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

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I. Introduction

The works has been undertaken at the D.V Efremov Scientific Research Institute of Electrophysical Apparatus (St. Petersburg) at the request of DESY (Hamburg, Germany).
The work concerns the technical proposal for the development and manufacturing of the magnets for the fast emergency extraction line for the TESLA Project. (FEELM).

II. Magnet system

The FEELM magnet system consists of 6 bending magnets, from which 2 of them are rated for an induction up to 0.12 ?, the rest for 0.9 -1.26 ?. Besides, the system comprises the septum-magnet with an induction of 0.75 ? and 11 quadrupole lenses with the pole tip field Bp=0.87-1.03T (Table II. 1). The magnetization curve of steel 2081 was used in the calculations (Fig. II, 1).
The problems concerning the field formation have not received special attention, but the chosen poles and pole tips provide, with the use of shims, the required field quality in the operation region. In this case taking into account the end effect and three-dimensional simulation are essential.

II.1. Dipoles

The dipoles (BENDH1, BENDH2) for 0.067 ? and 0.12 ? low fields have the operation region 20 × 20 mm2 in size and 1 m long. They are the same in design, the required induction values are provided by varying the excitation current.
Fig. II. 2 shows the sketch of this magnet.
Two dipoles for 0.9 ? induction, BENDH3 and BENDH4, and two dipoles for 1.2 ? induction, BENDV1, are divided into two modules each 4 m in length and have the same design. The operation region in these magnets is 100×100 mm2. The magnet cross-section is shown in Fig. II.3. The magnets are of ?-shaped type with a small overhang of the coil end parts.
The map of the lines ?=const is shown in Fig. II.4 and |B|= const in Fig. II.5. The field quality in the magnet operation region is shown in Fig. II.6. The numerical calculations were made by the code POISSON [1].
The main parameters of the dipoles are presented in Table II.2.

II.2. Septum – magnet

The septum-magnet (SEPTUMT) has the length L=10 m and is rated for an induction of 0.75 ?. The operation regime is steady. The septum is 20 m thick. The magnet consists of 7 similar modules 1.5 m each. The sketch of the magnet cross-section is shown in Fig. II.7.
The main parameters of the septum-magnet are presented in Table II.3.
SEPTUMT, unlike a conventional dipole, has different thickness in the frontal and slot parts of the coil. The general view of the septum and its main parameters are shown in Drawing 1?.516.850. The upper and lower coils of the septum have two turns each. The conductor is a copper tube 18.87 × 23.01 - ∅12.3 mm in size, to which one more identical tube is brazed in the slot part of the coils. The channel of this tube is plugged, the tube has no water cooling. Such a construction makes it possible to reduce by half the current density in the slot part of the coil, and hence the total energy consumption of the magnet.
To improve the cooling conditions each coil turn is made as a separate path. Pressure difference in the cooling system should be 0.5 bar so as to provide the optimal water velocity.

The cooling system allows the winding temperature to be maintained at ~5°? at a high current density in the frontal conductor (50 ? /mm2).
In order to fasten the frontal conductor the magnet slot is covered by a stainless steel strip 5 mm in thickness.
Deep within the magnet slot, behind the slot conductor, there are arranged additional correction turns closing around the upper and lower parts of the iron core. Eight turns from 10.8 × 16.3 - ∅6,6 mm copper tube let a current up to 750 ? pass.

II.3. Quadrupoles.

All 11 quadrupoles, QFOC1, QDFOC and QFOC, are of the same type, with an aperture of 100 mm and 1.5 m in length. In one of the qdrupoles the pole induction is 1.03 ? , in the rest - 0.87 ? . Transition is realized by varying the excitation current.
The lens pole profile QJ [2] from the Luminosity Upgrade Project with the same aperture and rated for about the same induction is used as an analog of the pole tip profile.
The attained field non-linearity in this lens amounts to (Δ? /B)r=25mm=10-4.
Fig. II.8 shows the magnet sketch. The map of the lines, i.e. ? =const and |B|=const for the regime ? ?=1.03? are given in Fig. II.9-10.
The main parameters of the qudrupoles are presented in Table II.4.

Conclusion

This work has been performed on the basis of 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.

III. Preliminary manufacturing cost estimate

The preliminary cost estimate of the magnets for the Fast Emergency 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 III.1.

Table III.1 Preliminary cost estimation , kDEM.

Or-dinal ?	Label	BENDH1 BENDH2	BENDH3 BENDH4 BENDV1	SEPTUMT	QFOC1 QDFOC QFOC
	Sketch ?	1A516809	1A516___	1A516850	1A516817
1.	Design of manufacturing drawings.	35,0	55,0	60,0	62,0
2.	Tooling.	65,0	170,0	110,0	304,0
3.	Materials:				
3.1.	Steel for magnet yoke.	1,2	41,2	2,9	16,9
3.2.	Copper conductor.	1,15	36,1	2,5	12,8
3.3.	Insulation materials.	0,65	12,2	2,6	6,1
	Total as per point 3 :	**3,0**	**89,5**	**8,0**	**35,8**
4.	Production :				
4.1.	Coils .	9,9	22,5	16,0	33,8
4.2.	Yoke.	7,5	23,8	8,2	21,5
4.3.	Other details, including material.	3,0	6,4	3,1	6,1
4.4.	Magnets assembly.	4,1	6,3	4,2	8,8
	Total as per point 4 :	**24,5**	**59,0**	**31,5**	**70,2**
5.	**Cost of one magnet (point 3+ point 4).**	**27,5**	**148,5**	**39,5**	**106,0**
6.	Quantity of magnets.	2	12	7	11
7.	**Total cost excluding p.1 and 2.**	**55,0**	**1782,0**	**276,5**	**1166,0**
8.	**Total cost including p.1 and p. 2.**	**155,0**	**2.007,0**	**446,5**	**1532,0**
9.	**TOTAL:**	**4.140,5**			

