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Three Dimensional Calculation on Toroidal Magnetic Field for RHIC Polarimeter

T. Kawaguchi

February 1996

Collider Accelerator Department
Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

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Alternating Gradient Synchrotron Department
Relativistic Heavy Ion Collider Project
BROOKHAVEN NATIONAL LABORATORY
Upton, New York 11973

Spin Note

AGS/RHIC/SN No. 019

**Three Dimensional Calculation on Toroidal Magnetic
Field for RHIC Polarimeter**

T. Kawaguchi

February 6, 1996

Three Dimensional Calculation on Toroidal Magnetic Field for RHIC Polarimeter

Takeo Kawaguchi

RIKEN

Feb 6, 1996

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Three Dimensional Calculation on Toroidal Magnetic Field for RHIC Polarimeter

Takeo Kawaguchi, RIKEN
1996-2-6

1. Abstract

I and Dr. Okamura have calculated the magnetic field of the toroidal magnet for RHIC polarimeter. A location of the polarimeters is shown on Fig. 1.

Here, I write the calculated results, and also write some problems on the calculation which I experienced, as one of the instruction manual for using TOSCA code.

2. Dimensions of Toroidal Magnet

Dimensions of the toroidal magnet which I got from Okamura, are as follows.

Iron pole: inner dia. 15 cm, outer dia. 80 cm, length 150 cm.

Pole gaps: 4 gaps, each gap angle 7 degree

Toroidal coils: 12 pcs, total AT= 0.36 MA

cross section of one coil is $2.0 \times 1.5 \text{ cm}^2$

current density 10000 A/cm^2

My opinion to the above geometry is that the inner diameter of the pole should be increased to get more space in inner region for coil arrangement.

3. Roughly Estimation of Magnetic Field

Magnetic field strength can be estimated using one dimensional method as follows.

$$L_g = \pi \cdot r \cdot 4 \theta_g / 360$$

$$= 0.244 r \quad (\text{m})$$

$$L_i = \pi \cdot r \cdot 4 \theta_i / 360$$

$$= 2.90 r \quad (\text{m})$$

$$AT = H_g L_g + H_i L_i$$

$$= B (L_g + L_i / \mu_r) / \mu_0$$

$$= (B L_g / \mu_0) (1 + L_i / (L_g \mu_r))$$

$$= (0.194 B_r) (1 + 11.88 / \mu_r) \times 10^6$$

L_g : total gap length (m)

L_i : total iron length (m)

θ_g : one gap angle = 7 degree

θ_i : one pole angle = 83 degree

r : radius of calculation point (m)

AT : total ampere turns (A)

B : magnetic field strength (T)
average value in gap and iron.

μ_0 : permeability of air = $4\pi \times 10^{-7}$

μ_r : permeability ratio of iron

Figure 3-1 shows the B-H characteristics of iron pole, and the permeability ratio shown on Fig. 3-2. was calculated from Fig. 3-1.

We can roughly estimate the magnetic field strength of this toroidal magnet using the above equation and Fig. 3-2.

The result is shown on Fig. 3-3, and it shows that the magnetic fields at $r=0.1\text{ m}$ and 0.35 m are 3.5 T and 2.3 T with the ampere turns of 0.36 MA .

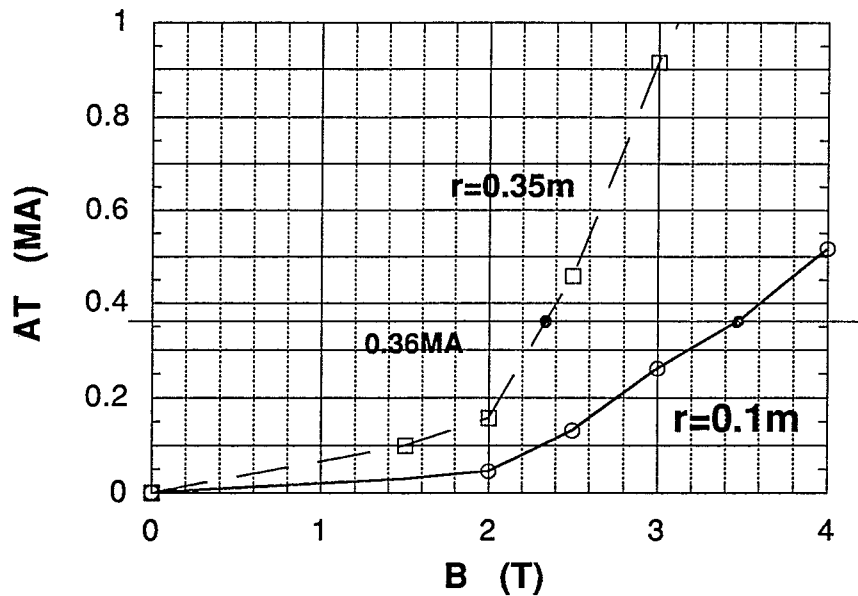


Fig.3-3. Estimated B-AT

4. Results of Three Dimensional Calculation

Results of the calculation are shown on following pictures.

Fig. 4-1 : TOSCA model

Here, full toroidal coils of 12 pcs. and a part of $1/8$ of the iron poles are used for the calculation.

Fig. 4-2 : Magnetic fields in Air gaps

Fields on x and y axes (in gap center) are shown.
Maximum field is 2.8T.

Fig. 4-3 : Bmod along radii

Bmod (absolute value) on $r=10$ cm and $r=35$ cm are shown.
Roughly estimated values are also compared.

Fig. 4-4 : Bmod vector on Pole face

Fig. 4-5 : Bmod vector in Inner area

Fig. 4-6 : Bmod vector in Outer area

5. Some Problems on the Calculation

I'd like to write some problems which I experienced on this calculation, as one of TOSCA manual.

(1) Error field and mesh size

Figure 5-1 shows a typical error field on this calculation. We can point out two problems on the figure; one is a some big fields and another is an opposite vector.

The opposite vector is described in next paragraph (2).

A reason of the big fields was the big mesh size, and we can find the following message in OPERA [.res] file after TOSCA calculation.

This error would be occurred with large mesh size on the boundary between Total potential area and Reduced potential one. This problem was improved by increasing the mesh number from 10,000 to 80,000 total elements.

Error Message on TOSCA[.res] file

NUMBER OF TOTAL/REDUCED INTERFACE NODES= 2584

Discretisation inadequate to model coil fields at:

| | | | | |
|--------|--------|--------------|----------------|--------------|
| (19.0 | , 38.9 | , -75.0 |) (cm), error= | 1.651% ***** |
| (38.9 | , 19.0 | , -60.0 |) (cm), error= | 1.279% ***** |
| (38.9 | , 19.0 | , -52.5 |) (cm), error= | 1.399% ***** |
| (38.9 | , 19.0 | , -45.0 |) (cm), error= | 1.429% ***** |
| (38.9 | , 19.0 | , -37.5 |) (cm), error= | 1.415% ***** |
| (38.9 | , 19.0 | , -30.0 |) (cm), error= | 1.388% ***** |
| (38.9 | , 19.0 | , -22.5 |) (cm), error= | 1.369% ***** |
| (38.9 | , 19.0 | , -7.50 |) (cm), error= | 1.349% ***** |
| (38.9 | , 19.0 | , 5.588E-07) | (cm), error= | 1.343% ***** |
| (38.9 | , 19.0 | , 7.50 |) (cm), error= | 1.349% ***** |
| (38.9 | , 19.0 | , 15.0 |) (cm), error= | 1.355% ***** |
| (38.9 | , 19.0 | , 22.5 |) (cm), error= | 1.369% ***** |
| (38.9 | , 19.0 | , 30.0 |) (cm), error= | 1.391% ***** |

