The SNS Injection Septum Magnet

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ABSTRACT
This technote presents the geometry, the magnetic field requirements, and the 2-dimensional magnetic field calculations (Ref. 1) for the DH1 injection septum magnet to be installed in the Spallation Neutron Source (SNS) accumulator ring. The magnetic field quality of the magnet, in the regions of interest, will be presented and discussed. In addition, a few modifications to the magnet will be proposed for improvement of the field quality..
The results of the magnetic field calculations of the modified versions of the magnet will be presented and compared with the magnetic field of the unmodified version of the magnet.
The version of the septum magnet that yields the best magnetic field, will also be compared to the field of the same magnet but with current carrying conductors missaligned within allowed limits.

Introduction

The SNS injection septum magnet will be installed in the injection-section of the SNS accumulator ring (Ref. 2) to deflect a proton beam of momentum p=1.7 Gev/c (Bρ=5.66 Tm) by an angle θ=0.1325 rad, from the HEBT beam transfer line into the SNS accumulator ring.
The beam parameters of the injected beam at the location of the injection septum are shown in the TABLE I below, and match those of the accumulator ring.

TABLE I		
	x-plane	y-plane
α	-1.7	1.0
β(m)	12.8	5.2
η(m)	0.26	0.0

The “rms” emittance of the injected beam at injection energy is ε_x=0.14π.mm.mrad, for the horizontal plane and ε_y=0.14π.mm.mrad for the vertical plane . These emittances in conjunction with the beam parameters dictate some of the geometrical characteristics of the septum magnet, that are presented in the following section.
The magnetic field calculations will provide information about the quality of the magnetic field in the various regions of the magnet. This information will be used to modify the magnet for field improvements which will satisfy the field requirements in the

various regions of the magnet. The field requirements ask for a field homogeneity of, $\Delta B/B_0 \sim 10^{-3}$ in the main magnet region, and low magnetic field strength, of B≤5 Gauss, in the region of the circulating beam adjacent to the septum magnet.

Magnet Geometry and field requirements

The geometry of the injection septum magnet and the field requirements are presented in TABLE II in conjunction with the figures 1a and 1b which show the magnet cross section in two different scales.

TABLE II									
B (kG)	L (m)	L_{eff} (m)	θ_{bend} (rad)	Coil turns	I (A)	R (Ωhms)	P (kW)	V_Gap (cm)	H_Gap (cm)
3.0	2.5	?	0.1325	4	1912	0.005	17.0	3.2	8.0

The components of the septum magnet (coils, iron yolk, and beam pipe) which affect the magnetic field, are shown in Figure 1a which is the cross section of the septum magnet. The dimensions of the magnet iron are big enough for the iron to be well below magnetic saturation at the nominal magnetic field (3.0 kGauss) of the magnet.
A detailed view of the septum region of the magnet, is shown in Fig. 1b. This figure shows in more detail the relative location of the coils and the beam pipe with respect to the yolk of the magnet. The coils at the septum region have dimensions (h=7mm,w=6.5mm) and are separated by 0.8 mm from each other and the magnetic poles of the magnet. A cooling channel of 3.17 mm in diameter is in the center of each conductor. The coils at the "return current region", (see Fig. 1a) have dimensions (h=7mm,w=12mm) with a cooling channel 5.0 mm in diameter. The flat section of the beam pipe of the circulating beam (see Fig. 1b) is located 0.5 mm away from the vertical surface of the magnet.
The thickness of the septum (see Fig. 1b) is defined as the distance from the surface of the inner wall of the circulating beam pipe (closer to the coil of the septum region), to the surface of the inner wall of the magnet chamber[1] (which is closer to the coil of the septum region). This distance is ~11.0 mm.
The magnetic field homogeneity in the main field region should be $\Delta B/B_0 \sim 10^{-3}$, and the maximum strength of the magnetic field at the region of the circulating beam, should be ≤5 Gauss.

[1] The magnet chamber does not show in Fig. 1b because it is made of non-magnetic material.

Magnetic Field Calculations

The 2-dimentional magnetic field calculations were all performed using the computer code opera2d of VECTOR FIELDS (1). In order to examine the field quality that the septum magnet generates, and also evaluate the effect of some modifications of the magnet for field improvement purposes, the following cases were studied:

a) The beam pipe for the circulating beam is non-magnetic. The coils in the septum region and in the "return current region" are positioned without misalignments. The yolk of the magnet is characterized by the magnetization curve which is shown in Fig. 2.[2] .

b) Same as in case (a) but beam pipe for the circulating beam is made of magnetic material. This case studies the effect of a ferromagnetic beam pipe on the magnetic field of the septum magnet.

c) Same as in case (b) but the separation distance between the flat part of the beam pipe (see Fig. 1b) and the from surface of the magnet has been reduced from 0.50 mm down to 0.25 mm.

d) Same as in case (b) but with the coils at the septum region misaligned as shown in Fig. 1c. This case studies the effect on the field due to an arbitrary coil misalignment.[3] The misalignment of each coil is given in the TABLE III.

e) Same as in case (a) but with current imbalance between the total current in the septum region and the total current in the "return region". Such current imbalance has a big effect on the field at the circulating beam region, with minimal effect on the main field of the septum magnet.

f) Same as in case (b) but magnetic pole of the magnet in the septum region, has been modified just above the septum coil (see Fig. 1d) in order to improve the field homogeneity in the main field region near the septum coil.

In all cases above the electric current flowing in each conductor has been adjusted to generate a B-field of 3 kGauss in the main septum region.

TABLE III

	Coil #1	Coil #2	Coil #3	Coil #4
Δx [mm]	+0.25	-0.1	+0.1	0.0
Δy [mm]	+0.1	-0.1	+0.1	0.0

Presentation of Results and Comparison

The results obtained from the magnetic field calculations performed on the various modifications of the septum magnets discussed in the previous section (cases a-f

[2] In all magnetic field calculation the magnetic materials are described by the magnetization curve shown in Fig. 2

[3] A misalignment of the same magnitude of the coils in the "return region", will produce a negligible effect on the field at the septum region.

above) are presented and compared with each other. Due to the large difference in the magnitude between the field of the circulating beam region and the field of the main magnet region, the results of the B-field will be plotted in separate graphs for each region.

Fig. 3a shows a plot of the B_y component of the magnetic field at the main field region, for the cases (a), (b), (c), (d), (e) and (f). In this figure the B_y component (at y=0 plane) is plotted from the distance x=8 mm (the surface of the inner wall of the magnet chamber closer to septum coil) to x=88 mm (surface of the inner wall of the magnet chamber return coil). From this figure we can deduce that there is a non-uniformity of the B_y component of the field near the septum region. The maximum non-uniformity is 0.8% for the cases (b) and (d) (pipe of the circulating beam is made of magnetic material).
For the cases (a) and (e) (pipe of the circulating beam is of non-magnetic material) the maximum non-uniformity is 0.4%.
For the case (f) the B_y field non-uniformity is reduced down to ~0.2%.
For the case (d) where the coils in the septum region are misaligned the B_y field non-uniformity is ~0.1%.