Table II. 1 Fast Emergency Extraction Line Magnets Data

DIPOLE

?	Label	type	Z (m)	Pole tip radius (mm)	core length (m)	bend angle (radian)	K1 (m^{-2})	Pole tip fields (Tesla)
1	BENDH1	Bend	0.90	10	1	-5.0043 e-5	0	0.06677
2	BENDH2	Bend	21.20	10	0.999997	-8.8145 e-5	0	0.11761
3	BENDH3	Bend	117.66	50	8.00001	5.4138 e-3	0	0.90290
4	BENDH4	Bend	746.84	50	7.99999	5.4053 e-3	0	0.90150
5	BENDV1	Bend	806.83	50	8.00002	7.5801 e-3	0	1.2642
6	BENDV1	Bend	815.33	50	8.00002	7.5801 e-3	0	1.2642

SEPTUM

?	Label	type	Z (m)	Pole tip radius (mm)	core length (m)	bend angle (radian)	K1 (m^{-2})	Pole tip fields (Tesla)
1	SETPUMT	Bend	63.17	50	9.99999	-5.6312 e-3	0	0.75134

Table II.1 (continued)

QUADRUPOLE

?	Label	type	Z (m)	Pole tip radius (mm)	core length (m)	bend angle (radian)	K1 (m^{-2})	Pole tip fields (Tesla)
1	QFOC1	Quadrupole	99.65	50	1.5	0.00000	0.0154997	1.03402
2	QDFOC	Quadrupole	166.91	50	1.5	0.00000	-0.0130779	0.87245
3	QFOC	Quadrupole	233.41	50	1.5	0.00000	0.0130779	0.87245
4	QDFOC	Quadrupole	299.91	50	1.5	0.00000	-0.0130779	0.87245
5	QFOC	Quadrupole	366.41	50	1.5	0.00000	0.0130779	0.87245
6	QDFOC	Quadrupole	432.91	50	1.5	0.00000	-0.0130779	0.87245
7	QFOC	Quadrupole	499.41	50	1.5	0.00000	0.0130779	0.87245
8	QDFOC	Quadrupole	565.91	50	1.5	0.00000	-0.0130779	0.87245
9	QFOC	Quadrupole	632.45	50	1.5	0.00000	0.0130779	0.87245
10	QDFOC	Quadrupole	698.91	50	1.5	0.00000	-0.0130779	0.87245
11	QFOC	Quadrupole	765.41	50	1.5	0.00000	0.0130779	0.87245

Table II. 2 The main parameters for the dipoles

?	Label	Air Gap (mm)	Core Length (M)	Number of magnets	Magnetic Fields (Tesla)	Current (A)	Voltage drop (V)	Power Loss (kW)	Total weight (kg)	Water Flow Rate (l /min)	Temperature overheating (°C)
1	BENDH1	20	1	1	0.06677	40	1.3	0.053	340	1.02	1
2	BENDH2	20	1	1	0.11761	60	2.0	0.120	340	1.02	2
3	BENDH3	100	4	2	0.90290	1297	52.1	67.5	14300	78	16
4	BENDH4	100	4	2	0.90150	1297	52.1	67.5	14300	78	16
5	BENDV1	100	4	4	1.2642	1875	80.5	151	14300	78	36

Table II. 3 The main parameters for the septum

?	Label	Air Gap (mm)	Core Length (m)	Number of magnets	Magnetic Fields (Tesla)	Current (A)	Voltage drop (V)	Power Loss (kW)	Total weight (kg)	Water Flow Rate (l /min)	Temperature overheating (°C)
1	SEPTUMT	105	1.5	7	0.75134	15750	11	173.9	800	80.7	31

Table II. 4 The main parameters for the 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	QFOC1	50	1.5	1	1.04	285.8	120	34.2	3350	33.5	15
2	QDFOC	50	1.5	5	0.88	235	104	24.4	3350	16.1	31
3	QFOC	50	1.5	5	0.88	235	104	24.4	3350	16.1	31

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

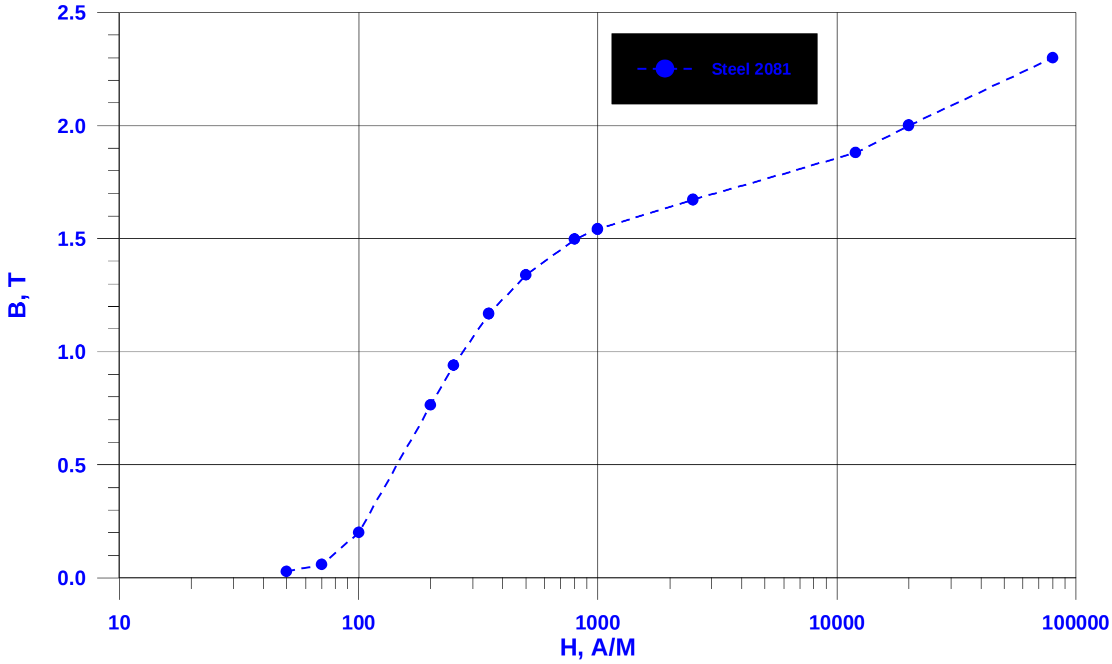

Fig. II. 1 The magnetization curve of the magnet steel.