| | | | | |
|--------|--------|---------|----------------|--------------|
| (38.9 | , 19.0 | , 45.0 |) (cm), error= | 1.431% ***** |
| (38.9 | , 19.0 | , 52.5 |) (cm), error= | 1.403% ***** |
| (38.9 | , 19.0 | , 60.0 |) (cm), error= | 1.276% ***** |
| (38.9 | , 19.0 | , 67.5 |) (cm), error= | 1.091% ***** |
| (38.9 | , 19.0 | , 75.0 |) (cm), error= | 1.652% ***** |
| (32.2 | , 15.7 | , -75.0 |) (cm), error= | 1.246% ***** |
| (35.8 | , 17.5 | , -75.0 |) (cm), error= | 1.908% ***** |
| (32.2 | , 15.7 | , 75.0 |) (cm), error= | 1.246% ***** |
| (35.8 | , 17.5 | , 75.0 |) (cm), error= | 1.908% ***** |
| (26.3 | , 30.0 | , -75.0 |) (cm), error= | 2.221% ***** |
| (26.3 | , 30.0 | , 75.0 |) (cm), error= | 2.220% ***** |

AVERAGE NUMBER OF CALLS TO SOURCE PER LINE INTEGRAL = 5.55

3:

: 63.3833 mins. Coil calculations: 1309.37 cp secs., elapsed

(2) One turn Total potential problem

The TOSCA code has two kinds of potential areas. One is Total potential area and another one is Reduced potential one.

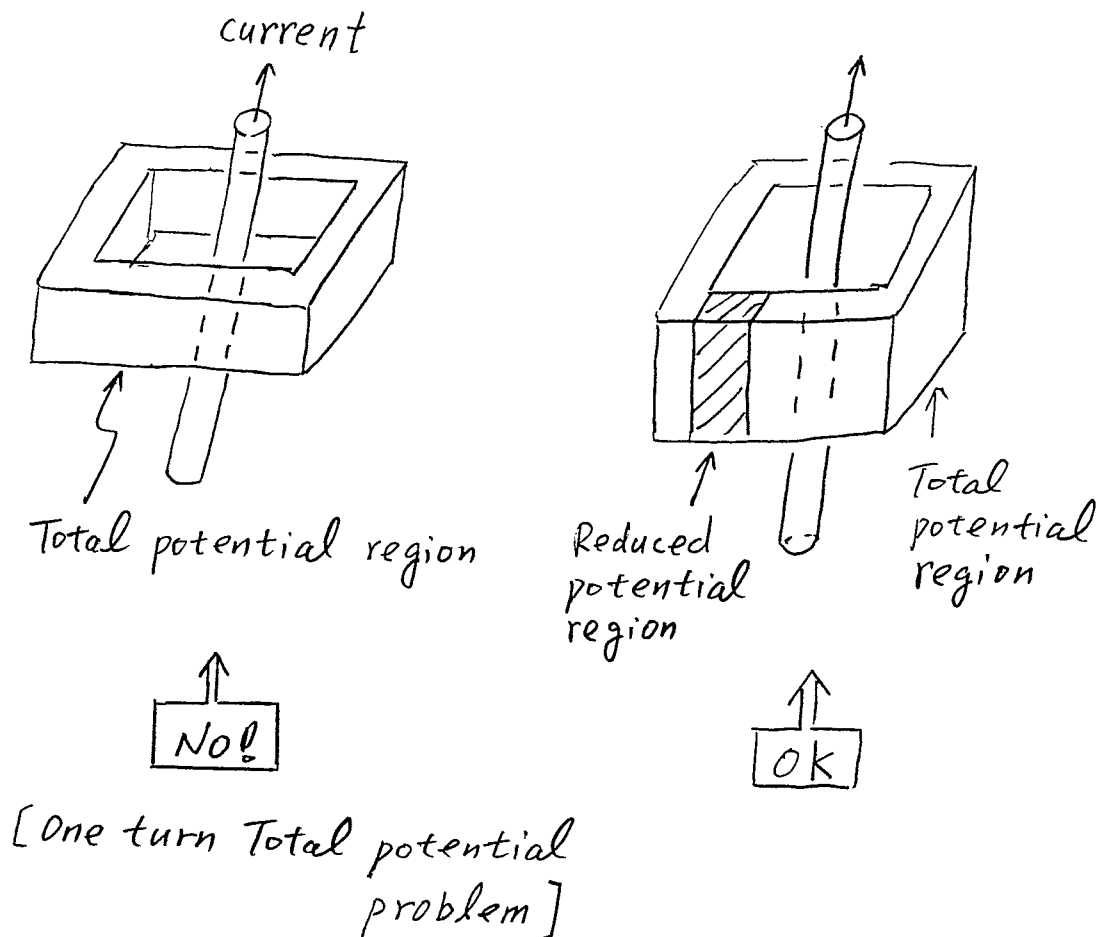
Total potential area must not include any current region.

So, in Total potential area $\oint H dl = 0$

If Total potential area surrounds a current, above Ampere's law does not consist.----- This is [one turn Total potential problem]. We must cut this one turn circuit with Reduced potential area, to get a correct TOSCA solution.

The opposite field vectors on Fig. 5-1 and 5-2 were occurred with above one turn Total potential problem.

I got collect solutions described in chapter 2 with a change of potential region shown on Fig.5-3.



(3) Error Field on Boundary Face

Both faces on x-axis and y-axis are set as Normal magnetic boundary condition for TOSCA calculation.

On the face of Normal boundary a tangential component must be zero. But on the Normal boundary face in Reduced potential region, the tangential component would be not-zero on TOSCA calculation. (In case of Normal boundary in Total potential region, the tangential component would be zero strictly.)

Figures 5-4 and 5-5 shows the not-zero tangential components on x-axis and y-axis with quarter coils (3 coils) .

So, we should use full coils (12 coils) for TOSCA calculation as shown Fig. 4-1.

