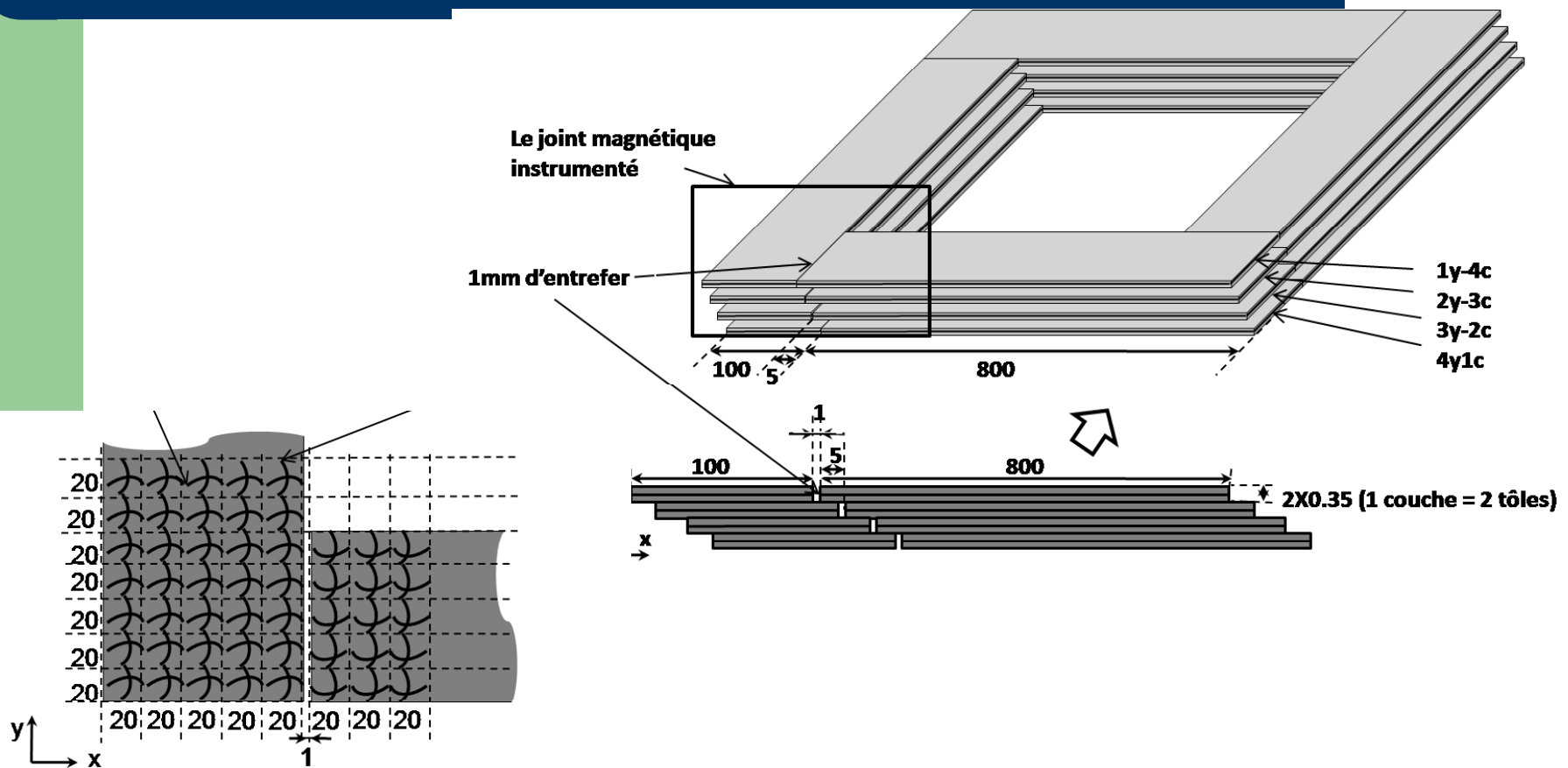


Identification of the Equivalent Permeability of Step-Lap Joints of Transformer

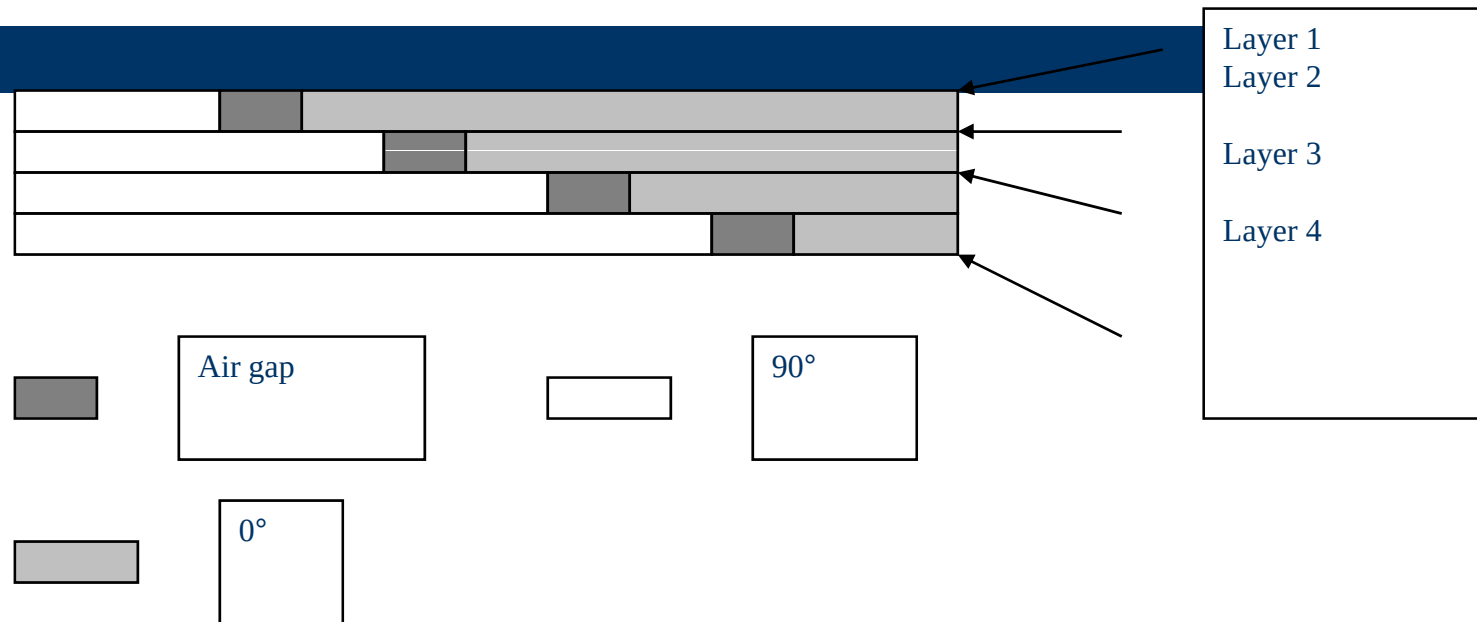
E.Napieralska Juszczak
Universite Artois, France

