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A Technical Proposal for the Development and Manufacturing of Electromagnets for the TESLA Main Extraction Line

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I. Introduction

The work has been made at the D.V. Efremov Scientific Research Institute of Electrophysical Apparatus (St. Petersburg, Russia) at the request of DESY (Hamburg, Germany) and is the technical proposal for development and manufacture of a number of magnets for the main extraction line of the TESLA Project (MELM).

II. Magnet system

The magnet system consists of two dipole magnets with the horizontal field, one septum-magnet, one quadrupole and two half-quadrupoles.
The main parameters are summarized in Table II.1.
All magnets are conventional resistive DC-magnets. The core of most magnets is made as steel lamination. The steel magnetization curve is shown in Fig.II.1. The magnet coils are made from square copper conductor with a water-cooled channel. The copper conductor specific resistance is no more than 17.2 mΩ/mm2/m. The coils are water cooled. A pressure drop up to 4 bar is allowed in each of the parallel cooling loop. The coil insulation will be made with vacuum impregnation.

II.1 Dipoles

All dipoles are 4 m in length. Therefore, the magnet BV2 is divided lengthwise into two parts. The iron core is C-shaped with the yoke thickened on the underside. Both magnets are with non-salient poles; the coil is one-section in BV1 and two-section in BV2 (Figs.II.2, II.3). With the chosen design the overhang of the end parts of the coil is small. Figs. II.4 – II.6 present the results of the 2D calculation of the BV1 dipole: the lines ? = const, /B/ = const and field distribution in the operation region of the magnet. The similar results for the BV2 dipoles are shown in Figs.II.7 – II.9.
When the occasion requires, the magnets can be shimmed so as to improve the distribution of the magnetic field.
The configuration of the C-type iron core facilitates the vacuum chamber installation and maintenance, as well as simplifies magnetic measurements. It makes no sense to manufacture the C-type dipoles as laminated, because it is difficult to provide the geometrical tolerances after stamping and welding.
The final decision on selecting the type of dipole iron core will be made at further design stages.
Each coil is made of a conductor with a water-cooled channel. The coils of the C-type magnets can be mounted on the iron core by slipping it through the gap, thus simplifying replacement of a damaged coil. The dipoles operate at different field strength values, as shown in Table II.1. The main parameters of the dipoles are presented in Table II.2.

II.2 Septums

The MSEP and VSEPTUM magnets are similar in design and are made as one-turn septum-magnets. The general view of the magnets and their main parameters are shown in Drawings 1? .516.810, 1? .516.819. The magnet turn consists of two parts, i.e. a thin frontal conductor and a thick slot conductor. This makes it possible to arrange the magnet in the region, where the vacuum chambers of two beams are located close to each other, to generate the necessary field on one of the beams and the minimum scattering field on the other.

The frontal conductor 5 mm thick is brazed by silver-content braze from twelve copper tubes 5× 7- ∅3 in size. Ten central holes of the conductor provide cooling water flow. Two outer holes are plugged. In their locations the conductor is fastened to clamping bars. The frontal conductor has no electric insulation and is in contact with the iron core. Sheets of the laminated iron core are cemented together by insulation compound. The clamping bars fastening the frontal conductor are made of aluminum alloy and have an oxide insulation coating.

The slot conductor is brazed from two copper tubes 23 × 41 - ∅8 mm in size. The conductor is insulated by glass tape with epoxy compound. The insulation thickness is 1.5 mm.

On one side of the magnet the frontal and slot conductors are brazed with each other to form the common water cooling path. On the other side of the magnet current and water are supplied through copper tubes, identical to those used for the slot conductor.

The iron core sheets are under potential of the frontal conductor. Therefore the magnet has a support plate insulated electrically against the iron core.

The winding turn is made as a very short cooling path. Hence, to reduce water velocity to an acceptable value it is necessary to provide a pressure difference on the winding no more than 1.5 bar. The calculations show that heating of the frontal conductor at a current density of 37 ? /m2 does not exceed 9°? .

Two design versions of the magnet are developed. In the first version (Drawing 1? .516.810) the frontal and slot conductors are divided in two in the end parts and folded in different directions. The magnet dimensions in this case are minimum.

In the second version (Drawing.1? .516.810) the end parts of the conductor are folded in one direction. The magnet dimensions are increased by 80 mm, but it becomes possible to remove the winding from the iron core and to insert the vacuum chamber with wide flanges into the magnet gap.

II.3 Quadrupole and half-quadrupoles

The major requirements for the quadrupole and half-quadrupole are given in Table II.1. The magnet system MELM contains one quadrupole in QED2 with the aperture 2?=120 mm and field on the pole Bp=1.04T and two half-quadrupoles (QED and QEF) with the radius ?=70 mm and field on the pole Bp=1.3 T. The length of each magnet is 5 m.

All magnets were simulated by the code OPERA2D[3].

Fig. II.10-12 shows the calculation model of the quadrupole QED2 and the results of its simulation. To simplify manufacturing the length of one quadrupole L=1.7 m, and QED2 consists of three such quadrupoles.

When developing the half-quadrupoles use was made of the experience in designing similar magnets for the Luminosity Upgrade [4] Project. To equalize flows in the central region of the mirror plate the iron core is thickened in the vicinity of the upper and lower coils. Fig. II.13 shows the quadrupole cross-section, and Figs..II.14 and II.15 present the simulation results. Each half-quadrupole consists of two magnets with the length L=2.5 m each. The septum size in the mirror plate is 10 mm.

The main parameters of the quadrupole magnets are given in Table II.4.

Conclusion

This work has been performed on the basis of the estimate of electromagnetic calculations and preliminary studies of the magnet construction.

Reference

[1] POISSON Group Programs User's Guide, 1975.
[2] N. Bogatov, E. Bondarchuk et al., Normal Conducting QI and QJ Quadrupoles for the ITER Luminosity Upgrade, Proc. EPAC-98, Stockholm, p.1963.
[3] OPERA 2D reference manual, VF-01-97-24, Vector Fields Limited, 24 Bankside, Kidlington, Oxford 0 x 5 IJE.
[4] E.Bondarchuk et al., Precision Septum Half-Quadrupoles for the HERA Lumi-Upgrade. MT-16, Florida, USA, 1999, p.p. 268-271.

III. Preliminary manufacturing cost estimate

The preliminary cost estimate of the magnets for the Main Extraction Line was made on assumption that all magnets will be produced by one supplier with appropriate experience and facilities. With such an approach the number of tooling sets and the cost of their production will be minimum.

This cost estimate was made by the D.V.Efremov Institute in 2000.

The following prices for the basic materials were taken for cost calculation:

· copper conductor ≈ 25 – 30 DEM/kg (depending on cross-section area);
· sheet steel for laminated yokes ≈ 2,5 DEM/kg;
· iron plates for solid yokes ≈ 2,0 DEM/kg.

In order to make into account possible complication in the final design when working out the drawings for manufacturing the need might arise to make appropriate corrections.

The results of cost calculation are presented in Table No. III.1.

Table III. 1 Preliminary cost estimation , kDEM.