Polarized Proton Collisions at BNL

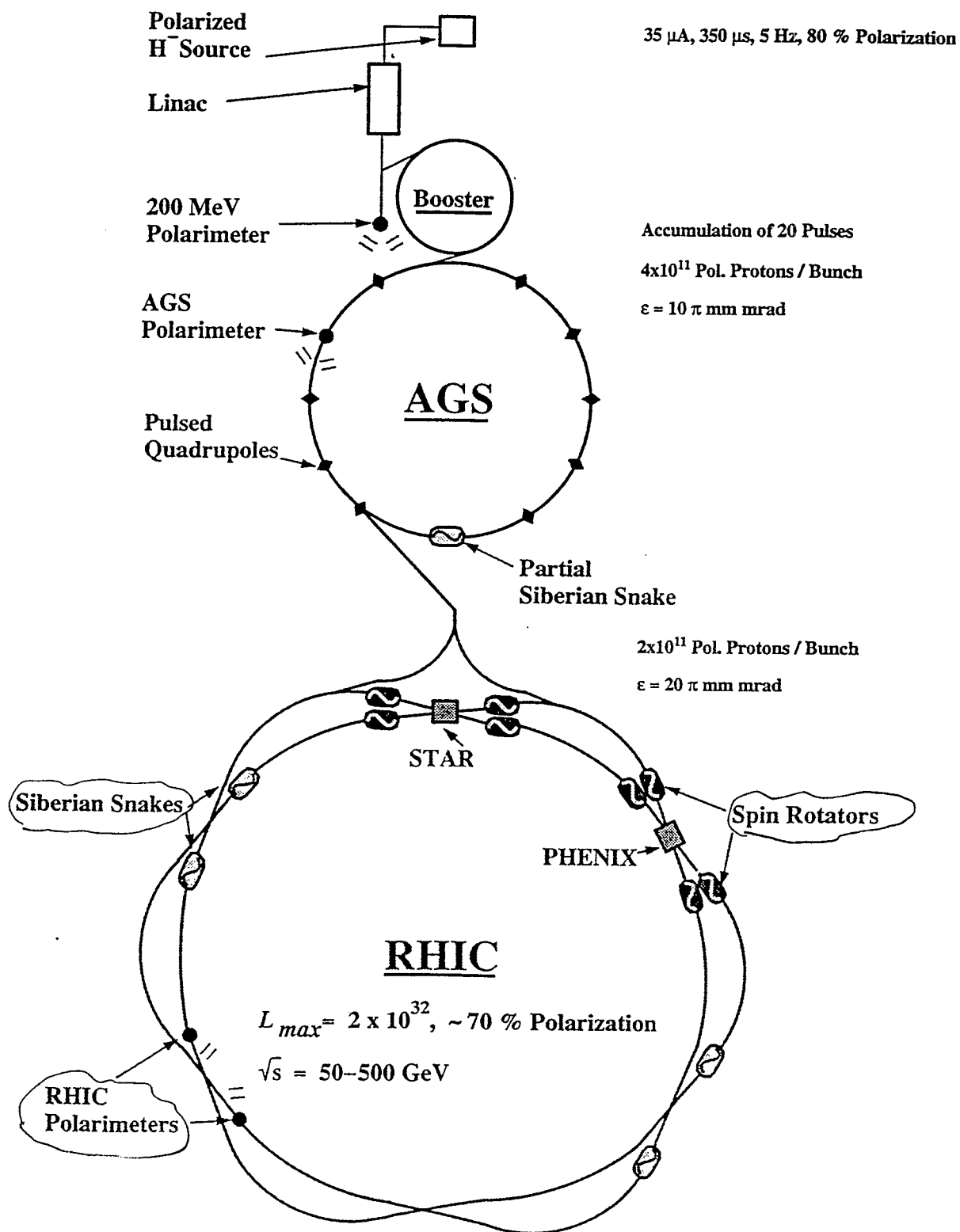


Figure 1

(8/)

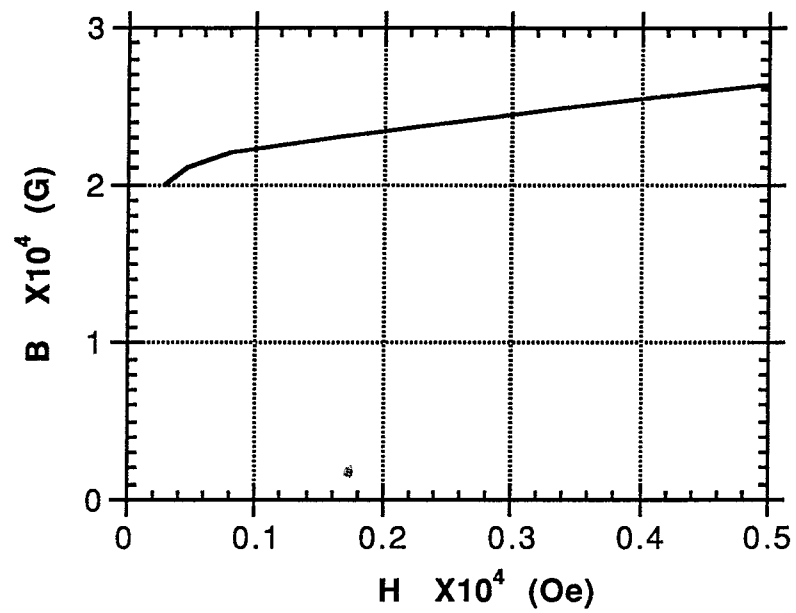


Fig. 3-1. B-H curve of iron pole

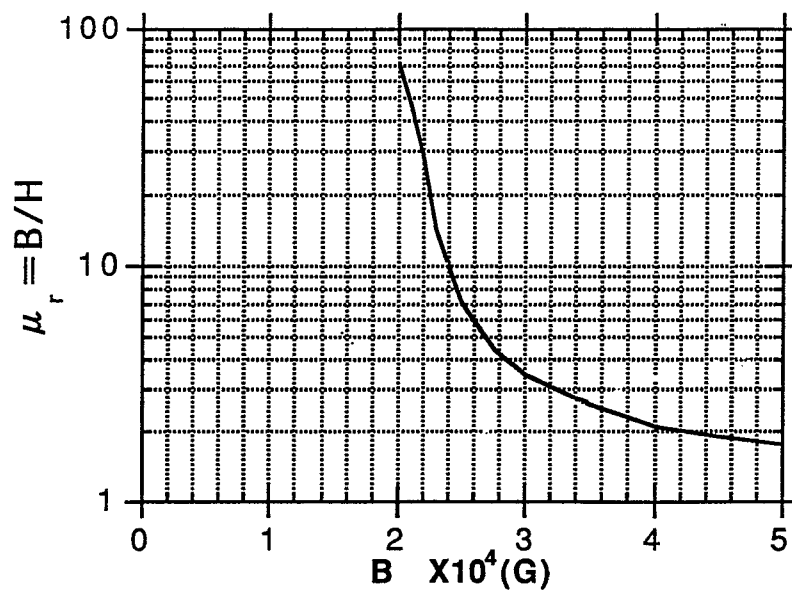


Fig. 3-2. B-(μ)_r curve

96-1-22.

餘心は 全体の $\frac{1}{8}$ のみ ヨシを表
してゐる。



| UNITS | |
|------------------|---------------------|
| Length | : cm |
| Flux density | : gauss |
| Magnetic field | : oersts |
| Scalar potential | : oersts |
| Vector potential | : gauss |
| Conductivity | : S/cm |
| Current density | : A/cm ² |
| Power | : W |
| Force | : N |
| Energy | : J |
| Electric field | : V/cm |

