Axial Symmetry of the GEM Magnetic Field

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The axial symmetry of the GEM magnetic field have been investigated. The axial symmetry have been considered in the terms of PHI-dependance of the absolute value of B [Tesla]. Magnetic field in the barrel region is symmetrical about the beam axis to 0.23% in full accordance to the GEM Magnet Engineering Design Report (GEM TN-92-116, December 1992). Magnetic field in the last superlayers of the endcap muon chambers is out of this requirement and non-symmetric about Z-axes to 10.5% in worse case. The main source of this non-uniformity is the ferromagnetic FFS support. So mapping procedure and muon reconstruction code in this areas have to be complicated than for the symmetrical field.
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ABSTRACT:

The axial symmetry of the GEM magnetic field have been investigated. The axial symmetry have been considered in the terms of PHI - dependance of the absolute value of B [Tesla]. Magnetic field in the barrel region is symmetrical about the beam axis to 0.23 % in full accordance to the GEM Magnet Engineering Design Report (GEM TN-92-116, December 1992). Magnetic field in the last superlayers of the endcap muon chambers is out of this requirement and non-symmetric about Z-axes to 10.5 % in worse case. The main source of this non-uniformity is the ferromagnetic FFS support. So mapping procedure and muon reconstruction code in this areas have to be complicated than for the symmetrical field.
The 3-dimensional magnetic analysis of the GEM detector was carried out using the OPERA-3d preprocessor program, TOSCA analysis program and OPERA-3d postprocessor program on UNIX workstation.

1. PROBLEM.

The problem has been investigated is the axial symmetry of the magnetic field of the GEM detector. The axial symmetry of the magnetic field is the important parameter, that defined the procedure of the mapping of the magnetic field, defined the particle reconstruction code and defined the tilting of the muon chambers to reduce the Lorentz-angle effect. If magnetic field is symmetrical around the beam axis the mapping procedure is more simple and more cheap than for non-symmetrical case, and particle reconstruction code is more simple and computer time is smaller than for non-symmetrical field. If Bz component of the magnetic field is non-symmetrical the tilting angle of the muon chambers in the barrel have to be different according to Bz.

2. PROCESS STREAM

To compute magnetic fields in 3-d the TOSCA analysis program have been used. The TOSCA analysis program have been used on the data prepared by the OPERA-3d preprocessor program.

The OPERA-3d preprocessor have been used to create and edit 3-d finite element models, define material characteristics, assign boundary conditions, specify conductor and output data files in the format accepted by the analysis programs.

To display the results and perform further calculations on results from analysis program the OPERA-3d postprocessor program have been used.

3. GEM MAGNET SYSTEM.

The GEM magnet system is a large superconducting solenoid assembly with field shaping in the forward region. The solenoid assembly is physically 31 m long with 18 m diameter inner bore and produces a central field of 0.8 Tesla. It consists of two half-length coil assemblies, each 14234 mm long, separated by a distance of 1532 mm at the midplane. In the forward direction the magnetic field is shaped to improve the muon resolution. This shaping is accomplished by large ferromagnetic structures, called Forward Field Shapers (FFS), which are roughly projective to the IP, coaxial with the beam axis, and occupy the volume from 10-18 m from the IP in both directions. The overall design of the GEM detector is presented in Fig 1, the FFS - in Fig. 2 and the FFS support - in Fig. 3.

4. PREPARING OF THE FEM-MODEL

For our analysis using the symmetry of the magnet system only 1/4 of the system was simulated. Although the symmetry of the finite element mesh allows only quarter of the complete problem to be modelled, the ALL 2 coils must be inclined. The partial differential equation formulation of
TOSCA requires that the AIR surrounding the object is also included in the model.

The FEM-model is preparing in the OPERA-3d preprocessor program. The model is created by four steps:
- creating the GEOMETRY,
- defining the PROPERTIES of the geometry volumes,
- defining the BOUNDARY CONDITION,
- creating the CONDUCTORS.

4.1 GEOMETRY

The GEOMETRY is created by defining the geometry of the three dimensional object projected onto a "base plane", discretising the projection into finite elements and then extruding it through space.

The "base plane" and the direction of the extrusion are defining in the local coordinate system (LCS) - (U,V,W). For our case we define U=X, V=Y, W=Z and "base plane" is placed in Z=-25000mm. The extrusion of the model have been done along Z-axis on the 20 planes. All dimensions have been used are according latest GEM design. The FFS support made from the steel plates 100 mm thickness.

4.2 PROPERTIES

The PROPERTIES of the geometry volumes include the MATERIAL CHARACTERISTICS, the POTENTIAL TYPES and other properties.