Or-dinal ?	Denomination	BV1	BV2	MSEP	QED QEF	QED2
	Sketch ?	1A516820	1A516821	1A516810	1A516823	1A516818
1.	Design of manufacturing drawings.	60,0	75,0	65,0	45,0	75,0
2.	Tooling.	140,0	170,0	160,0	256,0	280,0
3.	Materials:					
3.1.	Steel for magnet yoke.	62,8	36,0	1,5	20,4	18,6
3.2.	Copper conductor.	52,8	38,3	2,0	10,5	15,8
3.3.	Insulation materials.	14,1	11,6	0,3	4,8	5,9
	Total as per point 3 :	**129,5**	**85,9**	**3,8**	**35,7**	**40,3**
4.	Production :					
4.1.	Coils .	19,5	22,5	8,5	18,4	38,5
4.2.	Yoke.	28,8	23,0	13,2	25,2	20,9
4.3.	Other details, including material.	6,8	6,5	11,5	7,4	6,9
4.4.	Magnets assembly.	7,4	7,1	5,0	7,8	8,4
	Total as per point 4 :	**62,5**	**59,1**	**31,2**	**58,8**	**74,7**
5.	**Cost of one magnet (point 3+ point 4).**	**192,0**	**145,0**	**35,0**	**94,5**	**115,0**
6.	Quantity of magnets.	1	2	11	4	3
7.	**Total cost excluding p.1 and 2.**	**192,0**	**290,0**	**385,0**	**378,0**	**345,0**
8.	**Total cost including p.1 and p. 2.**	**392,0**	**535,0**	**610,0**	**679,0**	**700,0**
9.	**TOTAL:**	**2.916,0**				

Table II. 1 Main Extraction Line Magnets Data

DIPOLE

?	Label	type	number of magnets	core length m	z from IP m	angle mrad	K m^{-2}	Aperture half X mm	Aperture half Y mm	Pole tip fields, T
1.	BV1	V Dipole	1	4	105.51	4	0	65	30	1.3342
2.	BV2	V Dipole	1	8	140.508	7.332	0	45	40	1.2228

SEPTUM

?	Label	type	number of magnets	core length m	z from IP m	angle mrad	K m^{-2}	Aperture half X mm	Aperture half Y mm	Pole tip fields, T
1.	MSEP	V Septum	1	16	55	2.1	0	40	43	0.17512

QUADRUPOLE and HALF-QUADRUPOLES

?	Label	type	number of magnets	core length m	z from IP m	angle mrad	K m^{-2}	Aperture half X mm	Aperture half Y mm	Pole tip fields, T
1.	QED	Half-quad.	1	5	92.0	0	0.013	75	75	1.3009
2.	QEF	Half-quad.	1	5	100.01	0	-0.013	75	75	-1.3009
3	QED2	Quadrupole	1	5	133.009	0	0.0013	60	60	1.0407

Table II. 2 The main parameters for the dipoles

?	Label	Air Gap mm	Core Length m	Number of magnets	Magnetic Fields T	Current A	Voltage drop V	Power Loss kW	Total weight Kg	Water Flow Rate l /min	Temperature overheating °C
1	BV1	130	4	1	1.37	3600	43.3	156	25100	68.8	33
2	BV2	90	4	2	1.23	1364	73	99.5	13700	58	35

Table II. 3 The main parameters for the septums

?	Label	Air Gap mm	Core Length m	Number of magnets	Magnetic Fields T	Current A	Voltage drop V	Power Loss kW	Total weight kg	Water Flow Rate l /min	Temperature overheating °C
1	MSEP	90	1.5	11	0.175	12000	1.5	18.4	240	12.6	21

Table II. 4 The main parameters for the quadrupole and half-quadrupole magnets

?	Label	Pole tip radius (mm)	Core Length m	Number of magnets	Pole tip fields T	Current A	Voltage drop V	Power loss kW	Total weight kg	Water Flow Rate l/min	Temperature overheating °C
1	QED (half)	75	2.5	2	1.31	986	114	112.1	5000	47	42
2	QEF (half)	75	2.5	2	1.31	986	114	112.1	5000	47	42
3	QED2	60	1.7	3	1.04	372	204	75.7	4100	31.2	41

H, [A/M]	B, [T]
0.	0.000
50.	0.028
70.	0.059
100.	0.200
200.	0.764
250.	0.940
350.	1.168
500.	1.339
800.	1.497
1000.	1.542
2500.	1.672
12000.	1.880
20000.	2.000
80000.	2.300

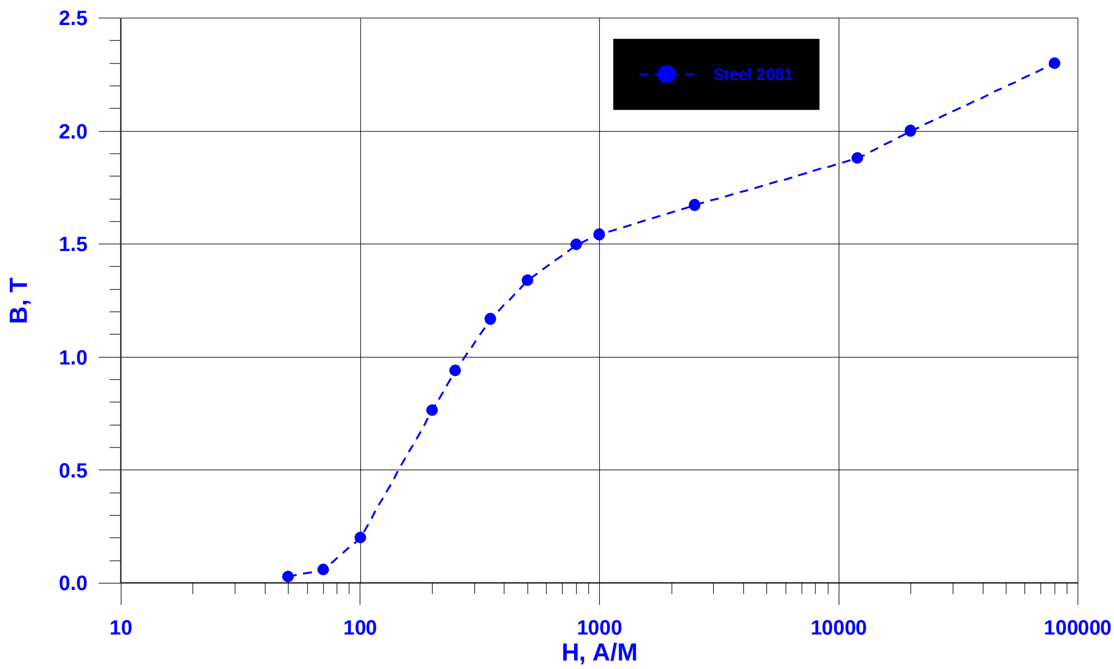

Fig. II. 1 The magnetization curve of the magnet steel 2081.

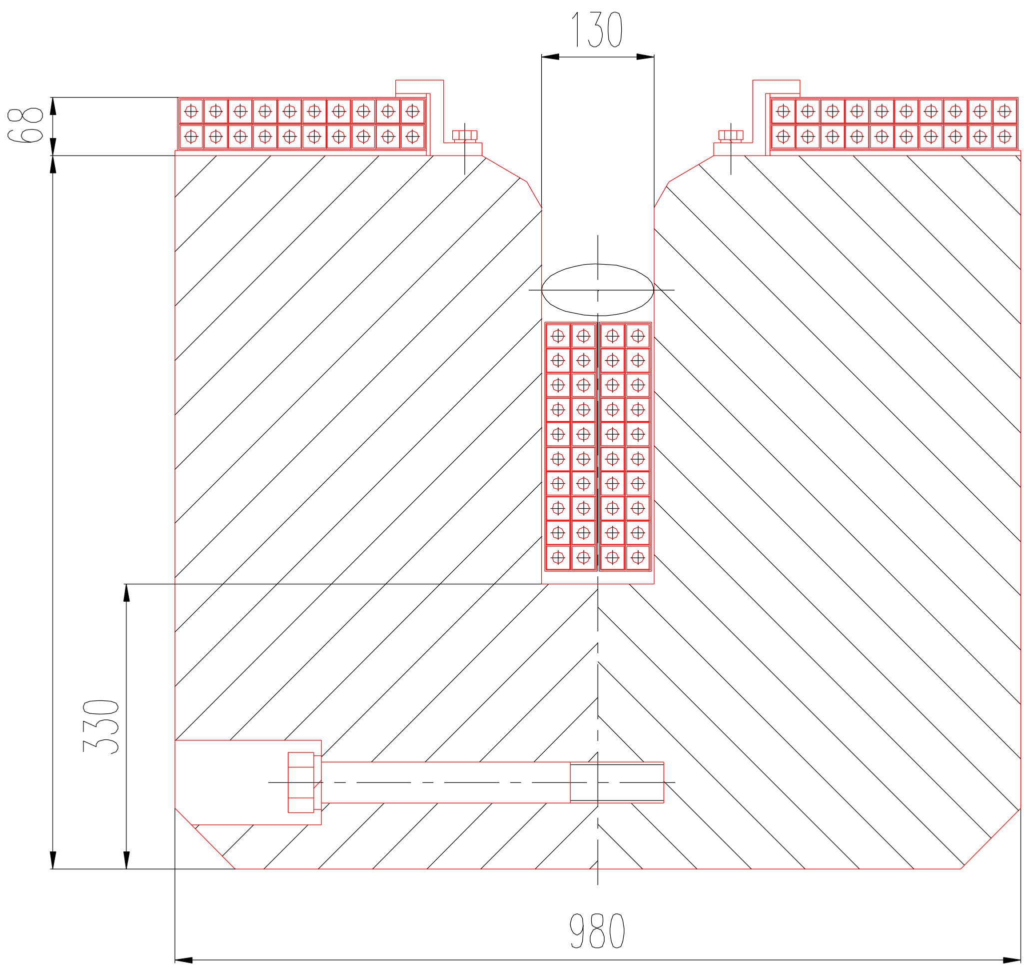

Fig. II. 2 The cross section of the dipole magnet BV1.