Fig. 3b shows a plot of the B_y component of the magnetic field at the circulating beam region, at the plane y=0, for the cases (a), and (e). The plotting range along the x-axis extends from x=-50 mm (where the field is less than 2 Gauss) to x=-3.1 mm (the inner surface of the beam pipe for the circulating beam). A current imbalance of 0.3% [see Fig. 3b case(e)] (between the current of the coils at the septum region and the coils at the "return current" region) reduces the magnitude of the field at the region of the circulating beam to ~5 Gauss, with no significant influence on the field in the main field region [see Fig. 3a case(e)]

Fig. 3c shows a plot of the B_y component of the magnetic field at the circulating beam region, at the plane y=0, for the cases (b), (c), (d) and (f). The plotting range along the x-axis extends from x=-50 mm (where the field is less than 2 Gauss) to x=-3.1 mm (the inner surface of the beam pipe for the circulating beam). From this figure we conclude that if the pipe for the circulating beam is made of magnetic material, the magnitude of the field inside the pipe is reduced well below the maximum allowed limit of 5.0 Gauss for all the cases (b, c, d, and f) where the beam pipe for the circulating beam is magnetic material.
Similar comparison of the B_y fields for the cases (b) and (c) shown in Fig. 3a, indicates that there is no significant change in the B_y component of the field at the main magnet region when the magnetic beam pipe approaches the magnet from 0.5 mm (case b) down to 0.25 mm (case c).
The improvement of the field uniformity in the case (e) (at y=0 plane) is due to the apparent increase of the septum thickness caused by the coil misalignment.
An alternative way of improving the field uniformity of the main field near the septum region, is to modify the pole shape near the septum region (see Fig. 1d). This modification reduces the field non-uniformity down to 0.3% (see Fig. 1a) without any significant effect on the field magnitude of the circulating beam region (see Fig. 3c)

In order to examine the field quality of the B_y component of the field off the median plane we generated similar plots as the ones shown in Fig. 3a,3b,3c but for the plane y=1cm. These plots appear in Fig. 4a,4b,4c.
Comparing the B_y components plotted in Fig. . 4a,4b,4c, we conclude that the magnetic pipe (cases b or c) provides the best field quality in all the regions of interest.
In spite of the fact that the intensity of the injected beam at y=1cm is reduced, one has still to pay attention at the field quality off the median plane. Thus by examining the curve of case (d) Fig. 4a, we can conclude that coil misalignements should be reduced to a minimum in order to maintain a good field uniformity off median plane. The coil misalignments (see Fig. 1c) destroys the median plane symmetry and introduces a B_x components along the median plane (y=0) as shown in Fig. 5. However the magnitude of the B_x component which introduced because of the misalignment of the septum coils, is comparable to the B_x component (at y=1cm) of an ideal magnet (cases b or f) plotted in Fig. 5.

CONCLUSIONS

The 2-dimensional magnetic field calculations for the SNS injection septum magnet have shown that:

a) The beam pipe of the SNS accumulator ring next to the injection septum region should be, if possible, of magnetic material. The effect of the magnetic pipe is to reduce the magnetic field in the region of the circulating beam.
b) There is no need for a special design to reduce the higher order multipoles in the main field region of the magnet. This conclusion can be drawn by looking at the variation of the B_y component along the horizontal and vertical direction, in the main field region of the magnet[4]. This variation is less than 0.3% in the area which is occupied by the beam envelope. (The beam envelope containing 95% of the particles is +-2.2 mm and 3.5 mm in the vertical and horizontal directions respectively).

[4] A more rigorous study of the multipole contend of the septum magnet could be done by using a harmonic analysis of the field.

References

1. “Opera” computer code of VECTOR FIELDS Inc.
2. Spallation Neutron Source Design Manual June 1998 E. Blesser BNL

FIGURE CAPTIONS

Figure 1a. Cross section of the injection septum magnet. The materials which affect the magnetic field (pipe of the circulating beam, magnet coils, and iron core of the magnet) are outlined in this figure.

Figure 1b. Same as in figure 1a, but “zooming in” near the septum region. This figure shows a detail view of the separation distance between the coils, pipe of the circulating beam and the iron of the magnet.

Figure 1c. Same as in figure 1b. This figure shows a detail view of the misalignment of the coils.

Figure 1d. Same as in figure 1b. This figure shows a detail view of the modification of the pole face of the magnet just above the septum conductor coil

Figure 2. The magnetization curve (B vs H) which is used in the calculations to characterize all the magnetic materials.

Figure 3a. The B_y component of the field at y=0, inside the magnet, for he cases (a) through (f) mentioned in the text.

Figure 3b. The B_y component of the field at y=0, inside the pipe of the circulating beam, for he cases (a) and (e) (beam pipe is of non-magnetic material).

Figure 3c. The B_y component of the field at y=0, inside the pipe of the circulating beam, for he cases (b), (c), (d) and (f) (beam pipe is of magnetic material).

Figure 4a. The B_y component of the field at y=1 cm, inside the magnet, for he cases (a) through (f) .

Figure 4b. The B_y component of the field at y=1 cm, inside the pipe of the circulating beam, for he cases (a) and (e) (beam pipe is of non-magnetic material).

Figure 4c. The B_y component of the field at y=1 cm , inside the pipe of the circulating beam, for he cases (b), (c), (d) and (f) (beam pipe is of magnetic material).

Figure 5. The B_x component of the field at y=1 cm, of inside the magnet, for he cases (b) and (f) compared with the B_x component of the field at y=0 and y=1 cm for the case (d) (coils misaligned).