The MATERIAL CHARACTERISTICS that defined the magnetic properties of the steel is BH-curve. The FFS have to be made from the steel with high permeability. For our analysis the steel A-87 (Russia) was taken. The material of the FFS support has not defined yet. For our analysis the steel A-87 has been taken as the FFS support material. BH-curve of the A87 steel is presented in Fig.4. This curve was based on the data provided by Westinghouse Electric Corporation.

The formulation of the TOSCA requires that source conductors within the problem are contained within volumes in which the REDUCED MAGNETIC SCALAR POTENTIAL is the solution potential, while in magnetic material volumes TOTAL MAGNETIC SCALAR POTENTIAL should be used. Other non-magnetic volumes may be of either potential type. According to this requirement the "reduced potential" (REDU) have been assigned to the air around the steel and "total magnetic potential" (TOTA) - to the steel.

4.3 BOUNDARY CONDITION

The BOUNDARY CONDITIONs define the symmetry of the problem and describe the behaviour of the field at the external surface. They are assigned after the geometry is created and properties are assigned. OPERA/TOSCA work with scalar potential F. The default boundary conditions is the Neumann condition ie. normal derivative of solution quantity is zero. TOSCA require the user to modify these defaults since, to
solve the linear simultaneous equations to which the finite element method leads, it is necessary condition that the value of potential solved be assigned for at least one node of the finite element mesh; otherwise the matrix of equations is singular and the solution algorithms are not able to converge to a unique solution.

For our case the Dirichlet boundary condition for the scalar potential - \( F = 0 \) (POT=0 in the OPERA-3d preprocessor) was used to define the boundary condition at the XY plane at \( Z = 0 \). For all other boundaries the default (Neumann) boundary condition - \( \frac{dF}{dn} = 0 \) was used.

4.4 CONDUCTORS

The GEM conductor consist of two half-length coil each 14234 mm long, about 9500 mm radius, separated by a distance of 1532 mm at the midplane. Each coil half is constructed out of 12 identical segments. Each segments consist of 19 turns. The baseline dimensions of the coil is presented in Fig.1. For analysis 228 turns of each coil were simulated by one turn with \( H = 69 \) mm and \( W = 14234 \) mm.

In the OPERA/TOSCA code the conductors are specified independently from the geometry. The formulation of TOSCA is such that conductors must be contained within a region of REDUCED potential. Although the symmetry of the finite element mesh allows only quarter of the complete problem to be modelled, the all 2 coils must be inclined.

OPERA have a wide range of pre-defined conductor geometries. For our calculations we take "generally oriented solenoid"-GSOL with the next parameters:

local coordinate system 1: \( X_{CEN} = 0 \), \( Y_{CEN} = 0 \), \( Z_{CEN} = 0 \), \( ANGL = 0 \),
local coordinate system 2: \( T = 90 \), \( P = 0 \), \( S = -90 \),
conductor cross-section: \( X_1 = 9459 \), \( Y_1 = 766 \), \( X_2 = 9459 \), \( Y_2 = 15000 \), \( X_3 = 9528 \), \( Y_3 = 15000 \), \( X_4 = 9528 \), \( Y_4 = 766 \),
current density and symmetry: \( CURD = 12 \) \( [A/mm^2] \), \( SYMM = 1 \),
reflections: \( IRXY = 1 \)
accuracy of the field calculations: \( TOLE = 0.0001 \) [Tesla]

Coil definitions have been stored in a file for subsequent use independently of the OPERA-3d.

4.5 UNITS

The OPERA/TOSCA programs allows the user to define data in either a CGS or SI system of units, with the SI system supporting metres, millimetres and microns as the unit of length. We used SI/mm system.

4.6 SPECIAL REQUIREMENTS

The requirement of the "simply connection of the reduced potential regions" lead to the necessity to introduce the slit into the FFS support to connect two reduced potential regions.
4.7 THE FEM-MODEL
The final FEM-model that has been used for the analysis is presented in Fig.5. It consists of 115710 elements (120120 nodes). Fig. 6 represents the model without mesh subdivision.

5. ANALYSIS
For the analysis, the TOSCA magnetostatics analysis program was used. The following parameters have been used:

UNIT=MM
PROB=MAGN - magnetostatic problem,
ELEM=LINE - linear type of element for the first iteration
FIELD=NODA - nodal averaging field calculating method,
MATE=NONL - non-linear material characteristics. The file A87.BH, has been used.

TOSCA stores the results of the calculations in a results "data base file" (file with ".toscab" extension) in binary format which can be accessed by the OPERA-3d post-processor. The FIELD=NODA (method of weighted averaging technique to evaluate a continuous field based on the nodal values), and COIL=INTE (method of integration of current density) method of field calculation have been used.