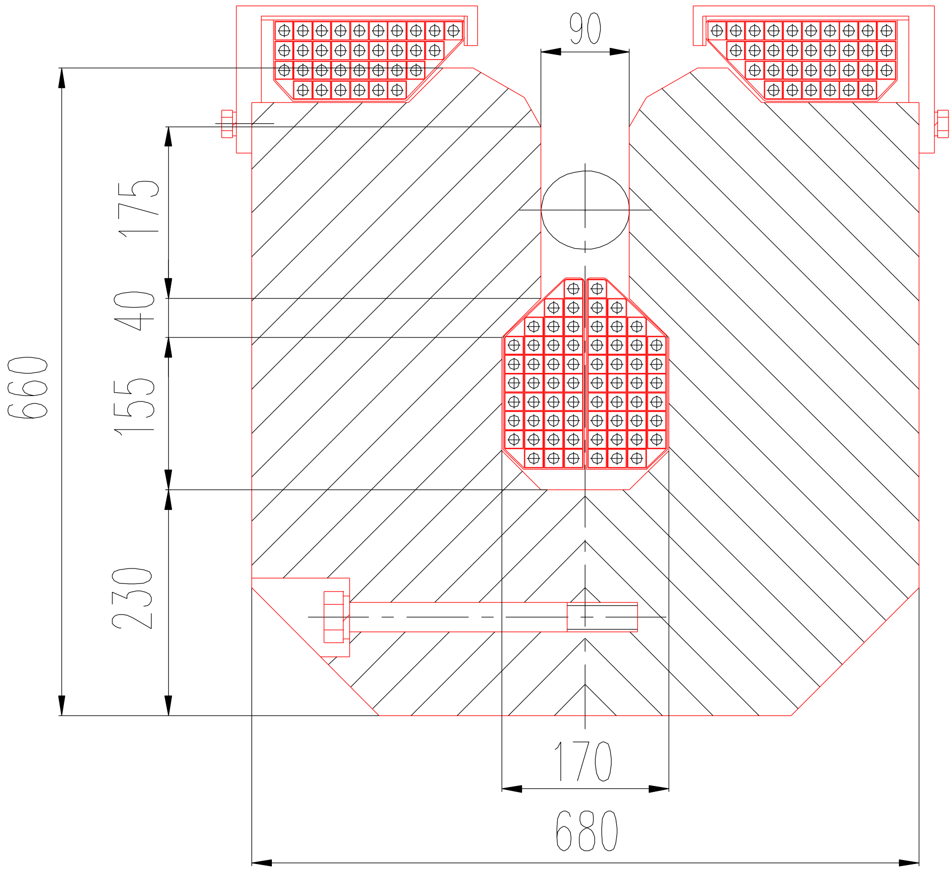

Fig. II. 3 The cross-section of the dipole magnet BV2.

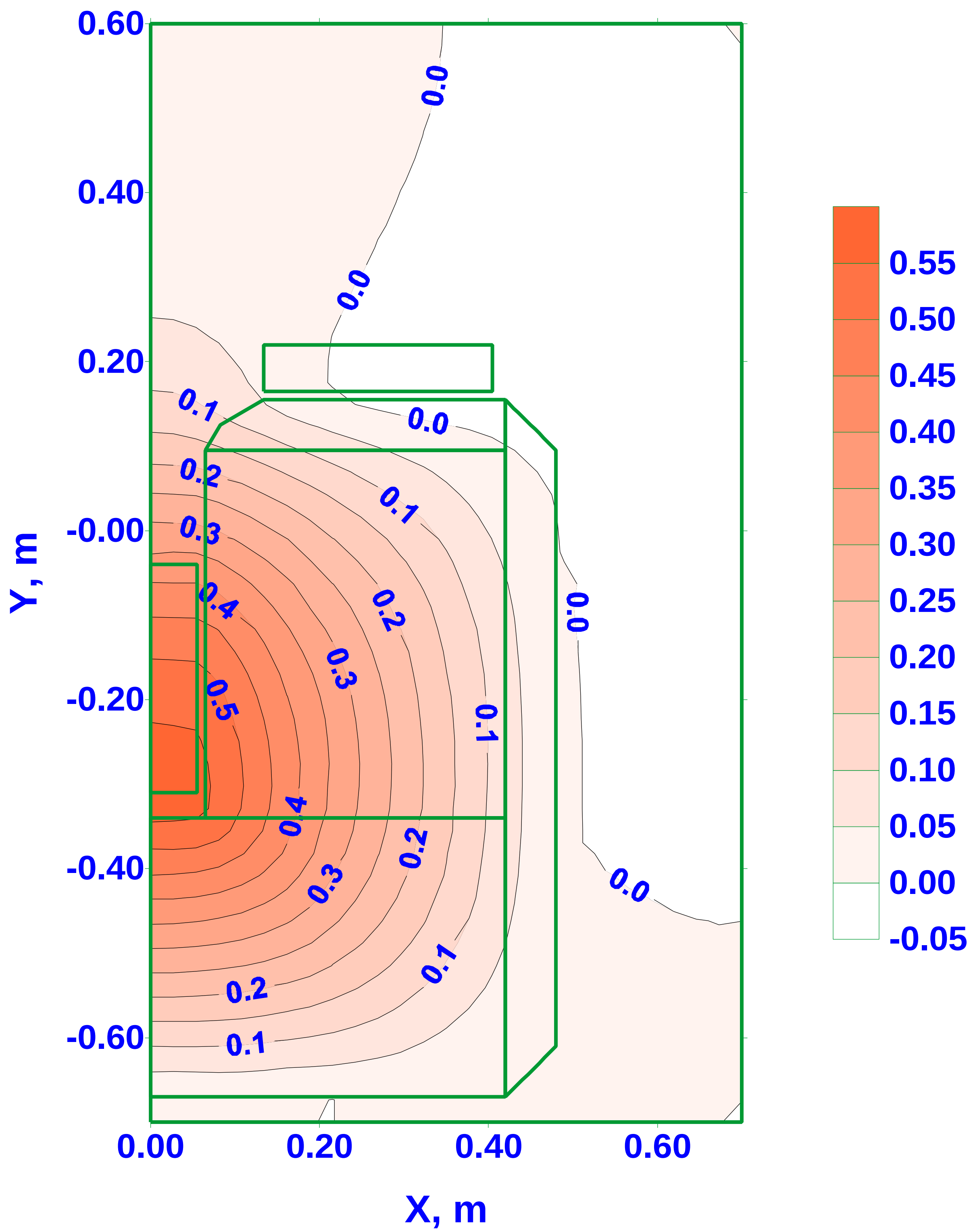

Fig. II. 4 BV1. The distribution of the magnetic potential function, [T×m].