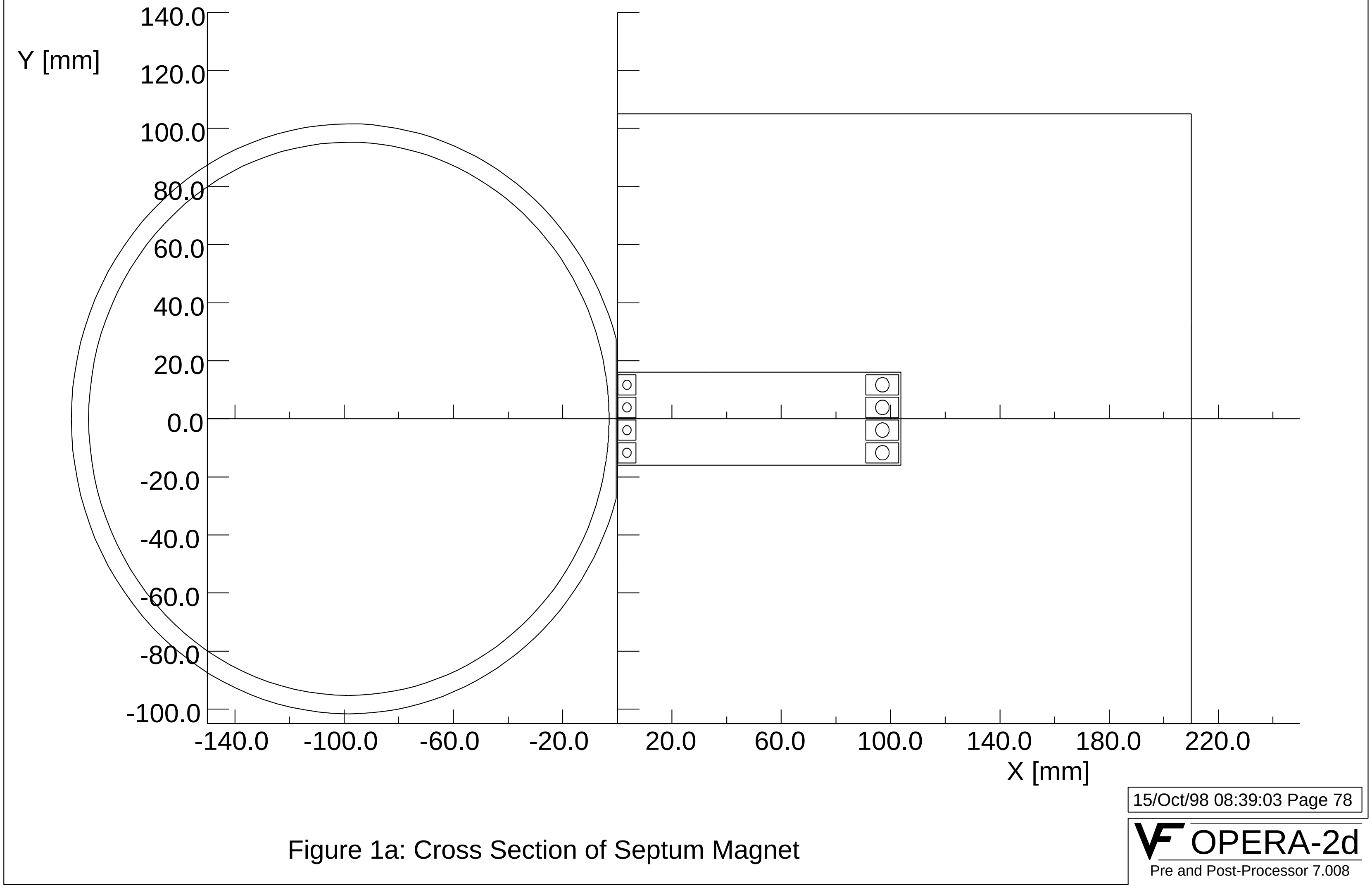


Figure 1a: Cross Section of Septum Magnet

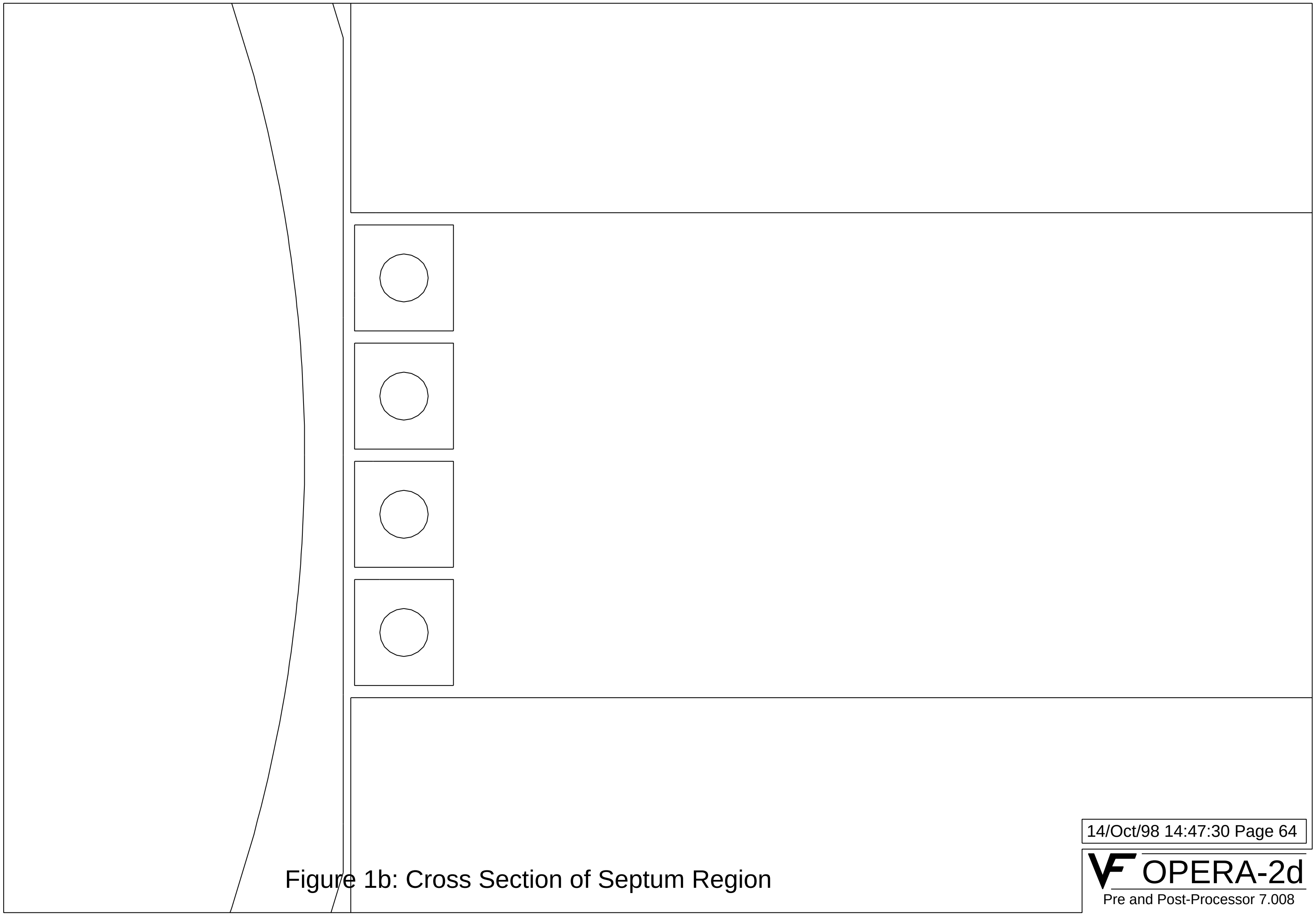


Figure 1b: Cross Section of Septum Region

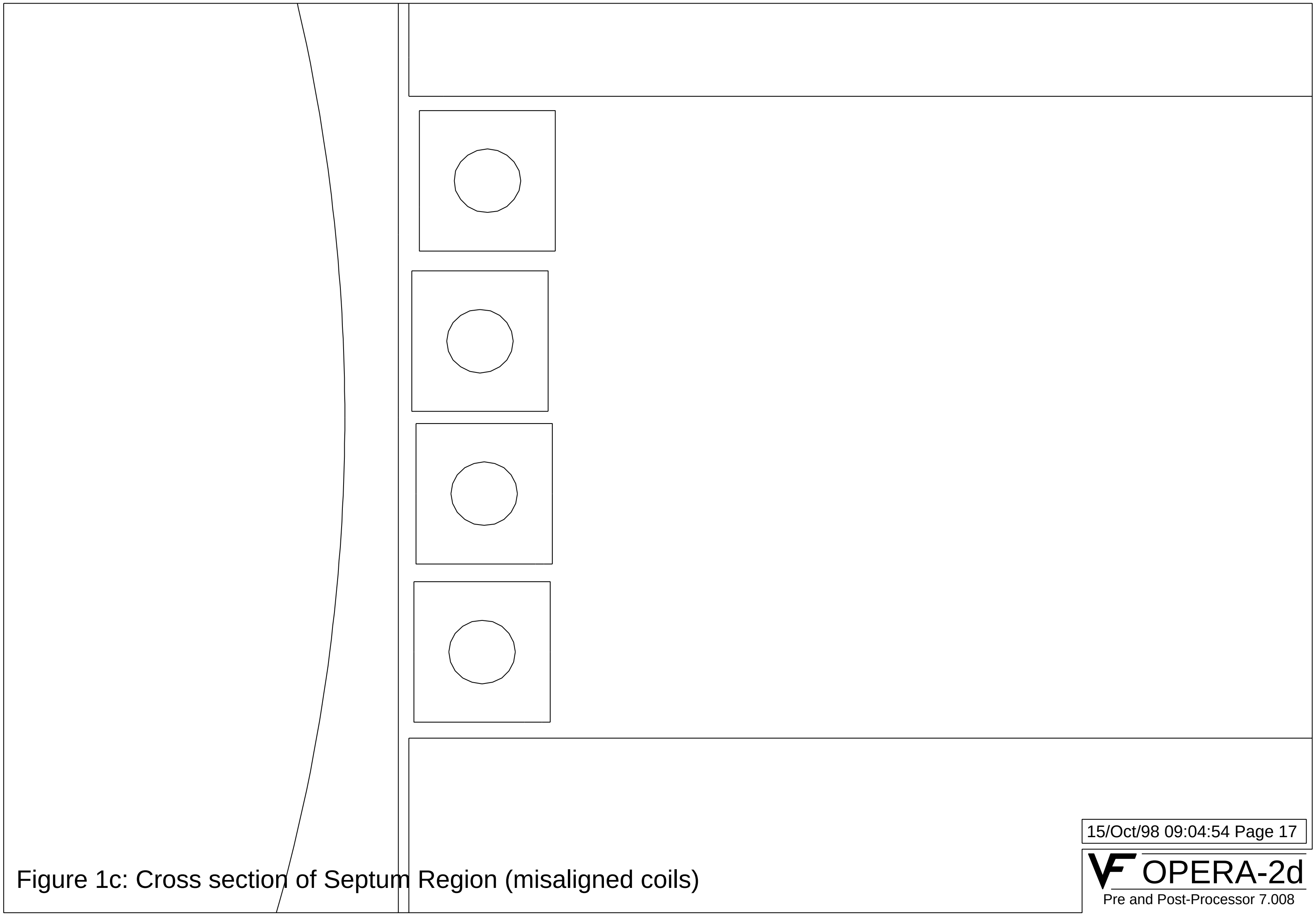


Figure 1c: Cross section of Septum Region (misaligned coils)