7. RESULTS.
The axial symmetry of the magnetic field have been investigated for the central tracking region and for the muon tracking region for the "barrel" and endcap areas separately. This regions have been defined according to the "Progress report on the GEM Detector Baseline Design", December 1992, GEM TN-92-231. The central tracking region has been defined as an area 700 mm in dia. and 2800 mm long centered on the interaction point. The muon tracking regions have been defined according to the muon chambers placements. The "barrel" muon region is defined as an area between Rmin=3854 mm and Rmax=8588 mm for THET=29.60 grad to THET=90 grad. The endcap muon region has been defined as an area between THET=9.75 grad and THET=29.60 grad from Z=5760 mm to Z=16250 mm (Fig. 1).

The axial symmetry have been considered in the terms of PHI-dependance of the absolute value of B [Tesla].

The map of B in the central tracking region is presented in Fig.7. The axial symmetry of the magnetic field in the central tracking region is presented by the distribution of B along the arc with radius 700 mm between PHI=90 grad and PHI=-90 grad for Z=0 (Fig.8). The axial symmetry of the magnetic field in the central tracking region is to 0.05%.

The map of B for the barrel muon region is presented in Fig.9. The axial symmetry of the magnetic field in the barrel muon region is presented by the distribution of B along the arcs with radius R1=3584 mm (first
superlayer of the barrel muon chambers), R2=6282 mm (second superlayer of the barrel muon chambers) and R3=8588 mm (third superlayer of the barrel muon chambers) for Z=3000 mm is presented in Fig.10. The axial nonsymmetry of the magnetic field in the barrel muon region is to 20 Gauss (0.23 %).

The endcap muon region have been divided on two areas, according to the placements of the endcap muon chambers. First area is the area between THET=9.75 grad and THET=17.01 grad, second area is the area between THET=17.01 grad and THET=29.60 grad (Fig.1).

The map of B for the first area is presented in Fig.11. The axial symmetry of the magnetic field in the first area is presented by the distribution of B along the arcs with radius 1134 mm and 1337 mm between PHI=90 grad and PHI=-90 grad for Z=6600 mm (first superlayer of the endcap muon chambers, Fig.12), along the arcs with radius 1933 mm and 3442 mm for Z=11250 mm (second superlayer of the endcap muon chambers, Fig.13) and along the arcs with radius 2792 mm and 4971 mm for Z=16250 mm (third superlayer of the endcap muon chambers, Fig.14). The axial symmetry of the magnetic field in the region of the first and second endcap muon chamber superlayers is to 20 Gauss (0.2 %) (Figs.12,13). In the area of third superlayer of the endcap muon chambers the non-symmetry is up to 400 Gauss (10.5 %) (Fig.14).

The map of B for the second area is presented in Fig.15. The axial symmetry of the magnetic field in the second area is presented by the distribution of B along the arcs with radius 1167 mm and 3025 mm between PHI=90 grad and PHI=-90 grad for Z=5760 mm (forth superlayer of the endcap muon chambers, Fig.16), along the arcs with radius 3044 mm and 5226 mm for Z=9950 mm (fifth superlayer of the endcap muon chambers, Fig.17) and along the arcs with radius 4512 mm and 8379 mm for Z=14750 mm (sixth superlayer of the endcap muon chambers, Fig.18). The axial symmetry of the magnetic field in the region of the forth and fifth forward muon chamber superlayers is to 20 Gauss (0.2 %) (Figs.16,17). In the area of sixth superlayer of the endcap muon chambers the non-symmetry is up to 170 Gauss (3.98 %) (Fig.18). The 3-dimensional plot of the magnetic field in the area of endcap muon chambers (12000 mm<Z<16250 mm, R=4971 mm) is presented in Fig.19. The "background" magnetic field (for the model without FFS support) is presented in Fig.20. The effect of the FFS support is obvious.

CONCLUSION.

The axial symmetry of the GEM magnetic field have been investigated. The axial symmetry have been considered in the terms of PHI - dependance of the absolute value of B [Tesla]. Magnetic field in the barrel region is symmetrical about the beam axis to 0.23 % in full accordance to the GEM Magnet Engineering Design Report (GEM TN-92-116, December 1992). Magnetic field in the last superlayers of the endcap muon chambers is out of this requirement and non-symmetric about Z-axes to 10.5 % in worse case. The main source of this non-uniformity is the ferromagnetic FFS support.
LIST OF DRAWINGS:

Fig.1 The overall design of the GEM detectors.

Fig.2 The overall design of the FFS.

Fig.3 The overall design of the FFS support.

Fig.4 BH-curve of the A-87 steel.

Fig.5 The final FEM model.