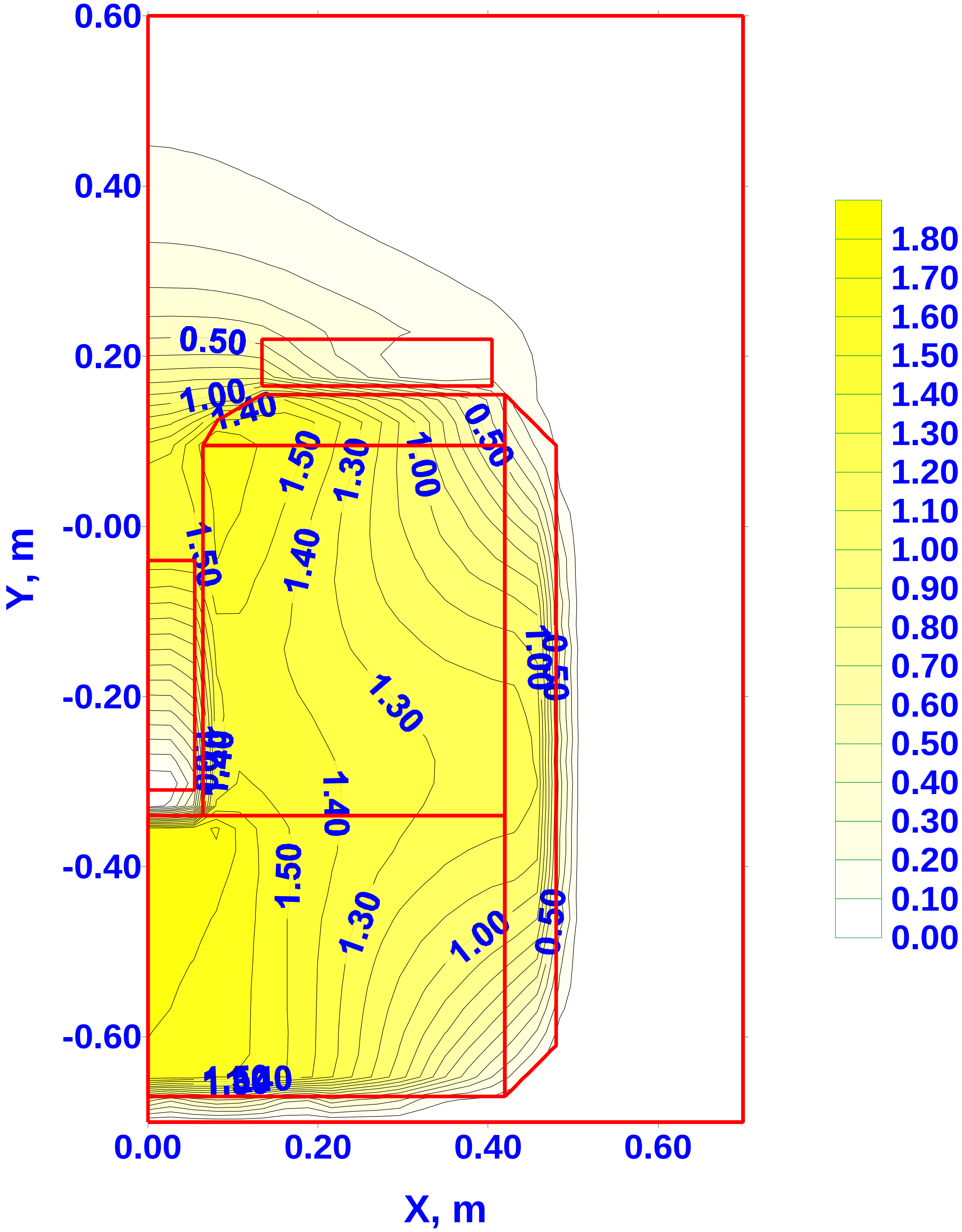

Fig. II. 5 BV1. The distribution of the magnetic flux density ½B½=const, [T].

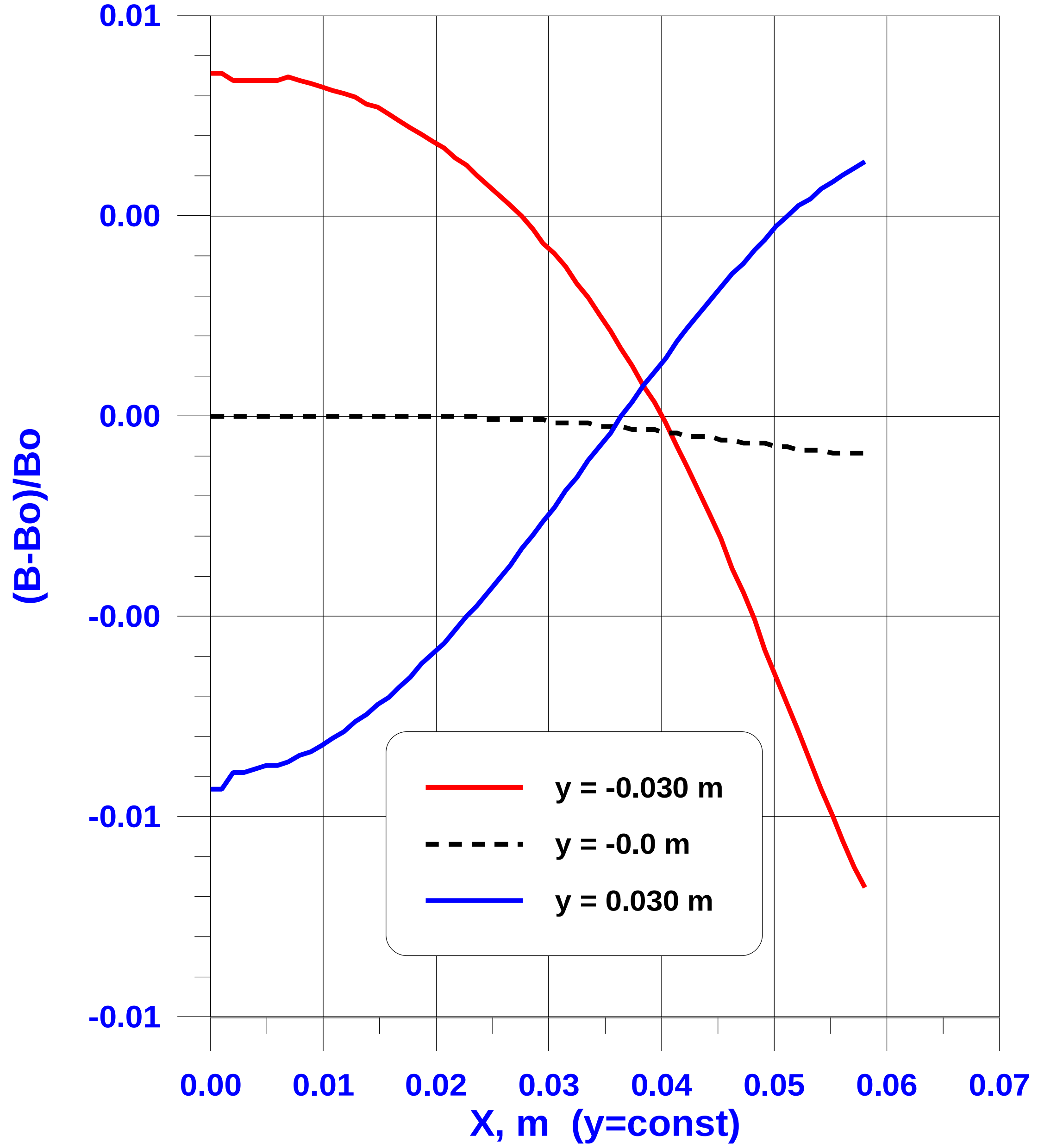

Fig. II. 6 BV1. Non- homogeneity of the magnetic flux density into the operation region.