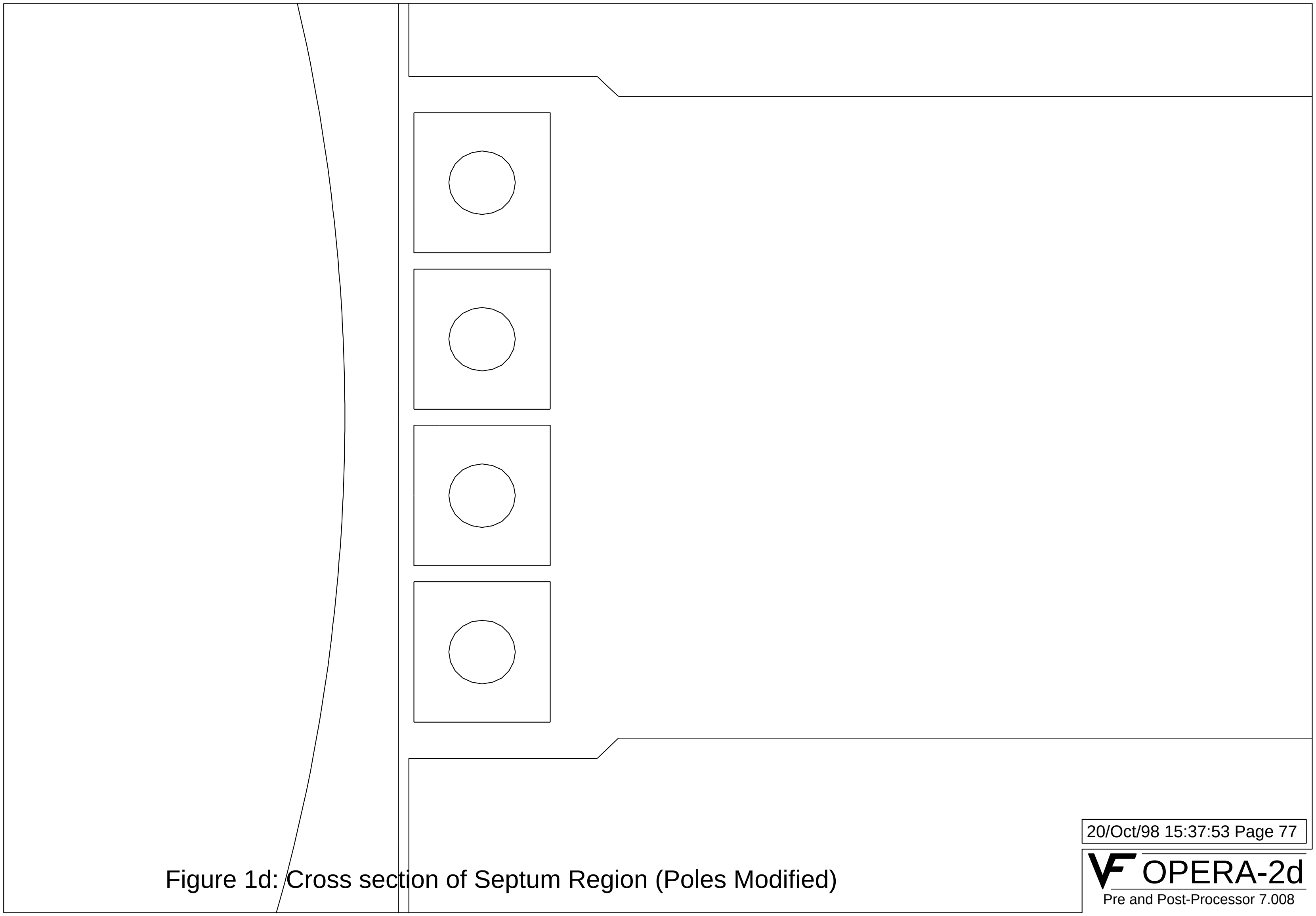


Figure 1d: Cross section of Septum Region (Poles Modified)