PROBLEM DATA
toroid122r.toscab
TOSCA analysis (122r)
Case No. 1
86000 elements
92004 nodes
Shape funct. fields
Nodal coil fields

```

LOCAL COOF
Xlocal = 0.0
Ylocal = 0.0
Zlocal = 0.0
Theta = 0.0
Phi = 0.0
Psi = 0.0

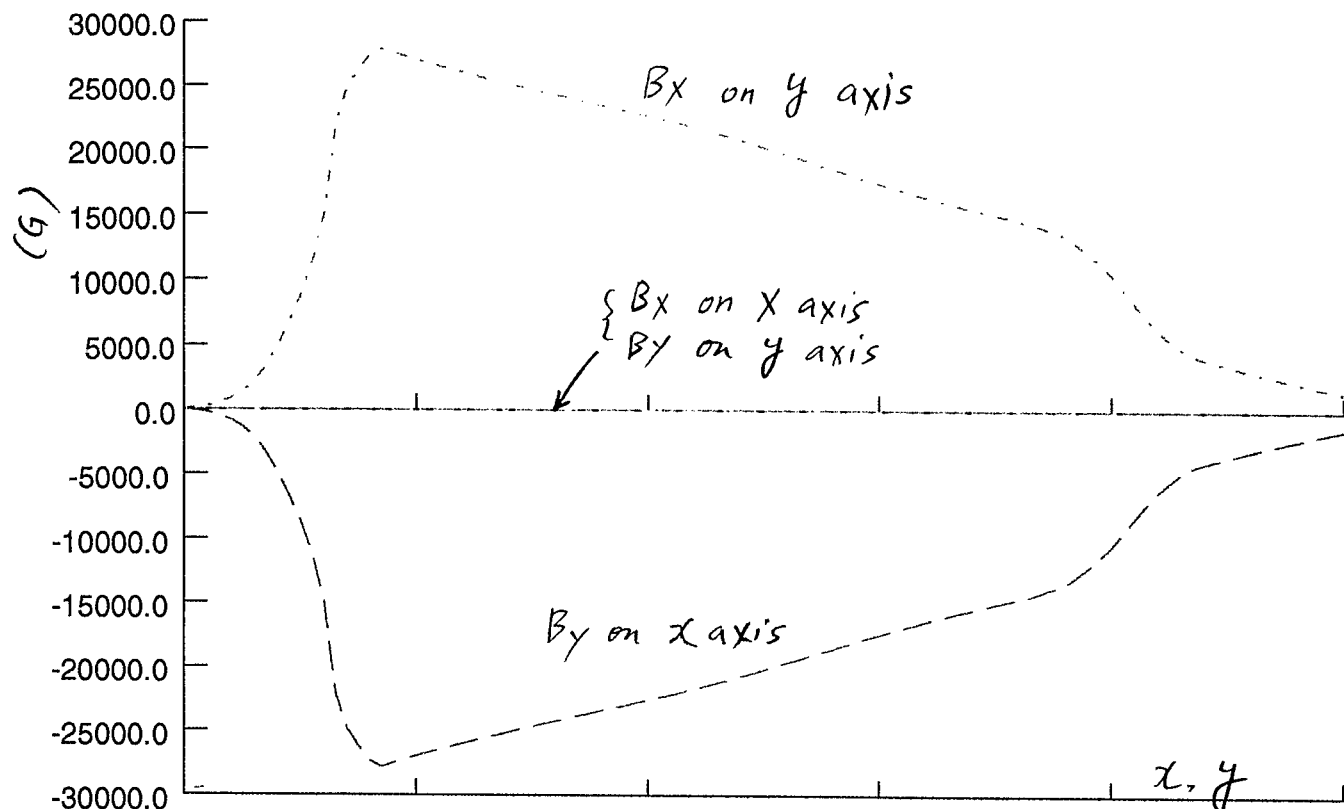
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22/Jan/96 22:35:47 F

VF OPERA
Post-processor 2

Fig. 4-1. TOSCA model

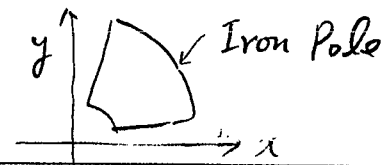
alltoroid with full coils



| | | | | | | |
|---------------|-----|------|------|------|------|------|
| Local X coord | 1.0 | 10.8 | 20.6 | 30.4 | 40.2 | 50.0 |
| Local Y coord | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Local Z coord | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

- — Component: BY, Integral = -750513.0
- - Component: BX, Integral = 1.664562
- ... Component: BX, Integral = 750521.0
- Component: BY, Integral = -1.66465

Fig. 4-2. Magnetic fields in air gaps



UNITS

Length : cm
 Flux density : gau
 Magnetic field : oer
 Scalar potential : oer
 Vector potential : gau
 Conductivity : S cm
 Current density : A cm
 Power : W
 Force : N
 Energy : J
 Electric field : V cm

PROBLEM DATA

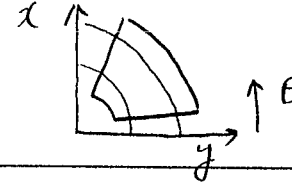
alltoroid.toscab
 TOSCA analysis (Case No 1
 86000 elements
