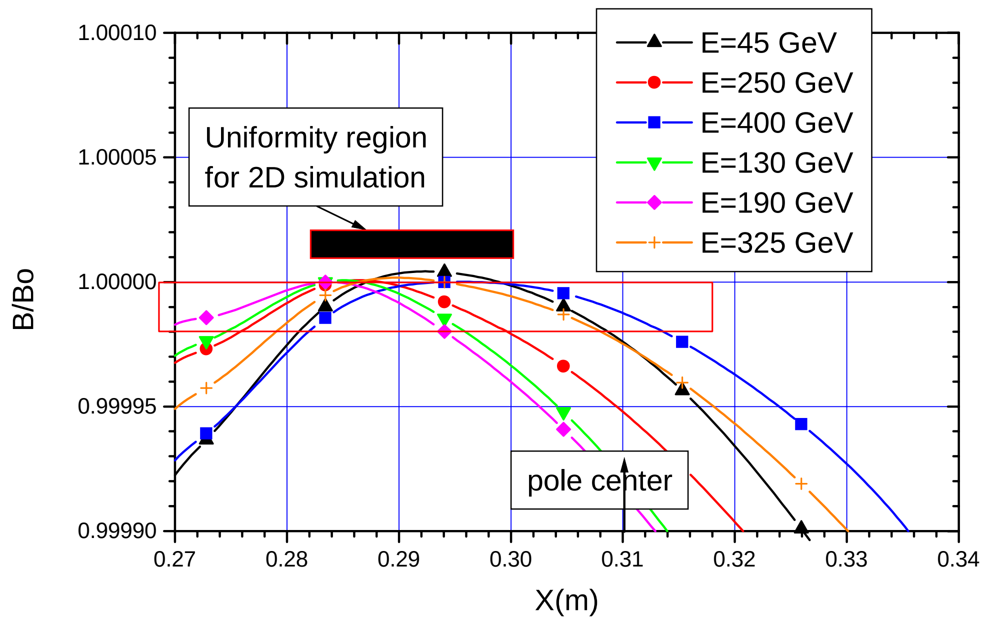

Fig.34. Normalized magnetic field in the middle cross-section of the main magnet

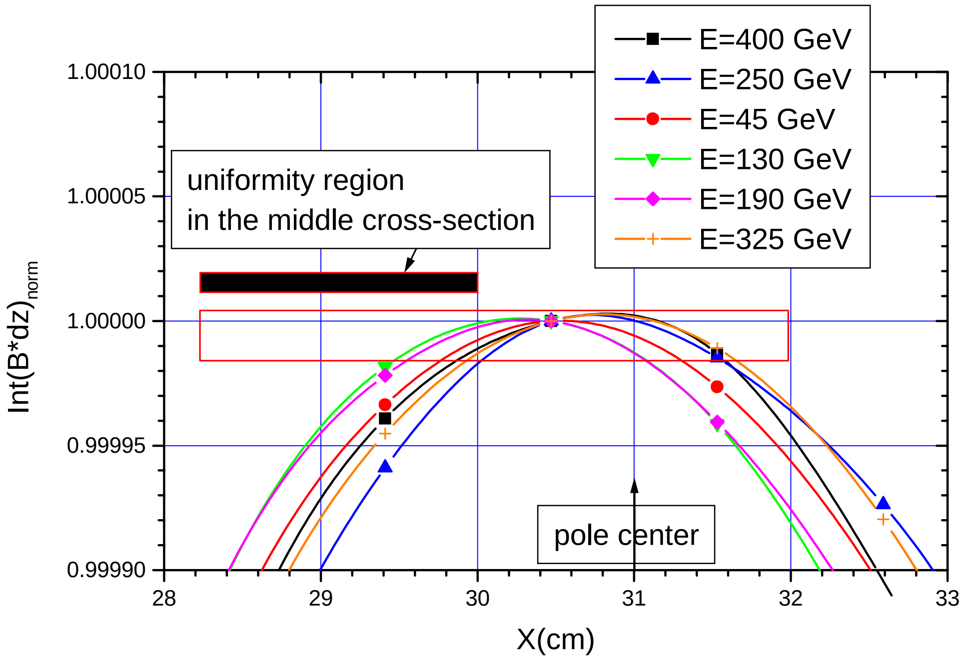

Fig.35. Longitudinal magnetic field integral (normalized)

The uniformity region (magnetic field integral) is equal to 13 mm in case of use of 3 reference beam energies for it's calculation. If to use the energies covering the whole spectrometer working region (Fig.34-35), the uniformity region is decreasing to 11 mm.

References

[1] Ricken H.J., Thimmel H.M. – Magnetic Problems in the Design of Isochronous Cyclotrons. Proc. MT-2, Oxford, 1967, p.256.
[2] Wilson N., Bunch P. – Magnetic Permeability of Stainless Steel for Use in Accelerator Beam Transport Systems. Proc of PAC-91, 1991, p.2332.
[3] Weber G., Fajans J. - Saturation in "nonmagnetic" stainless steel. Rev. of Scien. Instr. V.69, No.10, 1998, p.3695.
[4] Chavanne J., Chubar O., Elleaume P. - RADIA, a 3D Magnetostatic Computer Code. IMMW-12, ESRF, Grenoble, France, 2001.