Fig.6 The model without mesh subdivision.

Fig.7 Map of B in the central tracking region.

Fig.8 Distribution of B along the arc with radius 700 mm between PHI=90 grad and PHI=-90 grad for Z=0 mm and Z=1400 mm.

Fig.9 Map of B in the barrel muon region.

Fig.10 Distribution of B along the arcs with radius R1=3584 mm (first superlayer of the barrel muon chambers), R2=6282 mm (second superlayer of the barrel muon chambers) and R3=8588 mm (third superlayer of the barrel muon chambers) for Z=5000 mm.

Fig.11 Map of B for the first endcap muon area (between THET=9.75 grad and THET=17.01 grad).

Fig.12 Distribution of B along the arcs with radius R1=1134 mm and 1337 mm for Z=6600 mm (first superlayer of the endcap muon chambers).

Fig.13 Distribution of B along the arcs with radius R1=1933 mm and 3442 mm for Z=11250 mm (second superlayer of the endcap muon chambers).

Fig.14 Distribution of B along the arcs with radius R1=2792 mm and 4971 mm for Z=16250 mm (third superlayer of the endcap muon chambers).

Fig.15 Map of B for the second endcap muon region (between THET=17.01 grad and THET=29.60 grad).

Fig.16 Distribution of B along the arcs with radius R1=1167 mm and 3025 mm for Z=5760 mm (forth superlayer of the endcap muon chambers).

Fig.17 Distribution of B along the arcs with radius R1=3044 mm and 5226 mm for Z=9950 mm (fifth superlayer of the endcap muon chambers).
Fig.18 Distribution of $B$ along the arcs with radius $R_1=4512$ mm and 8379 mm for $Z=14750$ mm (sixth superlayer of the endcap muon chambers).

Fig.19 Plot of the magnetic field in the endcap region.

Fig.20 Plot of the magnetic field in the endcap region for the model without support.
GEM DETECTOR PARAMETERS
BASELINE 2
Forward Field Shaper (detail)
Baseline 2 - 11/18/92
B [Tesla]

Z=1400 mm
Z=0 mm

R=350 mm

\[ \text{Component: BMOD, Integral} = 894.59 \]
\[ \text{Component: BMOD, Integral} = 892.367 \]

VF/OPERA-3d (Post-processor)
Z = 3000 mm
Rmin = 3854 mm
Rmax = 8588 mm
Rmid = 6282 mm
\begin{center}
\includegraphics[width=\textwidth]{image.png}
\end{center}

\begin{itemize}
\item $B \text{ [Tesla]}$
\item $R = 1134 \text{ mm}$
\item $R = 1337 \text{ mm}$
\item $Z = -6600 \text{ mm}$
\end{itemize}

\begin{verbatim}
Component: BMOD, Integral = 3061.45
Component: BMOD, Integral = 3598.24
\end{verbatim}

\textit{VF/OPERA-3d (Post-processor)}
B [Tesla]

R = 1933 mm
R = 3442 mm

Z = -11250 mm

Component: BMOD, Integral = 4038.18
Component: BMOD, Integral = 7114.07

VF/OPERA-3d
(Post-processor)
Fig. 14

B [Tesla]

- R = 4971 mm
- Z = -16250 mm
- R = 2792 mm

VF/OPERA-3d

Component: BMOO, Integral = 1930.19
Component: BMOD, Integral = 5866.02
**B [Tesla]**

- **R=1167 mm**
- **R=3025 mm**

![Graph](image)

- **Z=-5760 mm**

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**VF/OPERA-3d**

*Post-processor*
B [Tesla]

R=3044 mm
R=5226 mm

Z=-9950 mm

X coord 0.001331 1789.22 2895.02 2895.02 1789.22 0.001331
Y coord 3044.0 2462.65 940.648 -940.648 -2462.65 -3044.0
Z coord 0.0 0.0 0.0 0.0 0.0 0.0

Component: BMOD, Integral = 7287.98
Component: BMOD, Integral = 12228.9

VF/OPERA-3d
(Post processor)
B [Tesla]

---

R = 8379 mm

Z = -14750 mm

R = 4512 mm

---

X coord: 0.0001972 2652.09 4291.17 -4291.17 2652.09 -0.0001972
Y coord: 4512.0 3650.28 1394.28 -1394.28 -3650.28 4512.0
Z coord: 0.0 0.0 0.0 0.0 0.0 0.0

Component: BMOD, Integral = 6011.53

Component: BMOD, Integral = 16435.2

VF/OPERA-3d
(Post processor)
Component: BMOD
Maximum = 0.59148, Minimum = 0.37392
Integral = 27350220.0

VF/OPERA-3d

R=4971 mm