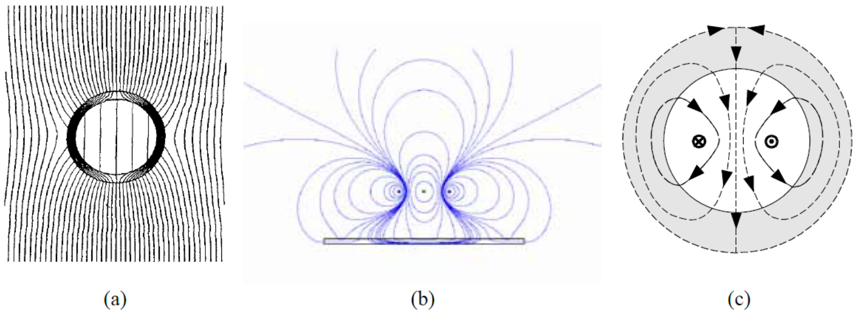


Figure 2.3.3 "Attracting-like" displacement of the magnetic field lines by a ferromagnetic shield: a) closed shield with external source (homogeneous field), b) open shield (three-phase field) and c) closed shield with internal source (single-phase field).

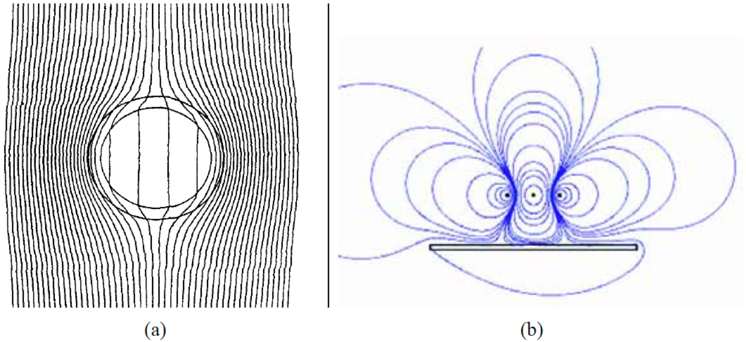


Figure 2.3.14 "Repelling-like" displacement of the magnetic field lines by a pure conductive shield: a) closed shield with external source (homogeneous field), b) open shield (three-phase source)

SHIELDING BENCHMARK

Static Shielding and Eddy Current Shielding

Tan H. Pham • Technical Director – LFEM – Flux • 04/11/2019

Altair

OBJECTIVES

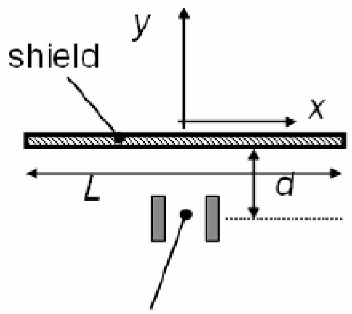
- 2D benchmarks
  - Static shielding
  - Eddy current shielding

- 3D benchmarks
  - Static shielding
  - Eddy current shielding

- Substation example
  - Import of HyperMesh model
  - Thin regions

BENCHMARK CASE

- CIGRE 373-2009 document: MITIGATION TECHNIQUES OF POWER-FREQUENCY MAGNETIC FIELDS ORIGINATED FROM ELECTRIC POWER SYSTEMS



The analysis is developed for simplicity making reference to a two-dimensional source, formed by a lead-and-return conductor. The shield (with thickness Δ and permeability μ) is realized by a planar sheet (having width *L*) or a by a U-shaped sheet, and it is placed at a distance *d* from the source (see Figure 2.3.8).

It must be noted that, in the U-shaped arrangement, each side has the same length *L* as the planar sheet. Hence, the U-shaped shield involves more shielding material than the planar shield.

The shielding factor depends on the position; the value is plotted along the y-axis (at x = 0) and along the x-axis (at y = d + 0.5, that is at 0.5 m from the shield).

STATIC SHIELDING BENCHMARK

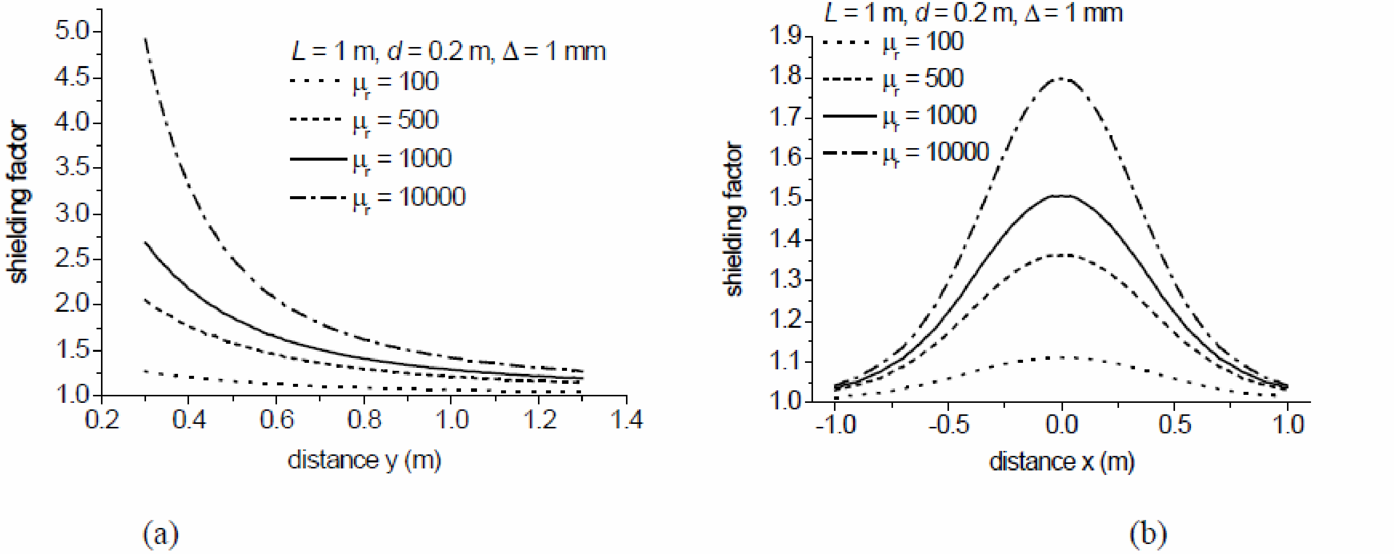
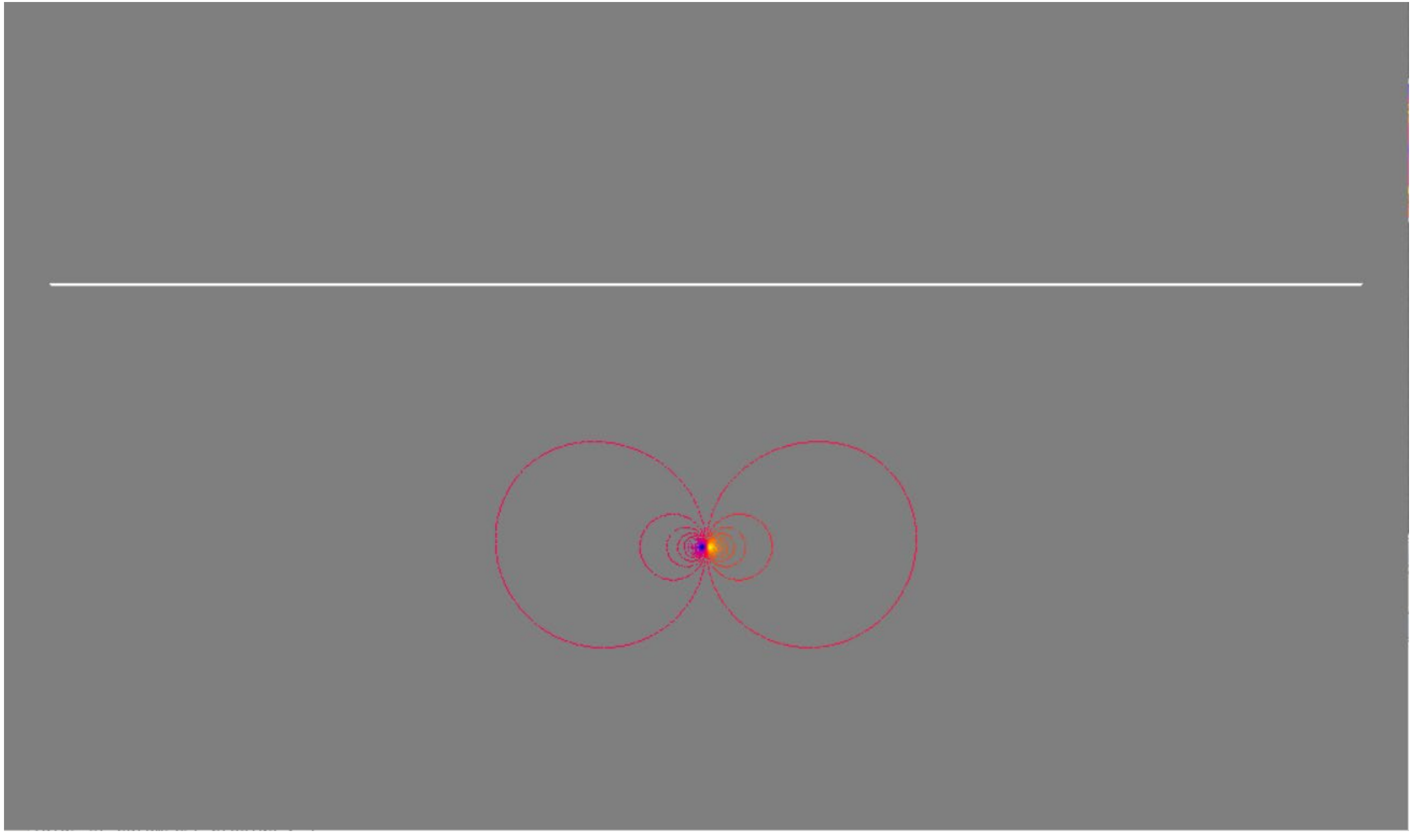


Figure 2.3.9 *SF* of the flat shield of Figure 2.3.8(a) for different values of magnetic permeability: (a) plot along y axis at $x = 0$, (b) plot along x axis at $y = 0.7$ m.

STATIC SHIELDING BENCHMARK FEA MODEL

- Source
  - Lead and return conductor with 4000 A DC
  - Infinite long conductor
- Plate dimensions
  - Length = 1000 mm
  - Thickness = 1 mm
  - Axial length = 1000 mm
    - 2D (infinite long)
    - 3D (actual length)
- Material
  - Linear steel Mur = 1000
- Model
  - 2D
  - 3D
  - 3D extruded
- Boundary conditions
  - Infinite box for 2D and 3D
  - 10000 mm radius for 3D extruded

STATIC SHIELDING BENCHMARK 2D FEA EQUIFLUX LINES

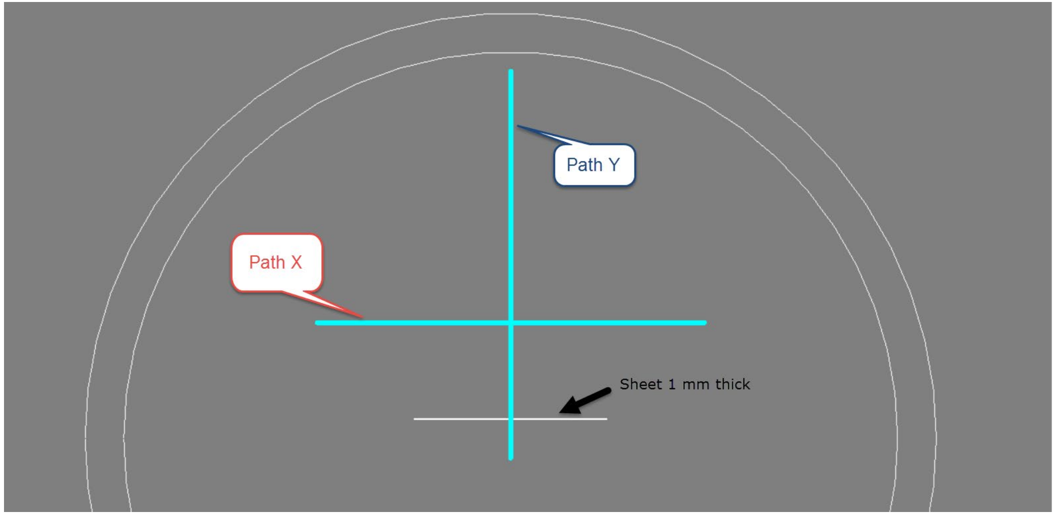


STATIC SHIELDING – 2D FEA POST-PROCESSING

- BX0: Magnitutde of B along Path X (no shield)
- BY0: Magnitude of B along Path Y (no shield)

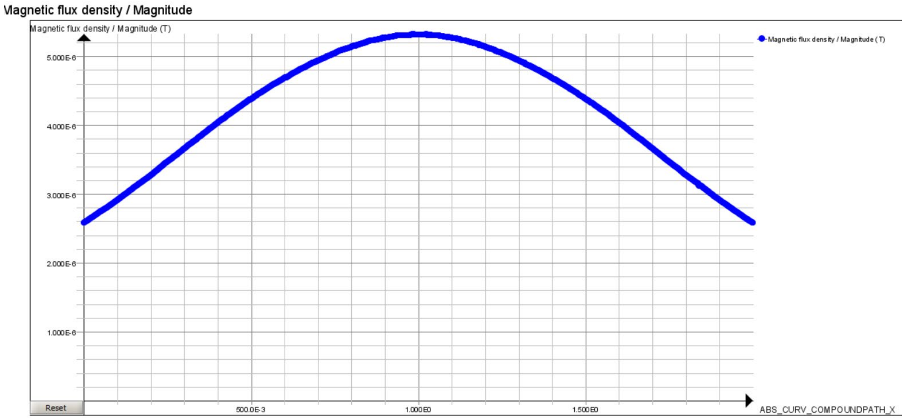
- BX: Magnitutde of B along Path X
- BY: Magnitude of B along Path Y

- SFX: Shielding factor = BX0/BX
- SFY: Shielding factor = BY0/BY

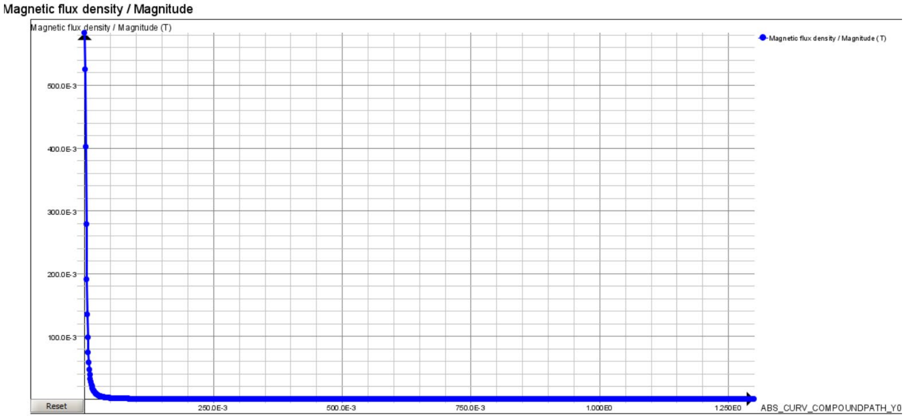


STATIC SHIELDING – 2D FEA POST-PROCESSING – BX & BY

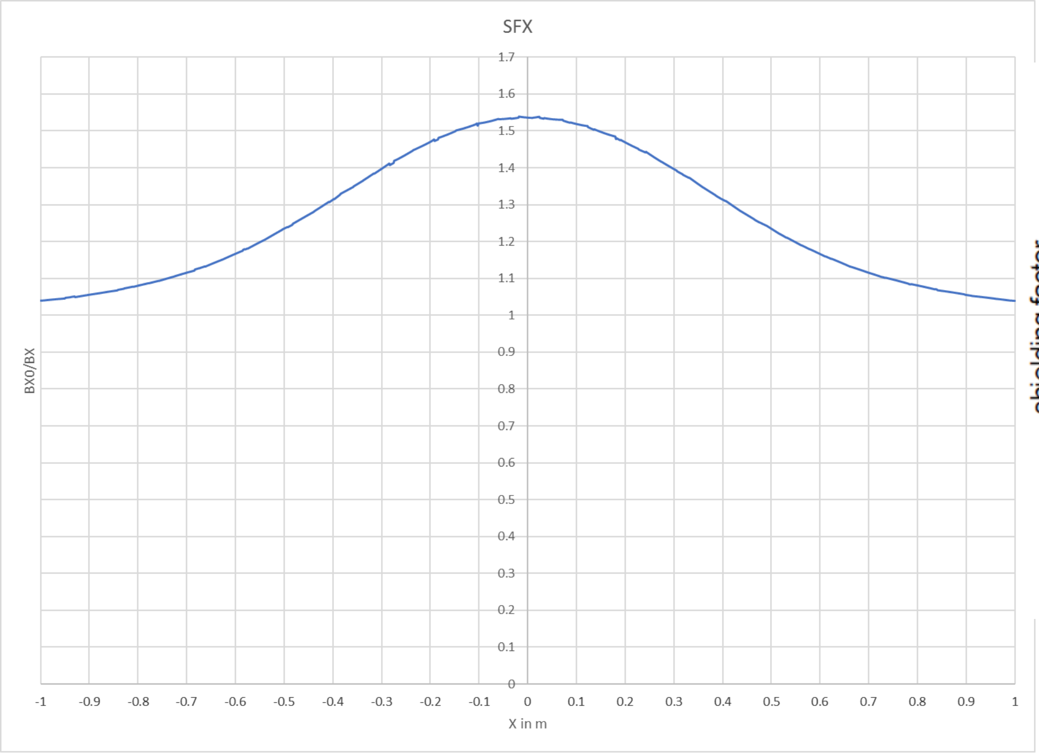
BX

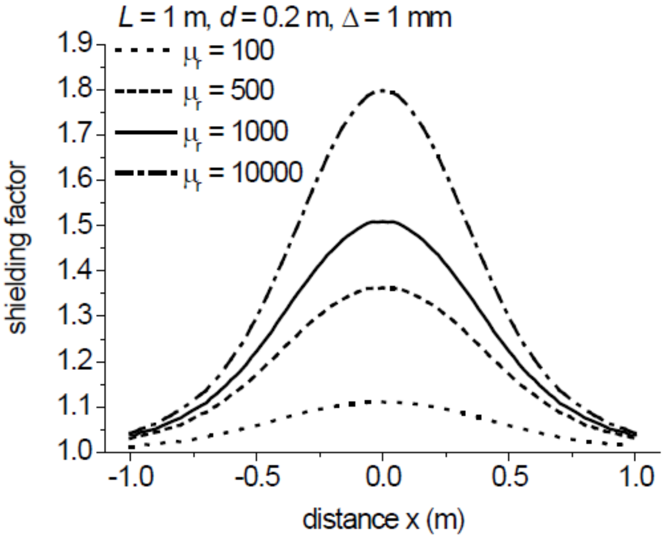


BY_1

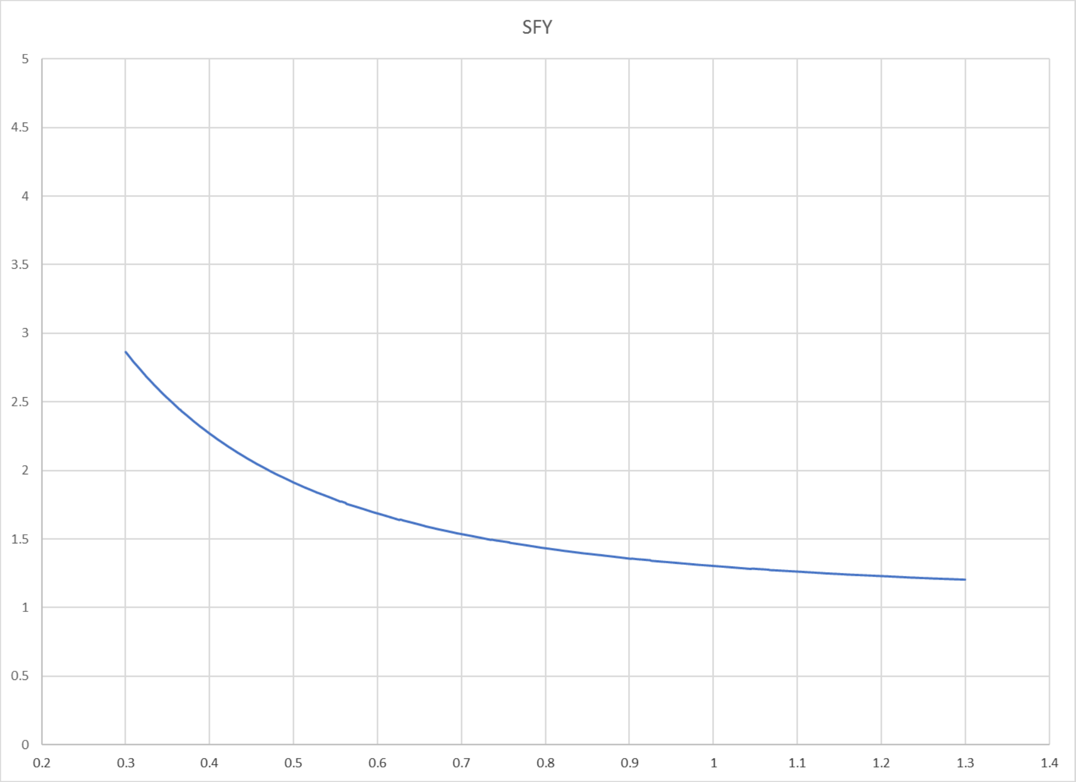


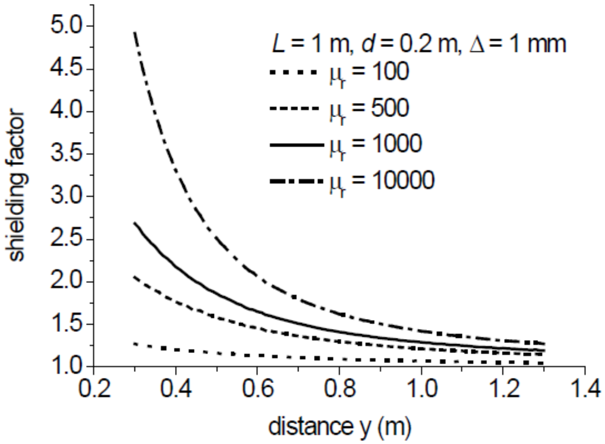
STATIC SHIELDING – 2D FEA POST-PROCESSING – SFX





STATIC SHIELDING – 2D FEA POST-PROCESSING – SFY





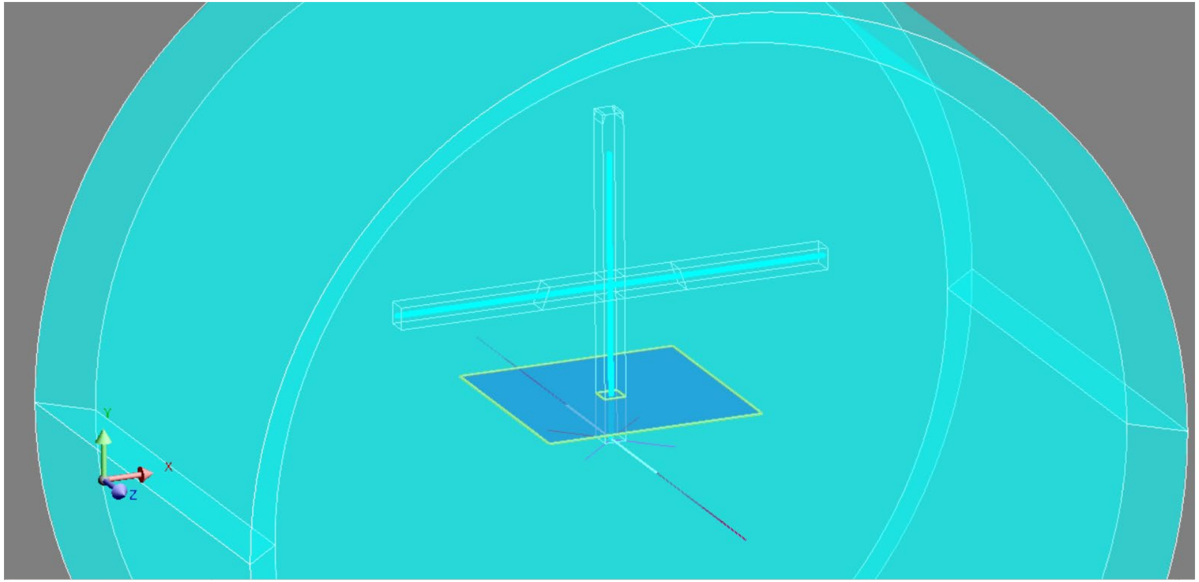
STATIC SHIELDING – 2D FEA MODEL - COMMENTS

- Good correlation between 2D FEA results with CIGRE data
  - Model of Fig. 238 a
  - Data of Fig. 239 a and b

- 2D FEA model
  - Assumes infinite long conductor
  - Assumes infinite long sheet (axially)
  - Even though the axial length is defined for 1000 mm
  - Uses of infinite box for open field boundaries

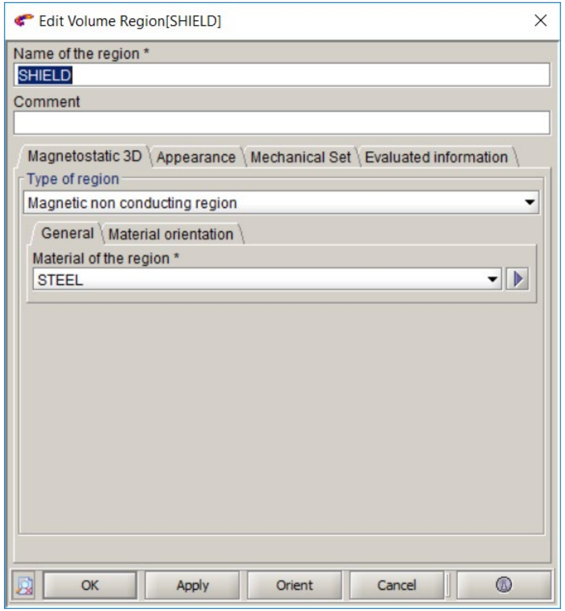
STATIC SHIELDING BENCHMARK – 3D MODEL

- Open field boundary conditions with Infinite Box
- Conductors
  - Non meshed coils
  - Infinitely long
- Sheet
  - Volume region with mesh
  - Thin magnetic face region with 1 mm thickness