 92004 nodes
 Shape funct. fields
 Nodal coil fields

LOCAL COORDINATES

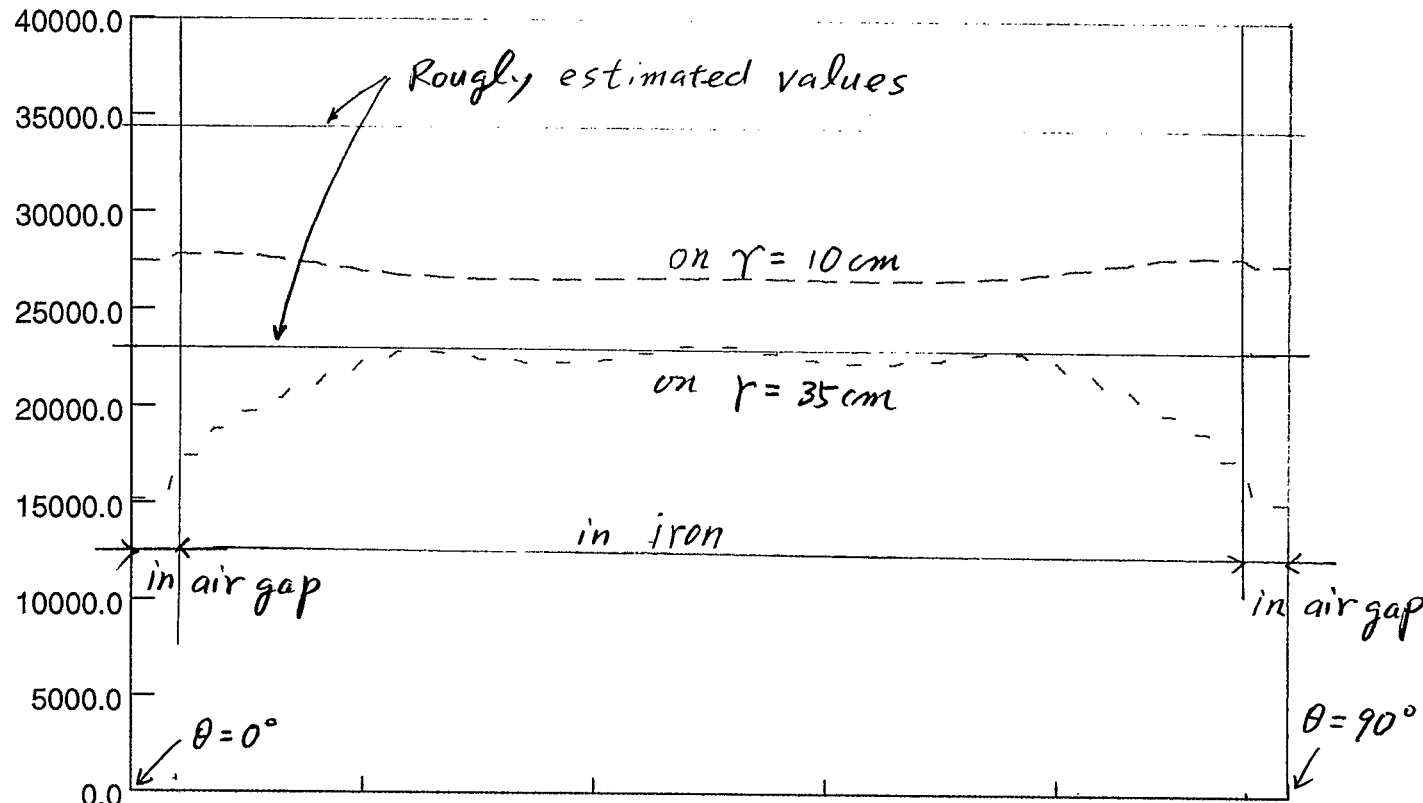
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 Ylocal = 0.0
 Zlocal = 0.0
 Theta = 0.0
 Phi = 0.0
 Psi = 0.0

23/Jan/96 10:14:48 F

FORP
 Post-processor 2



Bmod on r=10cm and 35cm



| | | | | | | |
|---------------|------|----------|----------|----------|----------|------------|
| Local X coord | 10.0 | 9.510566 | 8.09017 | 5.877852 | 3.09017 | -4.371E-07 |
| Local Y coord | 0.0 | 3.09017 | 5.877852 | 8.09017 | 9.510566 | 10.0 |
| Local Z coord | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

— — Component: BMOD, Integral = 424161.0

- - Component: BMOD, Integral = 1166425.0

UNITS

Length : cm
Flux density : gauss
Magnetic field : oer
Scalar potential : oer
Vector potential : gauss
Conductivity : S/cm
Current density : A/cm
Power : W
Force : N
Energy : J
Electric field : V/cm

PROBLEM DATA

alltoroid.toscab
TOSCA analysis (Case No 1
86000 elements
92004 nodes
Shape funct. fields
Nodal coil fields

LOCAL COORD

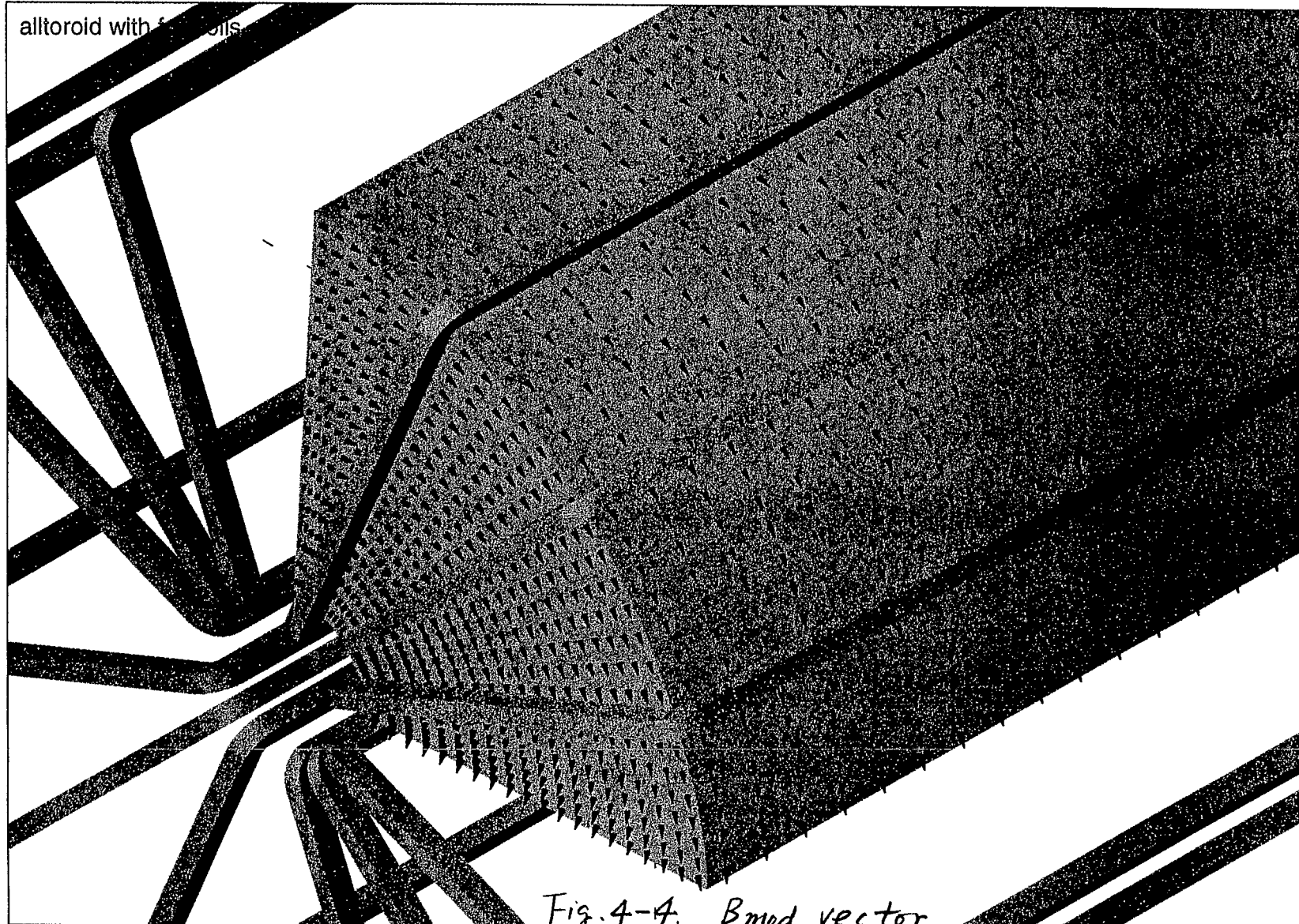
Xlocal = 0.0
Ylocal = 0.0
Zlocal = 0.0
Theta = 0.0
Phi = 0.0
Psi = 0.0

5/Feb/96 16:00:15 P

OPERA
Post-processor 2

Fig.4-3. Bmod along radii.