(B - ?0) ? ?0 , ?=const

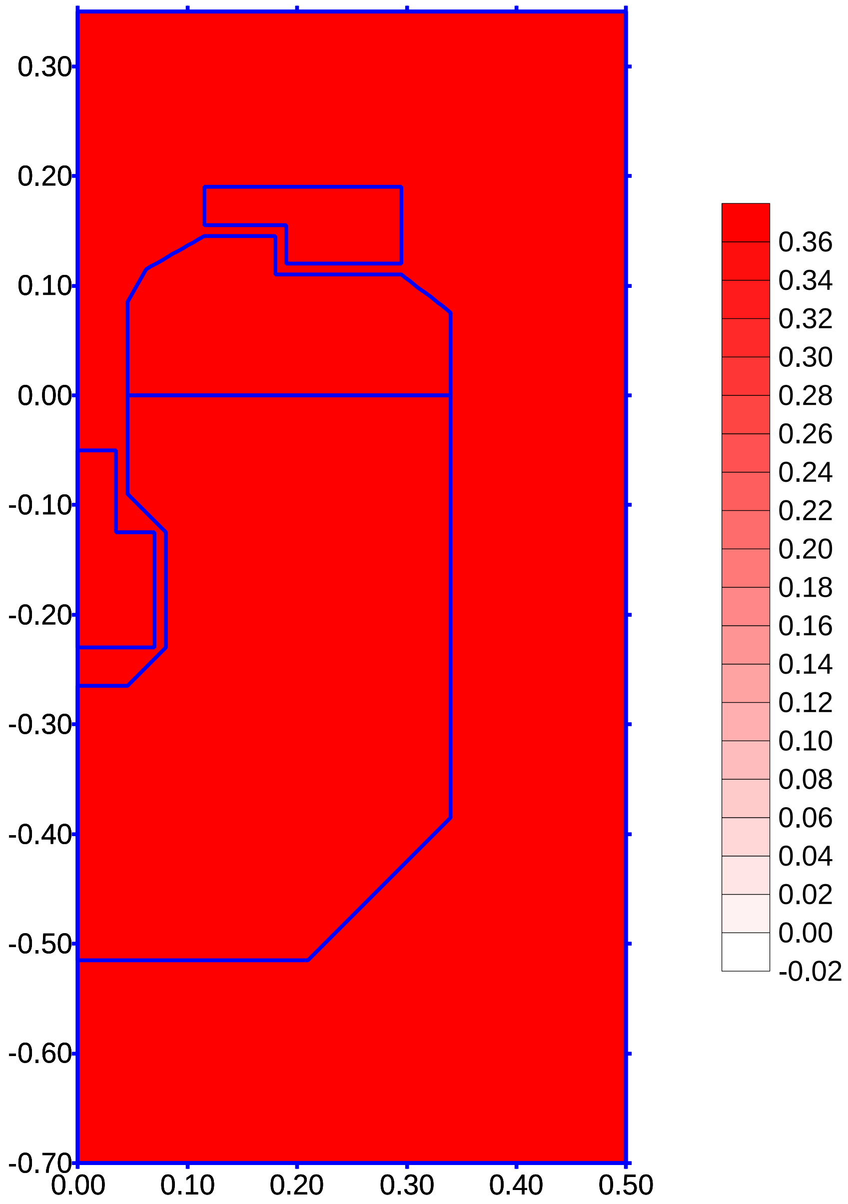

Fig. II. 7 BV2. The distribution of the magnetic potential function, [T·m].

A =const

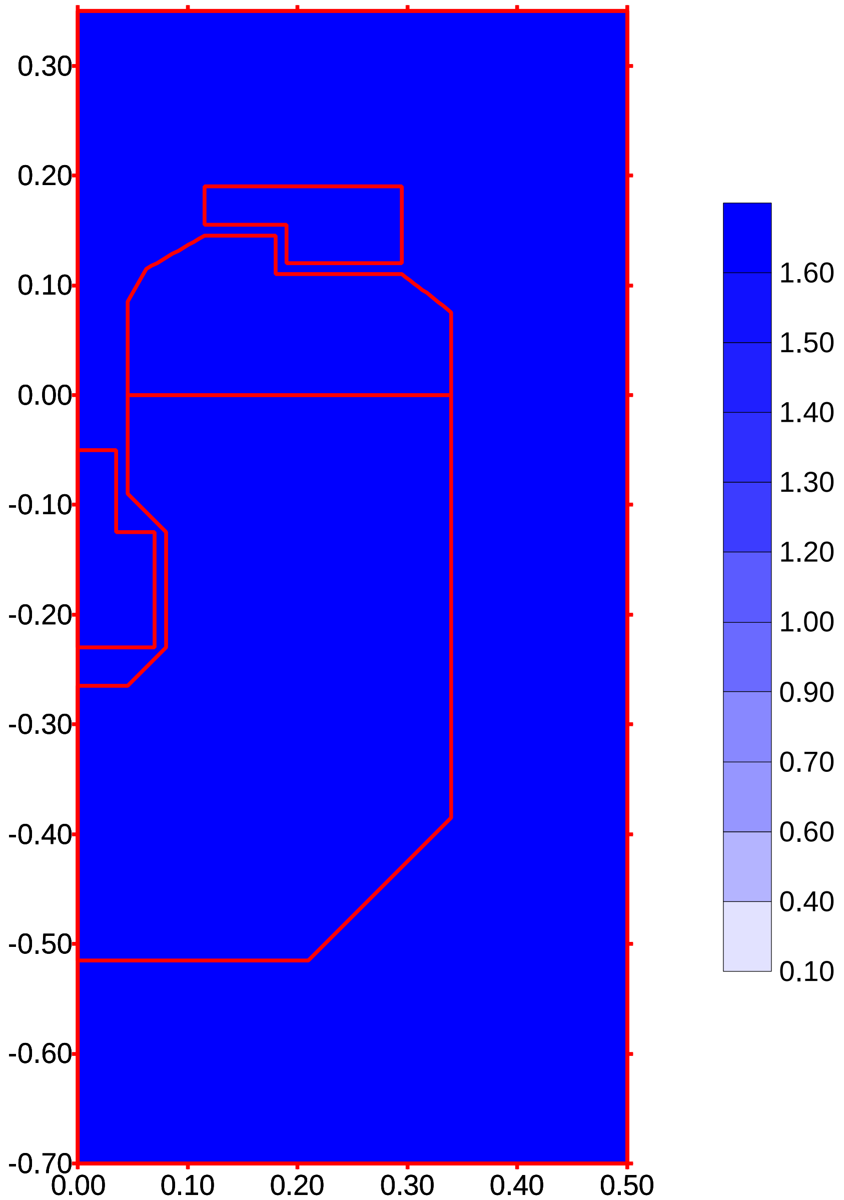

Fig. II. 8 BV2. The distribution of the magnetic flux density ½B½=const, [T].

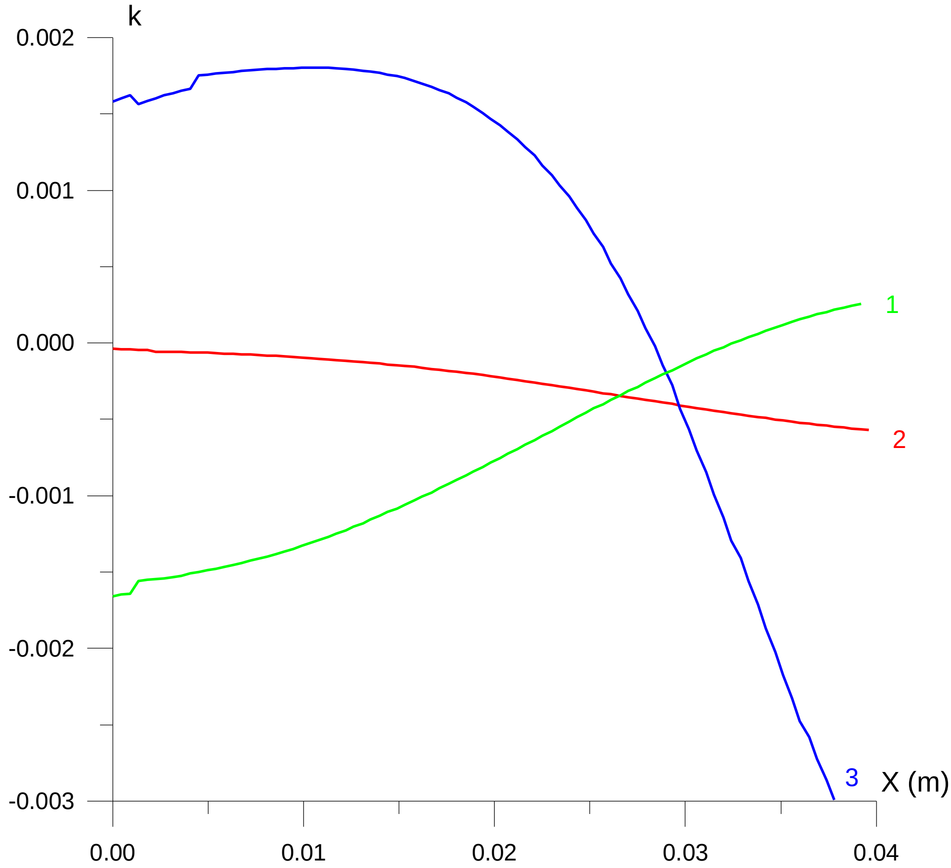

Fig. II. 9 BV2. The field distribution in the operation region. ? ?(?)½?=const

$$k = \left(B_x(x)\big|_{y=const} - B_x(0)\big|_{y=0}\right) / B_x(0)\big|_{y=0}$$

1 – y=0.04 ? ? .
2 – y=0.0
3 – y= - 0.04 ? ? .