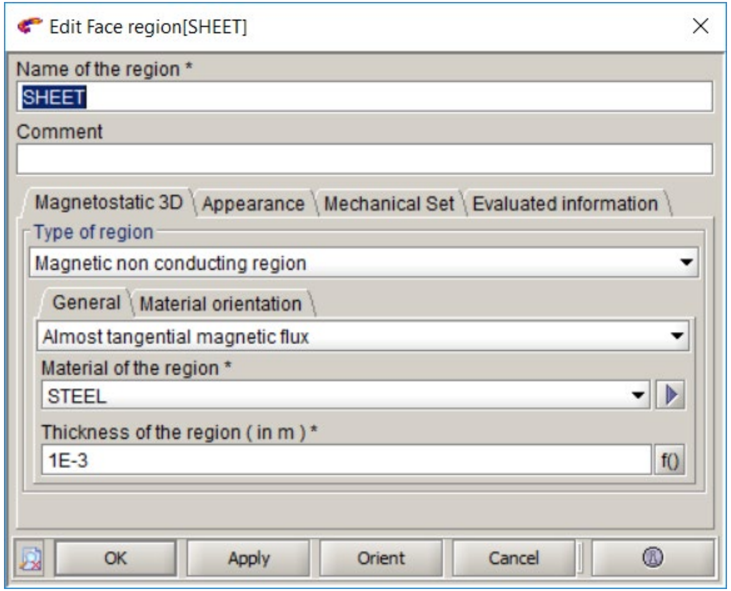


STATIC SHIELDING BENCHMARK – SHEET

- Sheet with volume region
  - Geometrically represented
  - Volume meshed
  - Magnetic region



- Sheet with thin faceregion
  - Geometrically represented by a face
  - Magnetic thin face region
  - Thickness of 1 mm

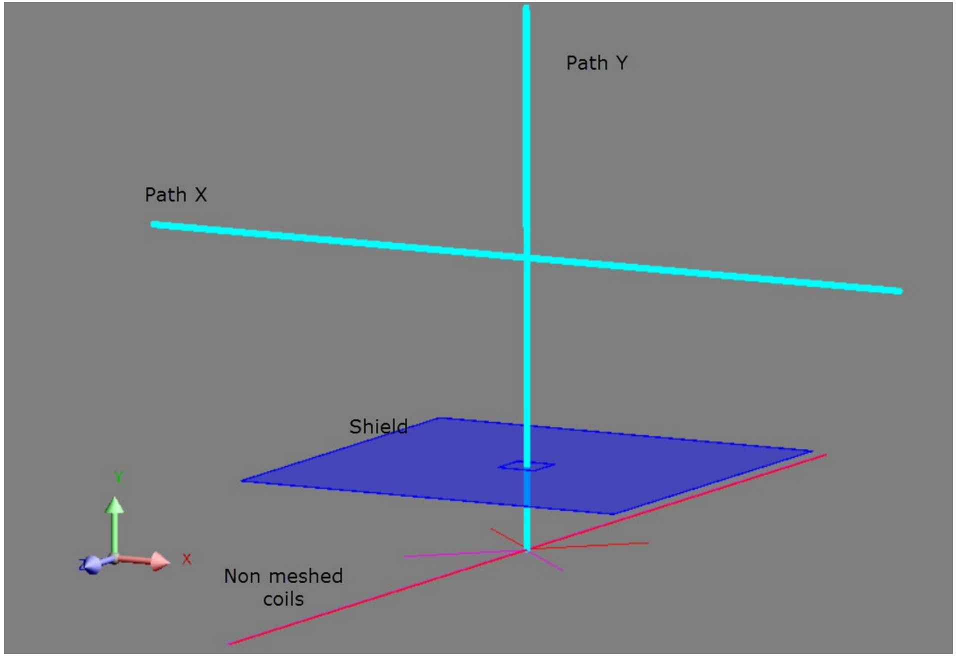


STATIC SHIELDING – 3D FEA POST-PROCESSING

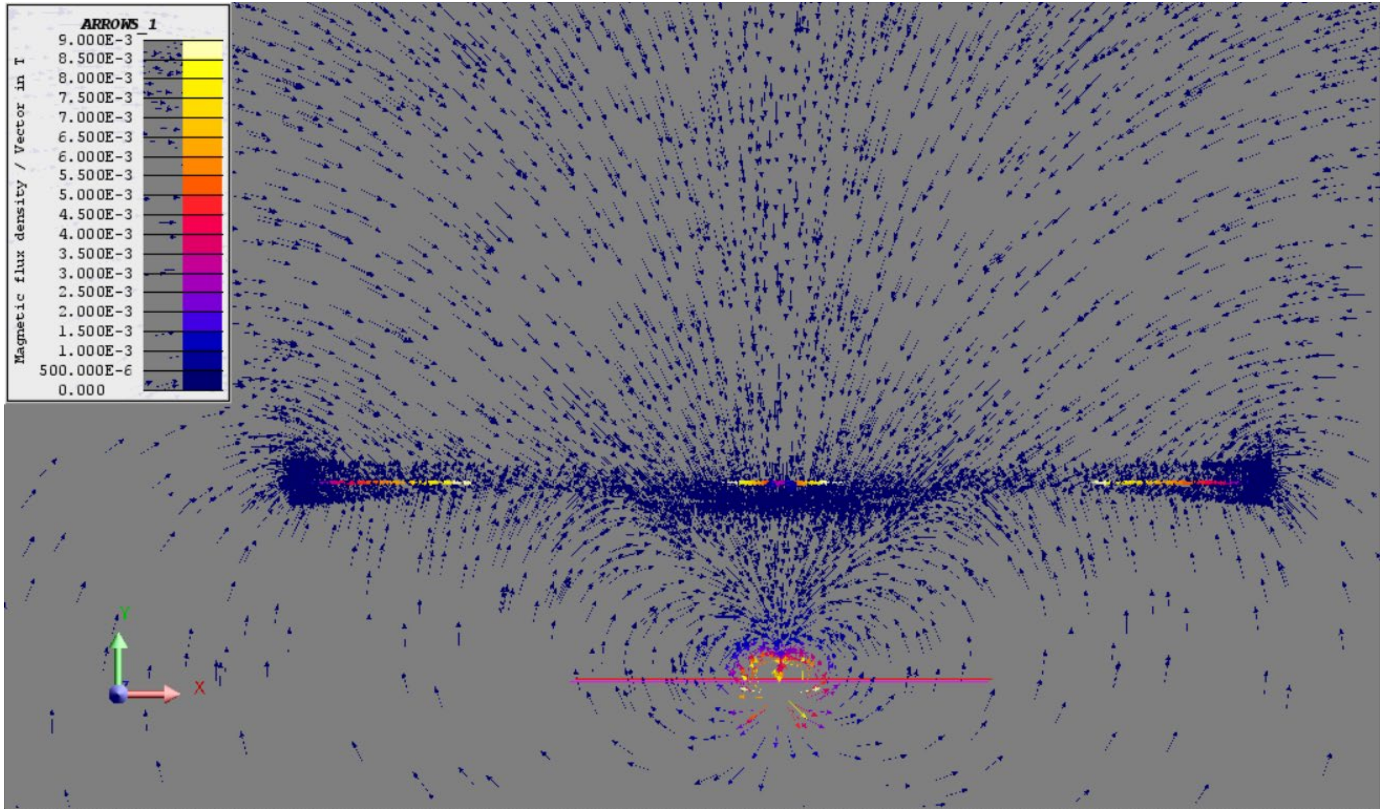
- BX0: Magnitutde of B along Path X (no shield)
- BY0: Magnitude of B along Path Y (no shield)

- BX: Magnitutde of B along Path X
- BY: Magnitude of B along Path Y

- SFX: Shielding factor = BX0/BX
- SFY: Shielding factor = BY0/BY

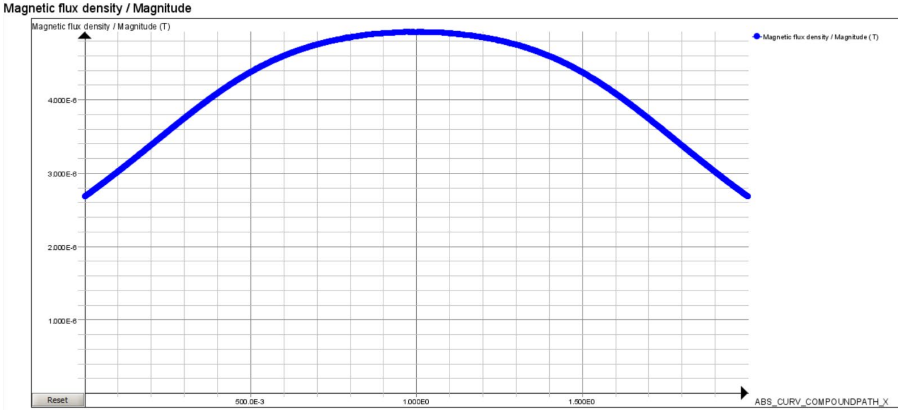


STATIC SHIELDING BENCHMARK 3D FEA – FLUX DENSITY B ON X-Y PLANE – 3D VOLUME REGION

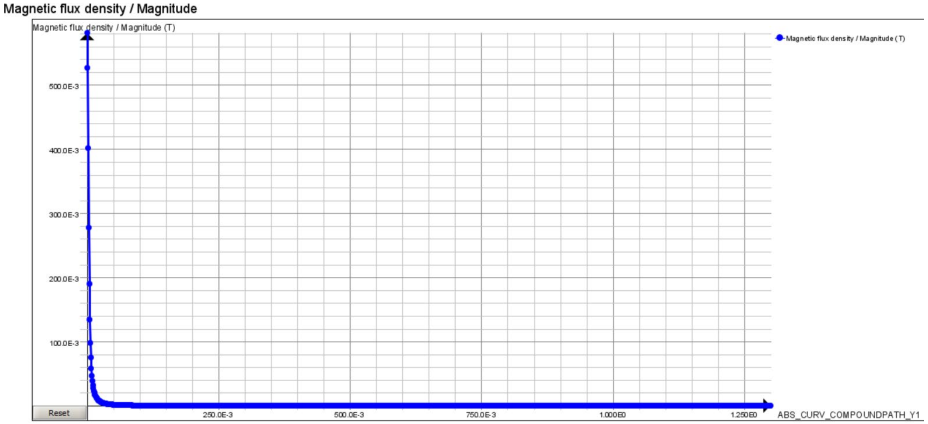


STATIC SHIELDING – 3D FEA POST-PROCESSING – BX & BY – VOLUME REGION SHIELD

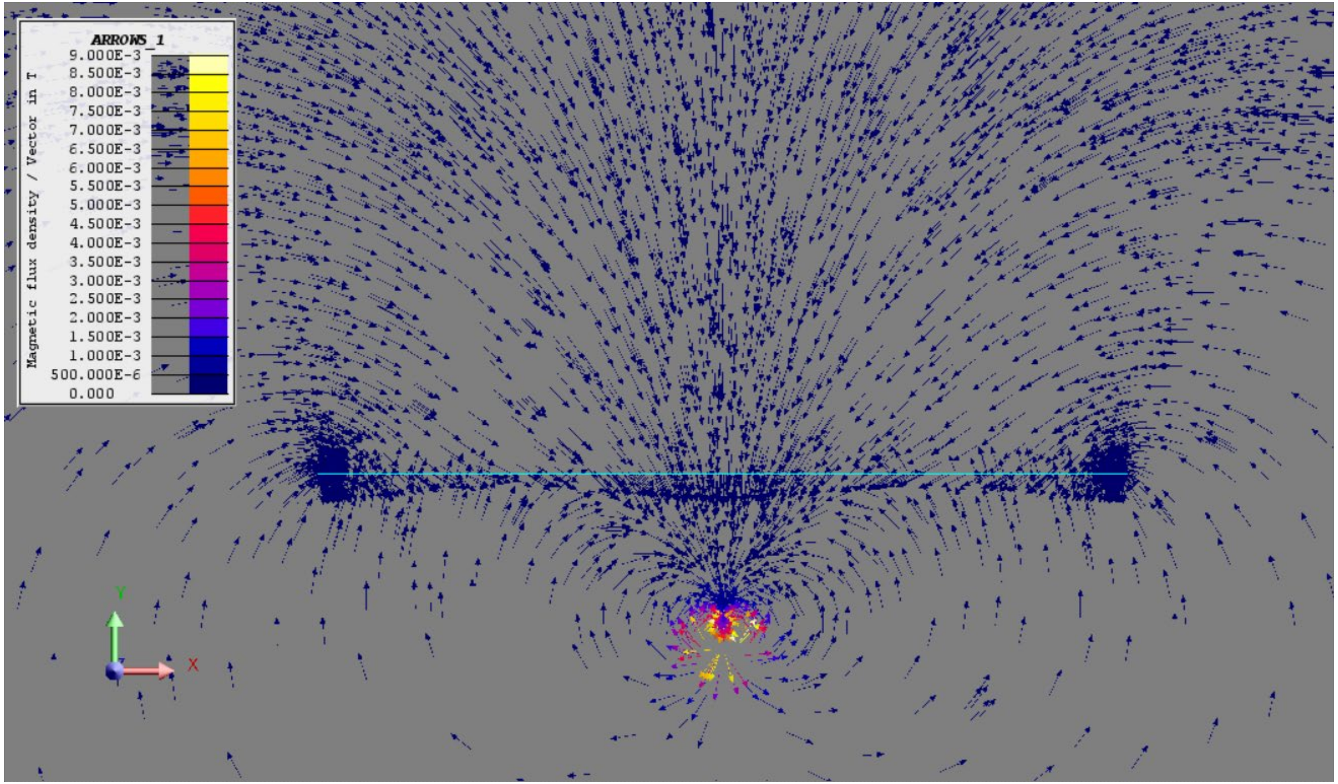
BX



BY

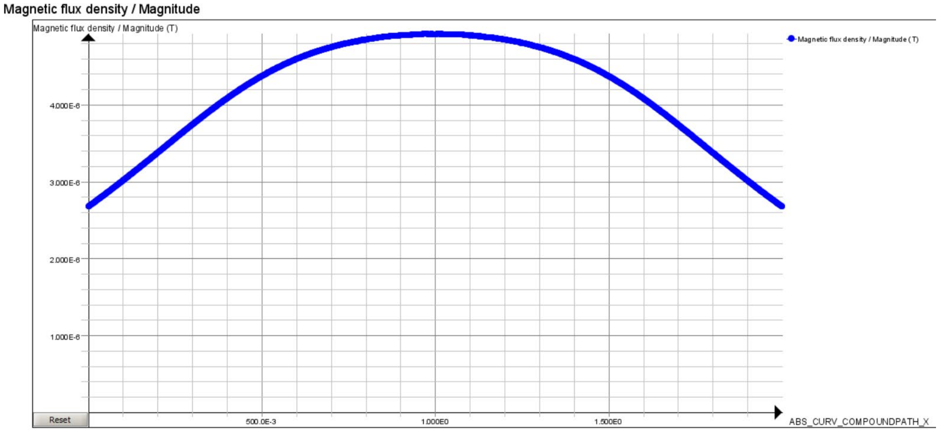


STATIC SHIELDING BENCHMARK 3D FEA – FLUX DENSITY B ON X-Y PLANE – SHEET THIN MAGNETIC FACE REGION



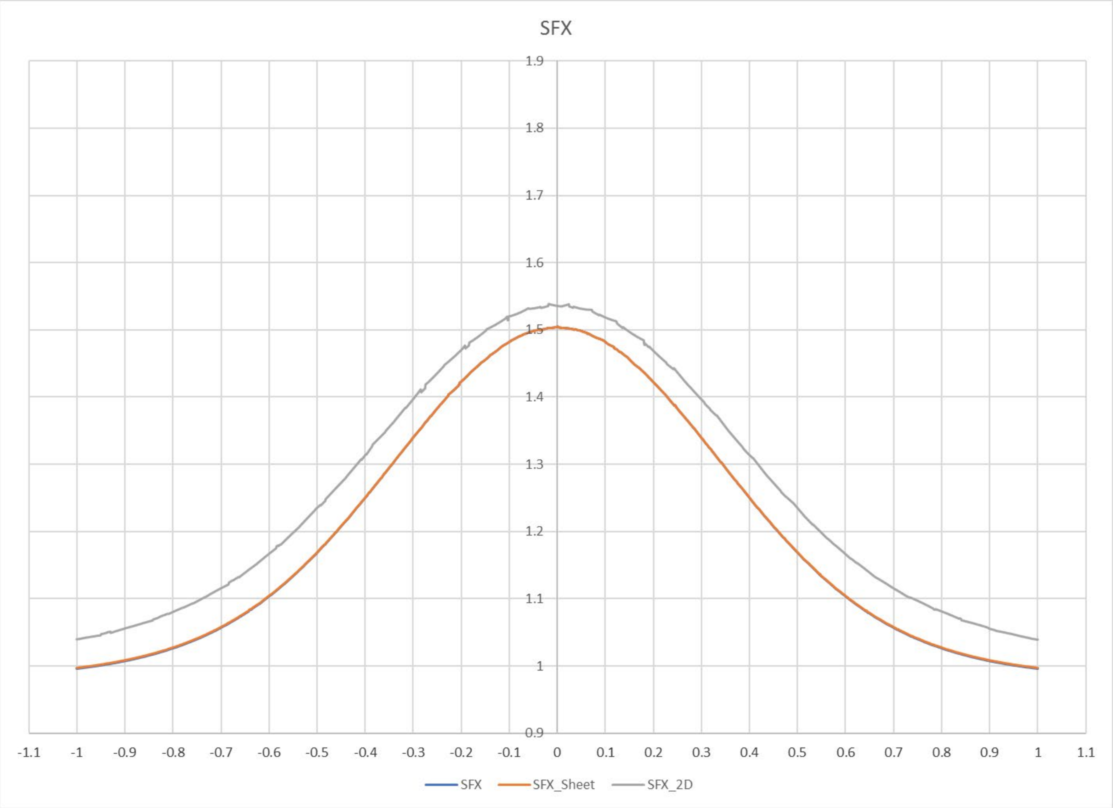
STATIC SHIELDING – 3D FEA POST-PROCESSING – BX & BY – THIN MAGNETIC REGION SHEET

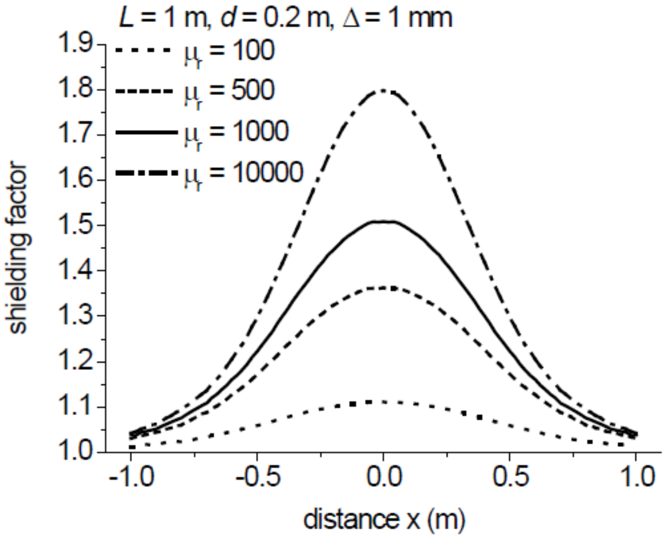
BXS



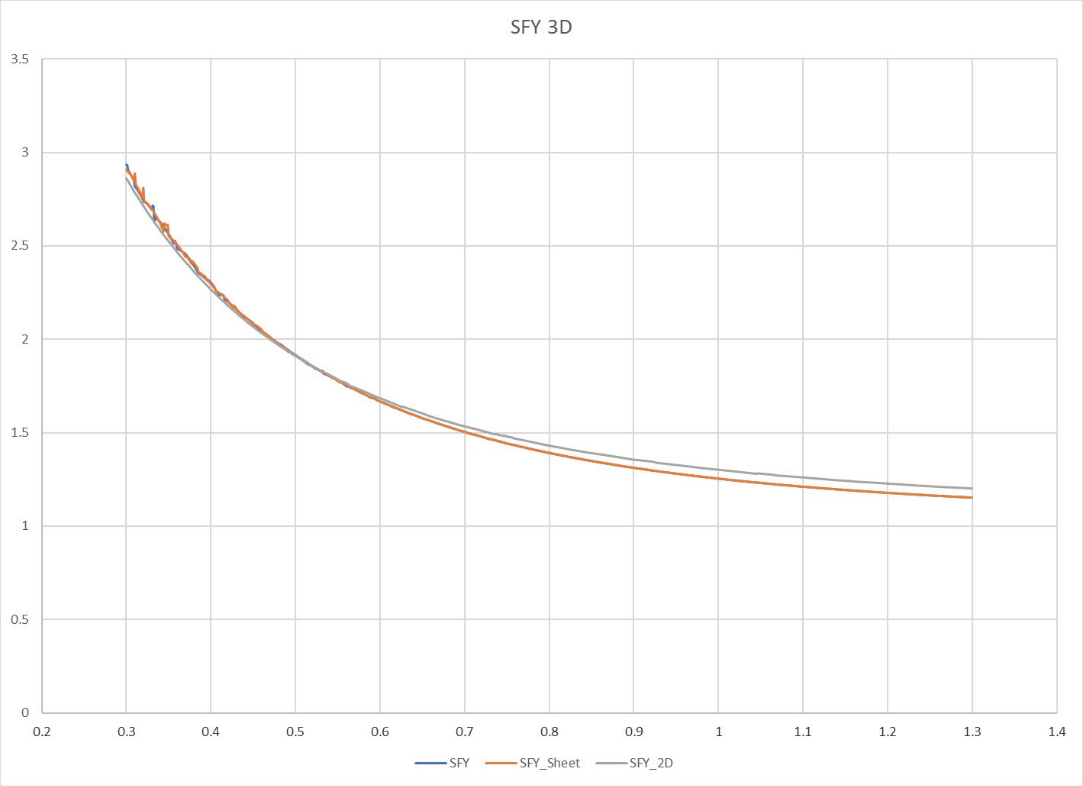
BYS1

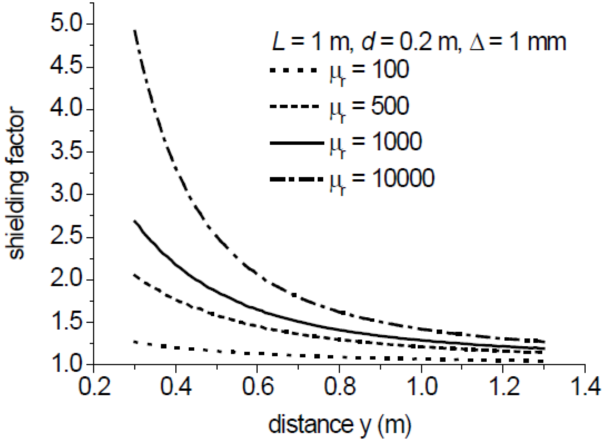
STATIC SHIELDING – 3D FEA POST-PROCESSING – SFX



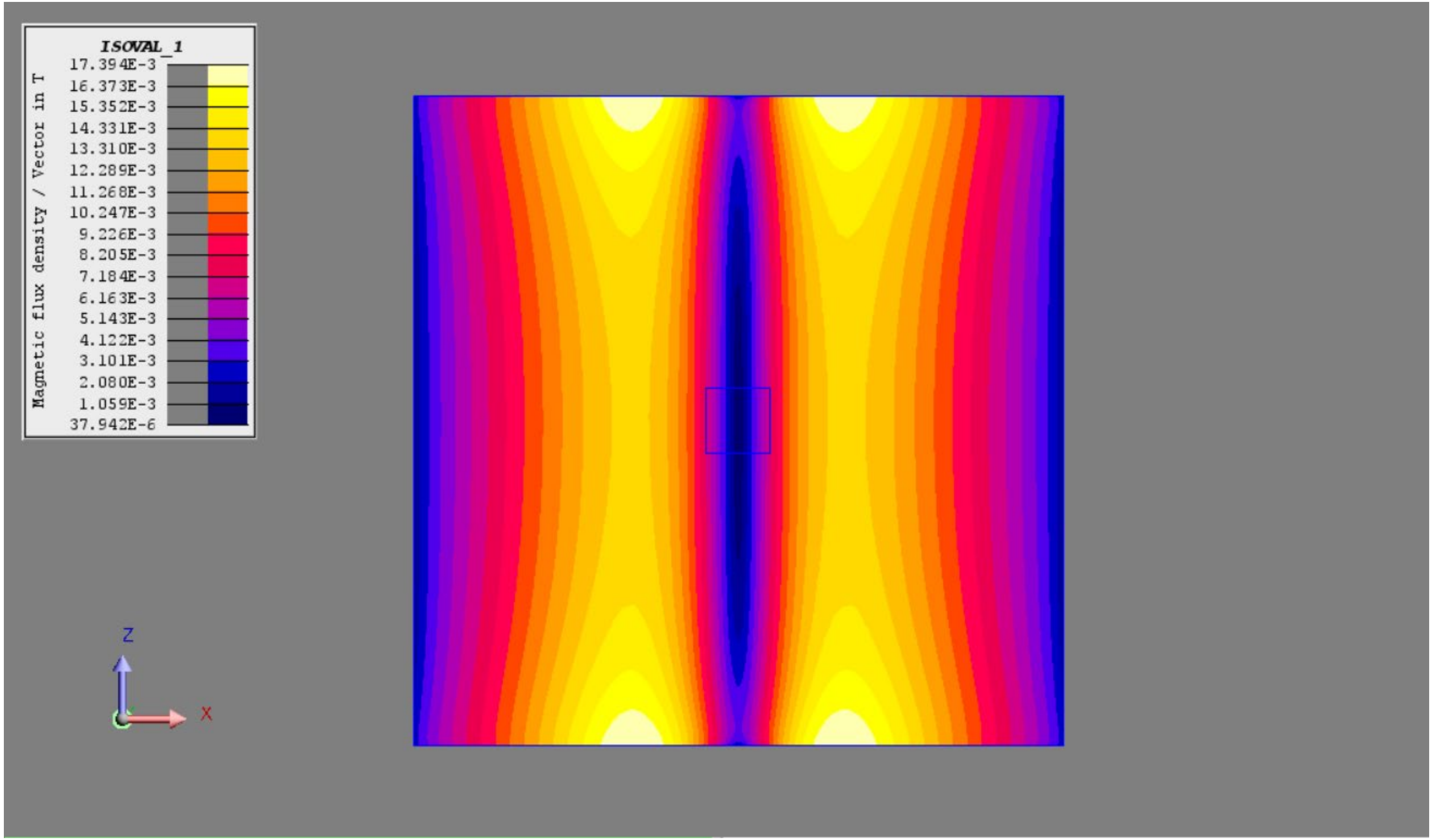


STATIC SHIELDING – 3D FEA POST-PROCESSING – SFY





STATIC SHIELDING – 3D FEA MODEL – Z DIRECTION EDGE EFFECTS



STATIC SHIELDING – 3D FEA MODEL - COMMENTS

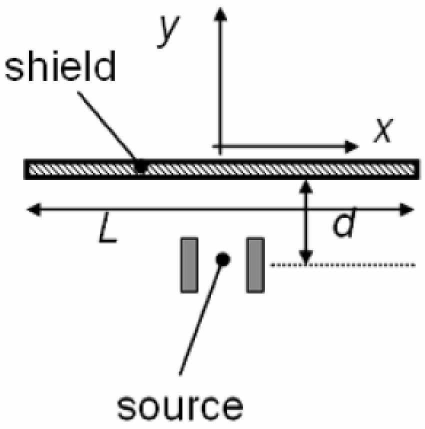
- 3D FEA model
  - Use infinite long conductor
  - Assumes finite axial length sheet (1000 mm)
  - Uses of infinite box for open field boundaries
  - Shield represented by 3D volume and thin magnetic face region of 1 mm thick show good agreement for SFX and SFY