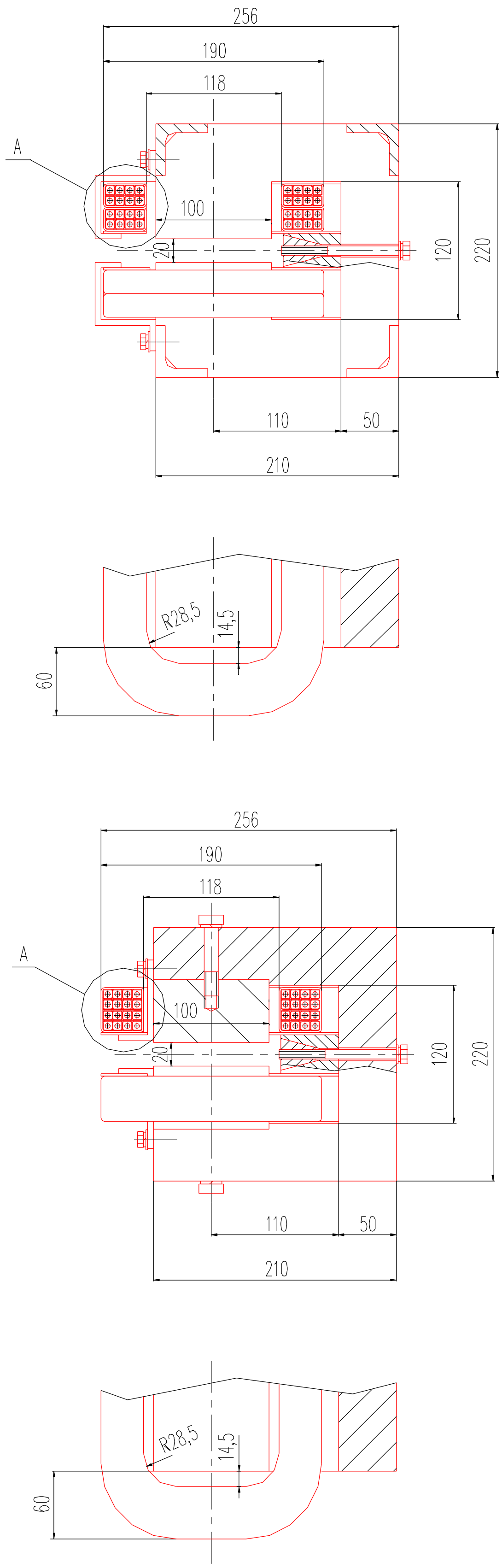

Fig. II. 2 The cross section of BENDH1 - BENDH2 magnets

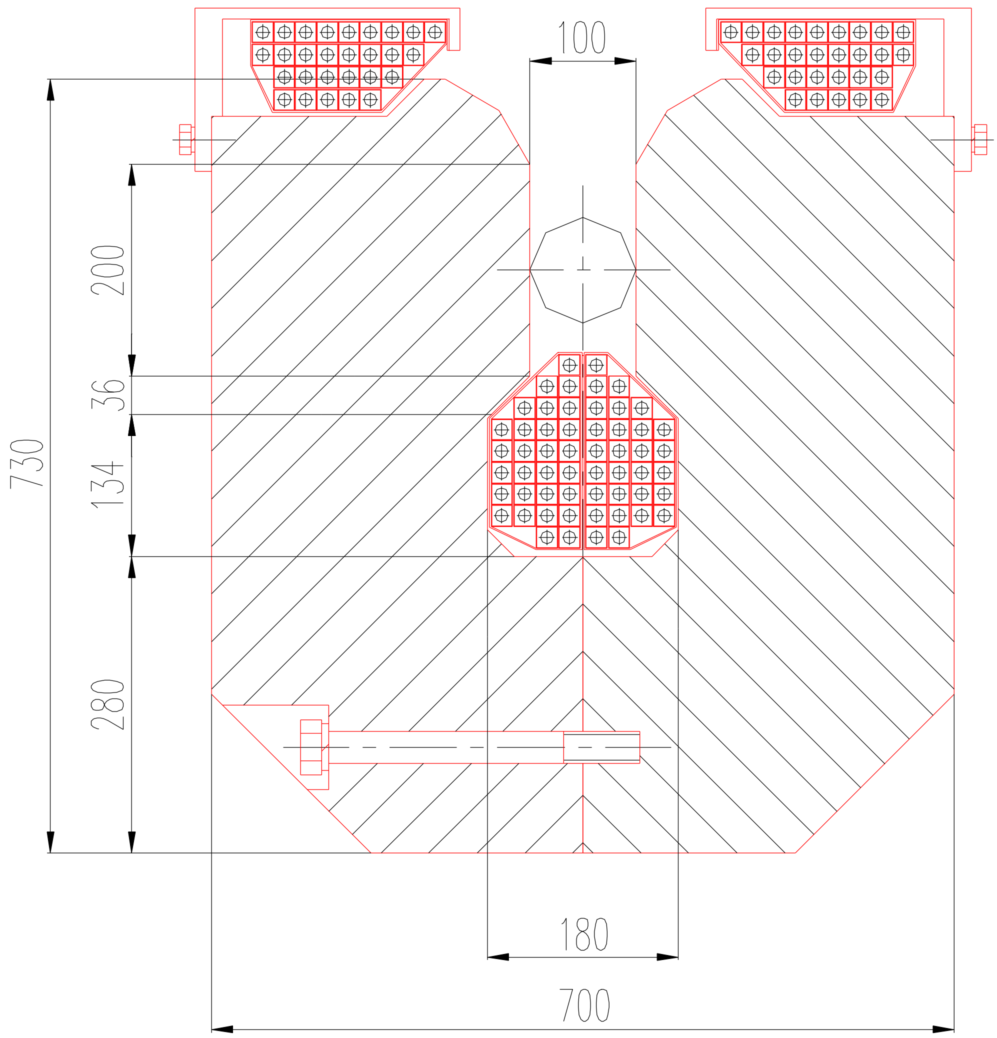