alltoroid with f coils



| UNITS | |
|------------------|-------|
| Length | : cm |
| Flux density | : gau |
| Magnetic field | : oer |
| Scalar potential | : oer |
| Vector potential | : gau |
| Conductivity | : S c |
| Current density | : A c |
| Power | : W |
| Force | : N |
| Energy | : J |
| Electric field | : V c |

PROBLEM DATA
alltoroid.toscab
TOSCA analysis (Case No 1
86000 elements
92004 nodes
Shape funct. fields
Nodal coil fields

LOCAL COORDINATES
Xlocal = 0.0
Ylocal = 0.0
Zlocal = 0.0
Theta = 0.0
Phi = 0.0
Psi = 0.0

23/Jan/96 10:20:59

VF OPERA
Post-processor

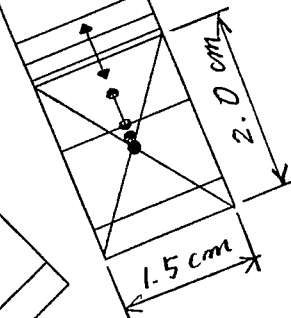
Fig.4-4. Bmod vector
on pole surface

(13/)

内径部の磁界ベクトル図

alltoroid with full coils

on $Z=0$,



$j = 10000 \text{ A/cm}^2$

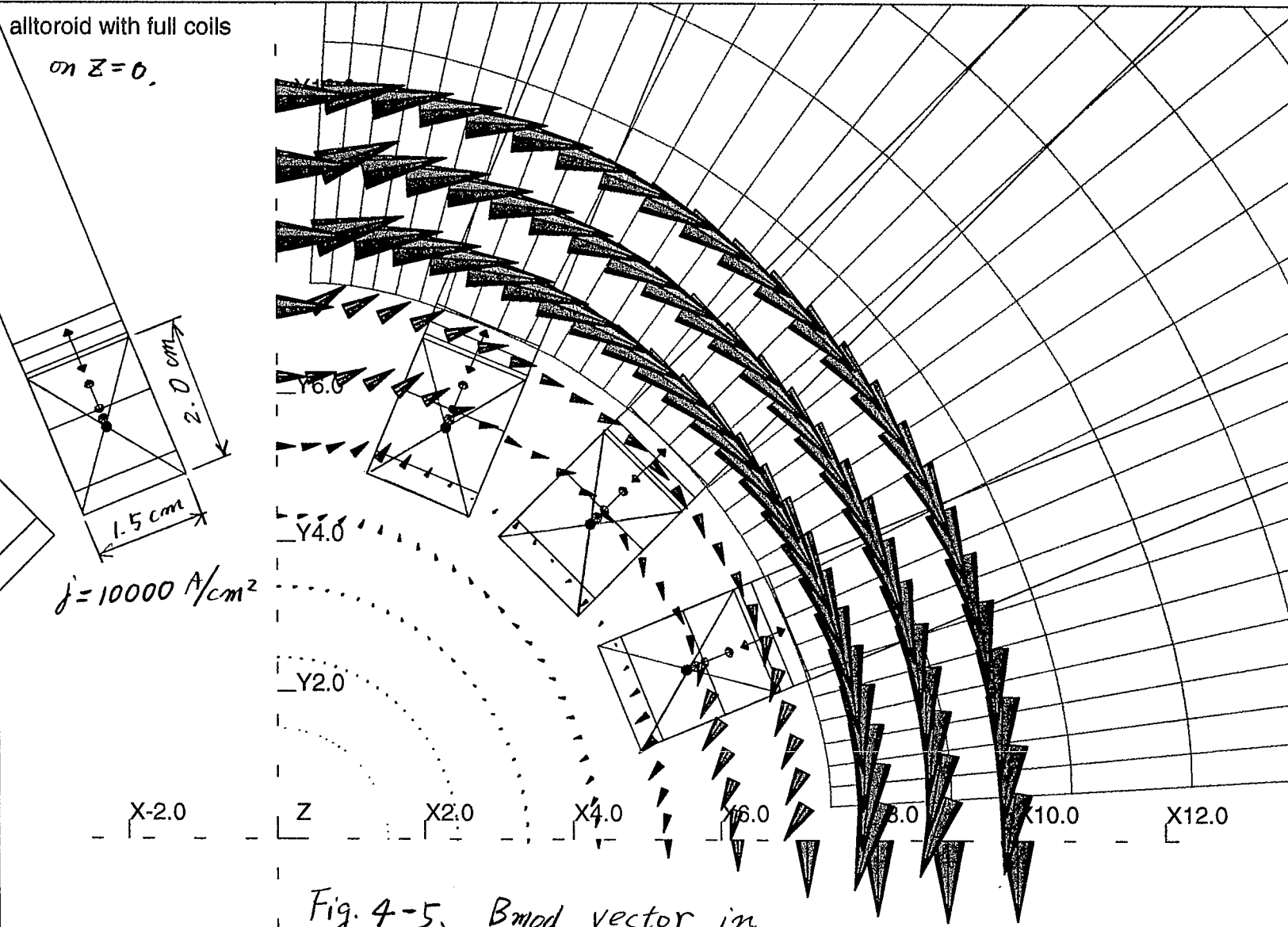


Fig. 4-5. Bmod vector in
Inner area

UNITS

Length : cm
Flux density : gauss
Magnetic field : oersted
Scalar potential : oersted
Vector potential : gauss
Conductivity : S/cm
Current density : A/cm²
Power : W
Force : N
Energy : J
Electric field : V/cm

PROBLEM DATA

alltoroid.toscab
TOSCA analysis
Case No. 1
86000 element
92004 nodes
Shape funct. field
Nodal coil fields

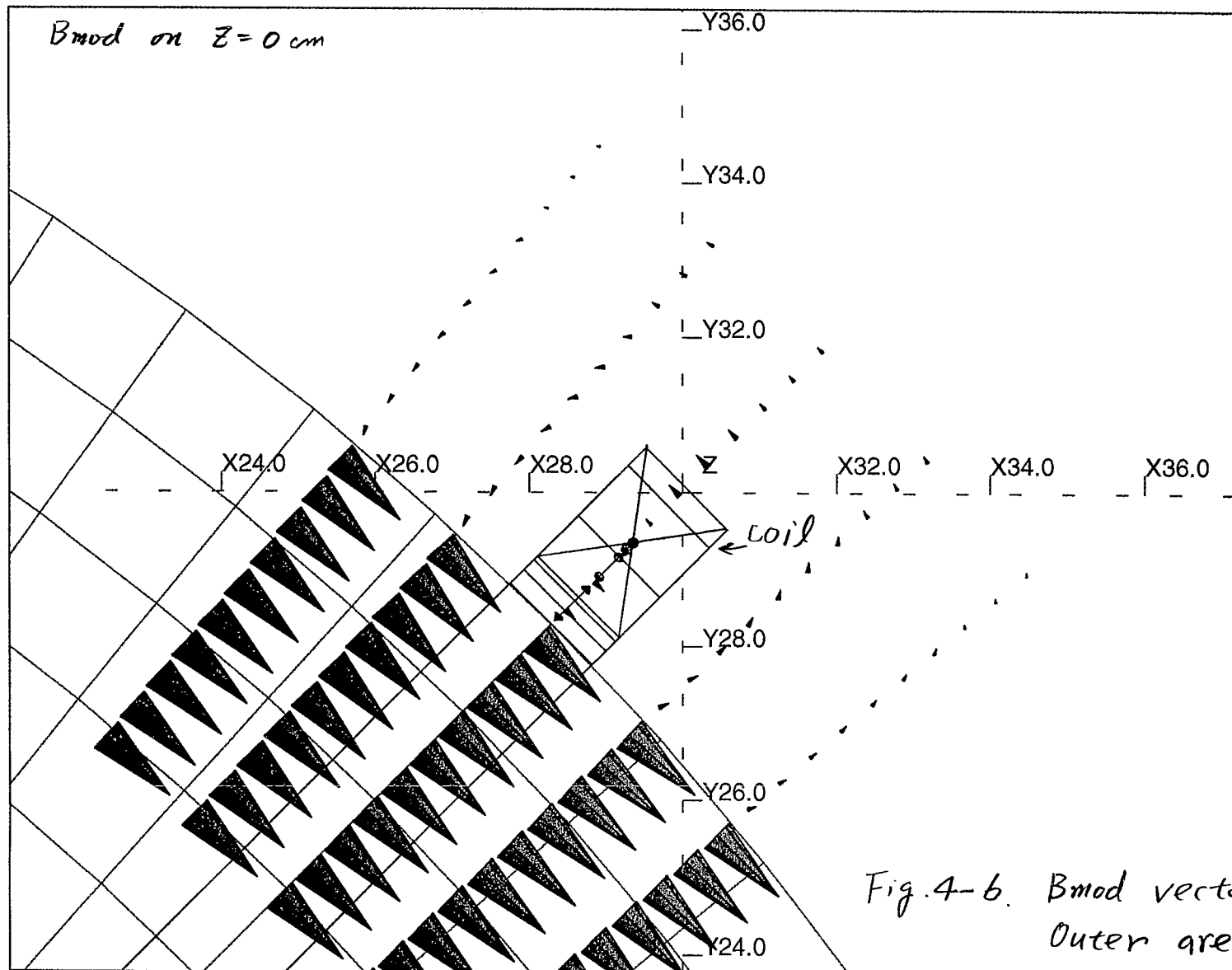
LOCAL COORDINATES

Xlocal = 0.0
Ylocal = 0.0