- Small delta in SFX and SFY between 2D and 3D model (less)
  - 3D edge effect in the axial direction Z
  - Longer 3D model will reduce delta on SFX and SFY

CONDUCTIVE SHIELDING – EDDY CURRENTS

- Conductive sheet with 10 mm thickness
  - Non magnetic: Mur = 1
  - Conductivity = 50 MS/m
- Current conductors at 4000 A rms and 50 Hz
- Plate dimensions
  - Length = 1000 mm
  - Thickness = 1 mm
  - Axial length = 1000 mm
    - 2D (infinite long)
    - 3D (actual length)
- Boundary conditions
  - Infinite box for 2D and 3D
  - 10000 mm radius for 3D extruded

- Model
  - 2D
  - 3D



CONDUCTIVE SHIELDING – EDDY CURRENTS

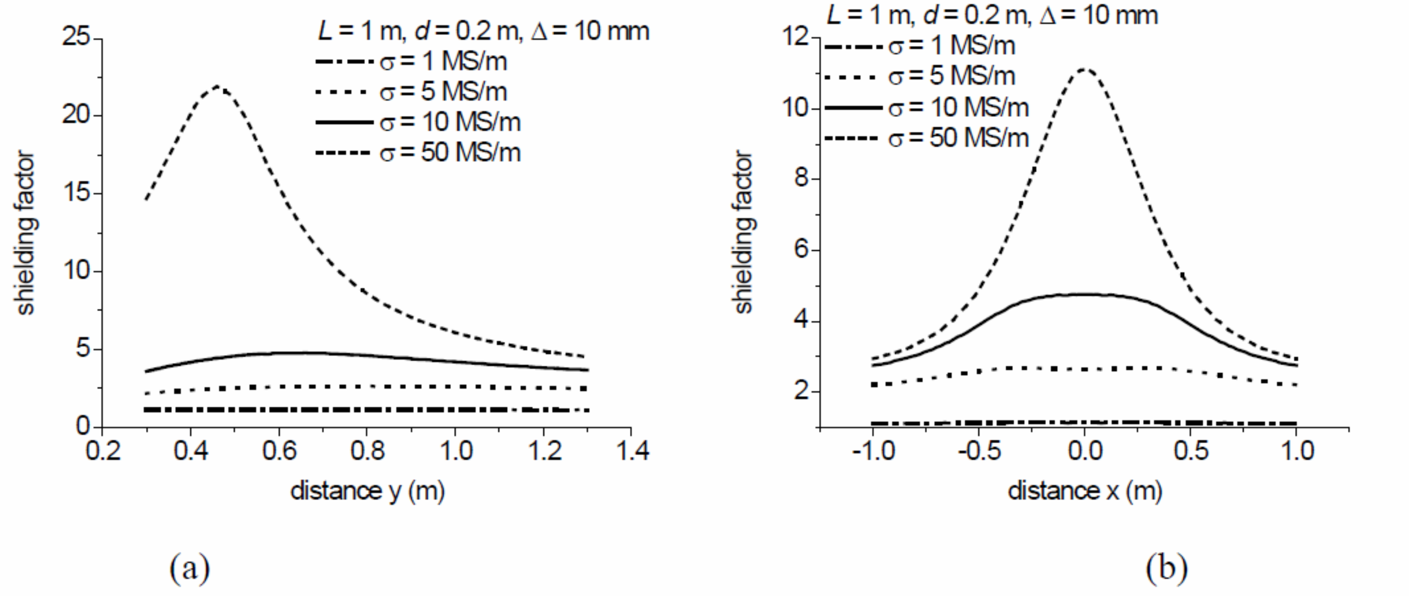
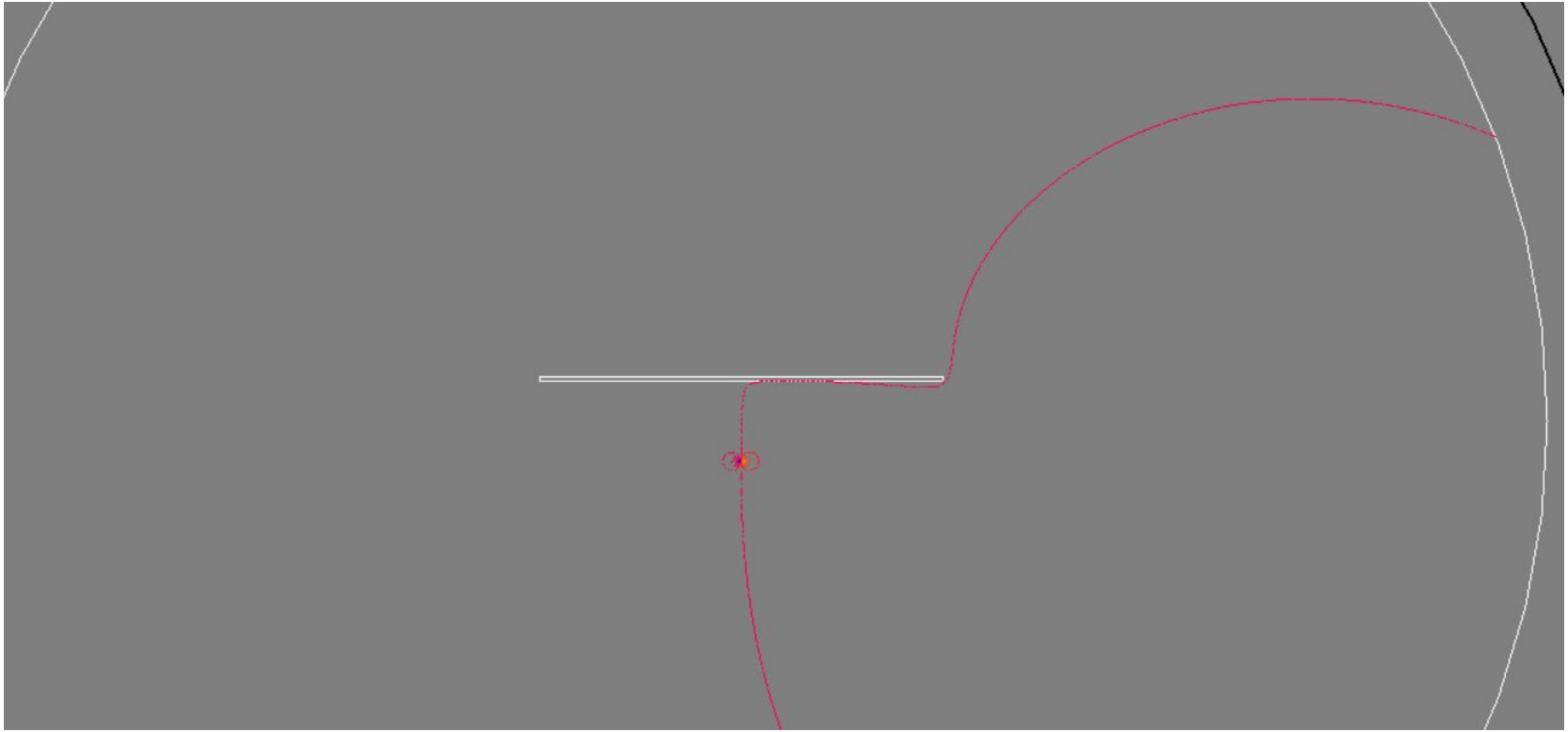
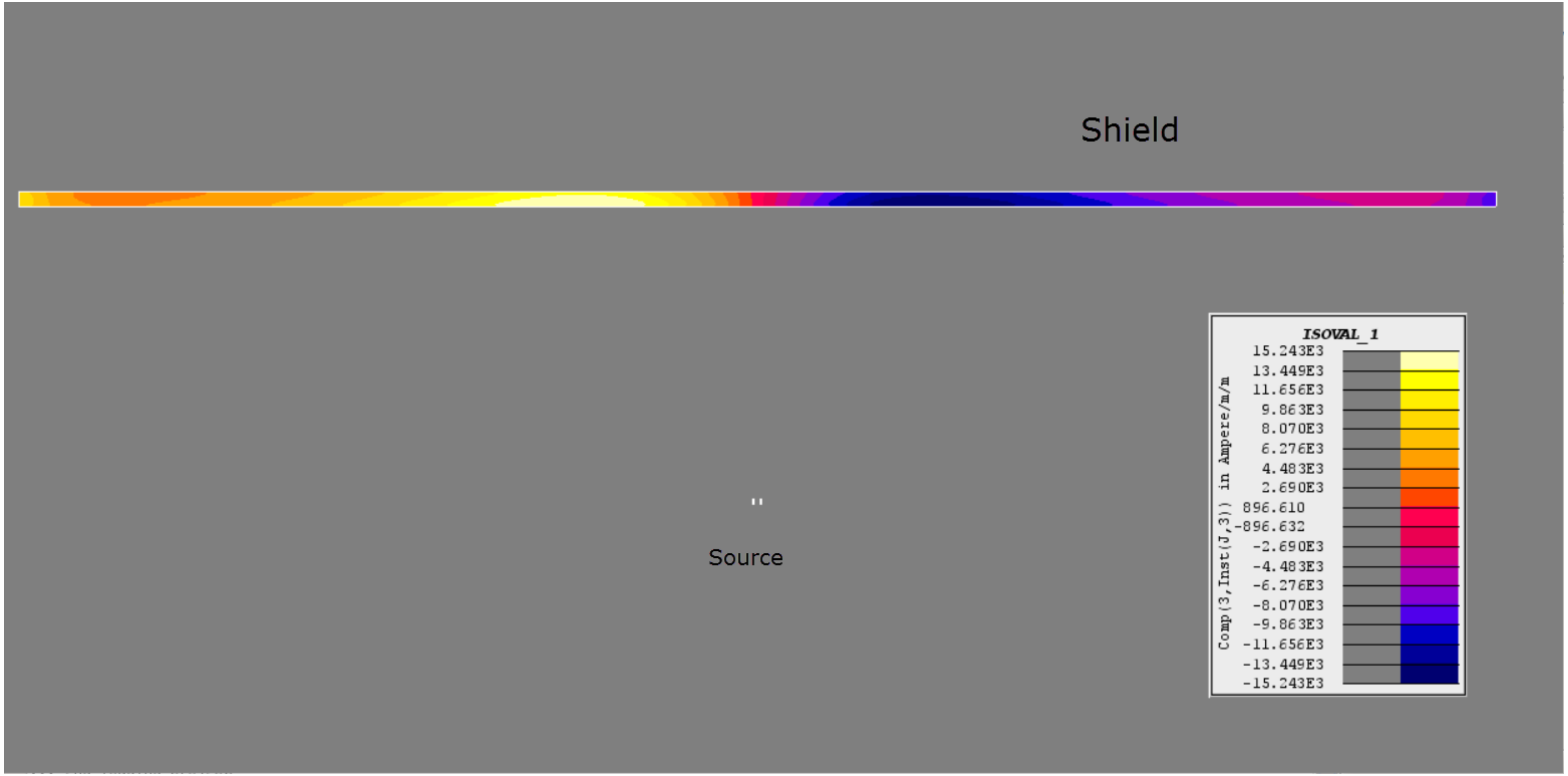


Figure 2.3.16 *SF* for different electrical conductivities of the shield of Figure 2.3.8(a): (a) plot along y axis at $x = 0$, (b) plot along x axis at $y = 0.7$ m.

CONDUCTIVE SHIELDING – 2D MODEL – ISOFLUX



CONDUCTIVE SHIELDING – 2D MODEL – EDDY CURRENTS IN SHIELD

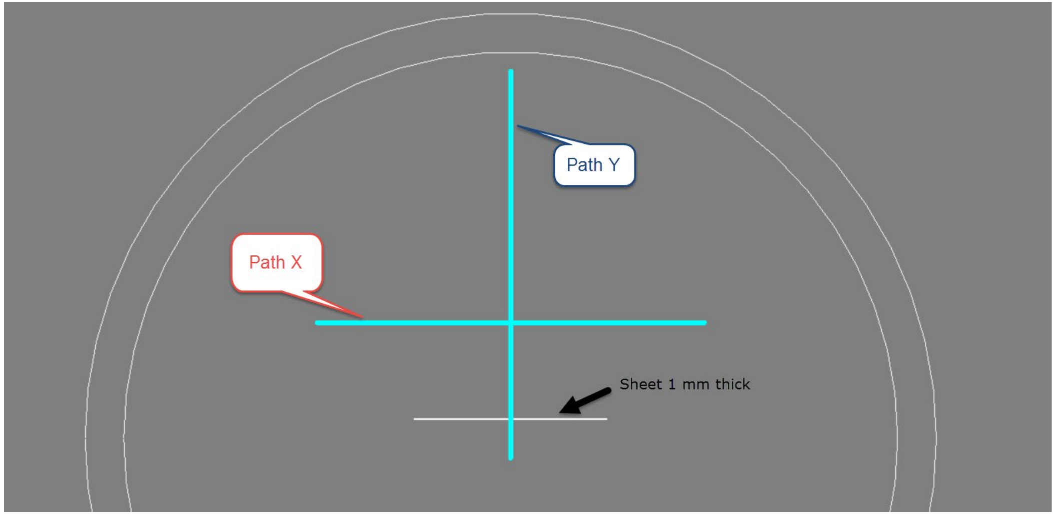


CONDUCTIVE SHIELDING – 2D FEA POST-PROCESSING

- BX0: Magnitutde of B along Path X (no shield)
- BY0: Magnitude of B along Path Y (no shield)

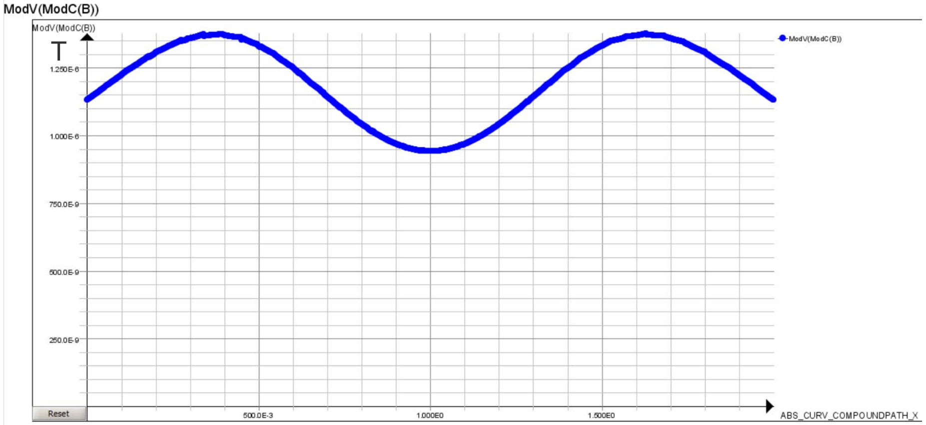
- BX: Magnitutde of B along Path X
- BY: Magnitude of B along Path Y

- SFX: Shielding factor = BX0/BX
- SFY: Shielding factor = BY0/BY

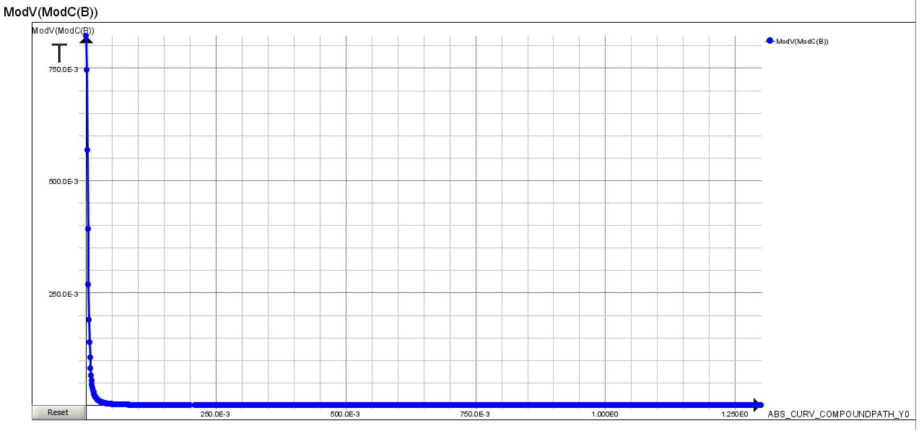


CONDUCTIVE SHIELDING – 2D FEA POST-PROCESSING – BX & BY

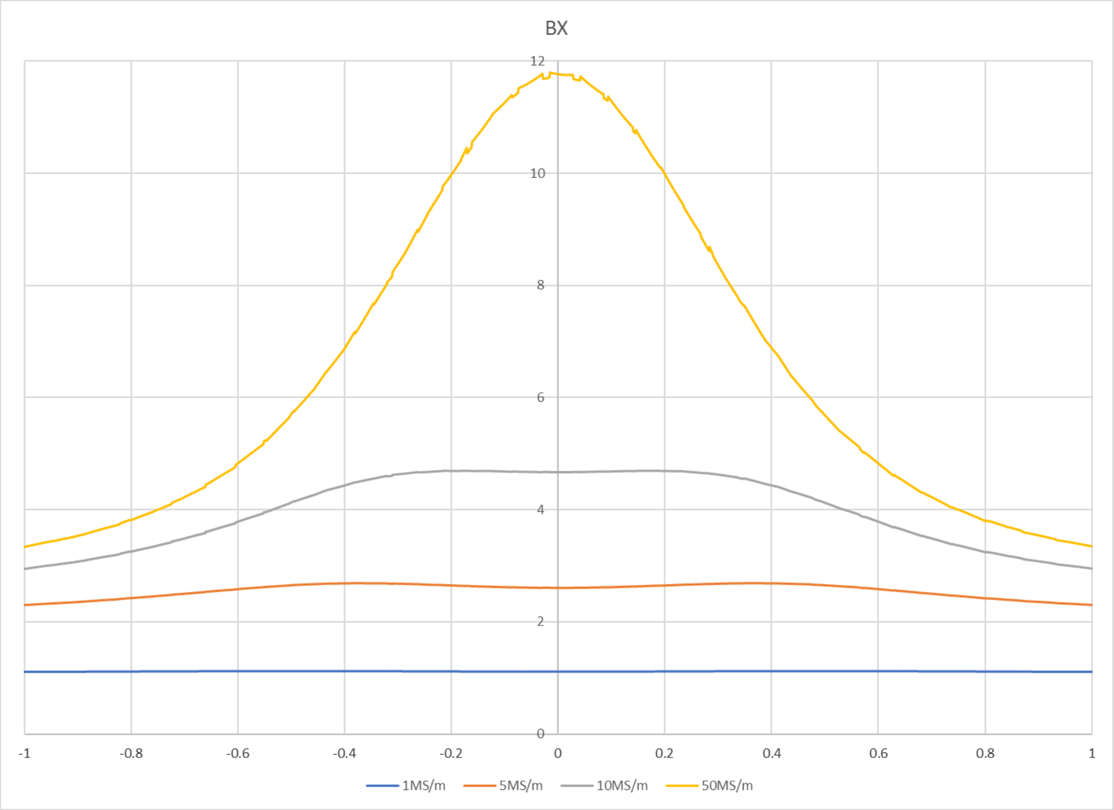
BX

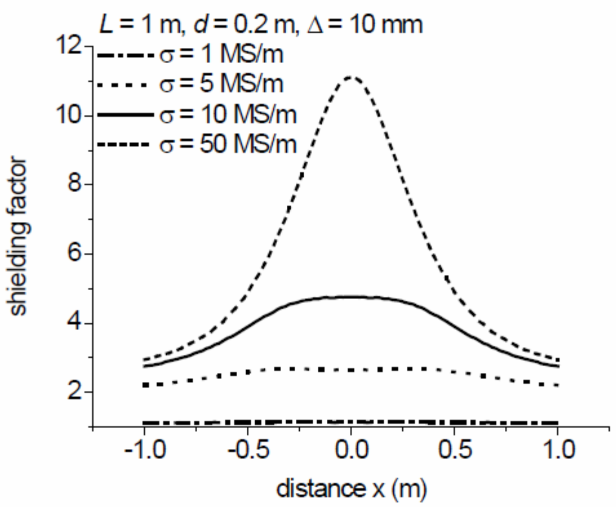


BY

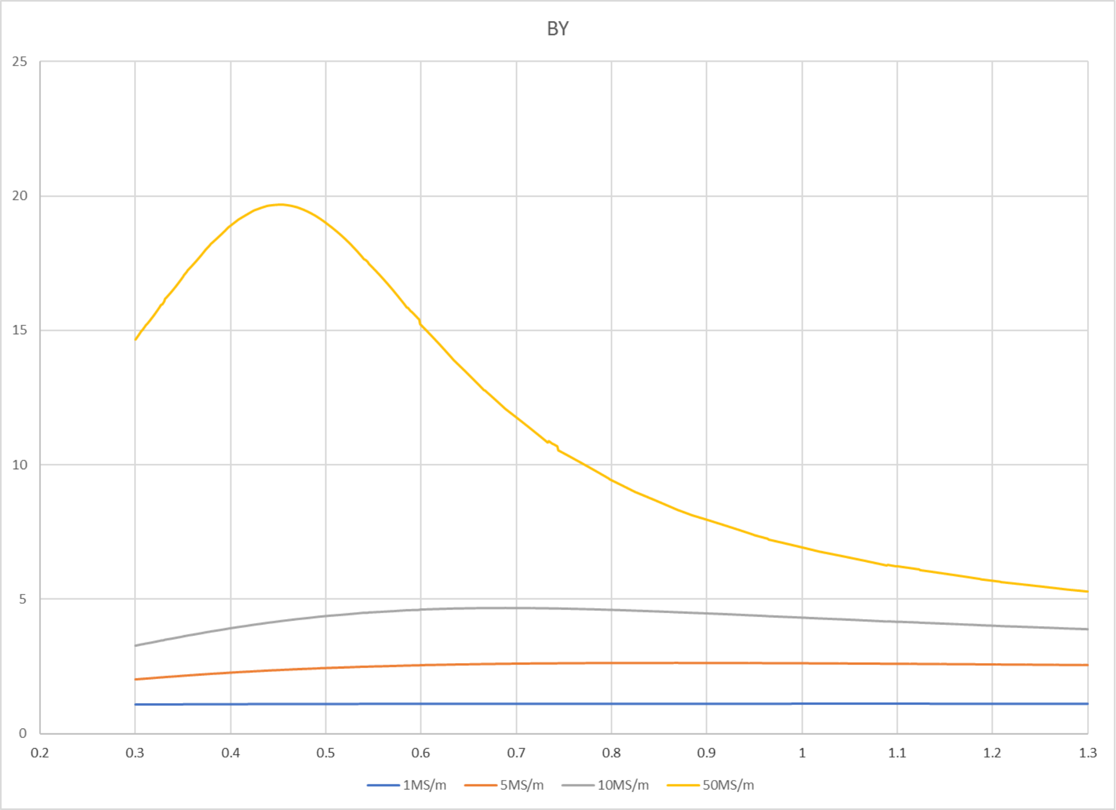


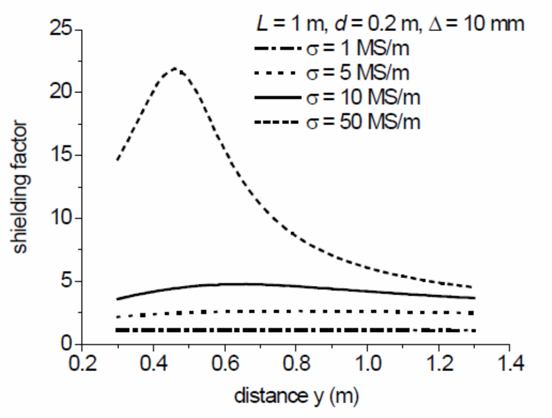
CONDUCTIVE SHIELDING – 2D FEA POST-PROCESSING – SFX





CONDUCTIVE SHIELDING – 2D FEA POST-PROCESSING – SFY





CONDUCTIVE SHIELDING – 2D FEA MODEL - COMMENTS

- Good correlation between 2D FEA results with CIGRE data
  - Model of Fig. 238 a
  - Data of Fig. 23.16 a and b