Figure 2

B vs H curve

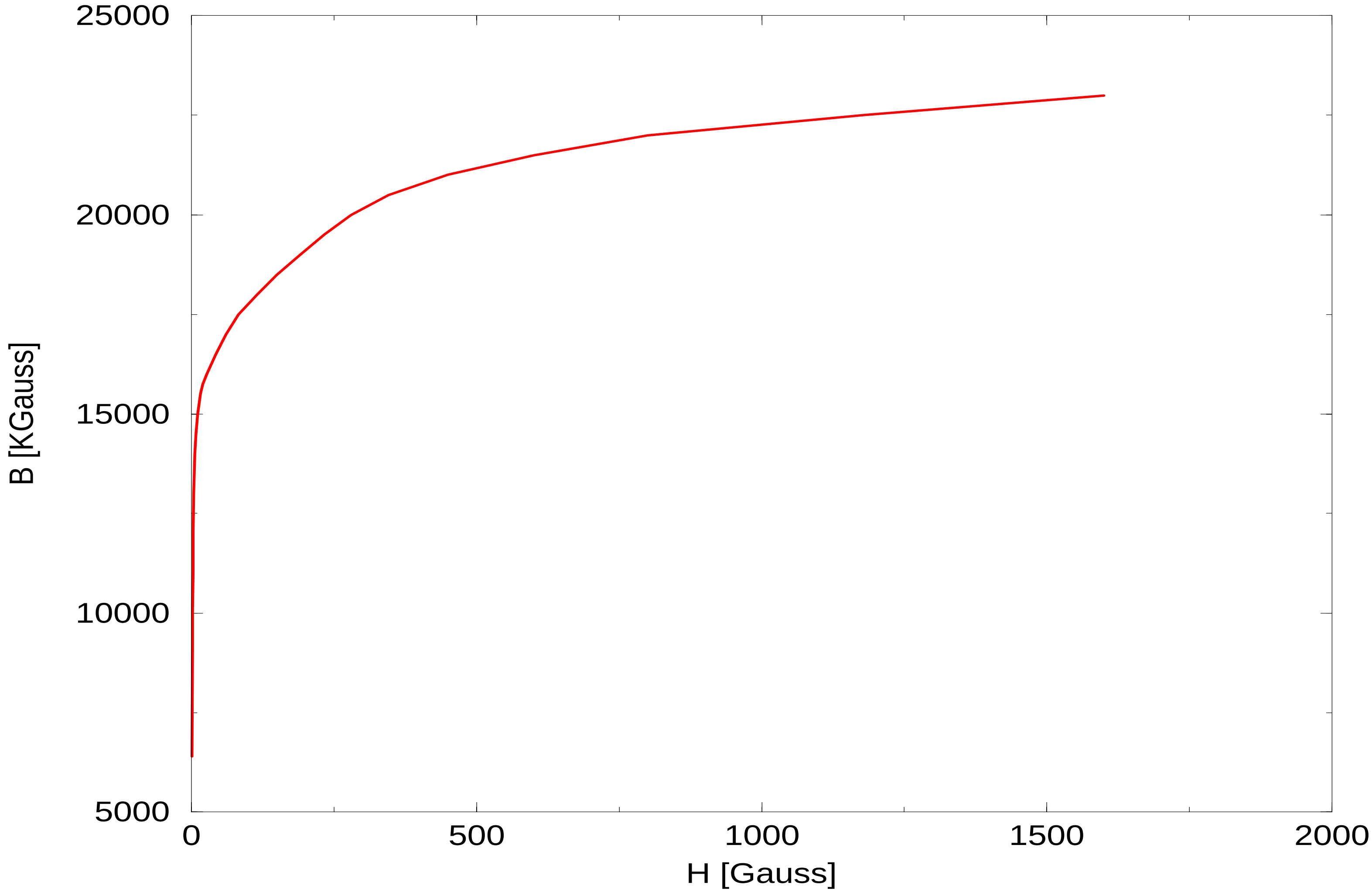
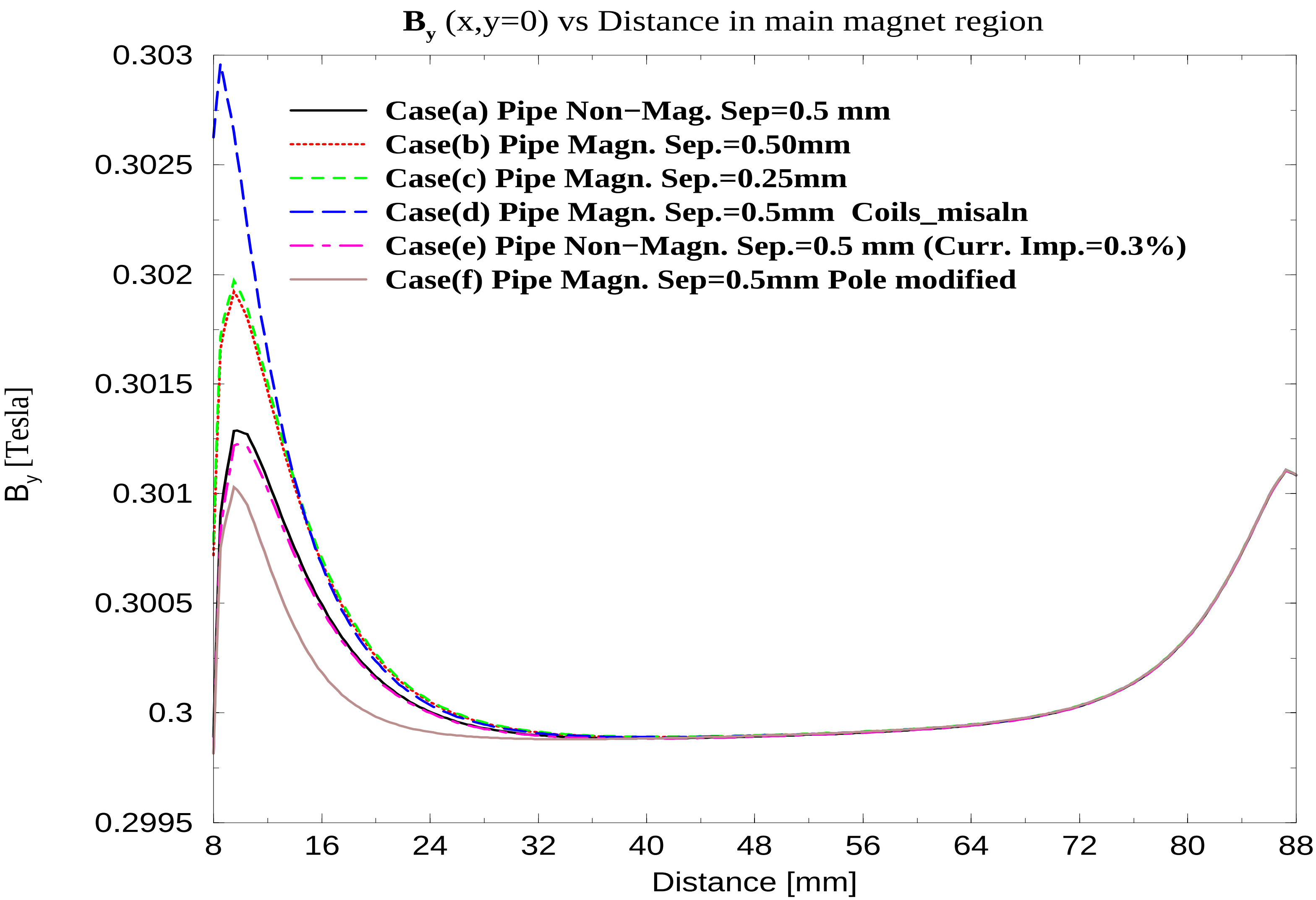
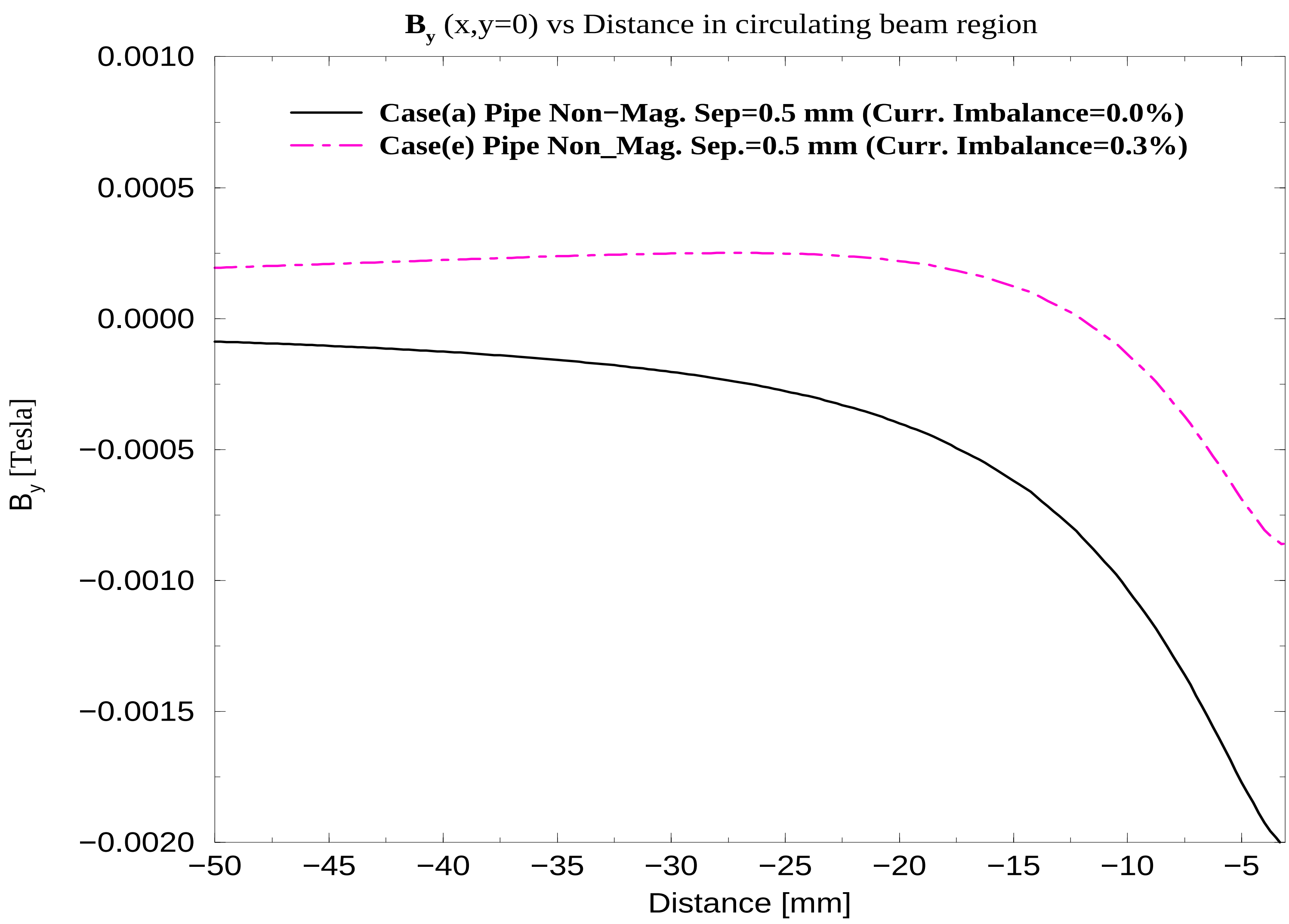