Zlocal = 0.0
Theta = 0.0
Phi = 0.0
Psi = 0.0

23Jan/96 10:12:57

OPER
Post-processor

B_{mod} on Z = 0 cm



| UNITS | |
|------------------|-----------|
| Length | : cm |
| Flux density | : gauss |
| Magnetic field | : oersted |
| Scalar potential | : oersted |
| Vector potential | : gauss |
| Conductivity | : S/cm |
| Current density | : A/cm |
| Power | : W |
| Force | : N |
| Energy | : J |
| Electric field | : V/cm |

PROBLEM DATA
alltoroid.toscab
TOSCA analysis (Case No 1)
86000 elements
92004 nodes
Shape funct. fields
Nodal coil fields

LOCAL COORDINATES
Xlocal = 0.0
Ylocal = 0.0
Zlocal = 0.0
Theta = 0.0
Phi = 0.0
Psi = 0.0

Fig.4-6. Bmod vector in Outer area

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OPERATOR
Post-processor 2

Problem points

- ① Big field!
- ② Vector direction on Y axis is opposite!

Fig. 5-1. Error field and mesh size

Vector direction
on Y axis
is opposite!
No!!

Fig. 5-2. One turn Total potential problem

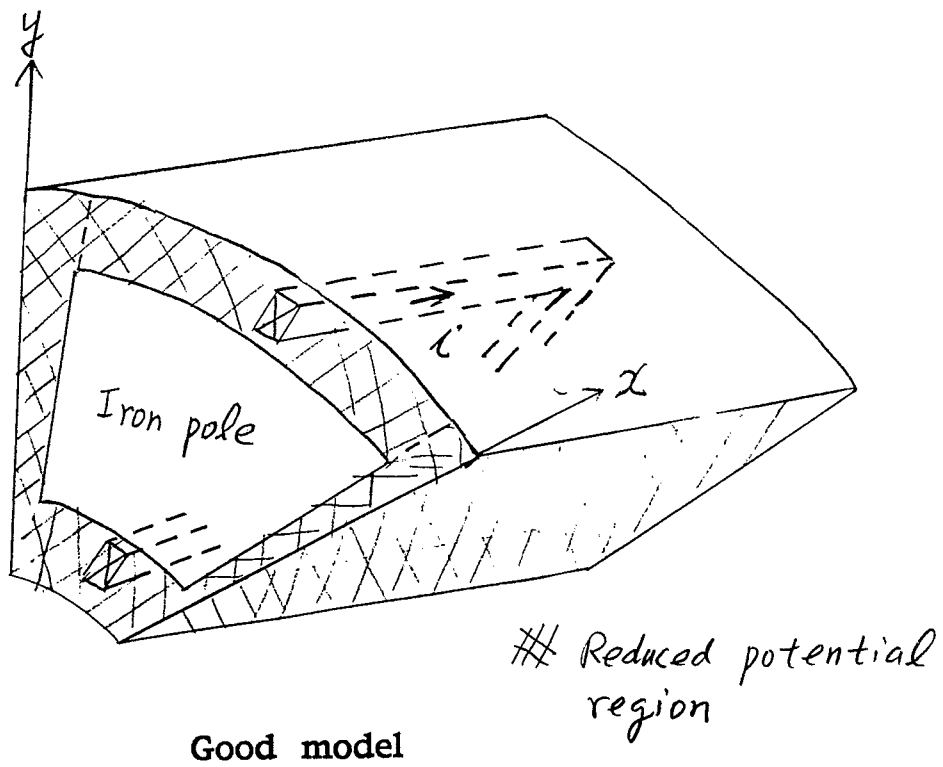
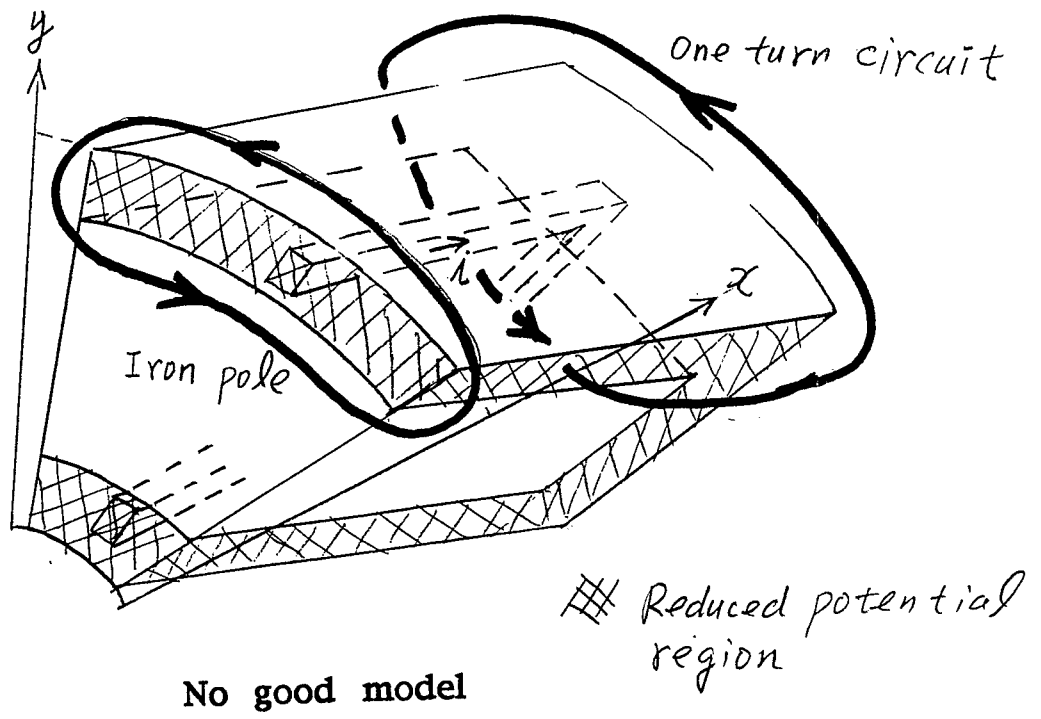


Fig. 5-3. One turn Total potential problem

toroid122rr with only three coils

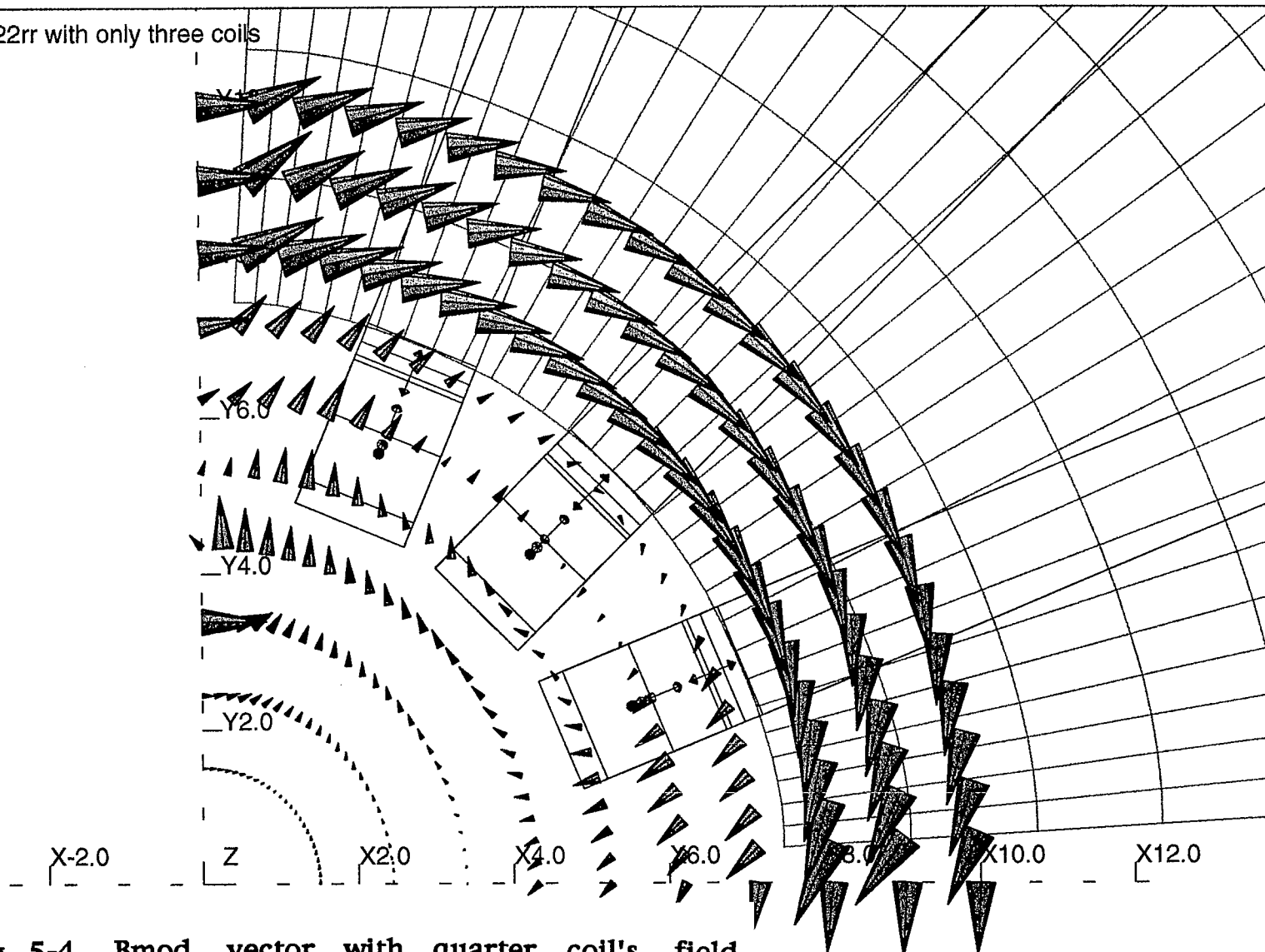


Fig. 5-4 Bmod vector with quarter coil's field

UNITS

Length : cm
Flux density : gau