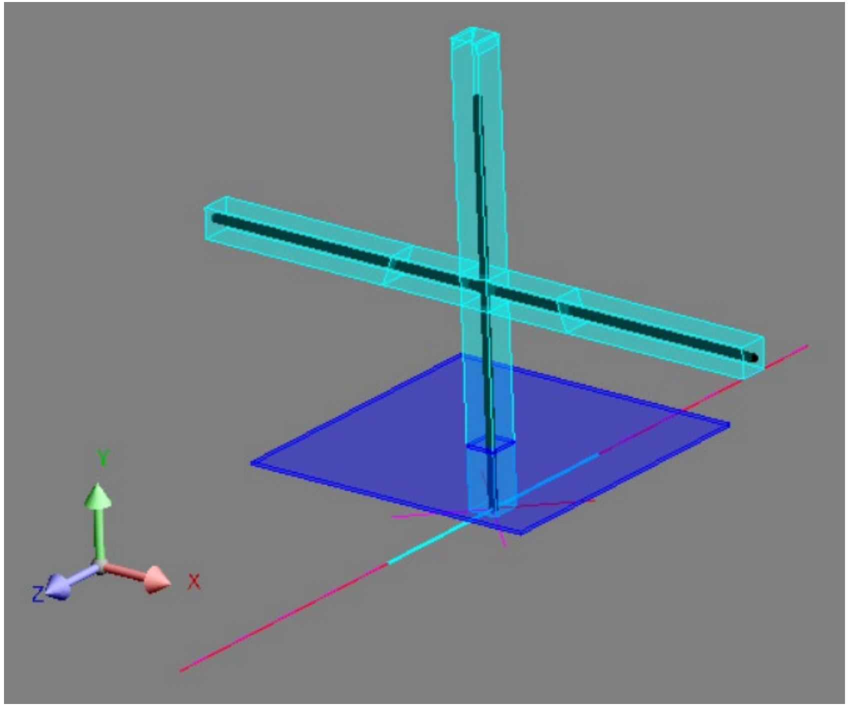
- 2D FEA model
  - Non magnetic conductive material
  - Assumes infinite long conductor
  - Assumes infinite long sheet (axially)
  - Uses of infinite box for open field boundaries

CONDUCTIVE SHIELDING BENCHMARK – 3D MODEL

- Open field boundary conditions with Infinite Box

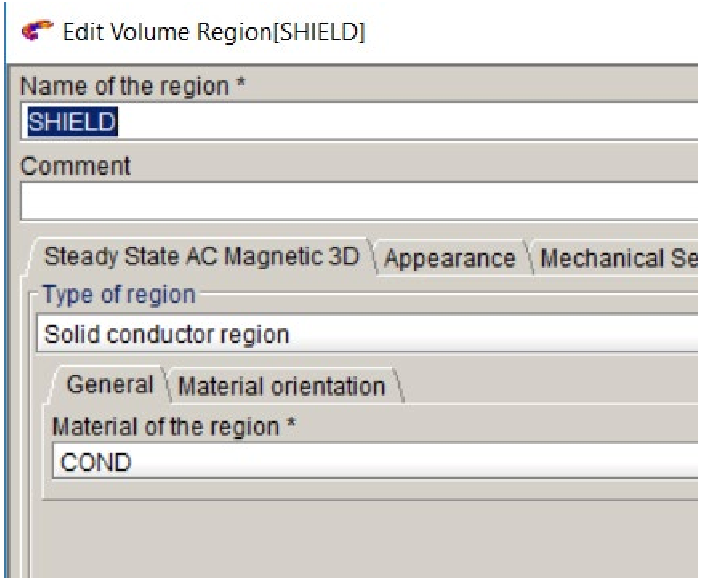
- Conductors
  - Non meshed coils
  - Infinitely long

- Sheet
  - Volume region with mesh
  - Thin conductive face region with 10 mm thickness

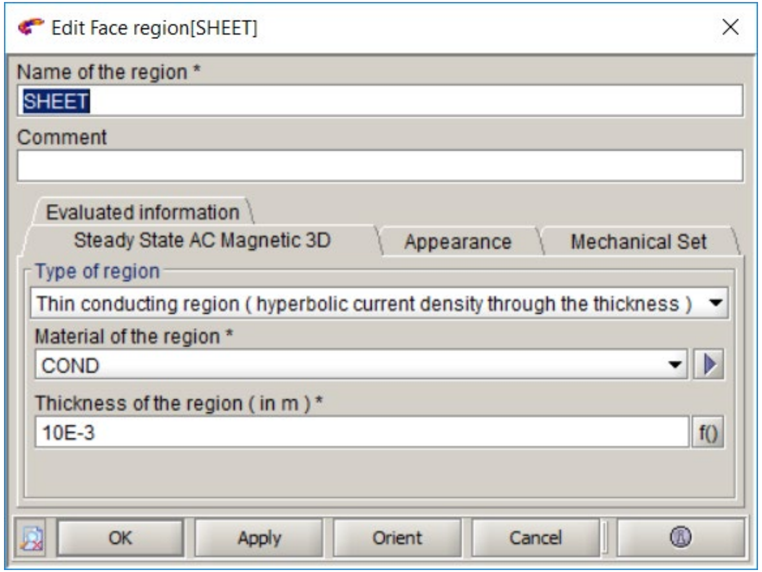


CONDUCTIVE SHIELDING BENCHMARK – SHEET

- Shield with volume region
  - Geometrically represented
  - Volume meshed
  - Solid conductor region



- Shield with thin face region: Sheet
  - Geometrically represented by a face
  - Conductive thin face region
  - Thickness of 10 mm

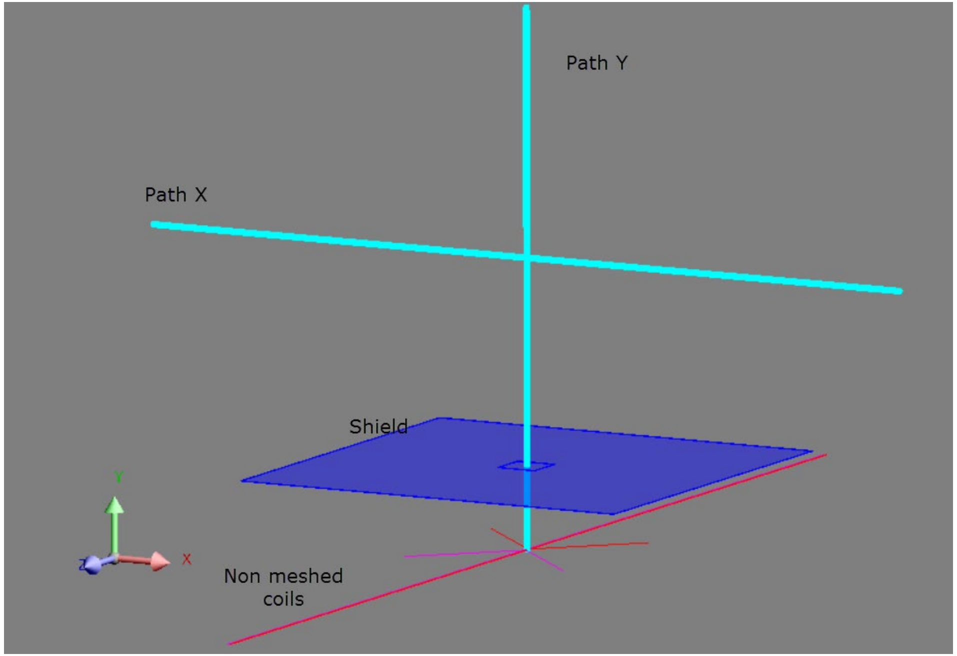


CONDUCTIVE SHIELDING – 3D FEA POST-PROCESSING

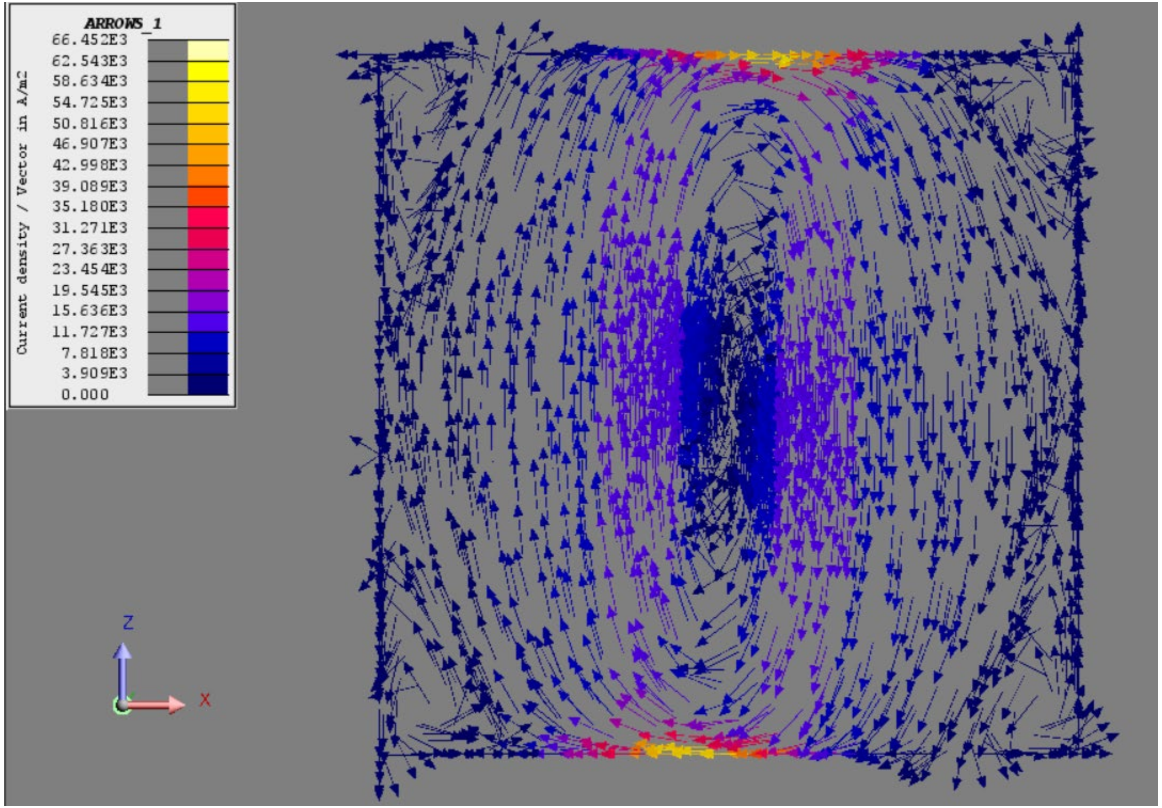
- BX0: Magnitutde of B along Path X (no shield)
- BY0: Magnitude of B along Path Y (no shield)

- BX: Magnitutde of B along Path X
- BY: Magnitude of B along Path Y

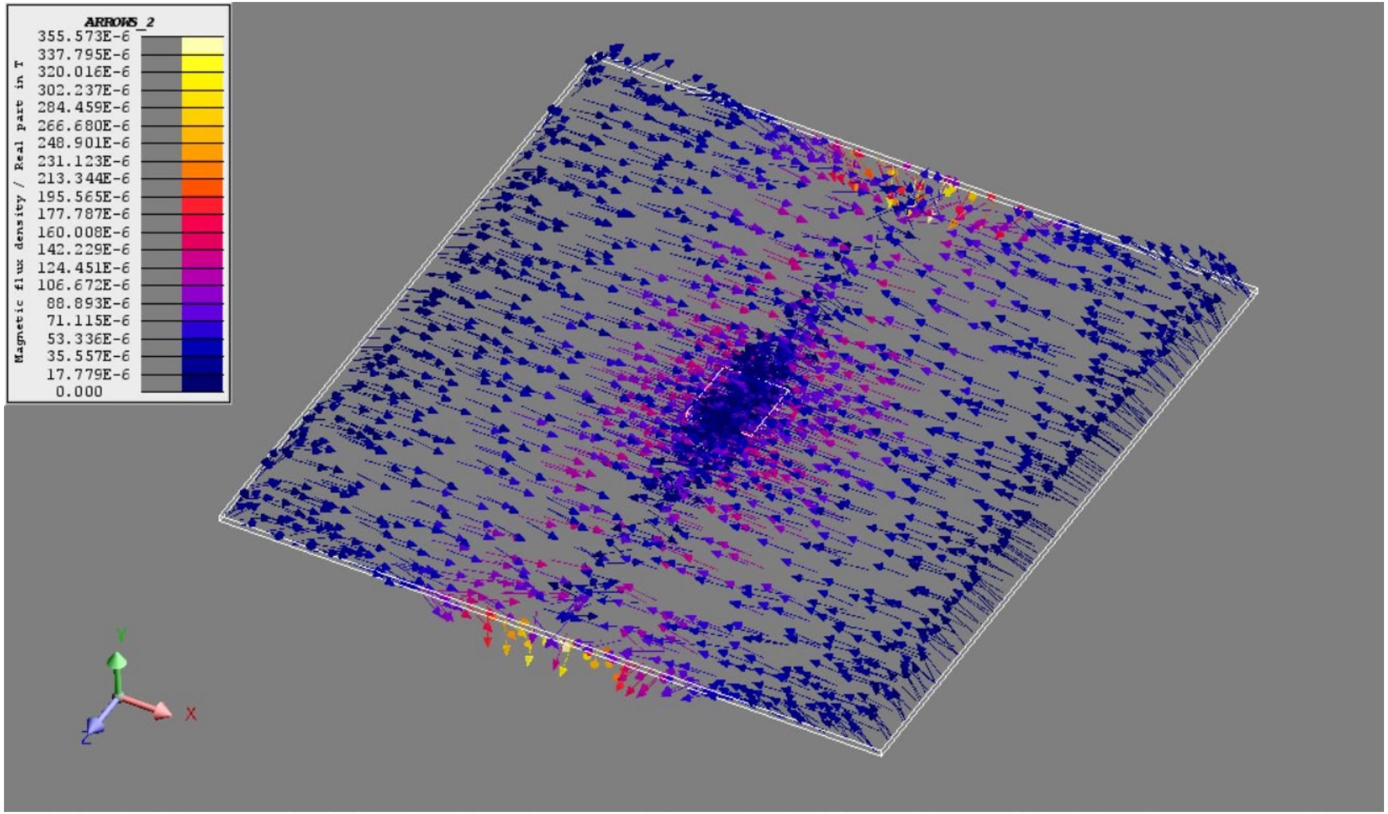
- SFX: Shielding factor = BX0/BX
- SFY: Shielding factor = BY0/BY



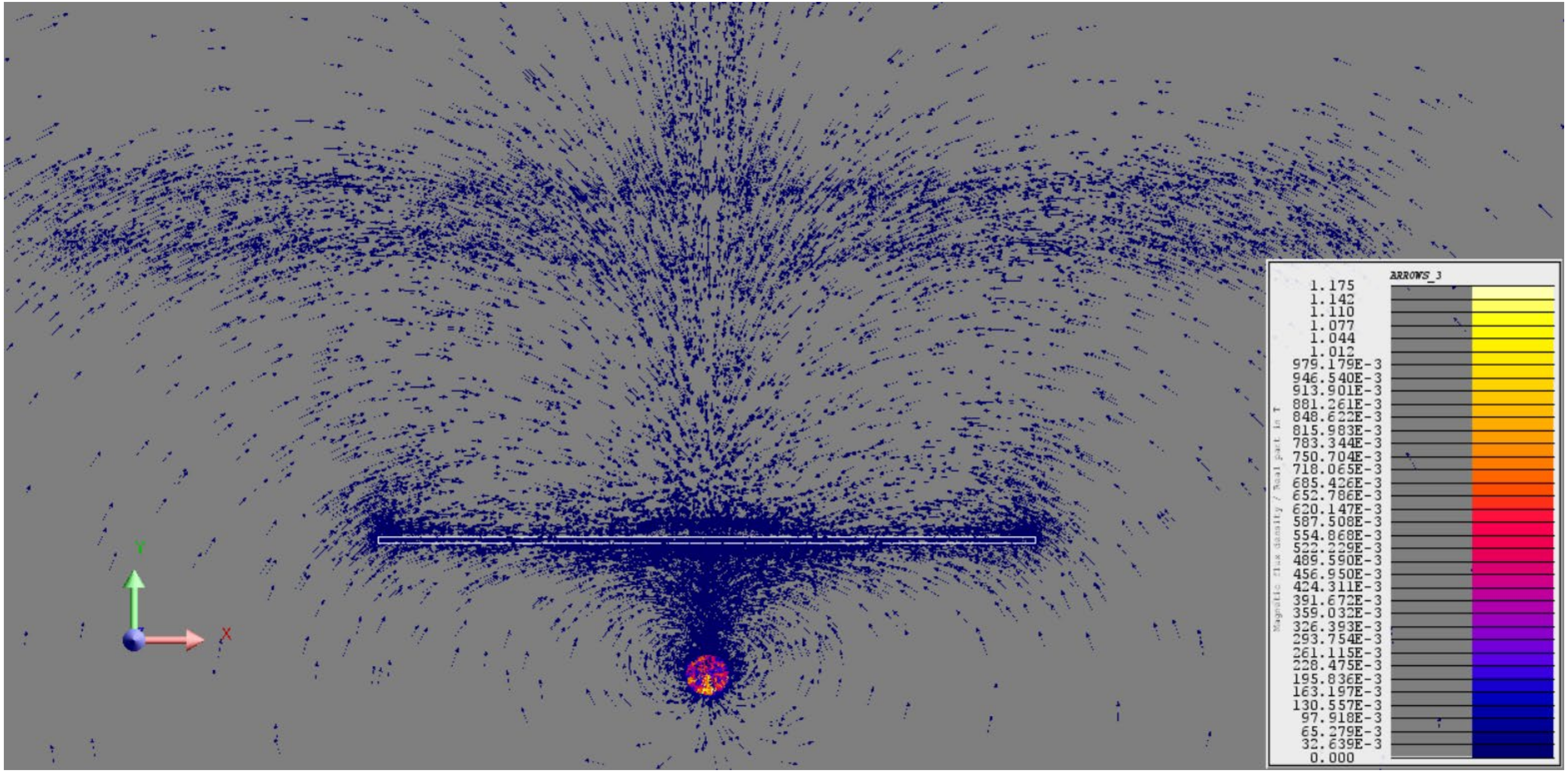
CONDUCTIVE SHIELDING BENCHMARK 3D FEA – CURRENT DENSITY J ON X-Y PLANE – 3D VOLUME REGION SHIELD