Fig. II. 3   The cross-section of BENDV1 - BENDH3 - BENDH4 magnets

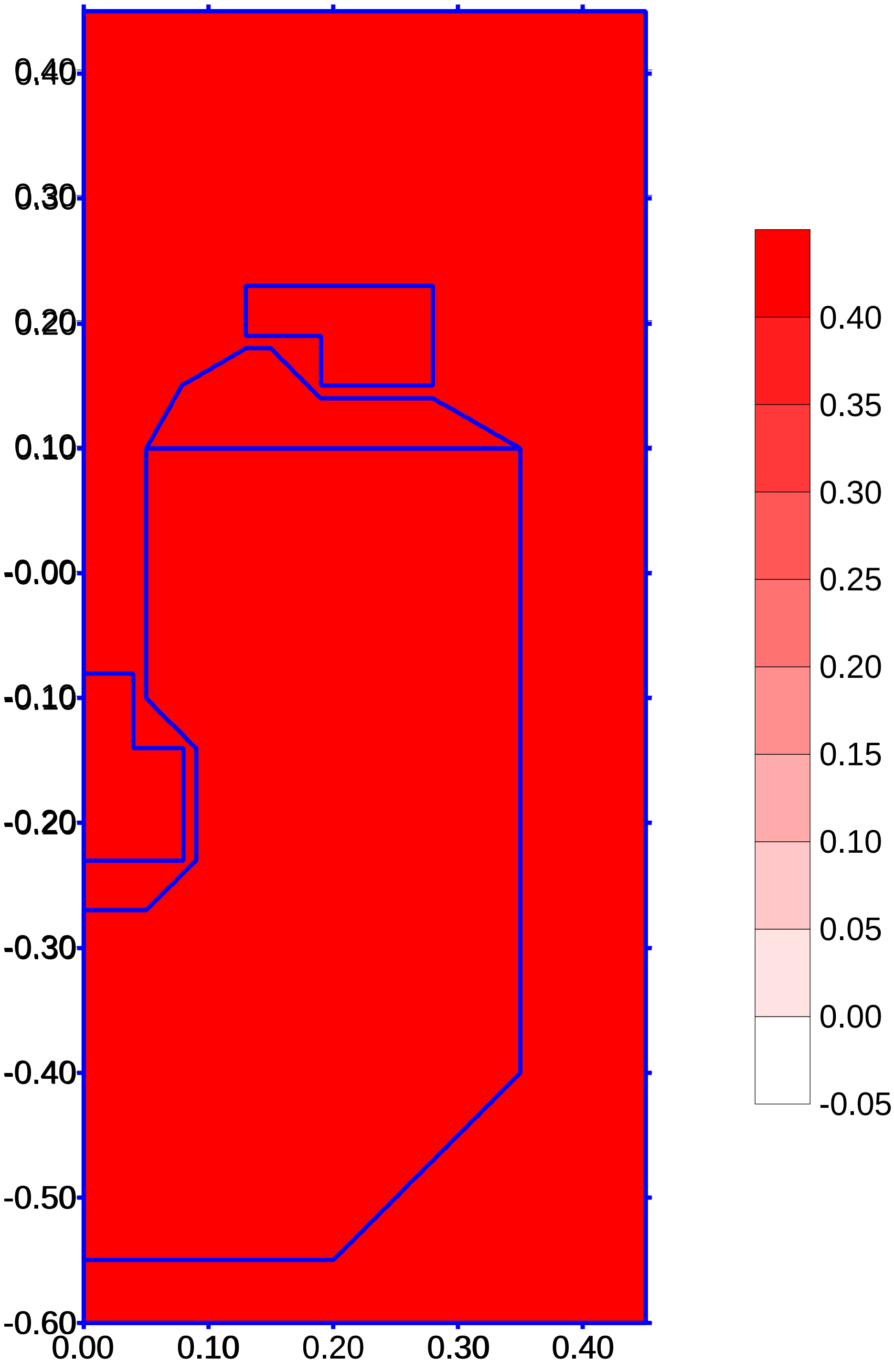

Fig. II. 4   BENDV1,H3,H4. The map of the lines A=const , [T☓m]