Magnetic field : oer:
Scalar potential : oer:
Vector potential : gau
Conductivity : S cm
Current density : A cm
Power : W
Force : N
Energy : J
Electric field : V cm

PROBLEM DATA

toroid122rr.toscab
TOSCA analysis (
Case No 1
86000 elements
92004 nodes
Shape funct. fields
Nodal coil fields

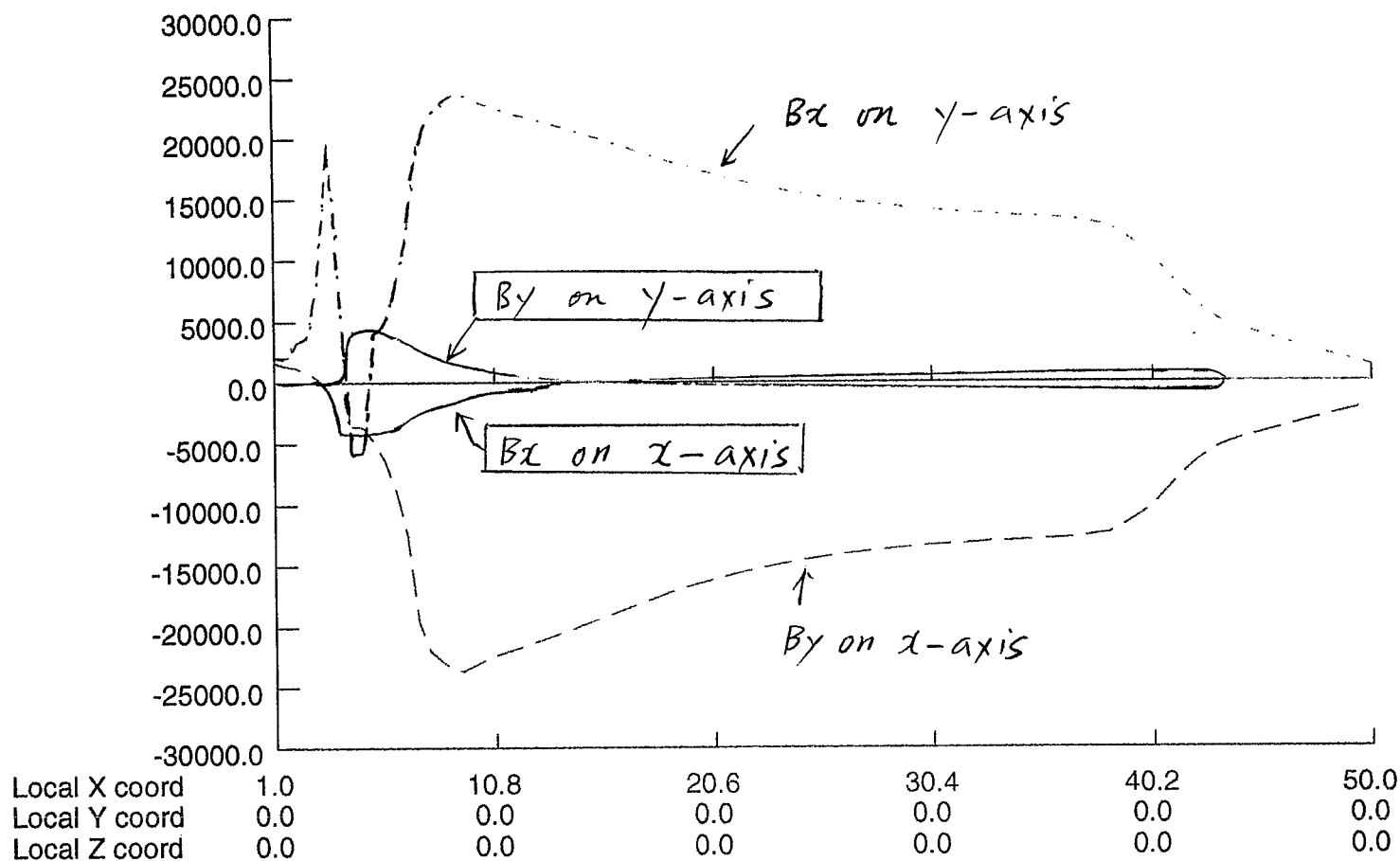
LOCAL COORDINATES

Xlocal = 0.0
Ylocal = 0.0
Zlocal = 0.0
Theta = 0.0
Phi = 0.0
Psi = 0.0

23/Jan/96 10:01:05 F

OPER
Post-processor 2

toroid122rr with only three coils



— — Component: BY, Integral = -602905.0
 - - - Component: BX, Integral = -5891.79
 . . . Component: BX, Integral = 628609.0
 Component: BY, Integral = 5891.26

Fig 5-5 Field components on boundary face with quarter coil's field

| UNITS | |
|------------------|--------|
| Length | : cm |
| Flux density | : gau |
| Magnetic field | : oer |
| Scalar potential | : oer |
| Vector potential | : gau |
| Conductivity | : S cm |
| Current density | : A cm |
| Power | : W |
| Force | : N |
| Energy | : J |
| Electric field | : V cm |

PROBLEM DATA
 toroid122rr.toscab
 TOSCA analysis (Case No 1)
 86000 elements
 92004 nodes
 Shape funct. fields
 Nodal coil fields

LOCAL COORD
 Xlocal = 0.0
 Ylocal = 0.0
 Zlocal = 0.0
 Theta = 0.0
 Phi = 0.0
 Psi = 0.0