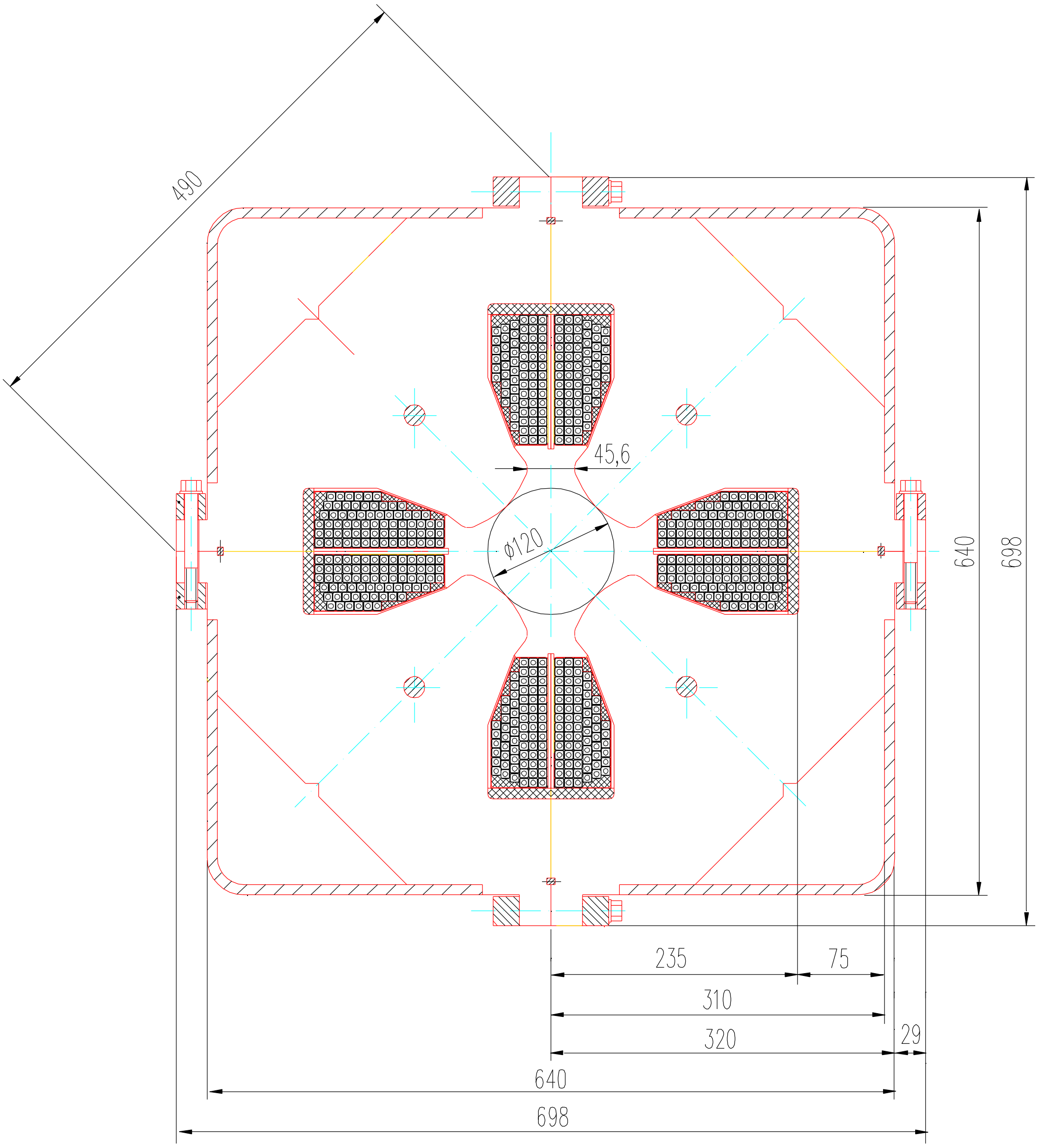

Fig. II. 10   The cross-section of the quadrupole magnet QED2 (MELM)

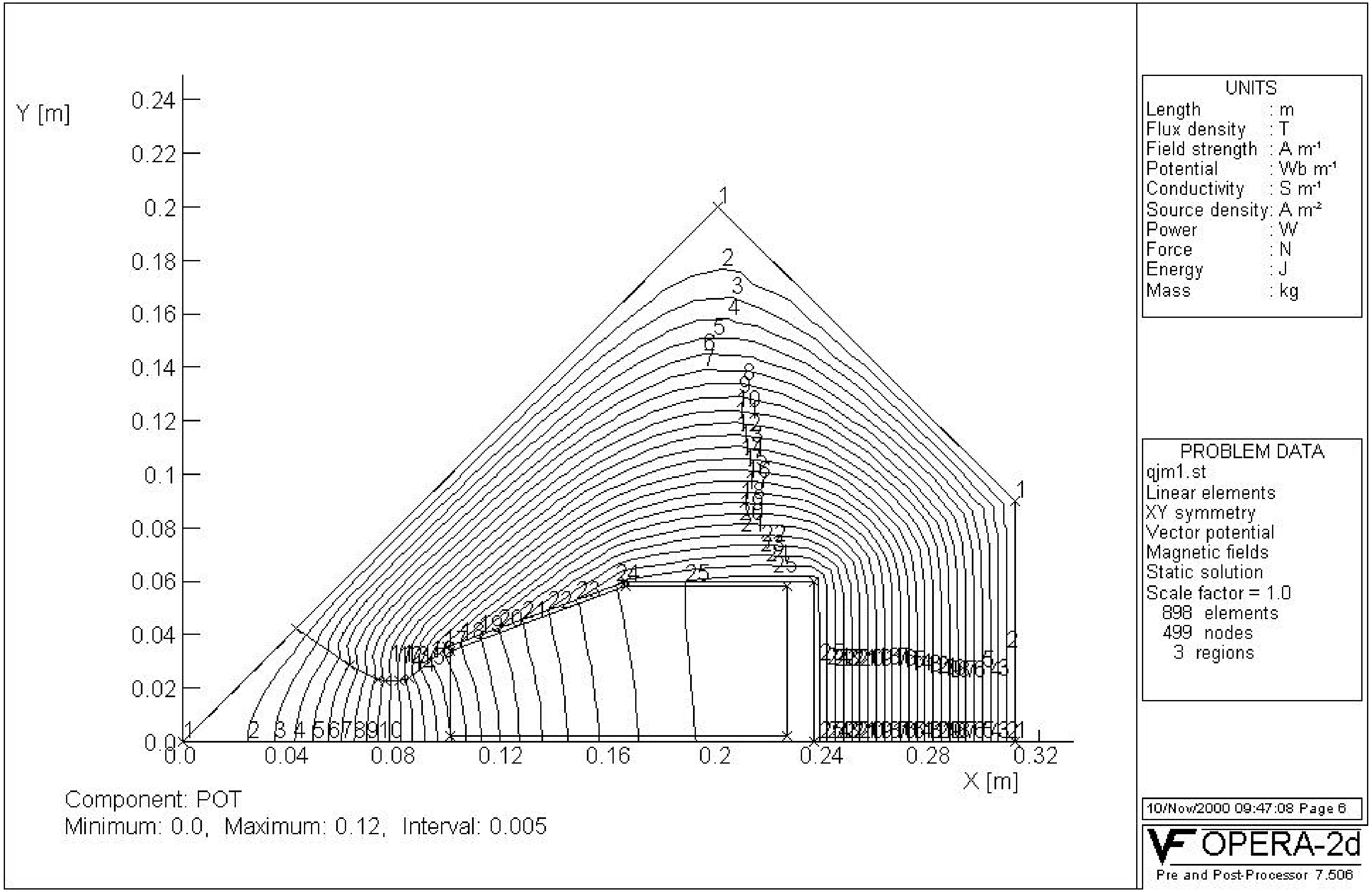

Fig. II. 11 Flux (T×m) lines pattern for QED2 quadrupole magnet (MELM)