Aw = 52.5 kA, B = 1.27 T

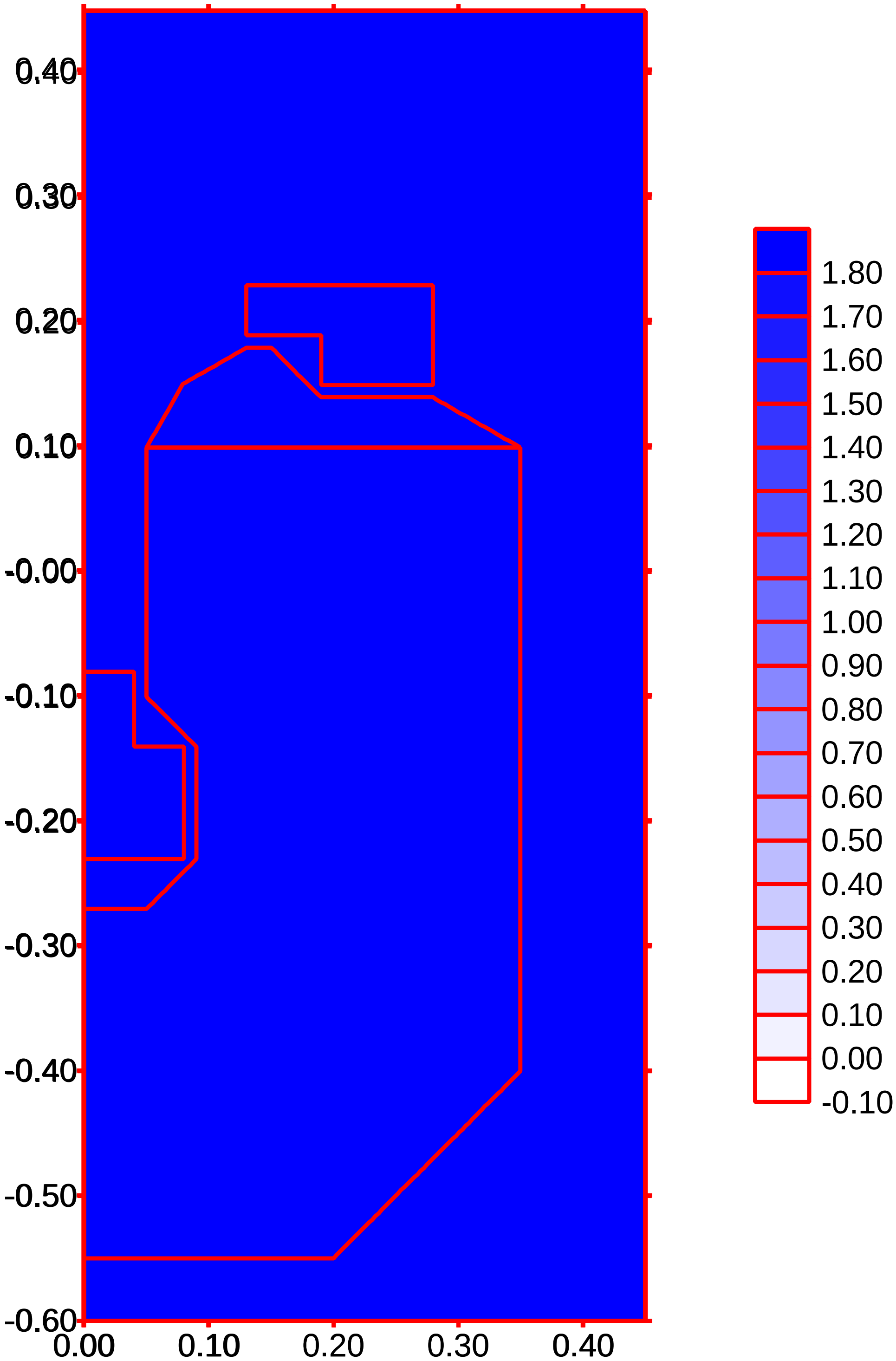

Fig. II. 5 BENDV1,H3,H4. The map of the lines ½B½ = const, [T]