Figure 3a



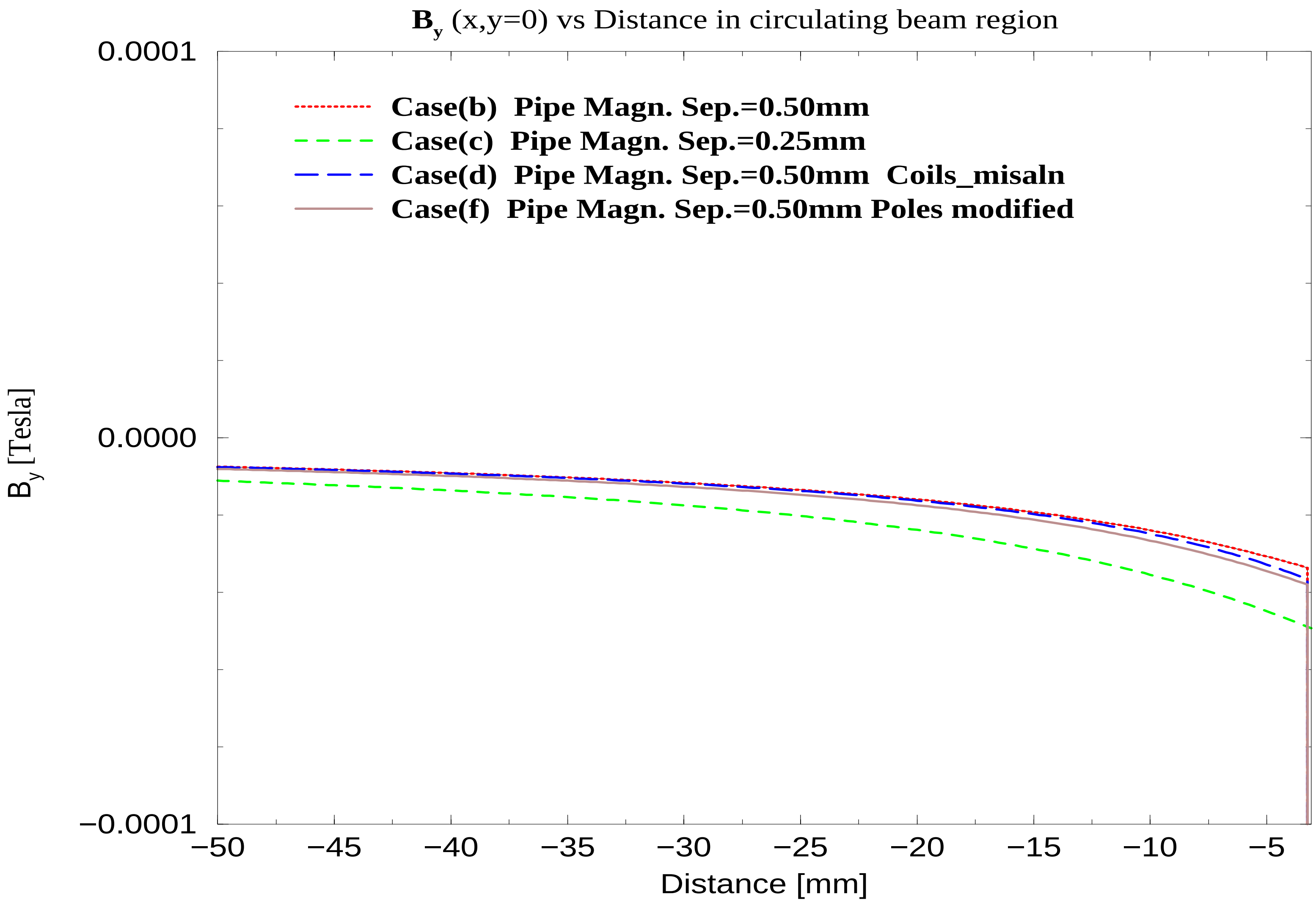
B_y (x,y=0) vs Distance in main magnet region
Case(a) Pipe Non−Mag. Sep=0.5 mm
Case(b) Pipe Magn. Sep.=0.50mm
Case(c) Pipe Magn. Sep.=0.25mm
Case(d) Pipe Magn. Sep.=0.5mm Coils_misaln
Case(e) Pipe Non−Magn. Sep.=0.5 mm (Curr. Imp.=0.3%)
Case(f) Pipe Magn. Sep=0.5mm Pole modified
B_y [Tesla]
0.303
0.3025
0.302
0.3015
0.301
0.3005
0.3
0.2995
8
16
24
32
40
48
56
64
72
80
88
Distance [mm]

Figure 3b



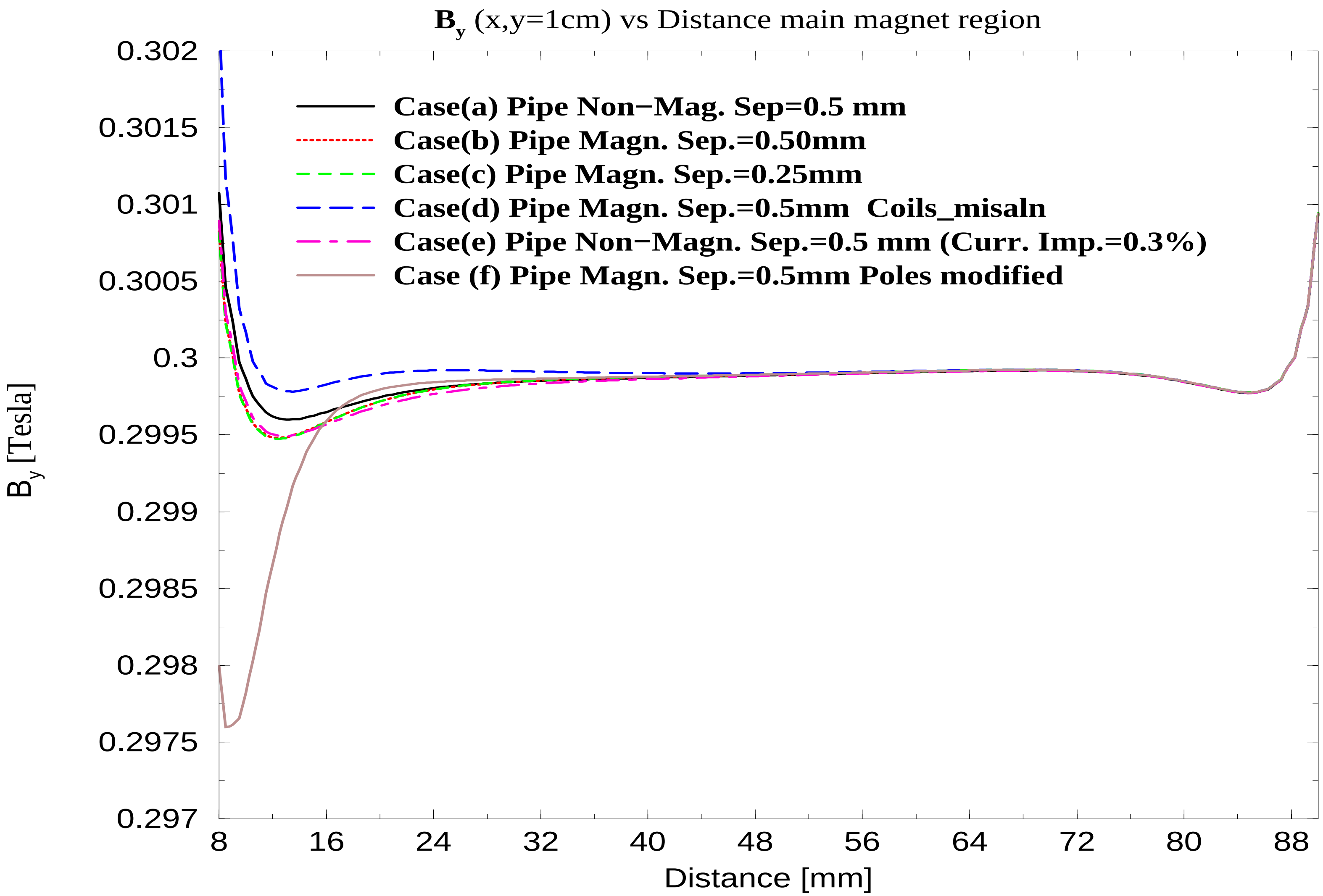
B_y (x,y=0) vs Distance in circulating beam region
Case(a) Pipe Non−Mag. Sep=0.5 mm (Curr. Imbalance=0.0%)
Case(e) Pipe Non_Mag. Sep.=0.5 mm (Curr. Imbalance=0.3%)
0.0010
0.0005
0.0000
−0.0005
−0.0010
−0.0015
−0.0020
B_y [Tesla]
−50
−45
−40
−35
−30
−25
−20
−15
−10
−5
Distance [mm]