(AW=25.645 kA, B_p=1.06T)

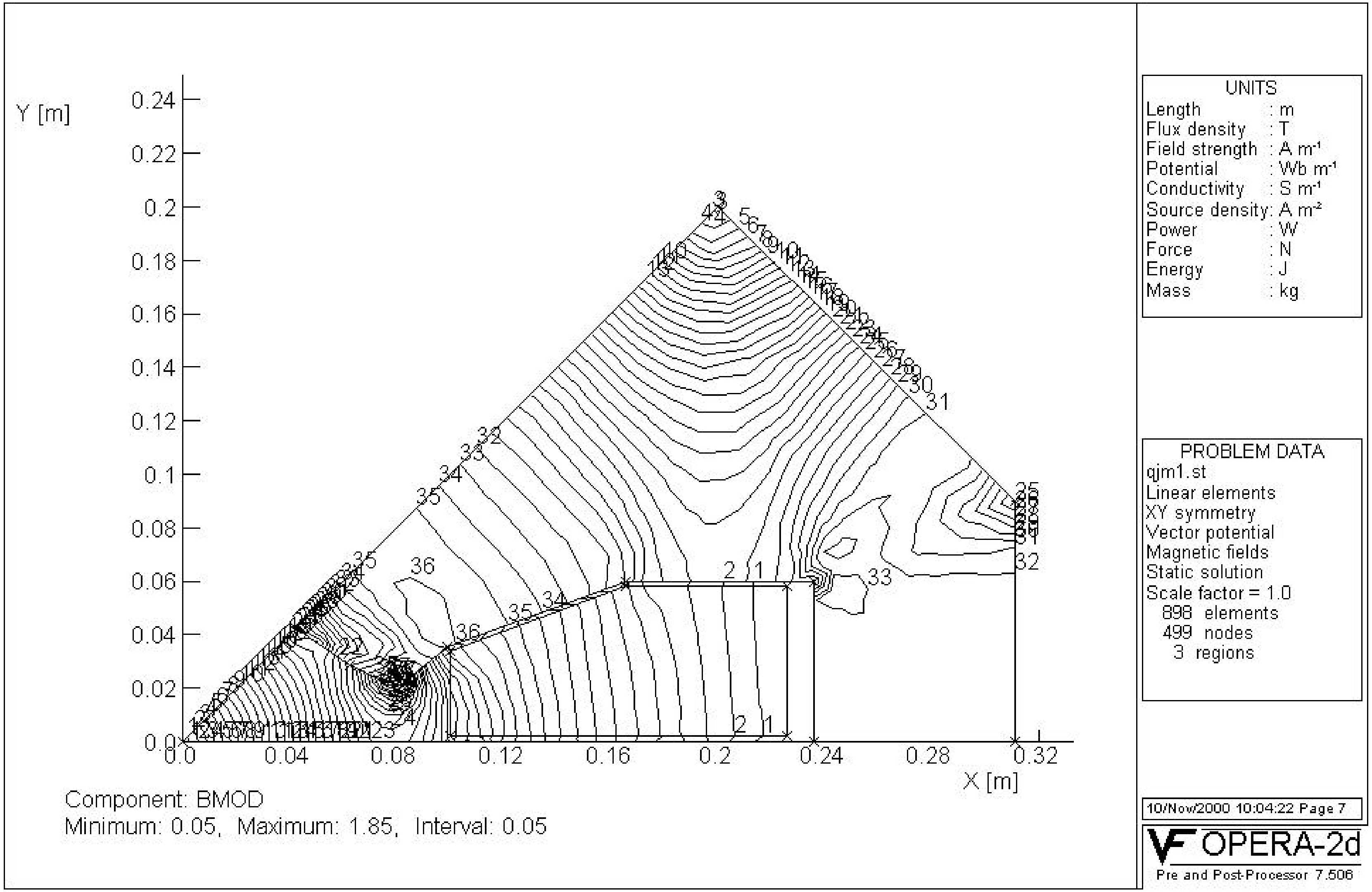

Fig. II. 12 Flux density module ½B½ lines pattern for QED2 quadrupole magnet (MELM)

(AW=25.645 kA, B_p=1.06T)

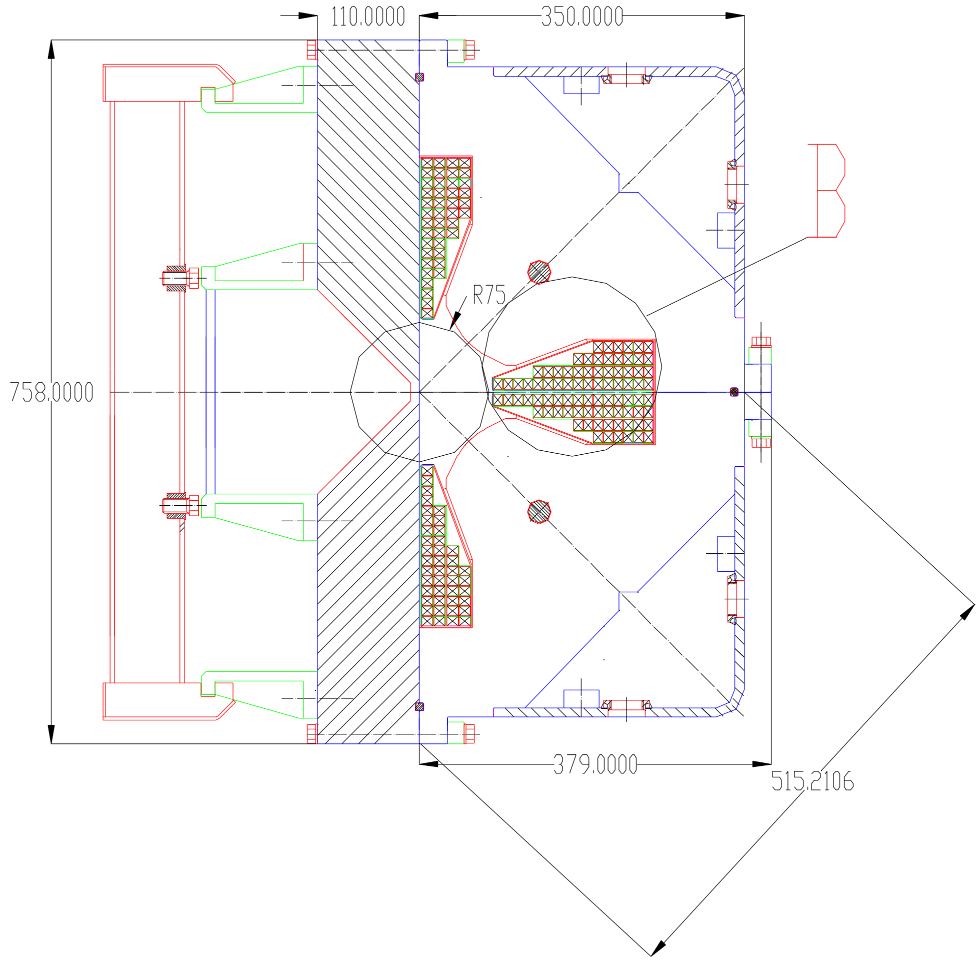

Fig. II. 13 The cross-section of the half-quadrupole magnet (QED-QEF) (MELM)