CONDUCTIVE SHIELDING BENCHMARK 3D FEA – FLUX DENSITY B – 3D VOLUME REGION SHIELD

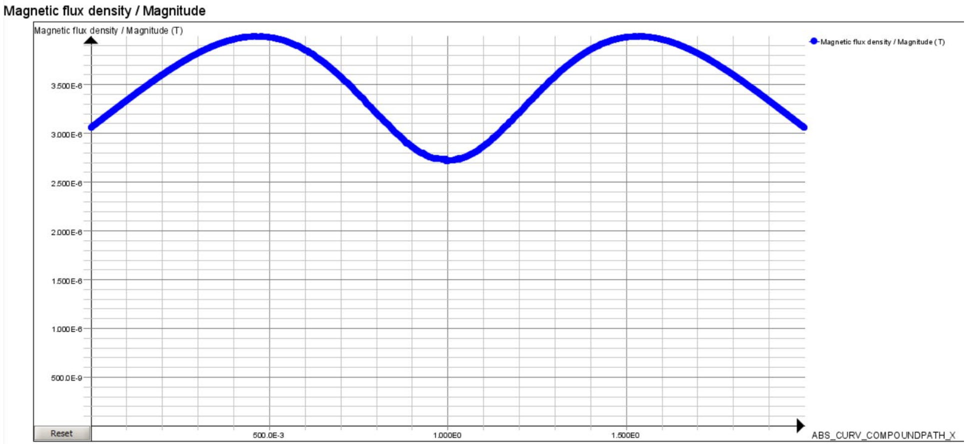


CONDUCTIVE SHIELDING BENCHMARK 3D FEA – FLUX DENSITY B ON X-Y PLANE – 3D CONDUCTIVE VOLUME REGION SHIELD

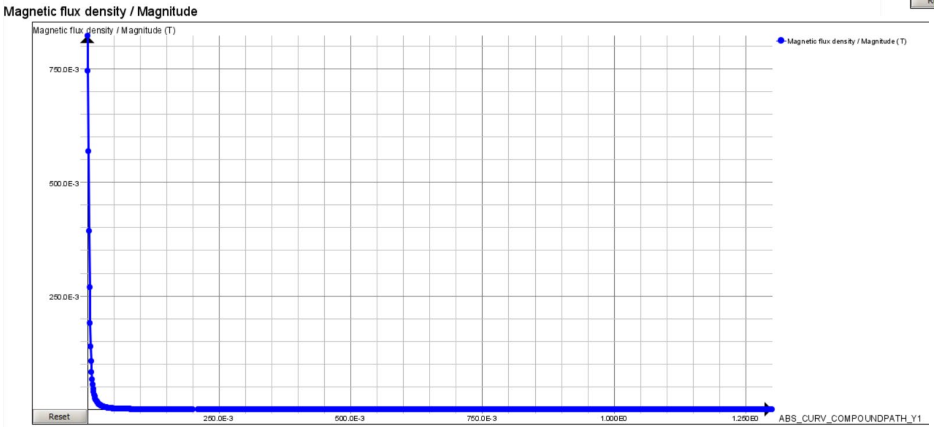


CONDUCTIVE SHIELDING – 3D FEA POST-PROCESSING – BX & BY – VOLUME REGION SHIELD

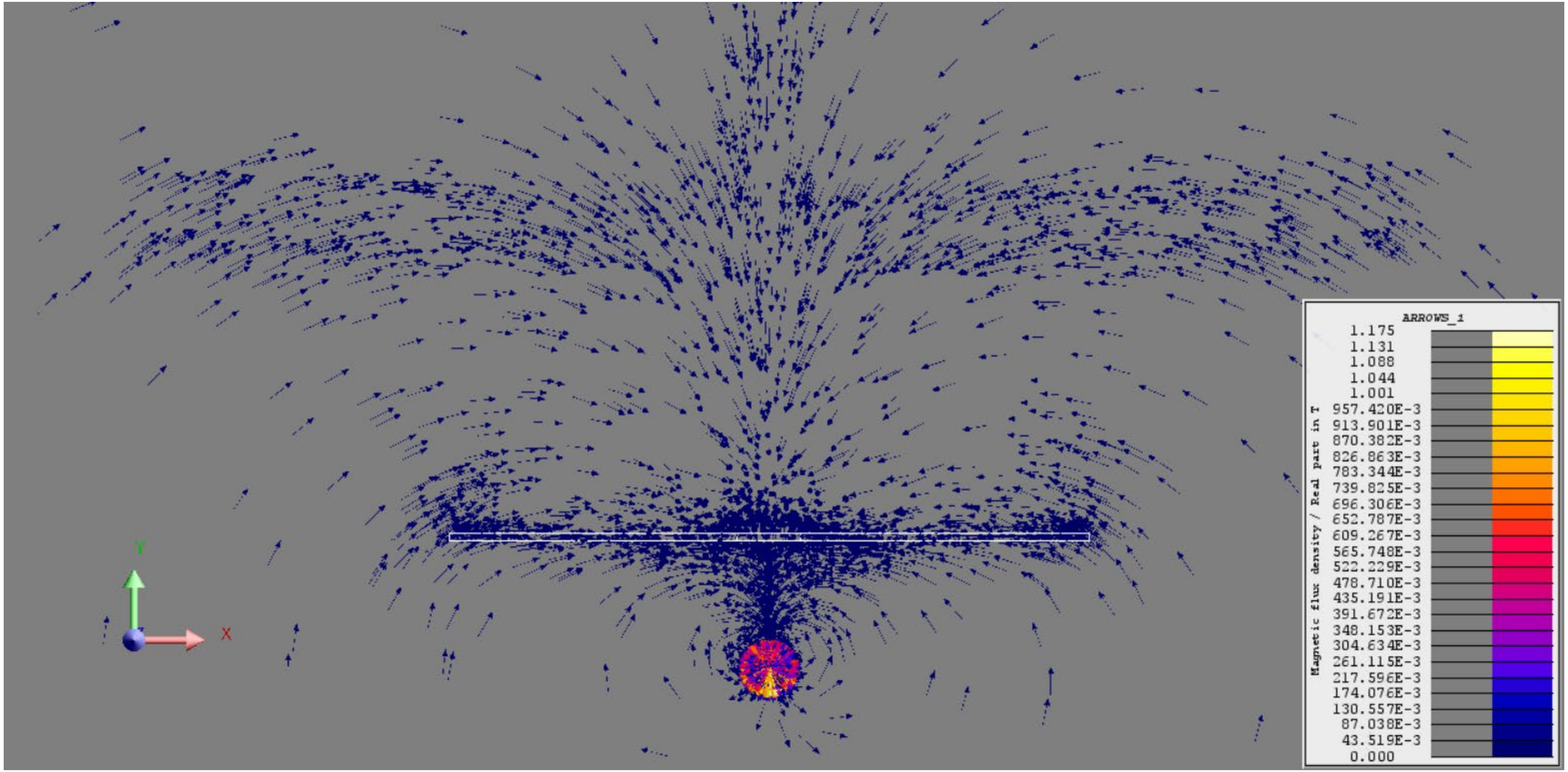
BX1



BY1

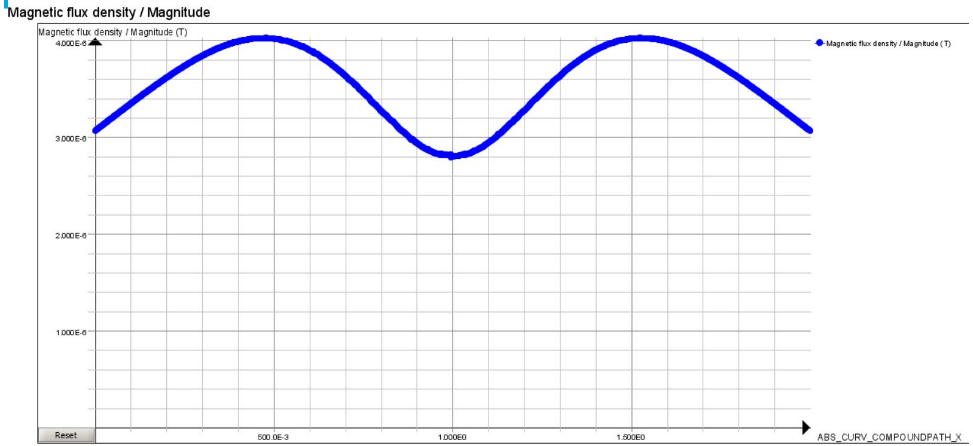


CONDUCTIVE SHIELDING BENCHMARK 3D FEA – FLUX DENSITY B ON X-Y PLANE – SHEET THIN CONDUCTOR FACE REGION

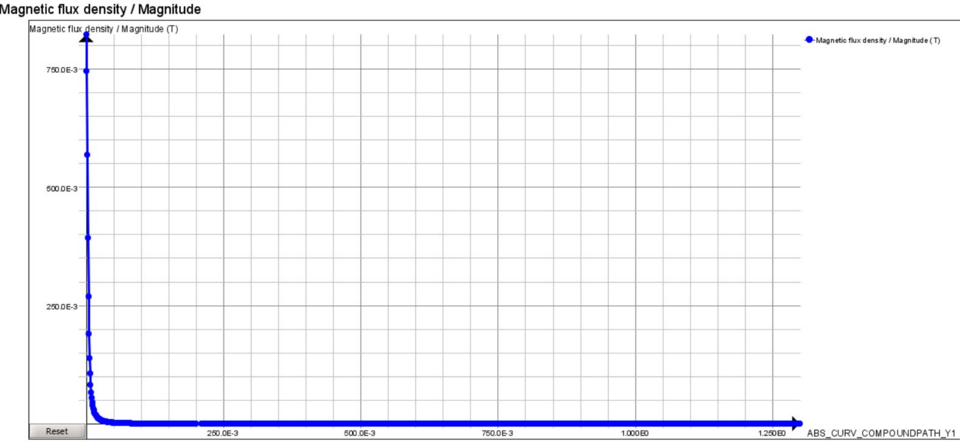


CONDUCTIVE SHIELDING – 3D FEA POST-PROCESSING – BX & BY – THIN CONDUCTOR REGION SHEET

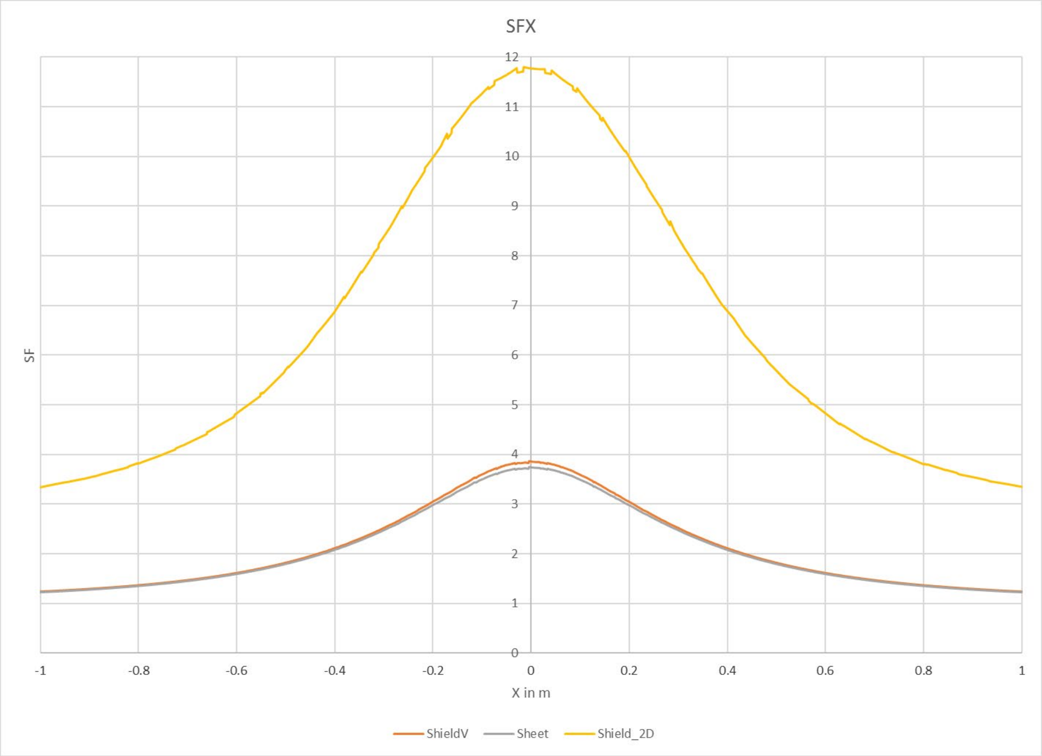
BXS

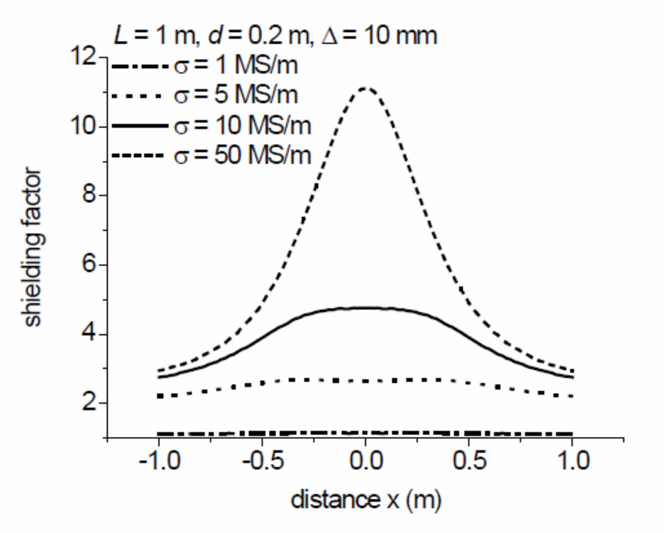


BYS

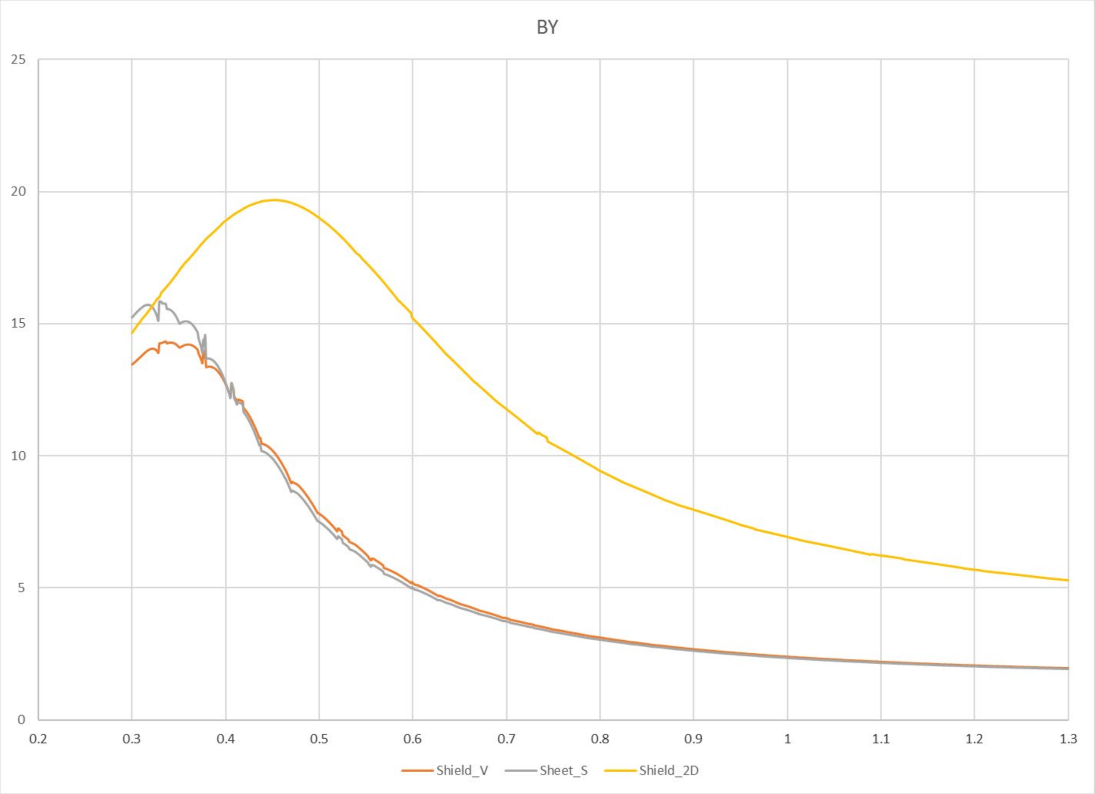


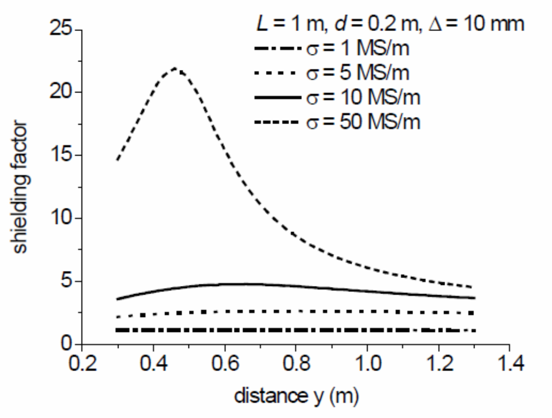
STATIC SHIELDING – 3D FEA POST-PROCESSING – SFX





STATIC SHIELDING – 3D FEA POST-PROCESSING – SFY



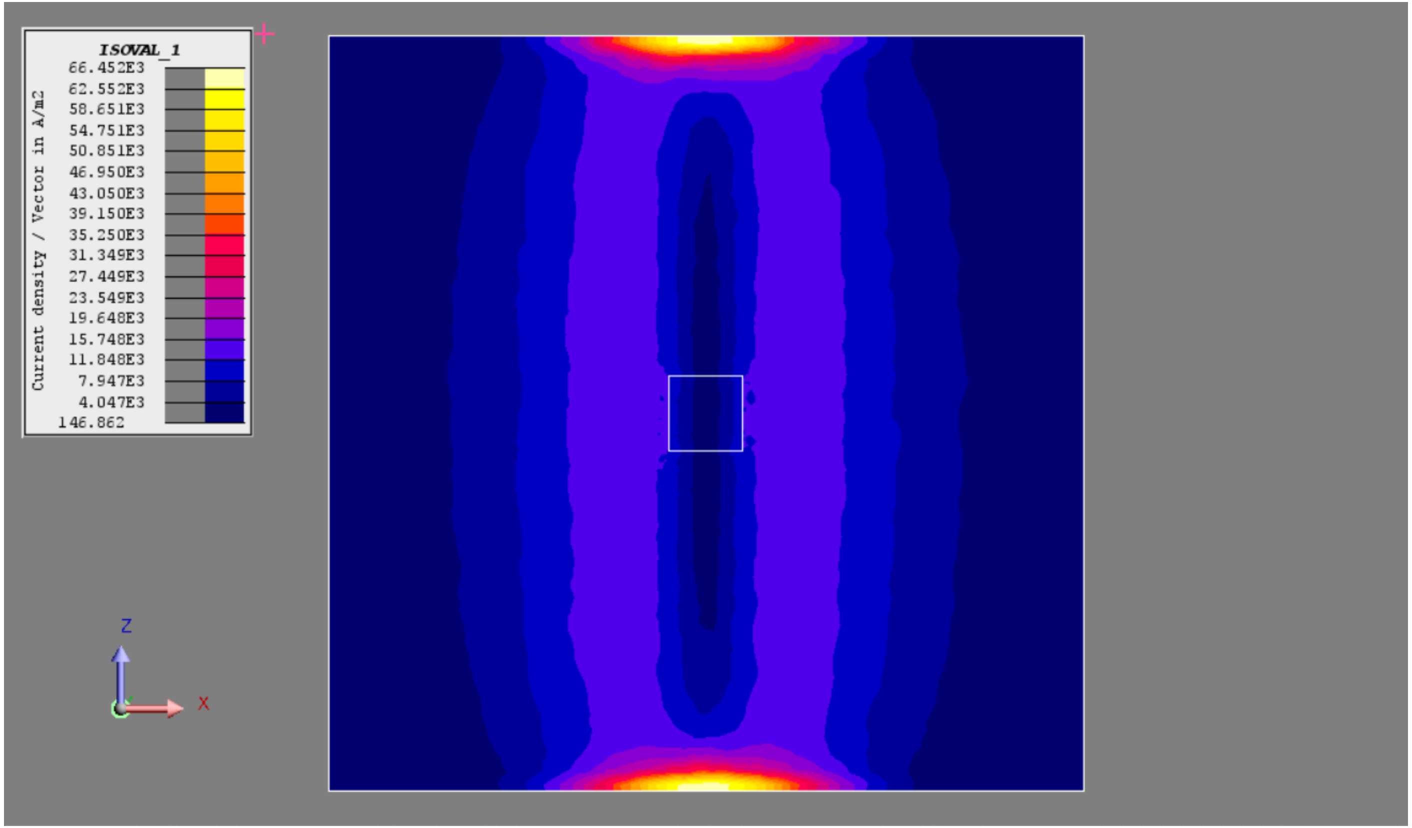


STATIC SHIELDING – 3D FEA MODEL - COMMENTS

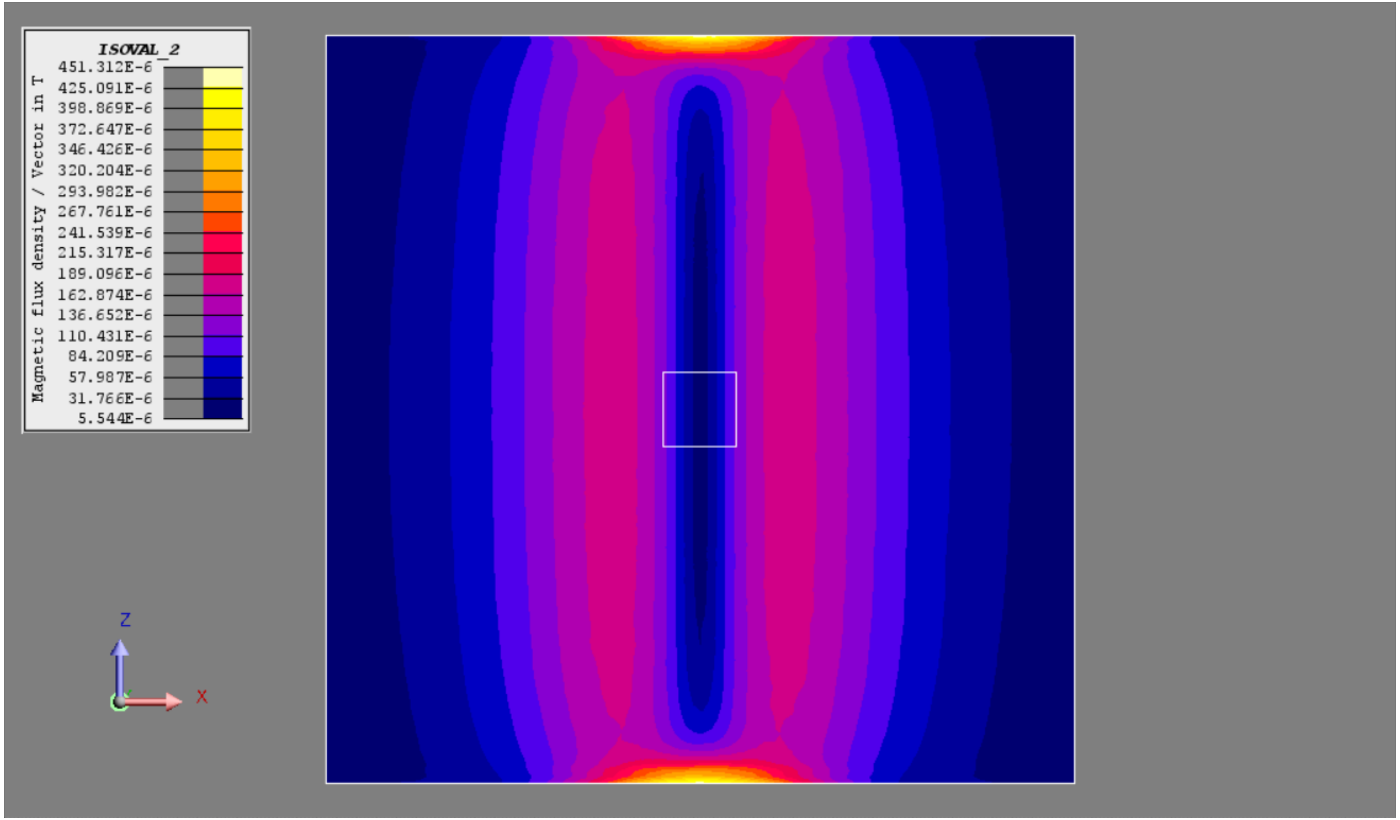
- 3D FEA model
  - Use infinite long conductor
  - Finite axial length shield (1000 mm)
  - Uses of infinite box for open field boundaries
  - Shield represented by 3D volume and thin conductor face region of 10 mm thick show good agreement for SFX and SFY

- Discrepancies in SFX and SFY between 2D and 3D model
  - 3D edge effect in the axial direction Z
    - Eddy current patterns
    - Flux density edge effects

CONDUCTIVE SHIELDING – 3D FEA MODEL – Z DIRECTION EDGE EFFECTS – CURRENT DENSITY J

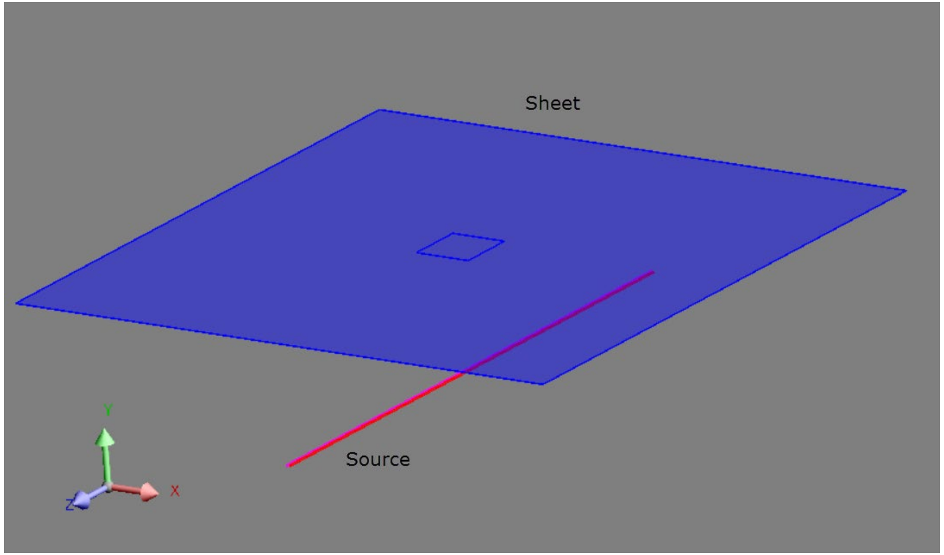


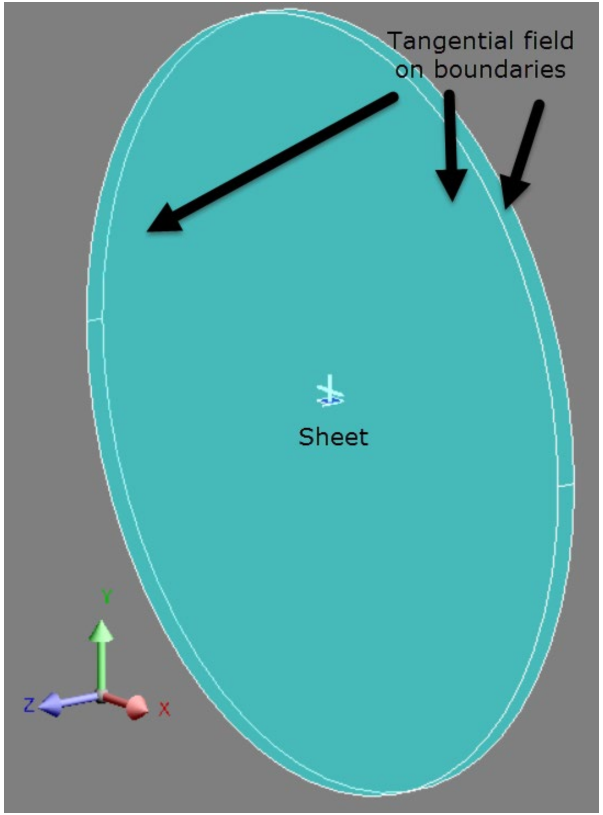
CONDUCTIVE SHIELDING – 3D FEA MODEL – Z DIRECTION EDGE EFFECTS – FLUX DENSITY B



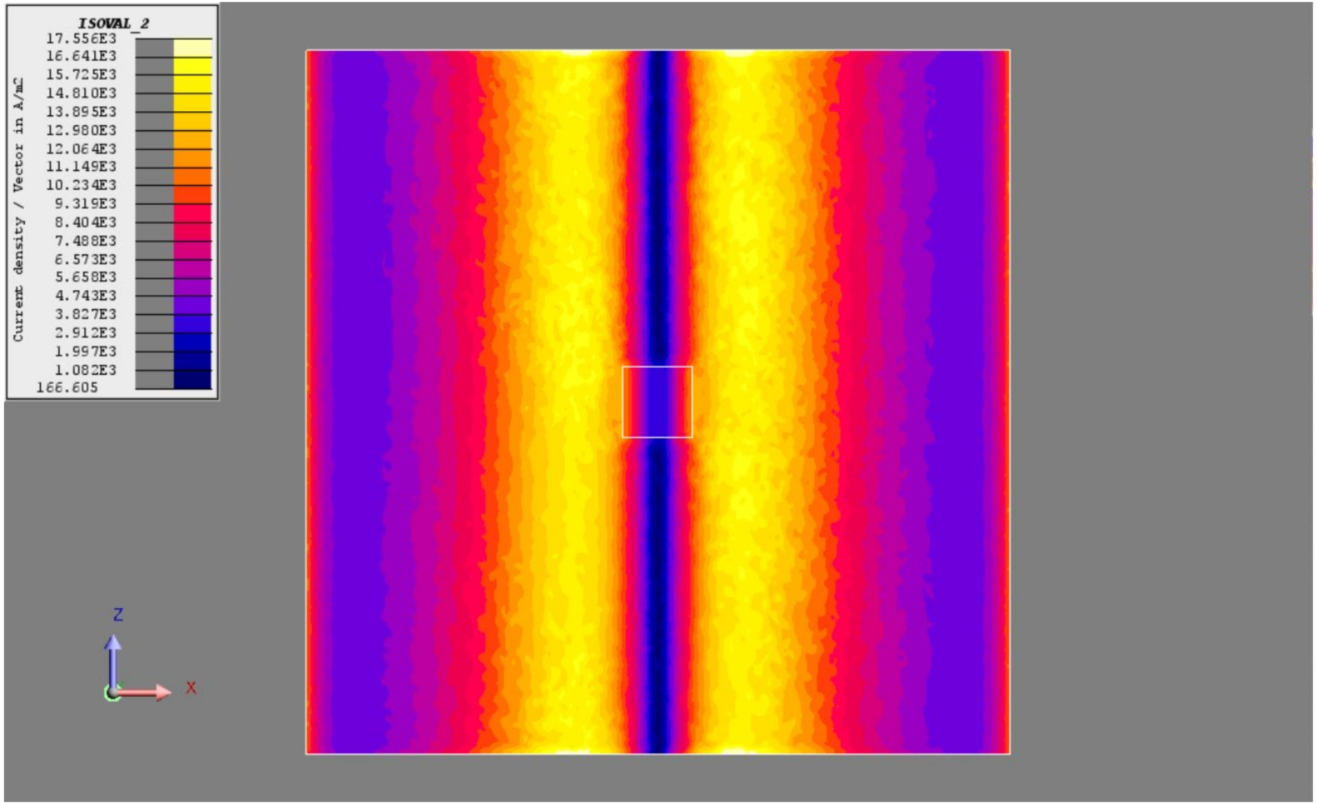
CONDUCTIVE SHIELDING – 3D FEA MODEL EXTRUDED

- 3D geometry extruded from 2D
- Tangential boundary conditions
- Outer diameter = 10 m to replicate infinite box