Figure 3c



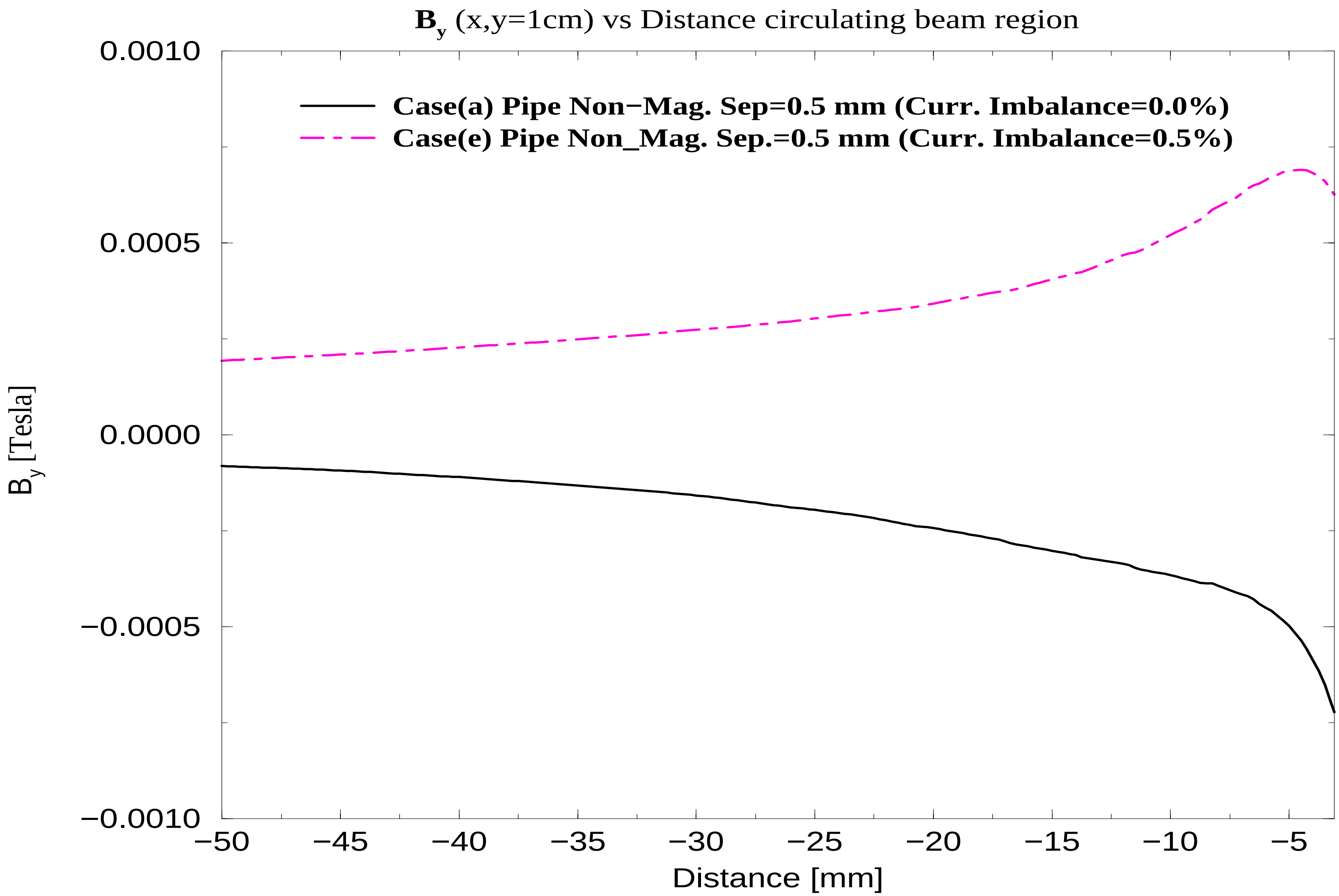
B_y (x,y=0) vs Distance in circulating beam region
0.0001
0.0000
−0.0001
B_y [Tesla]
Case(b) Pipe Magn. Sep.=0.50mm
Case(c) Pipe Magn. Sep.=0.25mm
Case(d) Pipe Magn. Sep.=0.50mm Coils_misaln
Case(f) Pipe Magn. Sep.=0.50mm Poles modified
−50
−45
−40
−35
−30
−25
−20
−15
−10
−5
Distance [mm]

Figure 4a



By (x,y=1cm) vs Distance main magnet region
Case(a) Pipe Non−Mag. Sep=0.5 mm
Case(b) Pipe Magn. Sep.=0.50mm
Case(c) Pipe Magn. Sep.=0.25mm
Case(d) Pipe Magn. Sep.=0.5mm Coils_misaln
Case(e) Pipe Non−Magn. Sep.=0.5 mm (Curr. Imp.=0.3%)
Case (f) Pipe Magn. Sep.=0.5mm Poles modified
By [Tesla]
0.302
0.3015
0.301
0.3005
0.3
0.2995
0.299
0.2985
0.298
0.2975
0.297
8
16
24
32
40
48
56
64
72
80
88
Distance [mm]

Figure 4b



B_y (x,y=1cm) vs Distance circulating beam region
Case(a) Pipe Non−Mag. Sep=0.5 mm (Curr. Imbalance=0.0%)
Case(e) Pipe Non_Mag. Sep.=0.5 mm (Curr. Imbalance=0.5%)
B_y [Tesla]
0.0010
0.0005
0.0000
−0.0005
−0.0010
−50
−45
−40
−35
−30
−25
−20
−15
−10
−5
Distance [mm]