Aw = 52.5 kA, B = 1.27 T

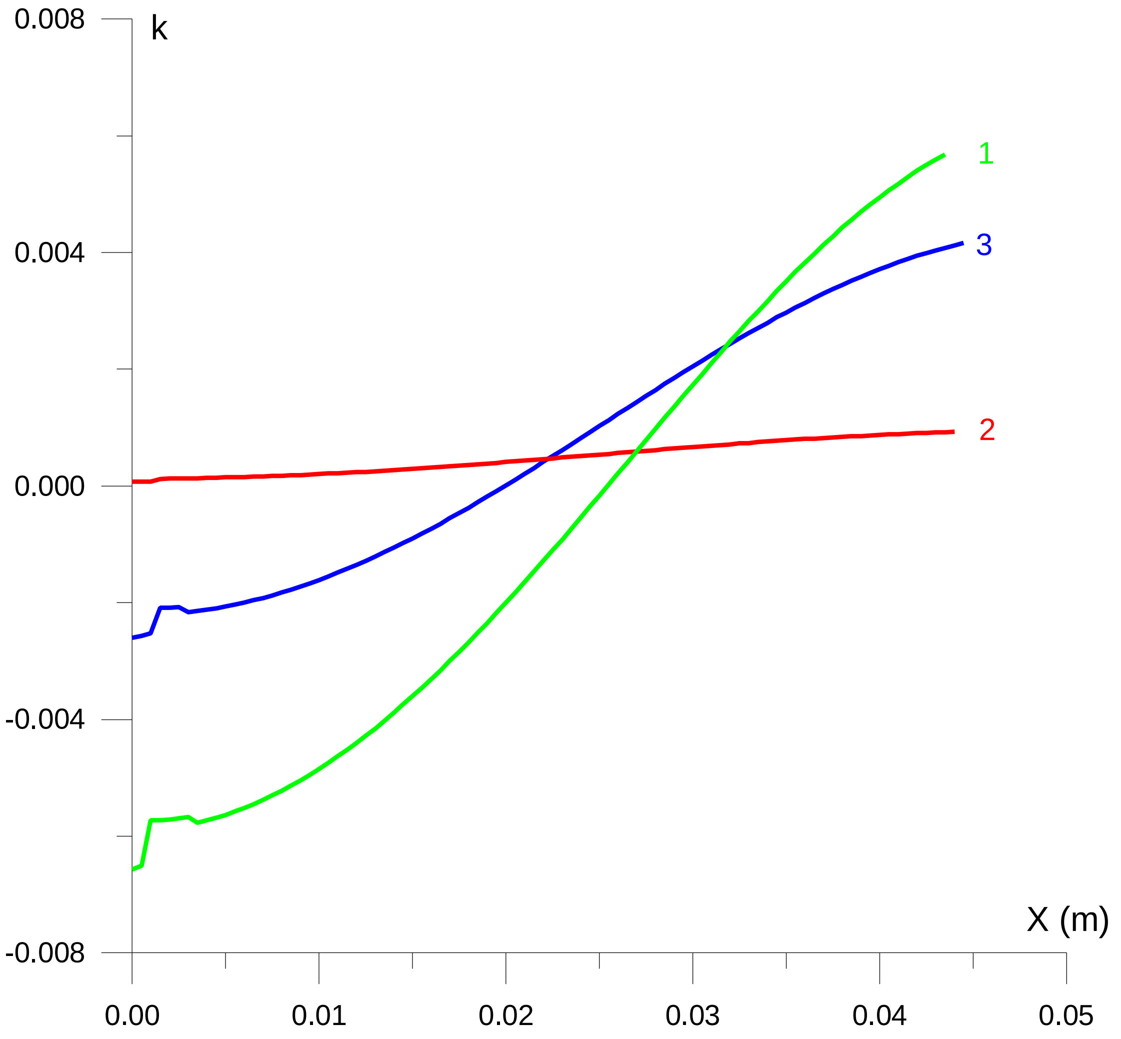

Fig. II. 6 BENDV1,H3,H4. The field distribution into operation region

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

1 – y = 0,05 m.
2 – y = 0
3 – y = -0,05 m.