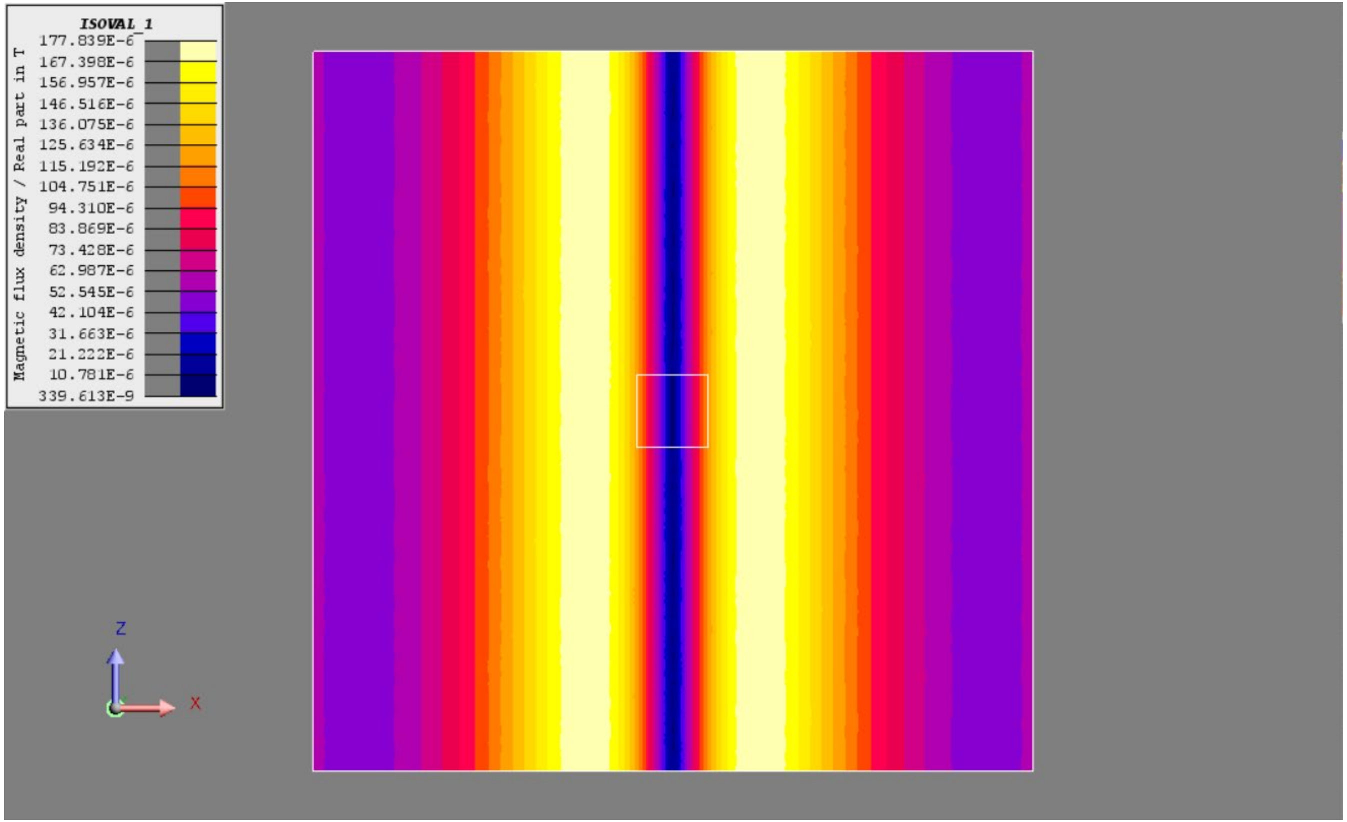




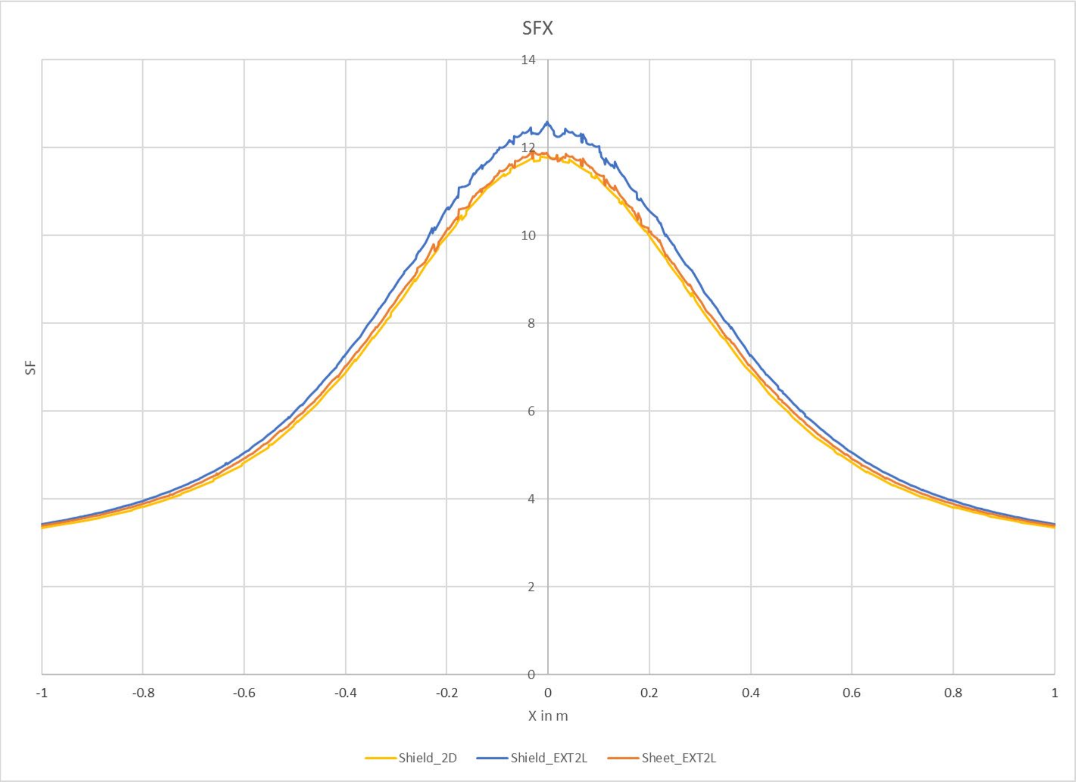
CONDUCTIVE SHIELDING – 3D EXTRUDED FEA MODEL – CURRENT DENSITY J

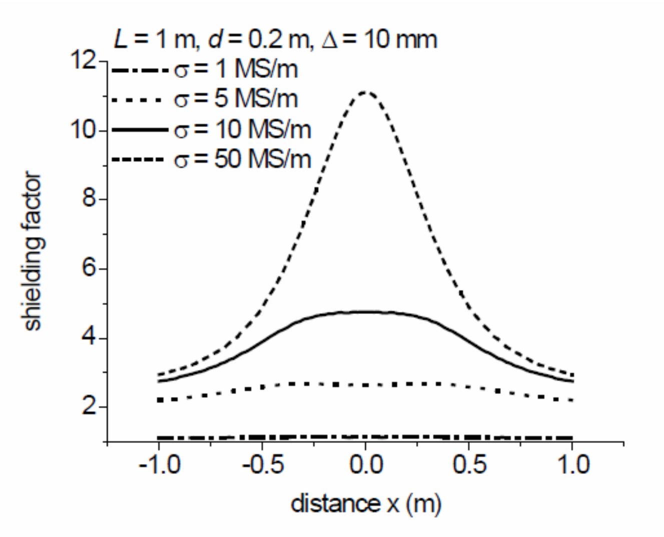


CONDUCTIVE SHIELDING – 3D EXTRUDED FEA MODEL – FLUX DENSITY B

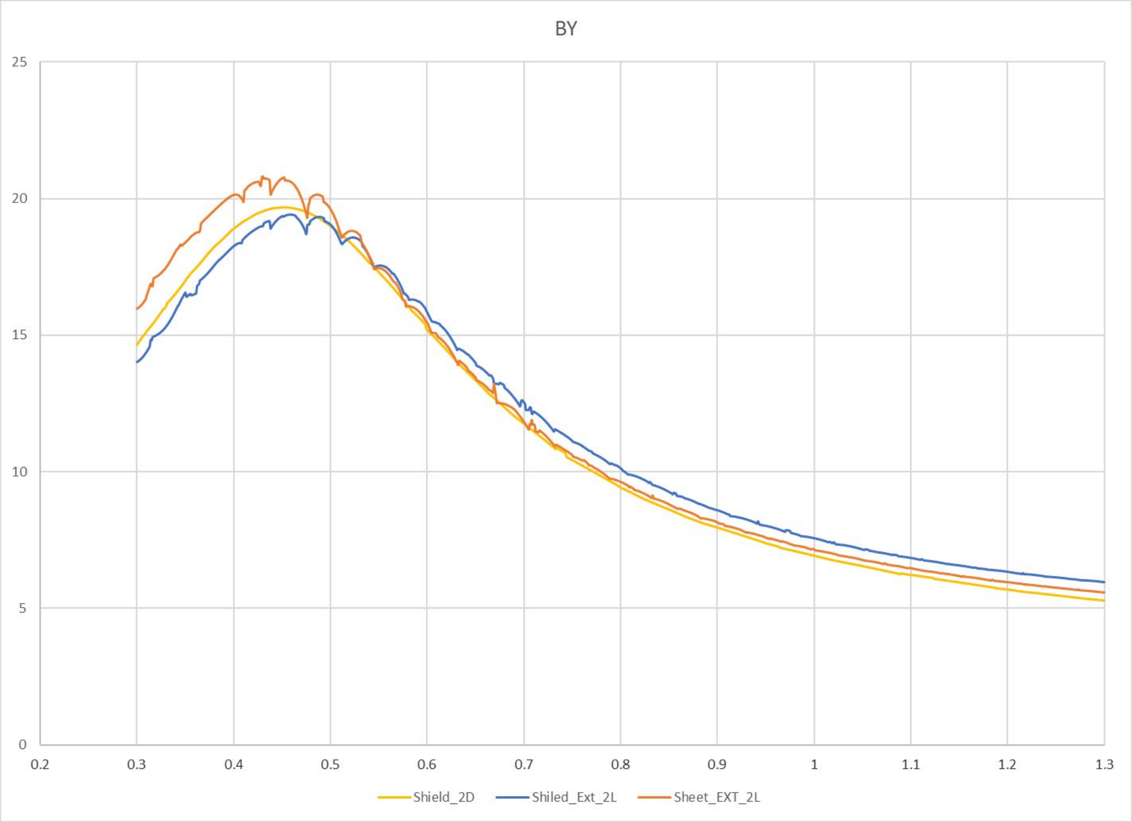


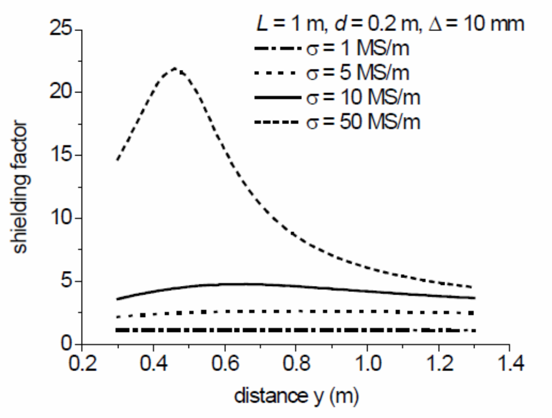
CONDUCTIVE SHIELDING – 3D FEA POST-PROCESSING – SFX





CONDUCTIVE SHIELDING – 3D FEA POST-PROCESSING – SFY





STATIC SHIELDING – 3D EXTRUDED FEA MODEL - COMMENTS

- 3D Extruded FEA model
  - Use infinite long conductor
  - Infinite long axially with tangential boundary conditions
  - 10 m radius for boundary conditions
  - Shield represented by 3D volume and thin conductor face region of 10 mm thick show good agreement for SFX and SFY

- Good agreement in SFX and SFY between 2D and 3D model
  - True representation of 2D is 3D “extruded” albeit Infinite Box is not available with 3D extruded and can be replaced with large radius boundary condition.

HYPERMESH MODEL OF SUBSTATION

- Substation
  - Wall
    - Wall thickness represented
      - Volume with volume elements
    - Metal sheet on both sides of the wall with much small thickness
      - No geometric representation with thickness
      - Face region with shell elements
  - Roof
    - Roof thickness represented
      - Volume with volume elements
    - Metal sheet for shielding on surfaces of roof
      - No geometric representation with thickness
      - Face region with shell elements
    - Steel Beam
      - Thin cross section not represented
      - Face region with shell elements
  - Room
    - Volume with volume elements

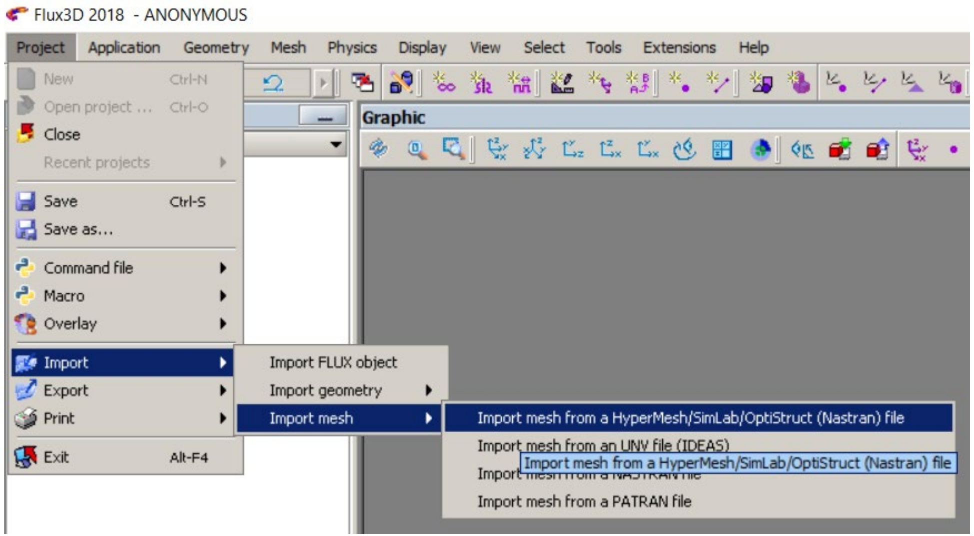
HYPERMESH MODEL OF SUBSTATION

- Preparations for Flux import
  - Air box: Volume in parallepiped shape to envelop the whole SubStation
  - Air box volume and elements

  - Shell or face where post-processing paths occurred
  - Uniform shell elements

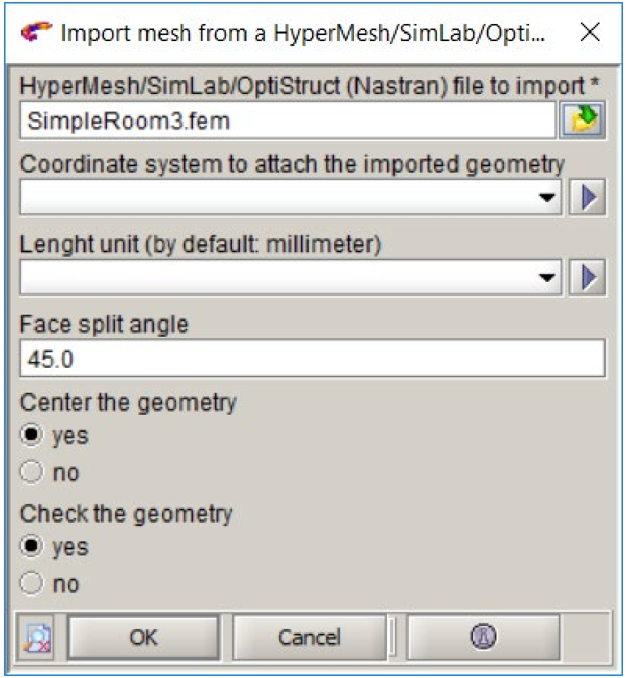
FLUX IMPORT OF SUBSTATION HYPERMESH MODEL

- Under Flux context
  - Import/Import mesh/Import mesh from HyperMesh-SimLab-OptiStruct (Nastran) file

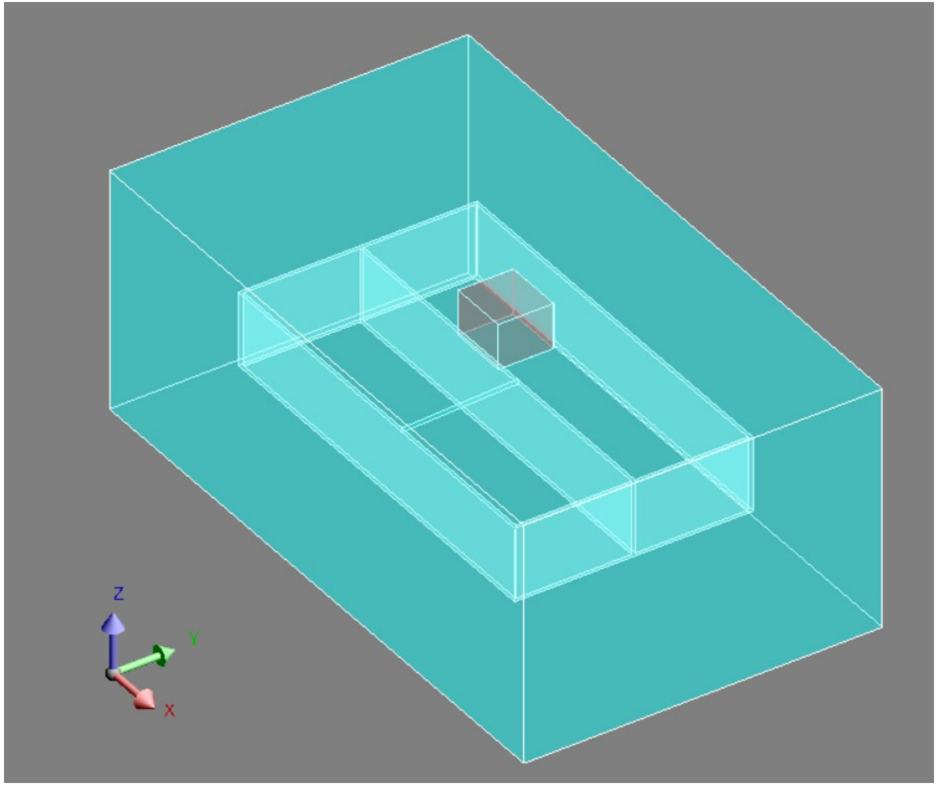


FLUX IMPORT OF SUBSTATION HYPERMESH MODEL

- File to import
- Face split angle: 45 (default)
- Center the geometry: (recommended yes)
- Check the geometry: yes (default)

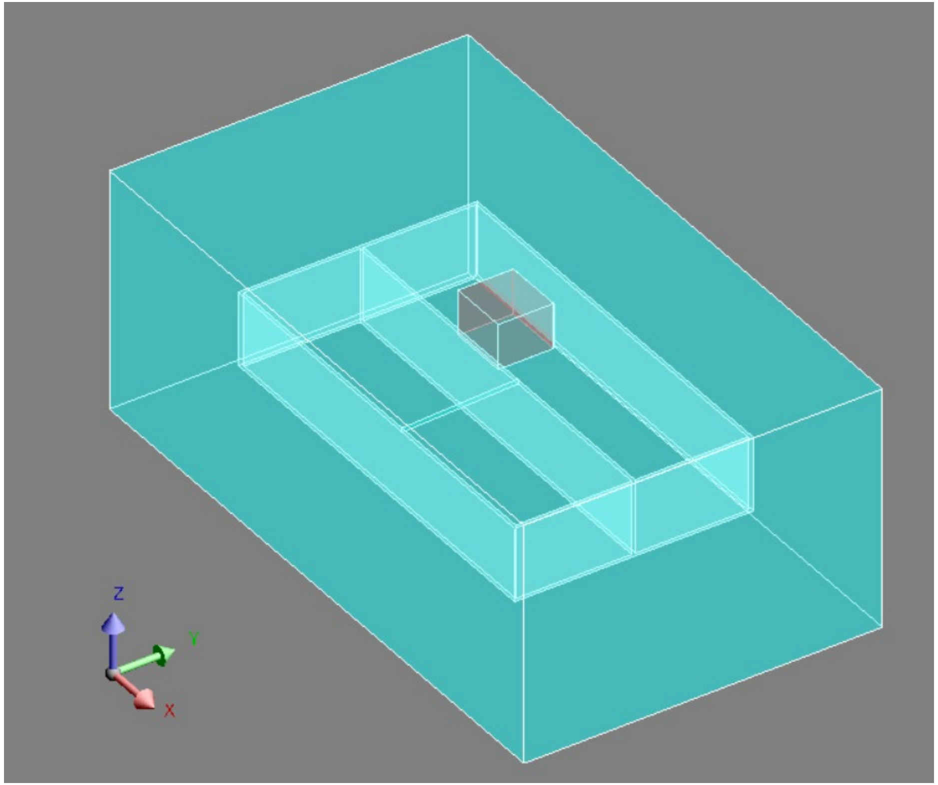


SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – FACES



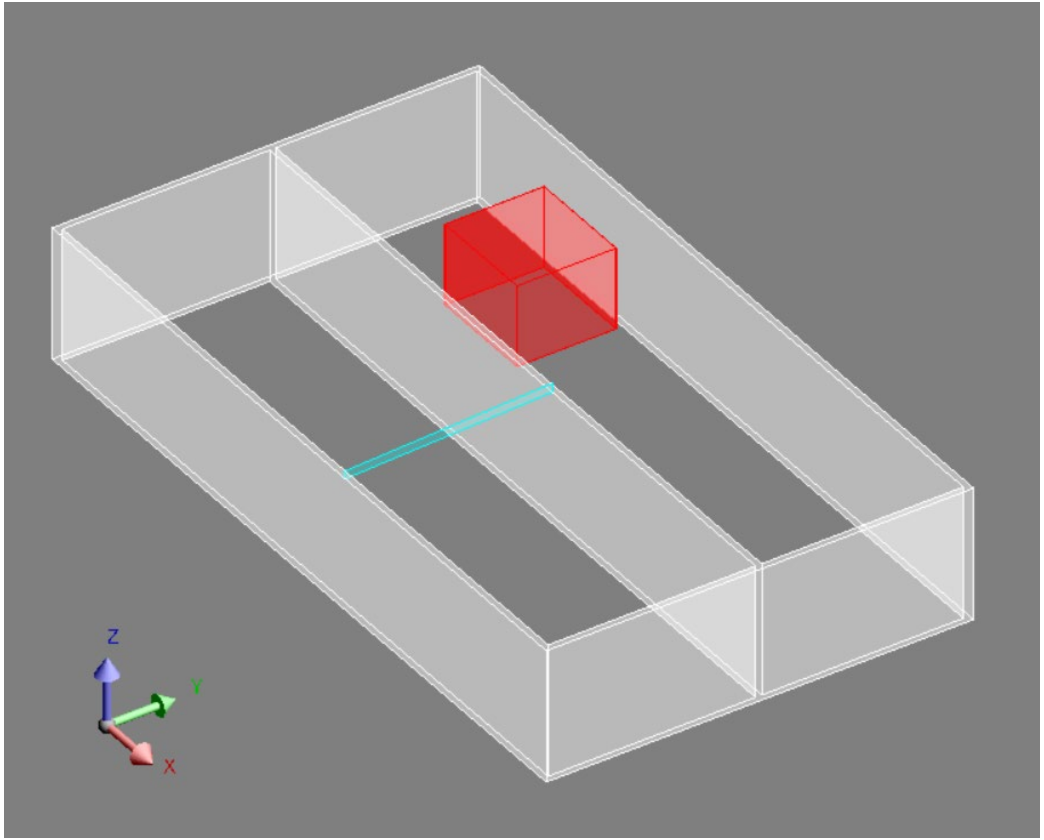
32 faces

SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – VOLUMES



3 volumes

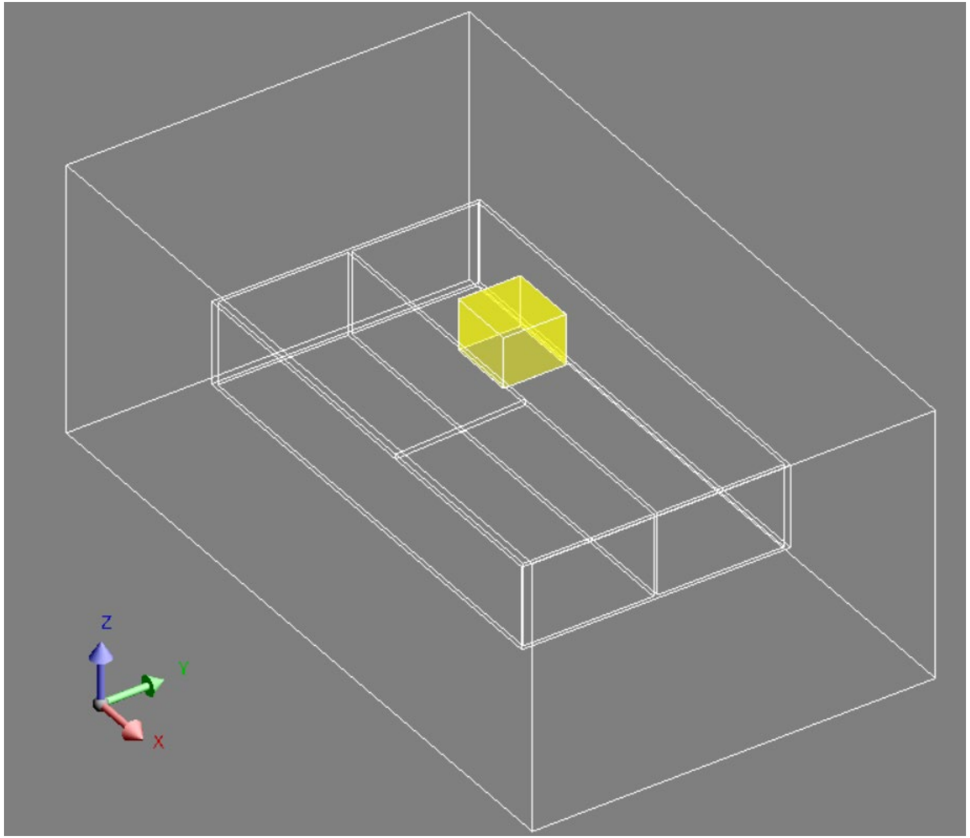
SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – FACE (SHELL) REGIONS



3 shell regions

- Roofbeam (turquoise)
- TransformerFace (red)
- WallSkins (white)

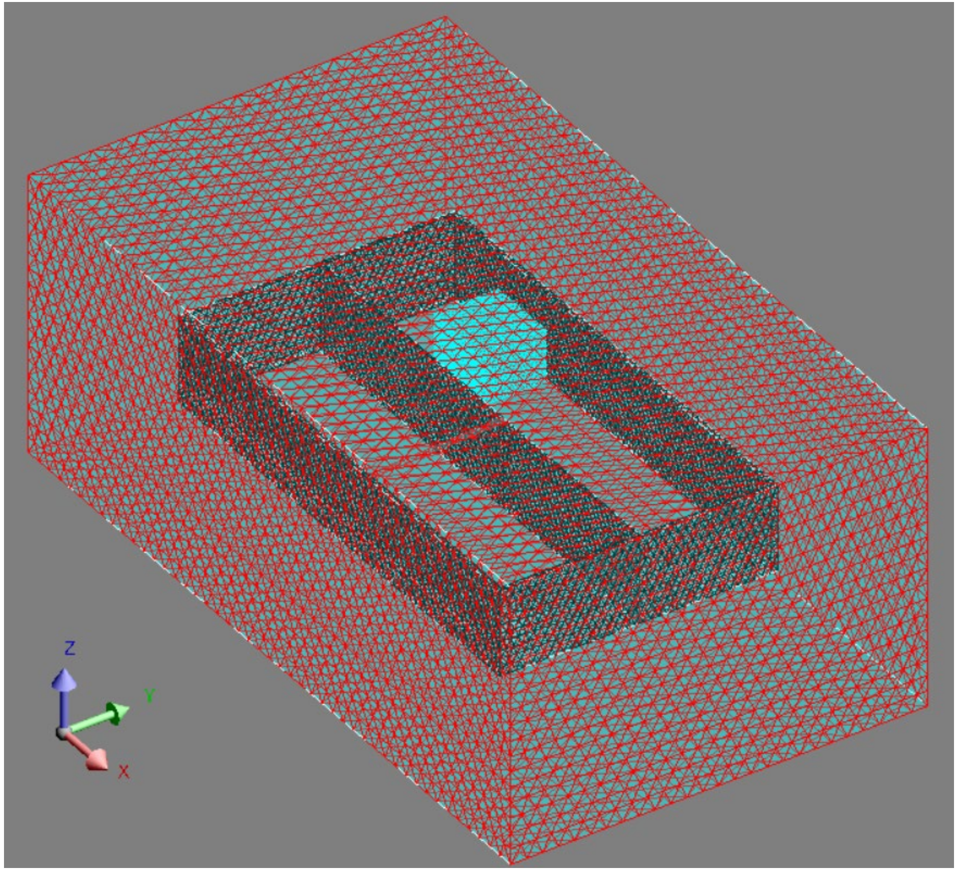
SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – VOLUME REGIONS