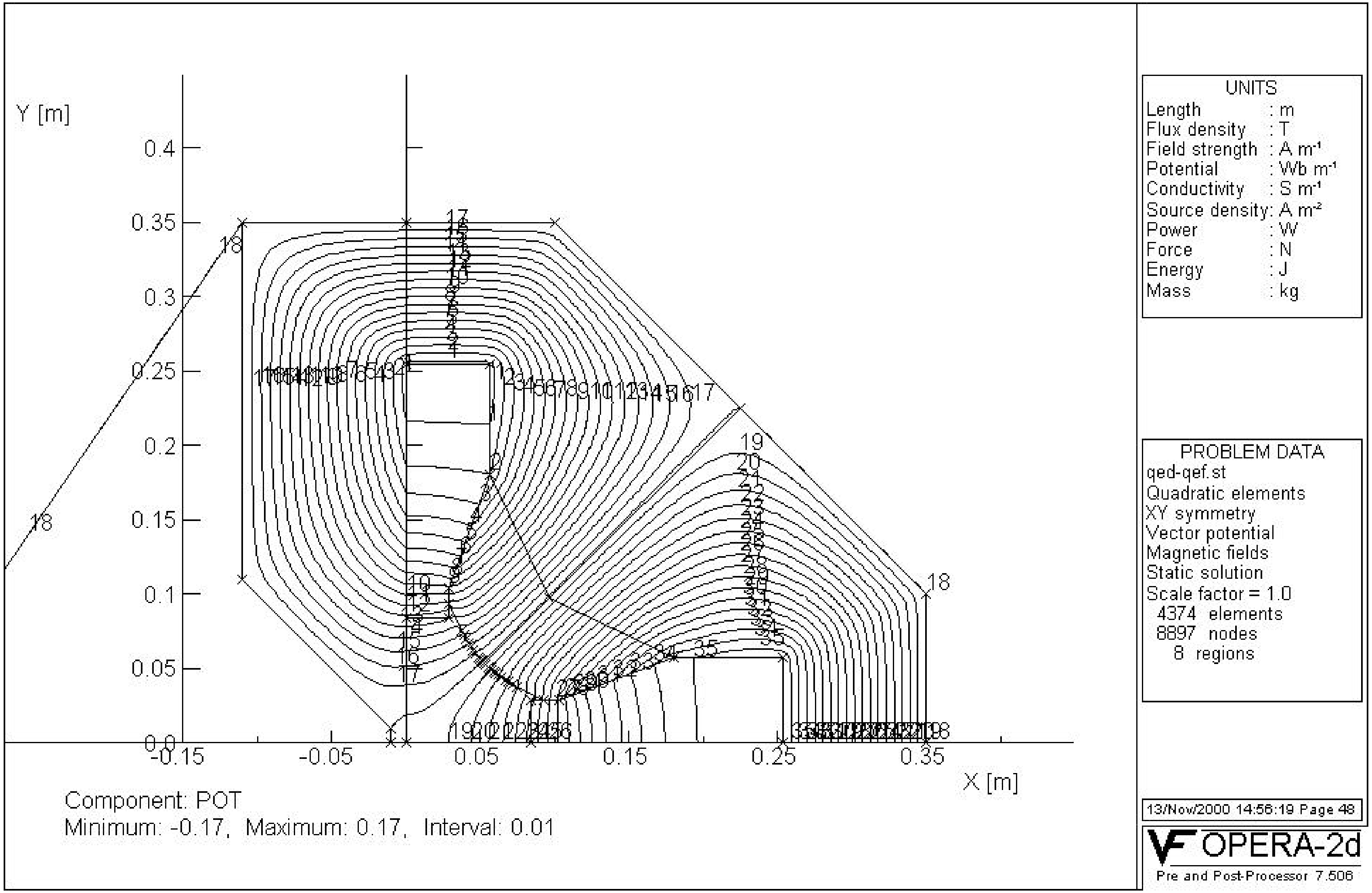

Fig. II. 14 Flux [$T\times m$] lines pattern for QED-QEF mirror quadrupole magnet (MELM)

(AW=41.413 kA, B_p=1.31T)

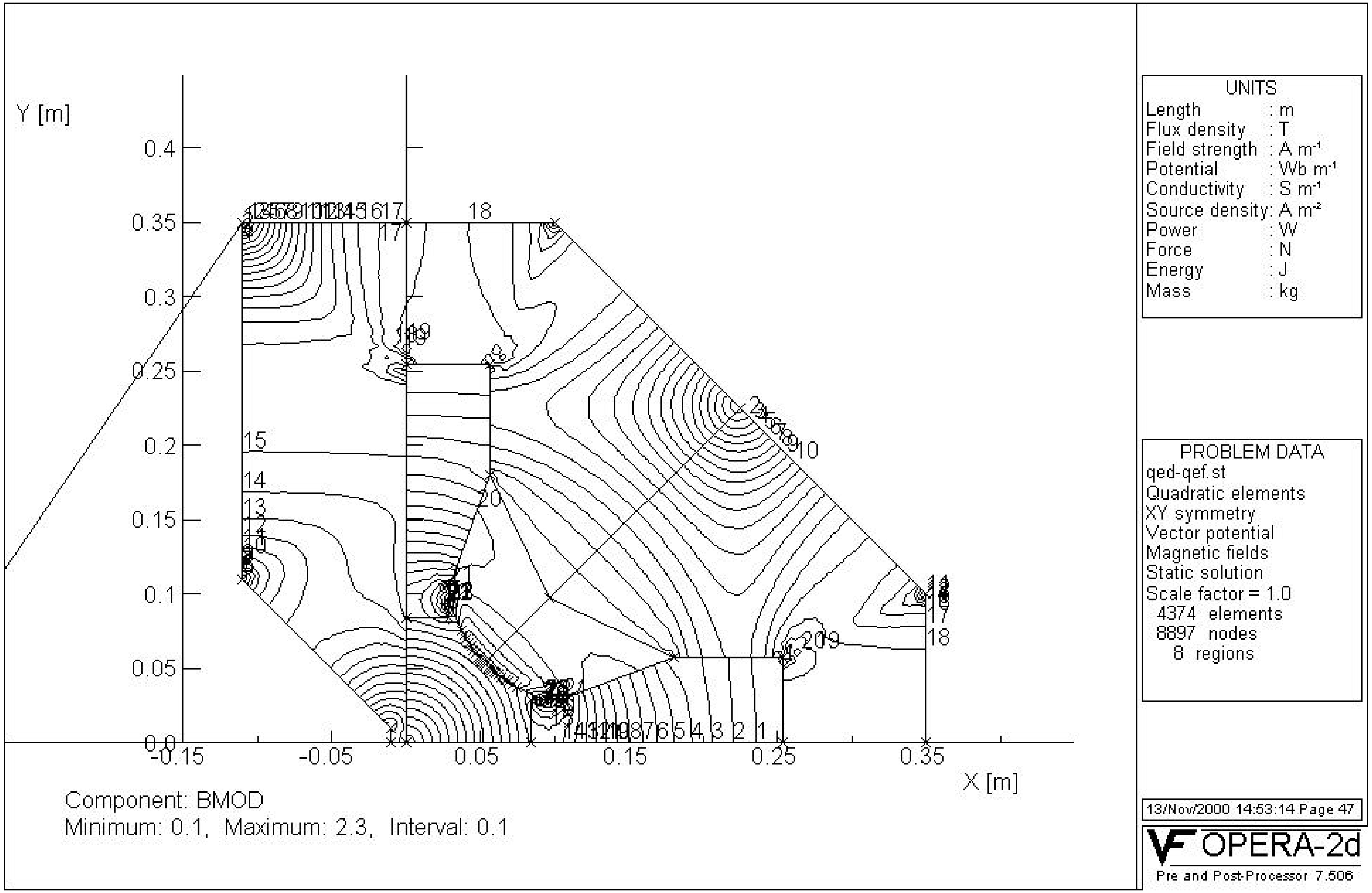

Fig. II. 15 Flux density module B, [T] lines pattern for QED-QEF mirror quadrupole magnet (MELM)

(AW=41.413 kA, Bp=1.31T)