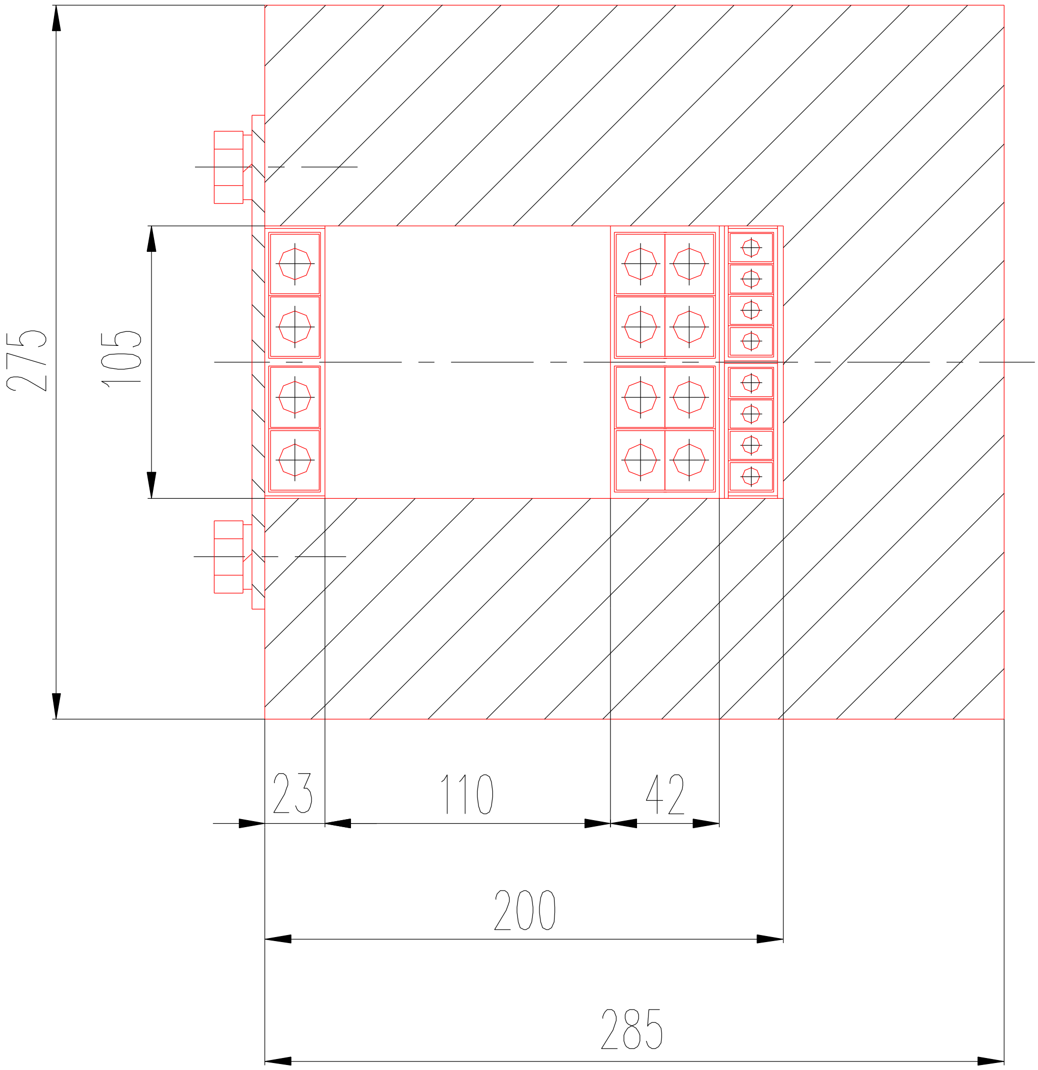

Fig. II. 7   The cross section of SEPTUMT magnet

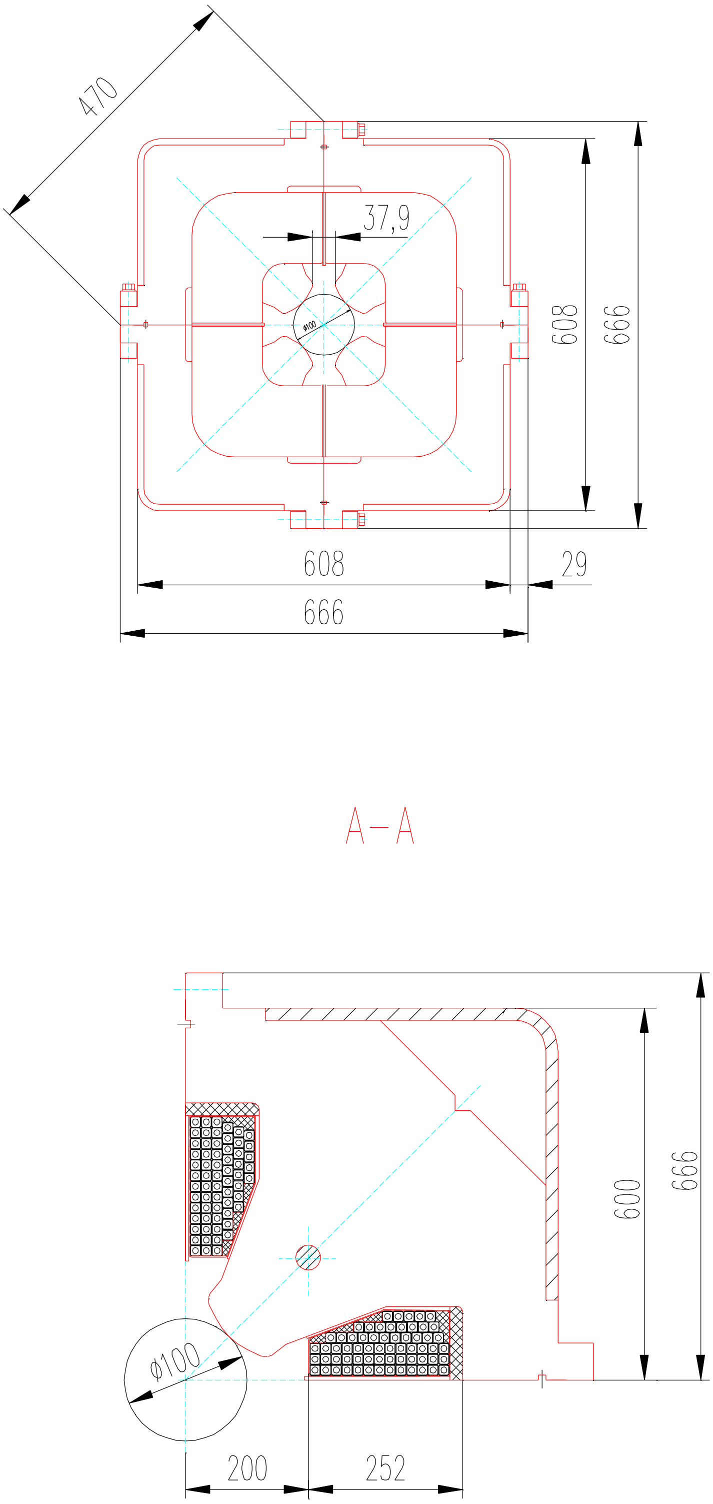

Fig. II. 8 The cross section of the QFOC1, QDFOC, QFOC quadrupoles