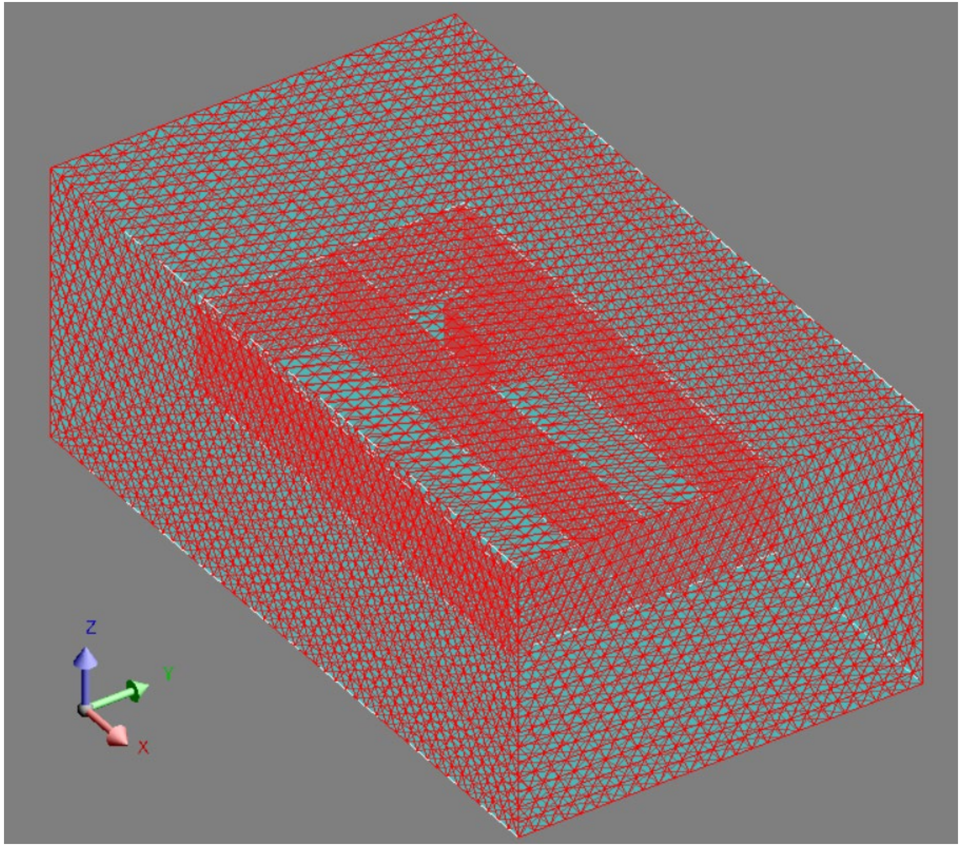
1 volume region

- TransformerFace (yellow)

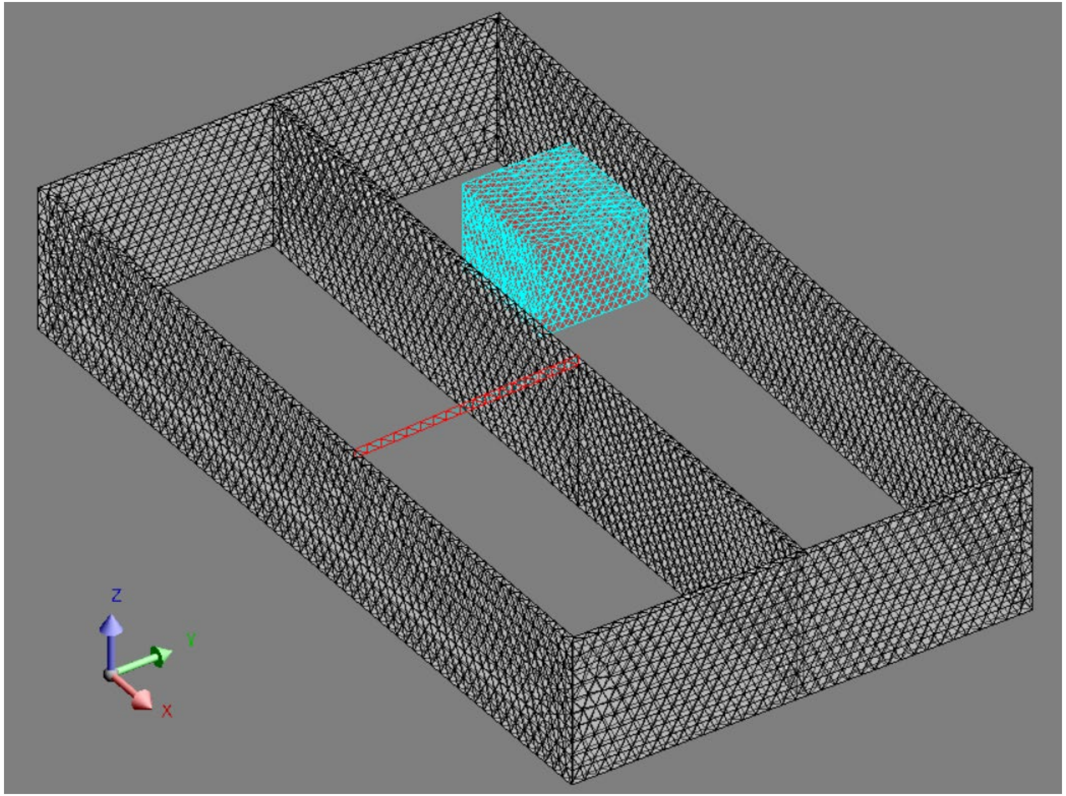
SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – FACE MESH



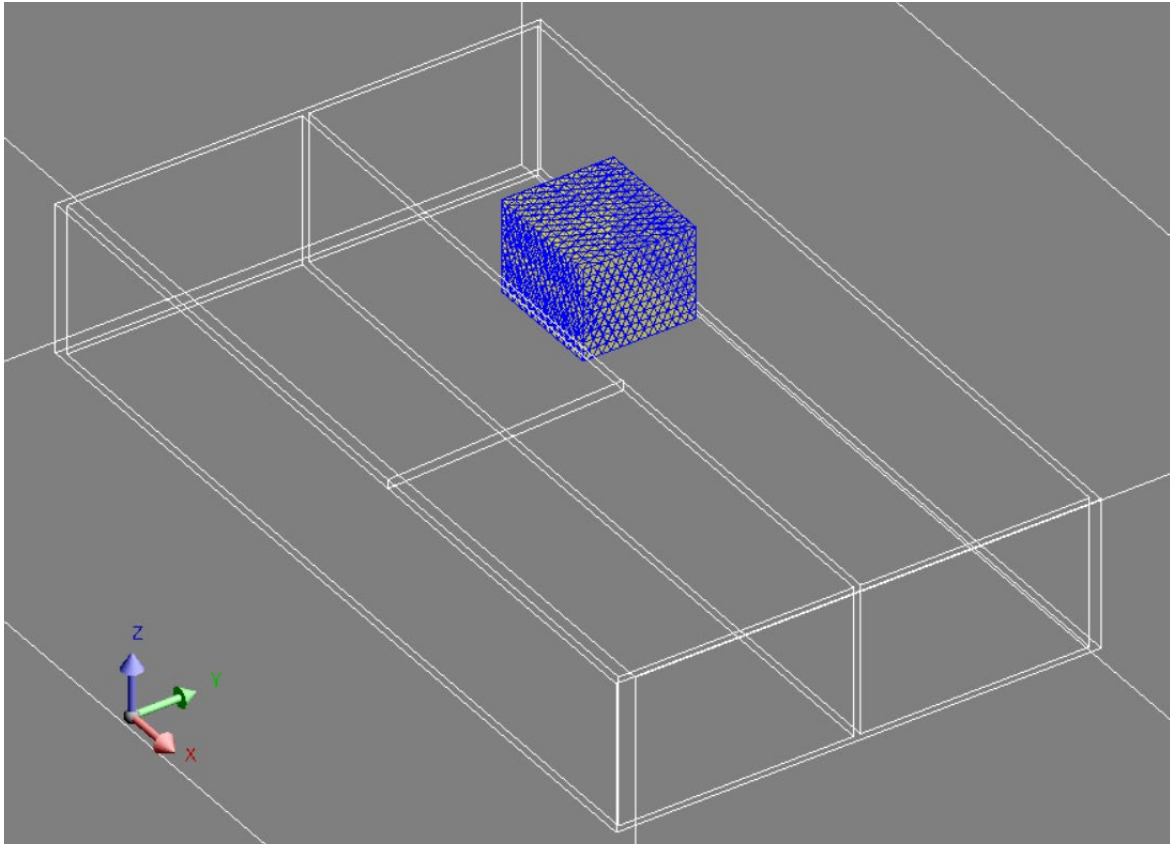
SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – VOLUME MESH



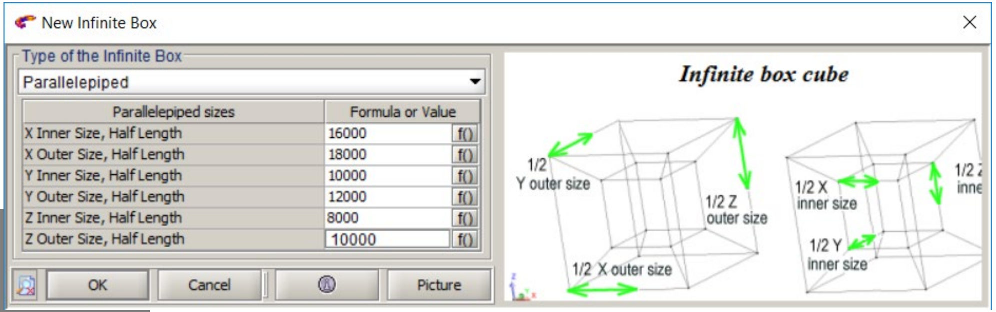
SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – FACE (SHELL) REGION MESH

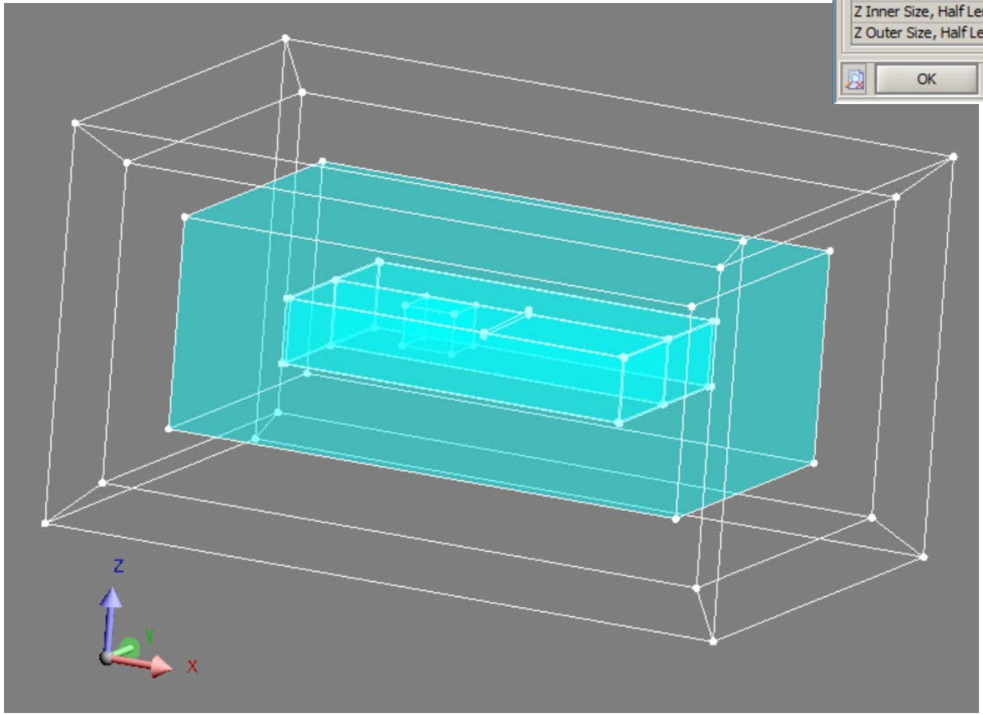


SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – VOLUME REGION MESH



SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – ADDING INFINITE BOX





- Geometry/Infinite Box/New
- Dimensions are in mm (default)

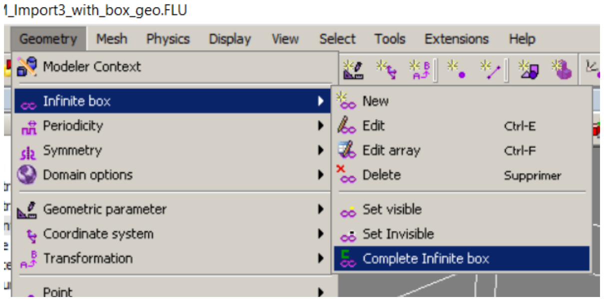
SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – COMPLETE INFINITE BOX

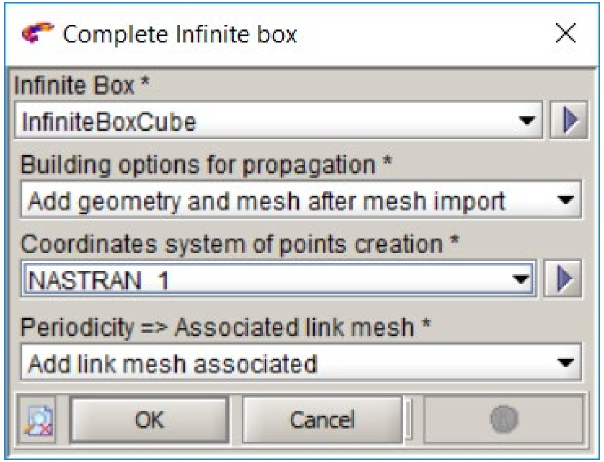
- Geometry/Infinite Box/Complete

- Building options for propagation
  - Add geometry and mesh after mesh import

- Coordinates system of points creation
  - Nastran_1

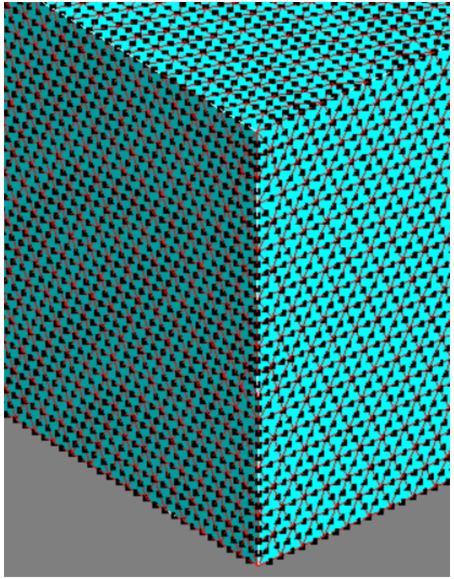
- Periodicity
  - Add link mesh associated

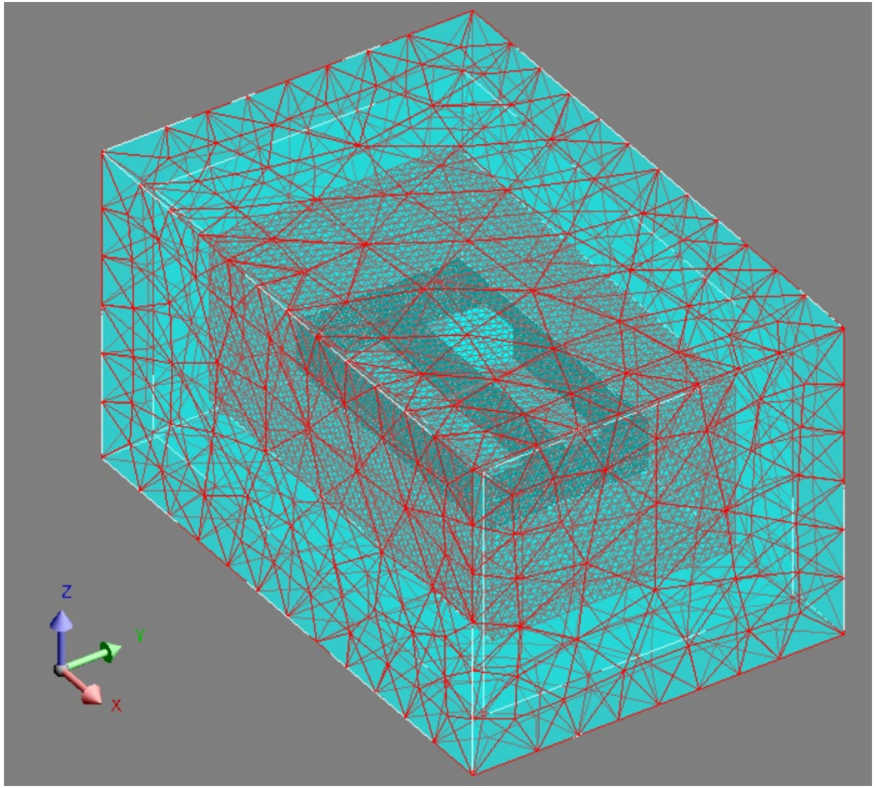




SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – INFINITE BOX MESH

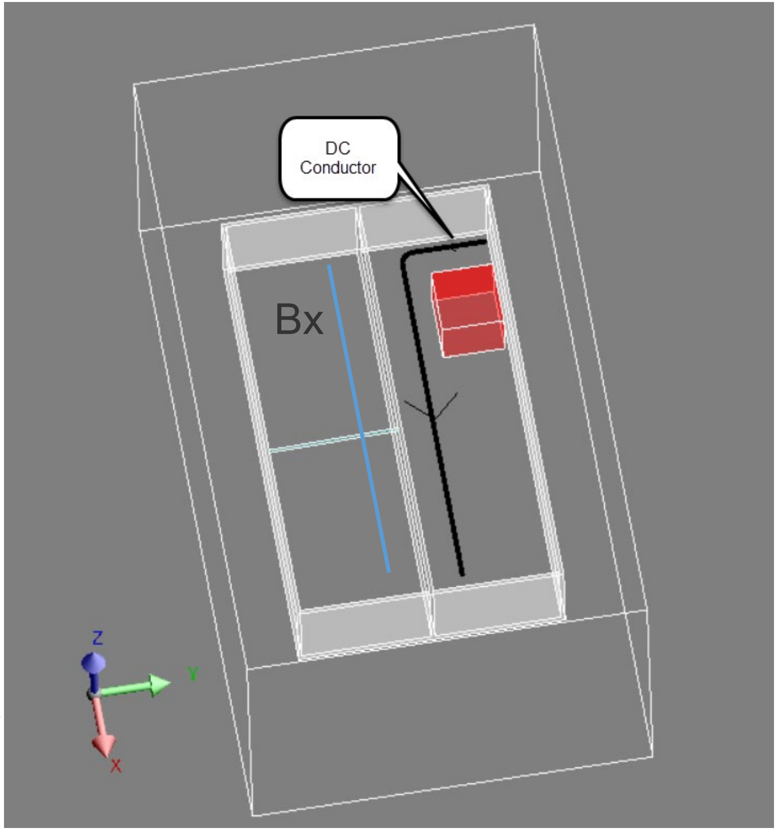
- First order mesh
- Generate second order mesh if needed





SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – MS TEST CASE

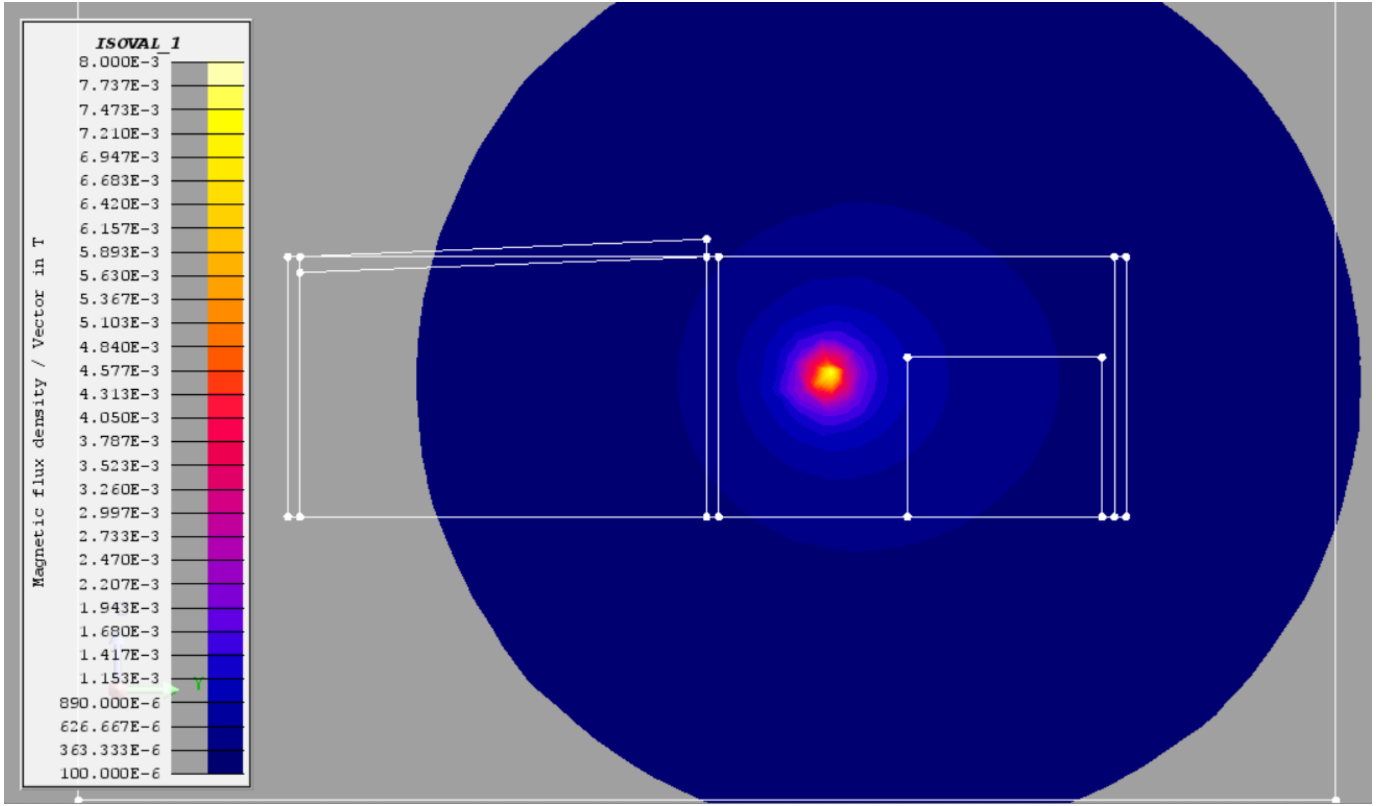
- 4000 A DC conductor
- Steel with Mur = 1000
- Roofbeam with 10 mm wide thick xsection
- Transformerface with 1 mm thick sheet
- Wallskins with 1 mm thick sheet
  - Middle wall
    - No sheet
    - 1 sheet
    - Sheets on both side
- Transformercore and wall are non magnetic
- Flux density along the middle wall Bx



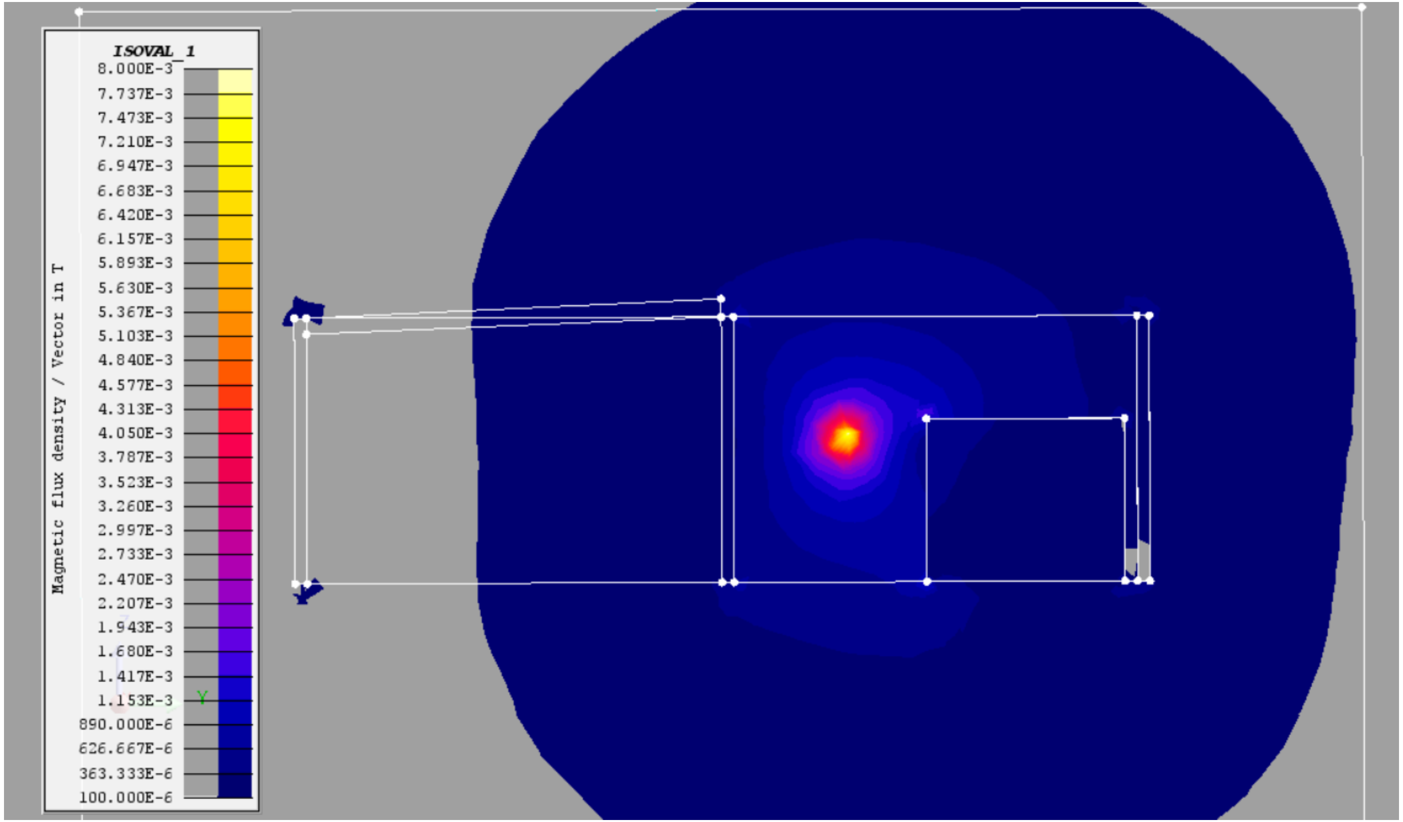
SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – MS TEST CASE – SIMULATIONS