Figure 4c

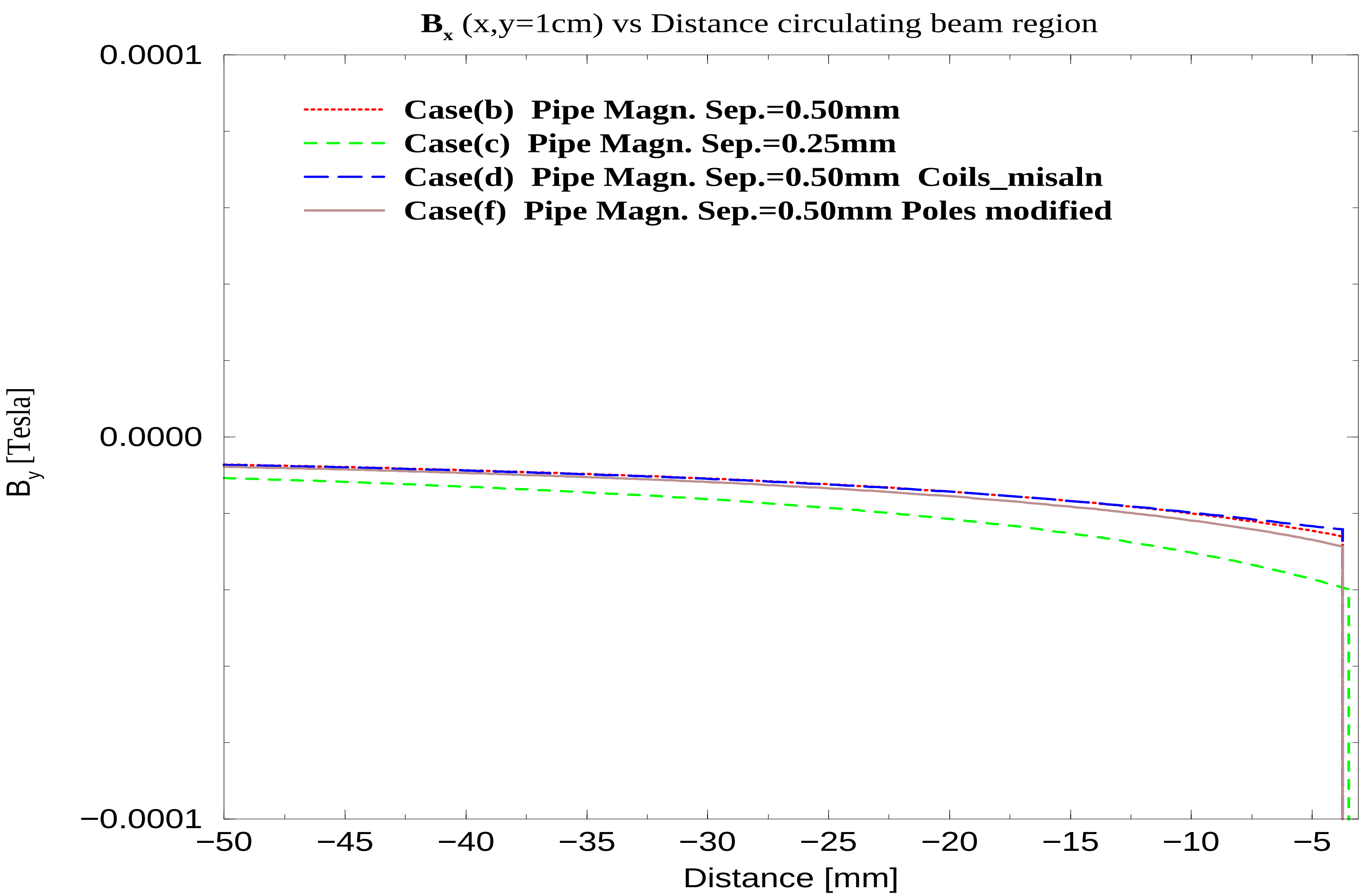
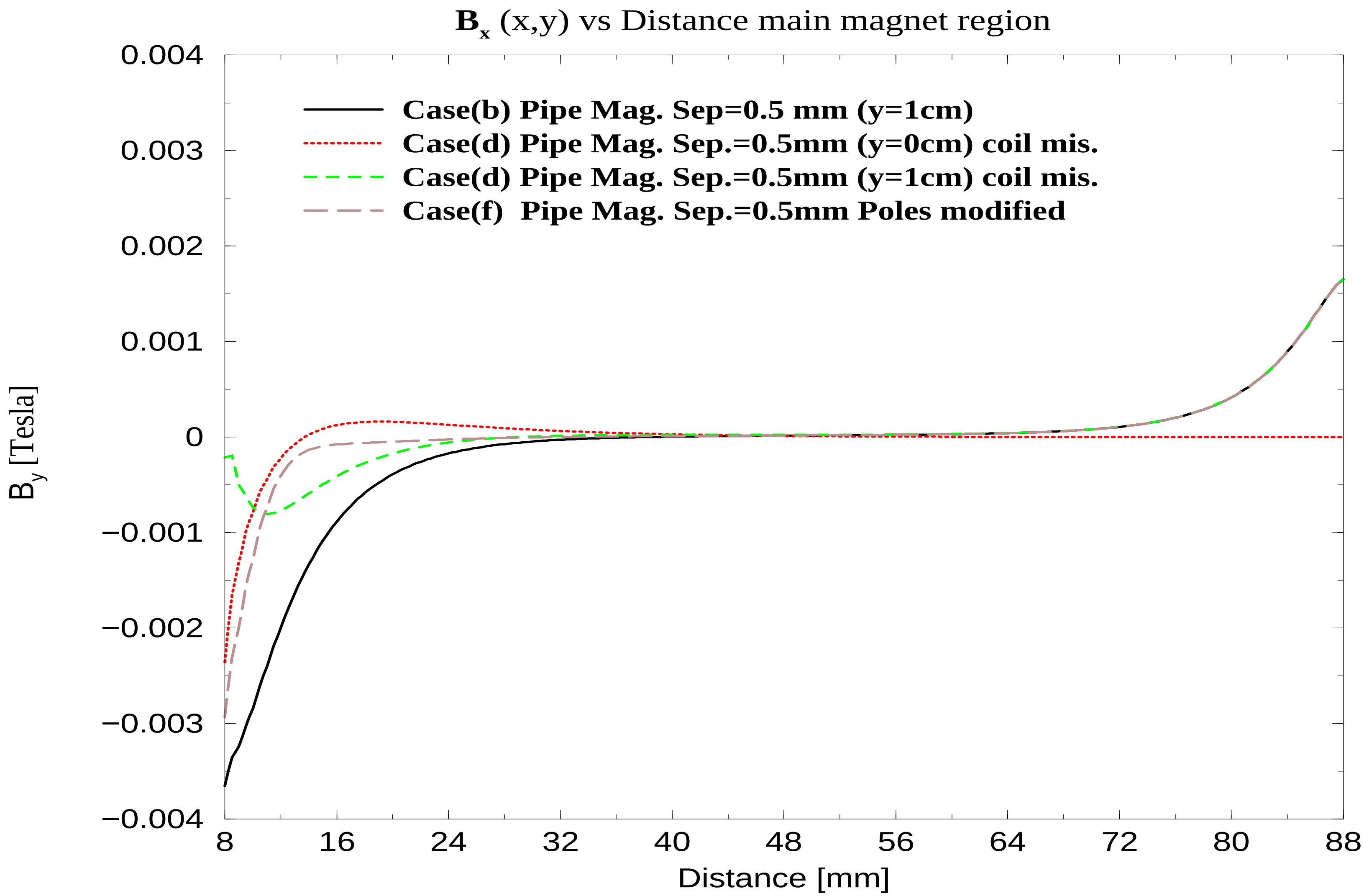

B_x (x,y=1cm) vs Distance circulating beam region
Case(b) Pipe Magn. Sep.=0.50mm
Case(c) Pipe Magn. Sep.=0.25mm
Case(d) Pipe Magn. Sep.=0.50mm Coils_misaln
Case(f) Pipe Magn. Sep.=0.50mm Poles modified
0.0001
0.0000
−0.0001
B_y [Tesla]
−50
−45
−40
−35
−30
−25
−20
−15
−10
−5
Distance [mm]

Figure 5



B_x (x,y) vs Distance main magnet region
Case(b) Pipe Mag. Sep=0.5 mm (y=1cm)
Case(d) Pipe Mag. Sep.=0.5mm (y=0cm) coil mis.
Case(d) Pipe Mag. Sep.=0.5mm (y=1cm) coil mis.
Case(f) Pipe Mag. Sep.=0.5mm Poles modified
B_y [Tesla]
Distance [mm]
0.004
0.003
0.002
0.001
0
−0.001
−0.002
−0.003
−0.004
8
16
24
32
40
48
56
64
72
80
88