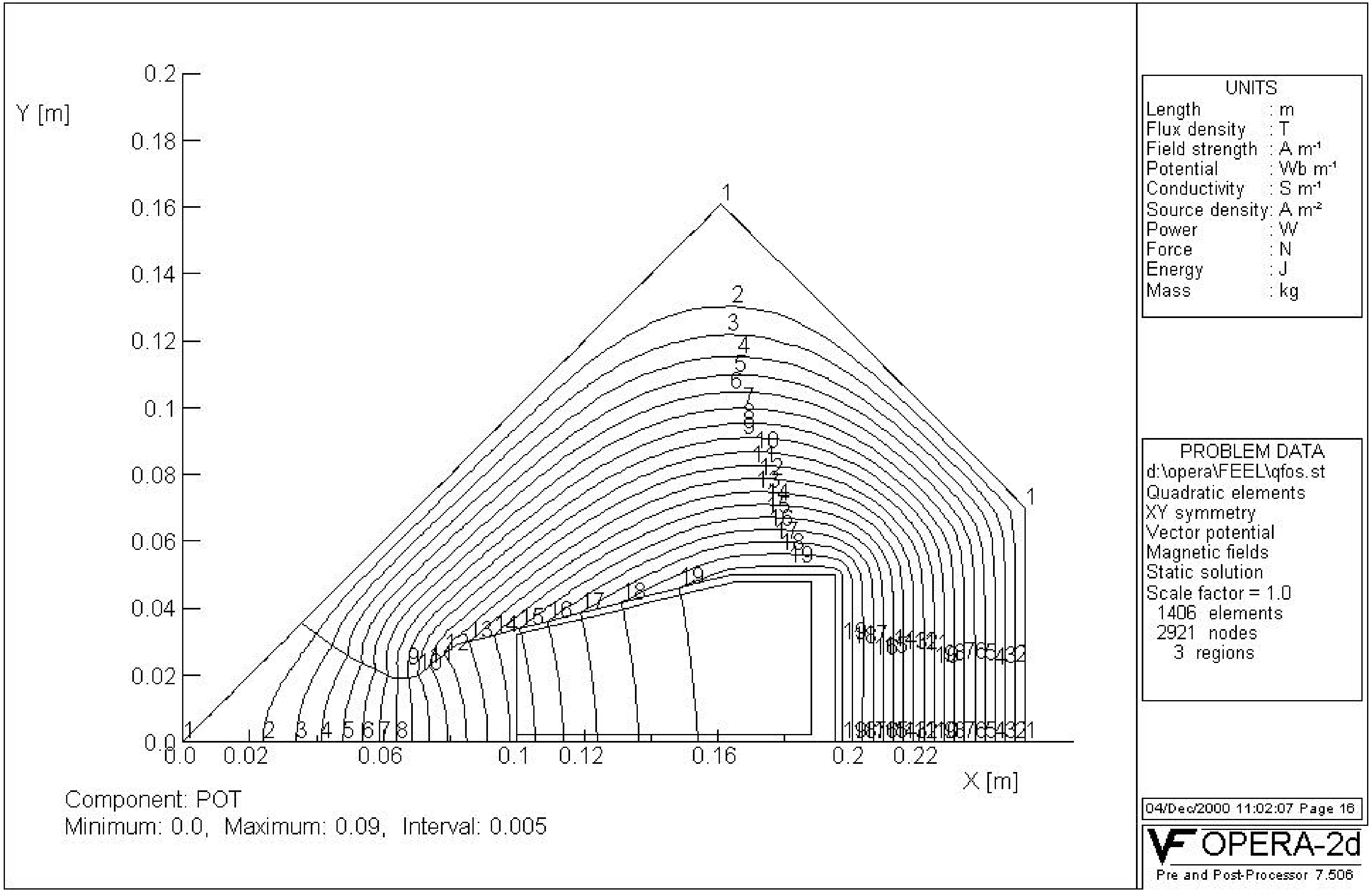

Fig. II. 9 QFOC1. The map of the lines A=const , [T×m]

Aw = 18 kA, B = 1.04 T

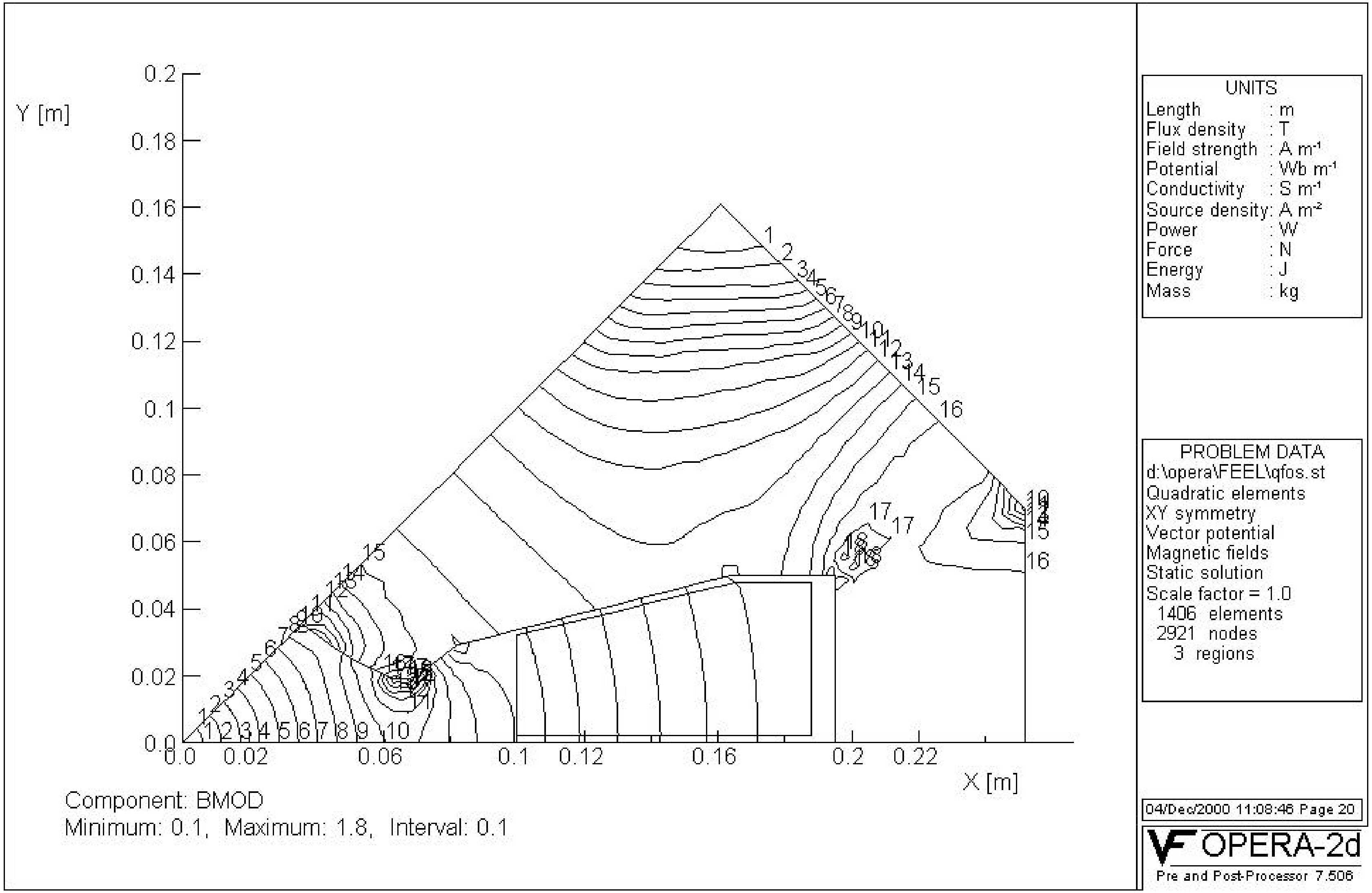

Fig. II. 10 QFOC1. The map of the lines ½B½ = const, [T]

Aw = 18 kA, B = 1.04 T