- Reference case: NoMag – No magnetic materials – Just DC source in the air
- Middle wall has no magnetic sheets: NoSheet
- Middle wall has magnetic sheet on 1 side: 1Sheet
- Middle wall has magnetic sheets on both sides: 2Sheets

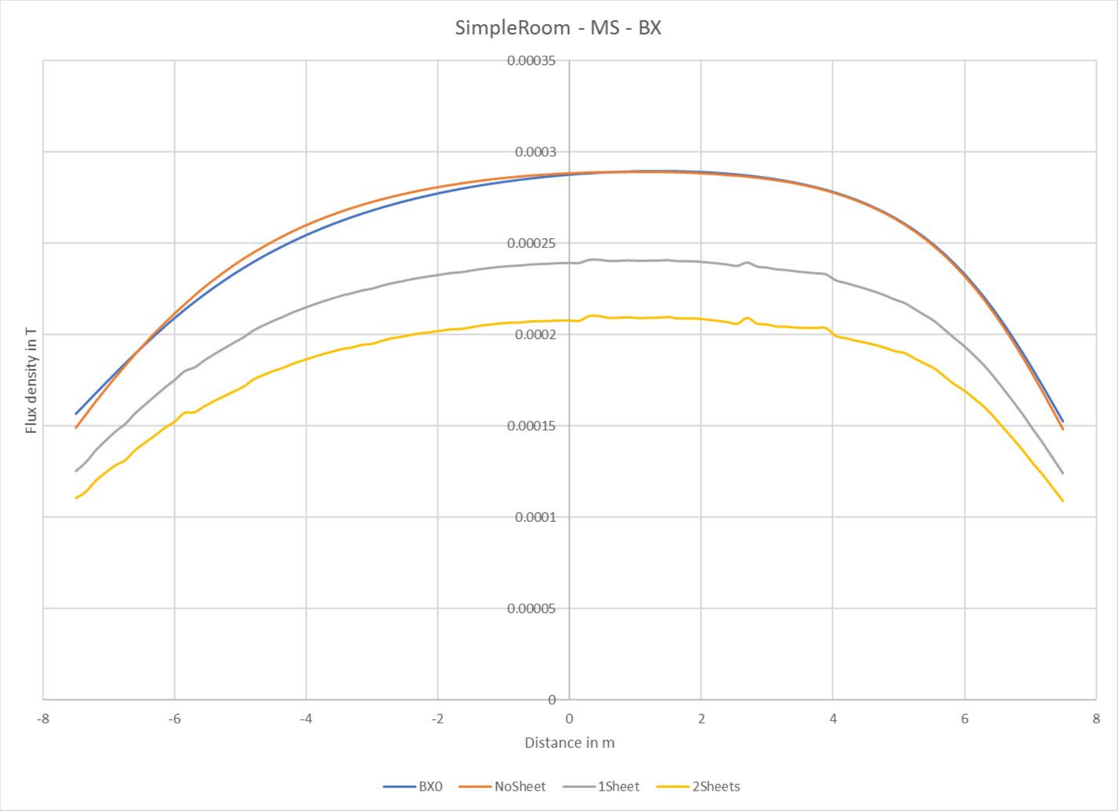
SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – MS TEST CASE – AIR ONLY (REFERENCE) – BMAP ON YZ XSECTION



SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – MS TEST CASE – 2 SHEETS MIDDLE WALL – BMAP ON YZ XSECTION

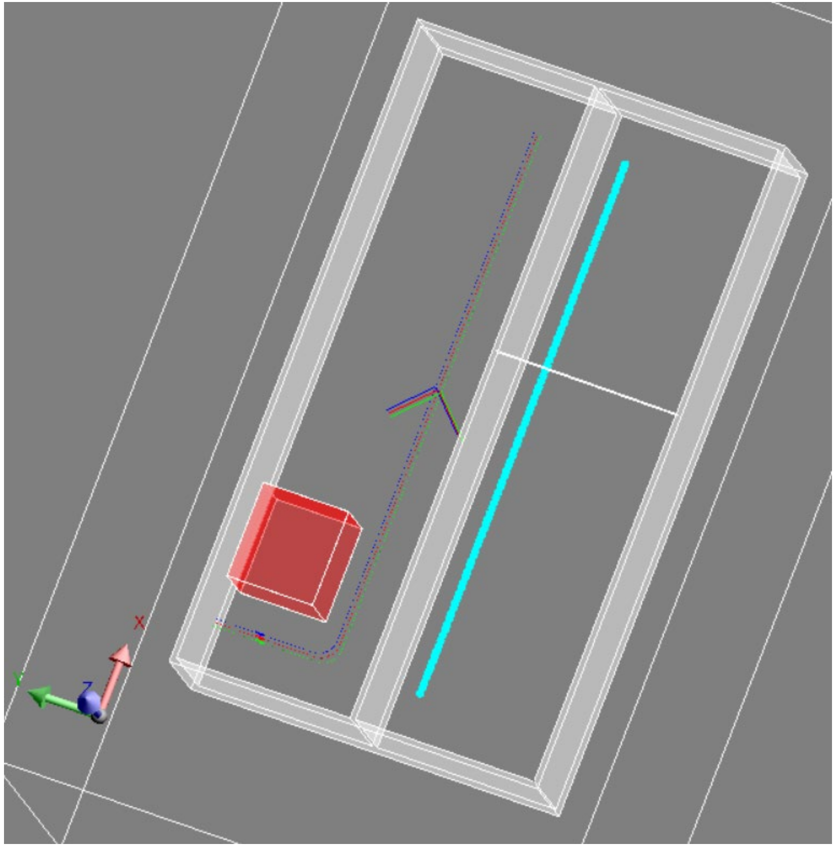


SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – MS TEST CASE – FLUX DENSITY BX ALONG THE MIDDLE WALL



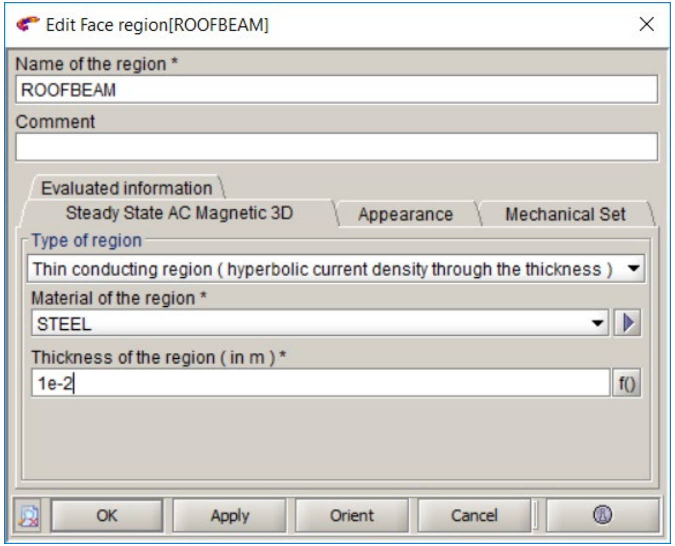
SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – AC TEST CASE

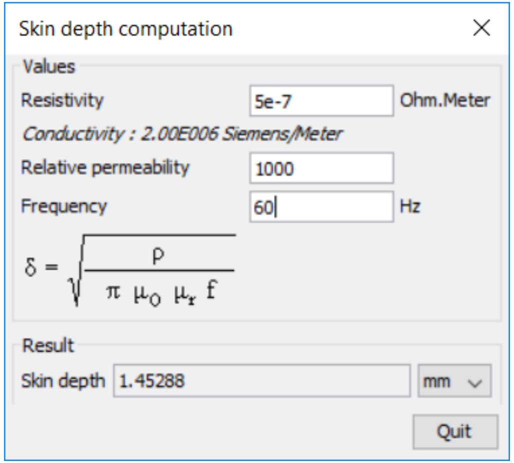
- Source 3 Phase
  - A (red): 4000 A rms – 0 deg.
  - B (green): 4000 A rms – 120 deg.
  - C (cyan): 4000 A rms – -120 deg.
- Steel with Mur = 1000 and Sigma = 2 MS/m
- Roofbeam with 10 mm wide thick xsection
- Transformerface with 1 mm thick sheet
- Wallskins with 1 mm thick sheet
  - Middle wall
    - No sheet
    - 1 sheet
    - Sheets on both side
- Transformercore and wall are non magnetic
- Flux density along the middle wall Bx



SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – AC TEST CASE – THIN CONDUCTOR REGIONS

- Roofbeam with 10 mm wide thick xsection
  - Thin conductor region

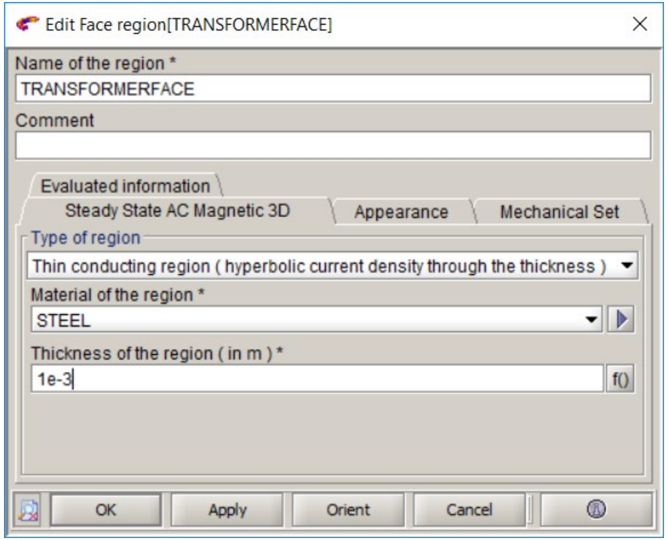


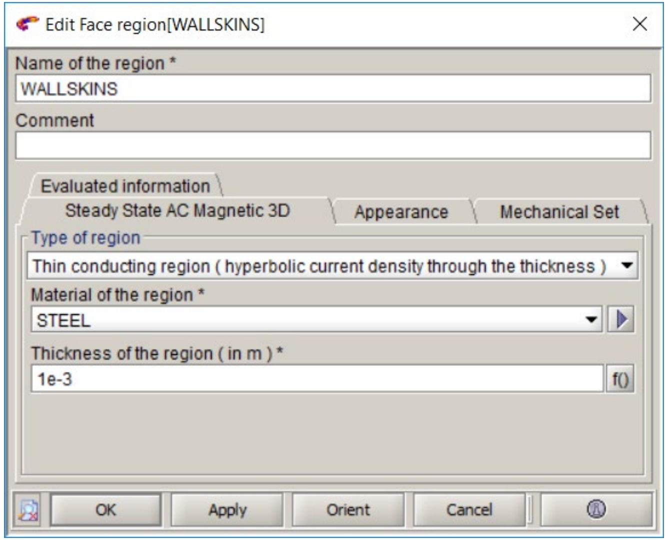


SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – AC TEST CASE – THIN CONDUCTOR REGIONS

- Transformerface with 1mm thick sheet
  - Thin conductor region

- Wallskins with 1mm thick sheet
  - Thin conductor region



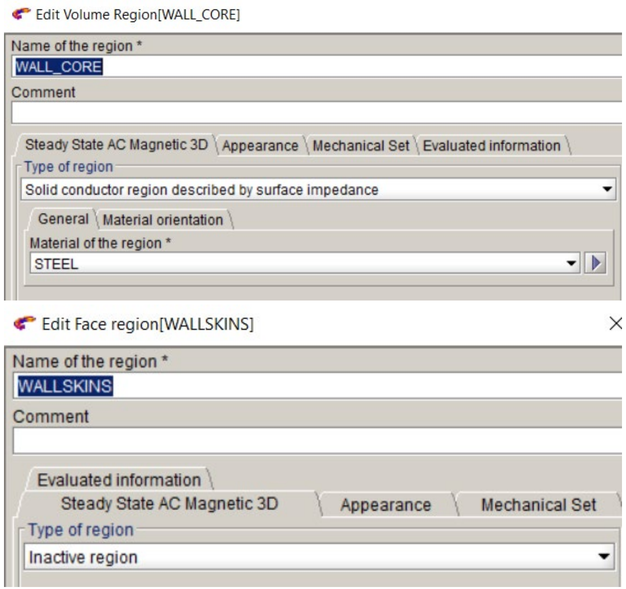


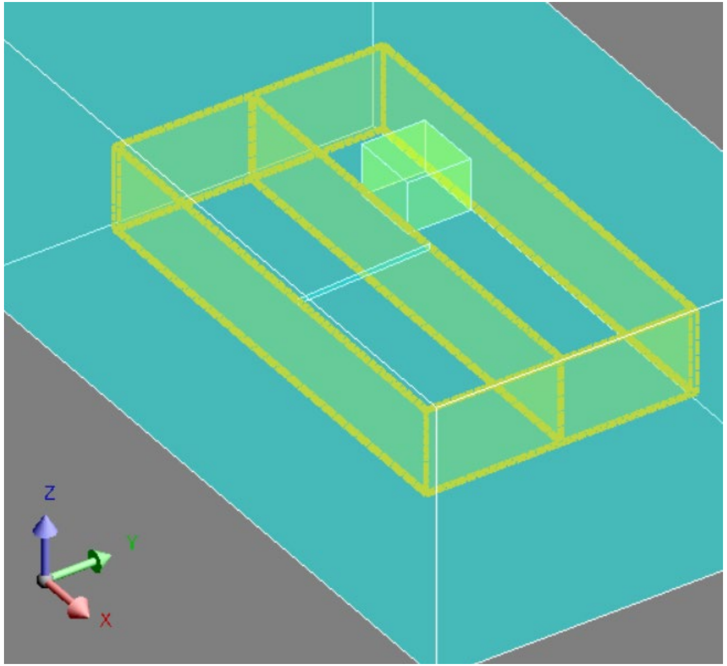
SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – AC TEST CASE – SIMULATIONS

- Reference case: NoMag – No magnetic and conductive materials – Just 3 phase sources in the air
- Middle wall has no magnetic & conductive sheets: NoSheet
- Middle wall has magnetic and conductive sheet on 1 side: 1Sheet
- Middle wall has magnetic and conductive sheets on both sides: 2Sheets
- Middle wall has magnetic and conductive sheets on both sides and surface impedance method: Surf_Imp

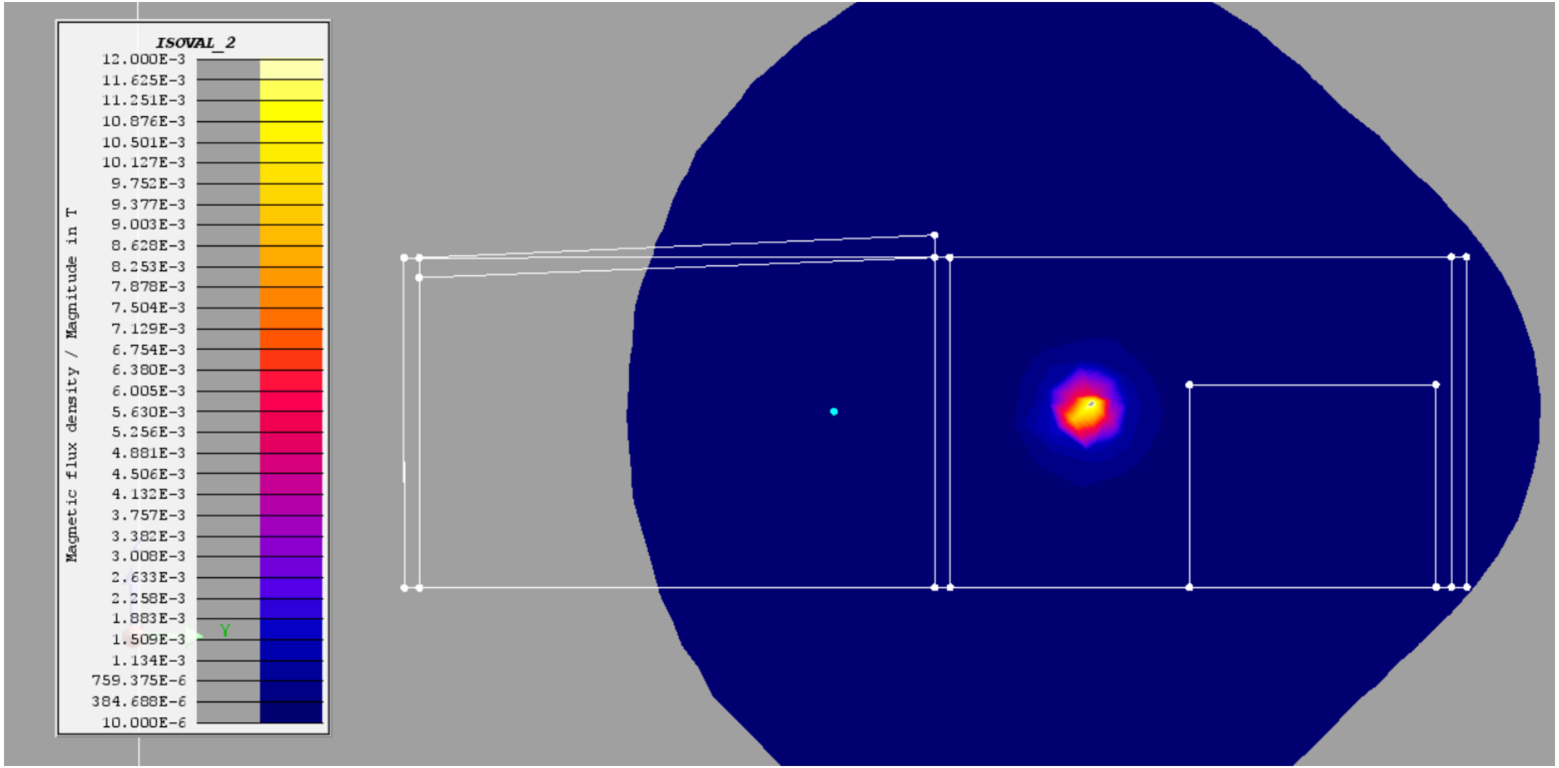
SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – AC TEST CASE – SURFACE IMPEDANCE

- Surface impedance for the magnetic and conductive sheets of the wall
- Apply to outer surface of wall volume region Wall_Core
- Shell region WallSkins inactive

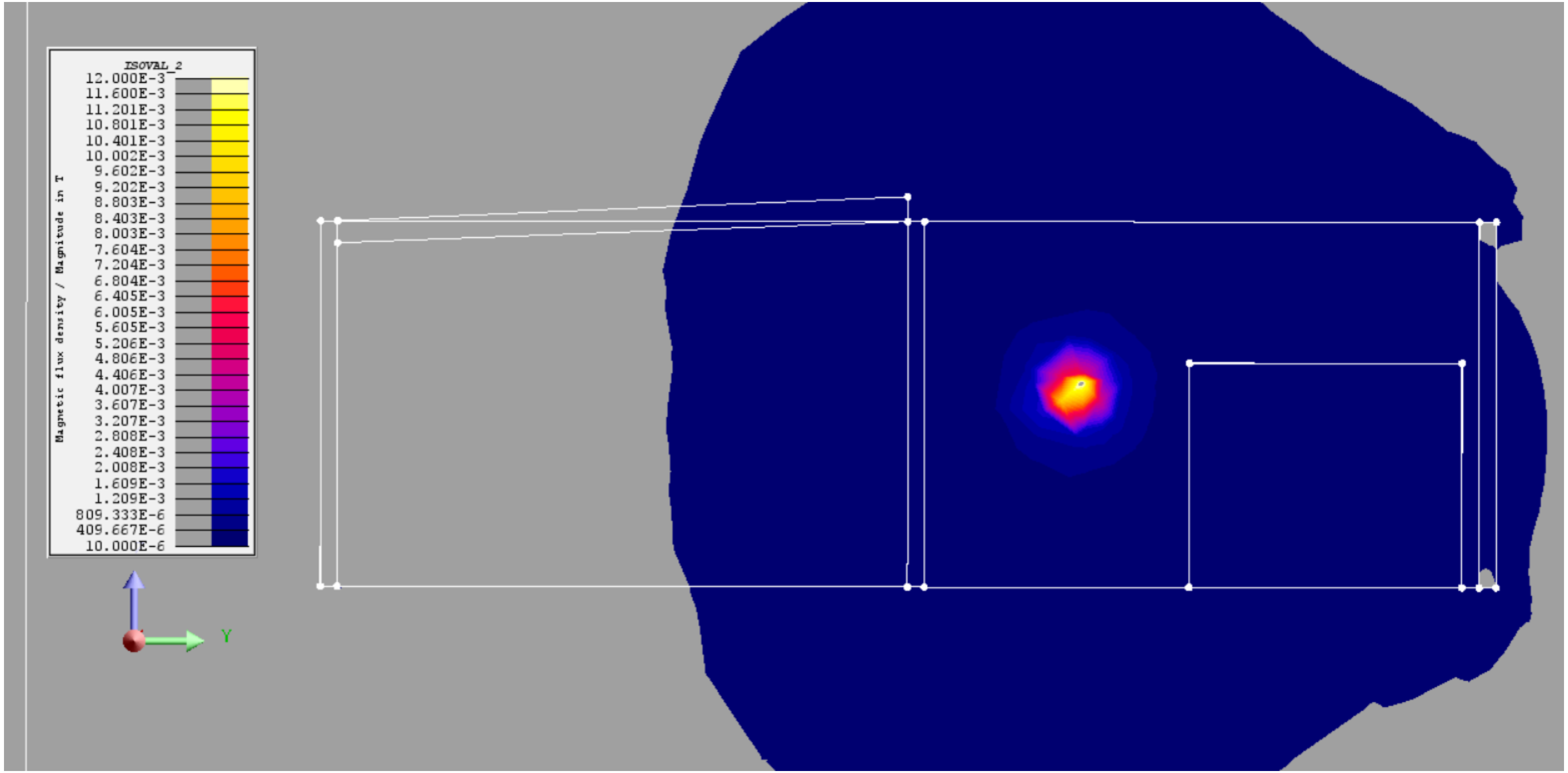




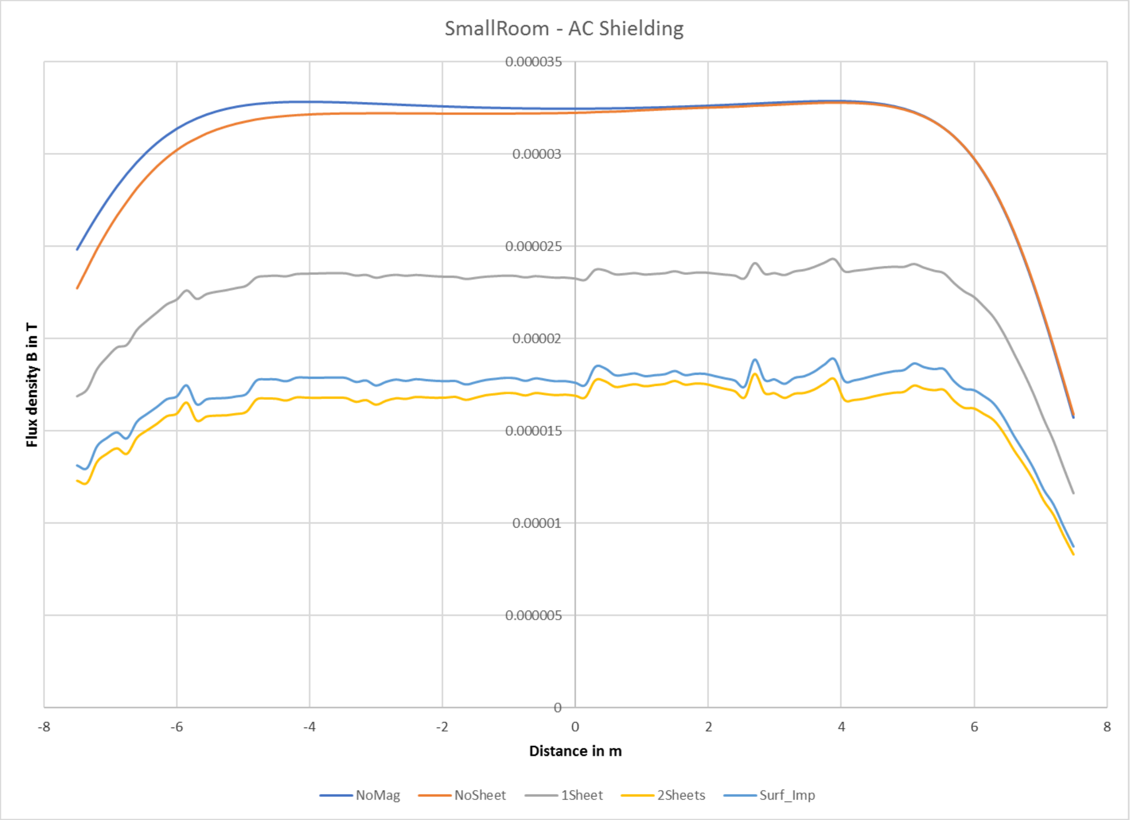
SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – AC TEST CASE – AIR ONLY (REFERENCE) – BMAP ON YZ XSECTION



SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – AC TEST CASE – 2 SHEETS MIDDLE WALL – BMAP ON YZ XSECTION



SUBSTATION HYPERMESH MODEL – SIMPLEROOM3 – MS TEST CASE – FLUX DENSITY BX ALONG THE MIDDLE WALL



SUBSTATION HYPERMESH MODEL – CONCLUSIONS

- 3D substation example – Process and requirements developed
  - Import of HyperMesh model
    - Volumes and Shells
    - Mesh
  - Thin regions
    - Magnetic thin region
    - Conductor thin region
      - Thickness > skin depth: hyperbolic
      - Thickness < skin depth: surface impedance
- Test cases – Validation of conductive shielding effectiveness with thin conductor regions
  - Static field with 4000 A DC conductor
  - AC field with 3 phase 60 Hz 4000 A rms conductors