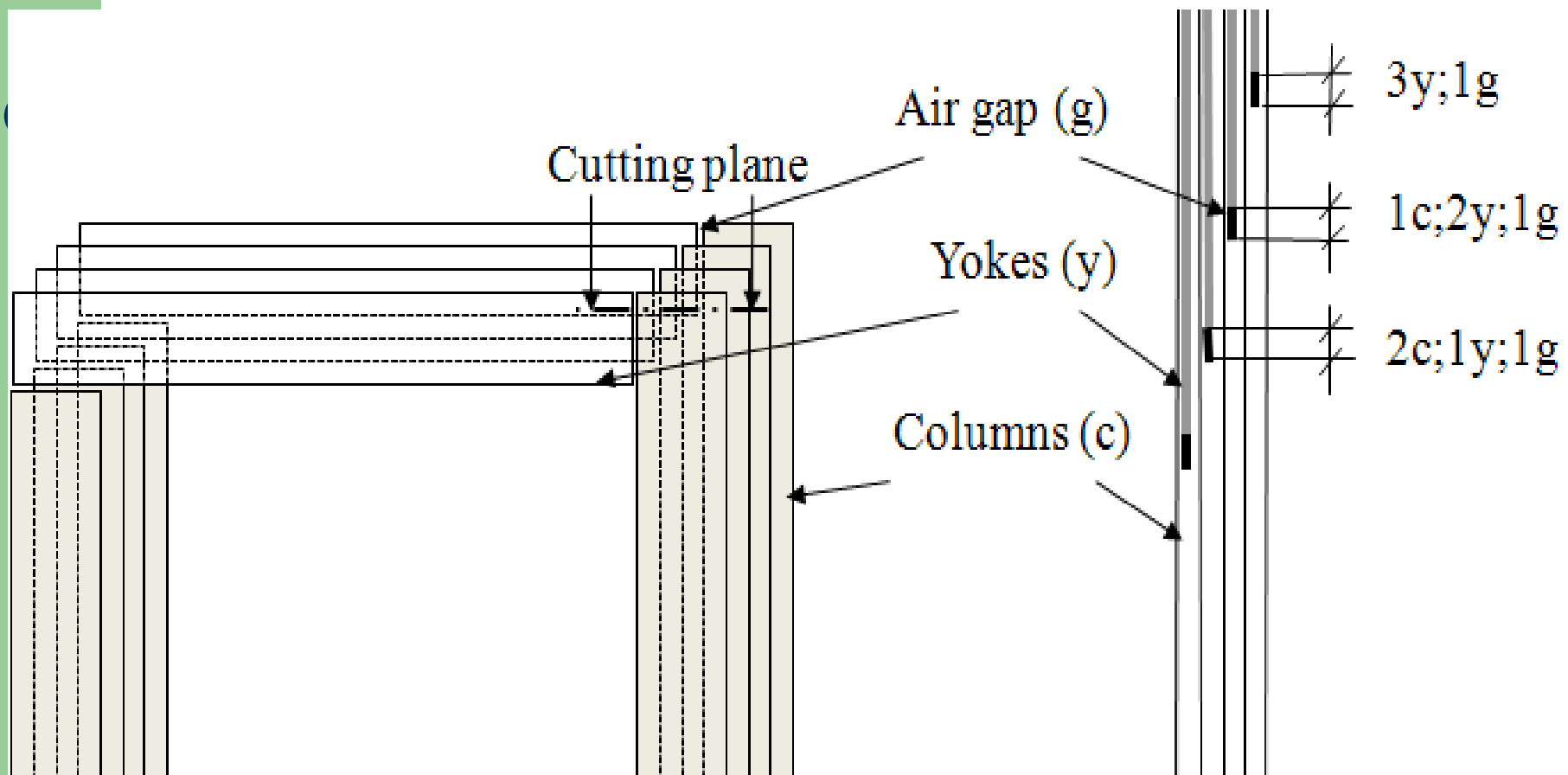


COMPUTATION OF THE EQUIVALENT CHARACTERISTICS OF LAMINATED ANISOTROPIC MAGNETIC CORES



Presentation of the structure





Method of establishing equivalent characteristics for various structures

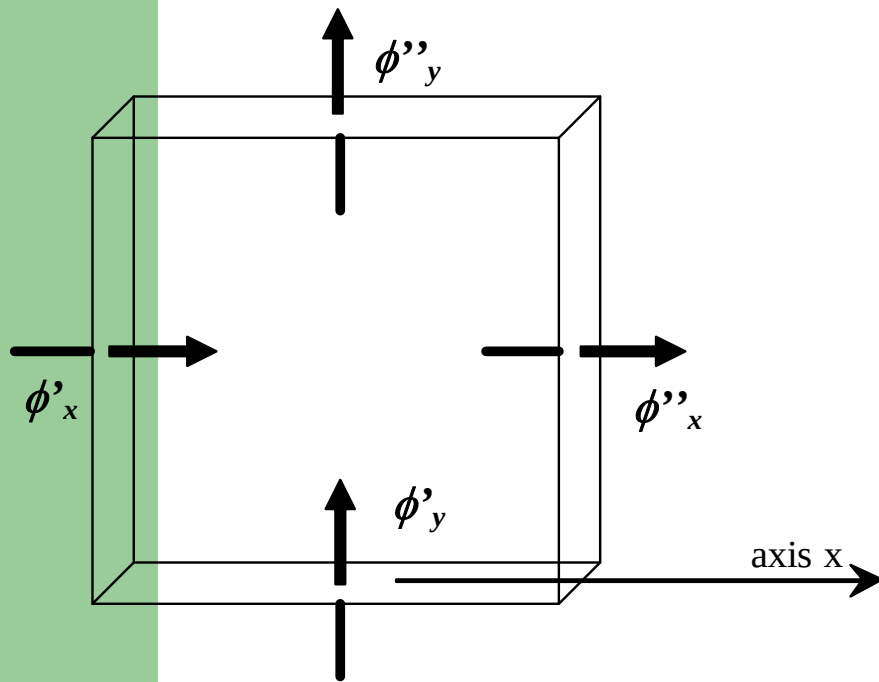
- Using the homogenization technique makes it possible to replace real 3D structures by simpler homogeneous 2D.
- In the homogenization technique, two concepts are of importance: macrostructure and microstructure.
- In the considered problem, the macrostructure is a complete assembly of layers in the overlap, while the microstructure is a repeatable structure of two or more layers made of sheets with the different rolling direction.

The relation between the flux density vector in the repetitive structures

$$\vec{B} = \frac{1}{dx \cdot dy \cdot H} \sum_{i=1}^n \vec{B}_i \cdot dx \cdot dy \cdot h_i$$

The calculation of components B_{ix} and B_{iy} is based on the total flux penetrating through the limiting surfaces of the volume V .

The calculation is based on the total flux penetrating through the limiting surfaces of the volume V .



$$B_{ix} = \frac{\phi'_{ix} + \phi''_{ix}}{2 \cdot dy \cdot h_i}$$

$$B_{iy} = \frac{\phi'_{iy} + \phi''_{iy}}{2 \cdot dx \cdot h_i}$$

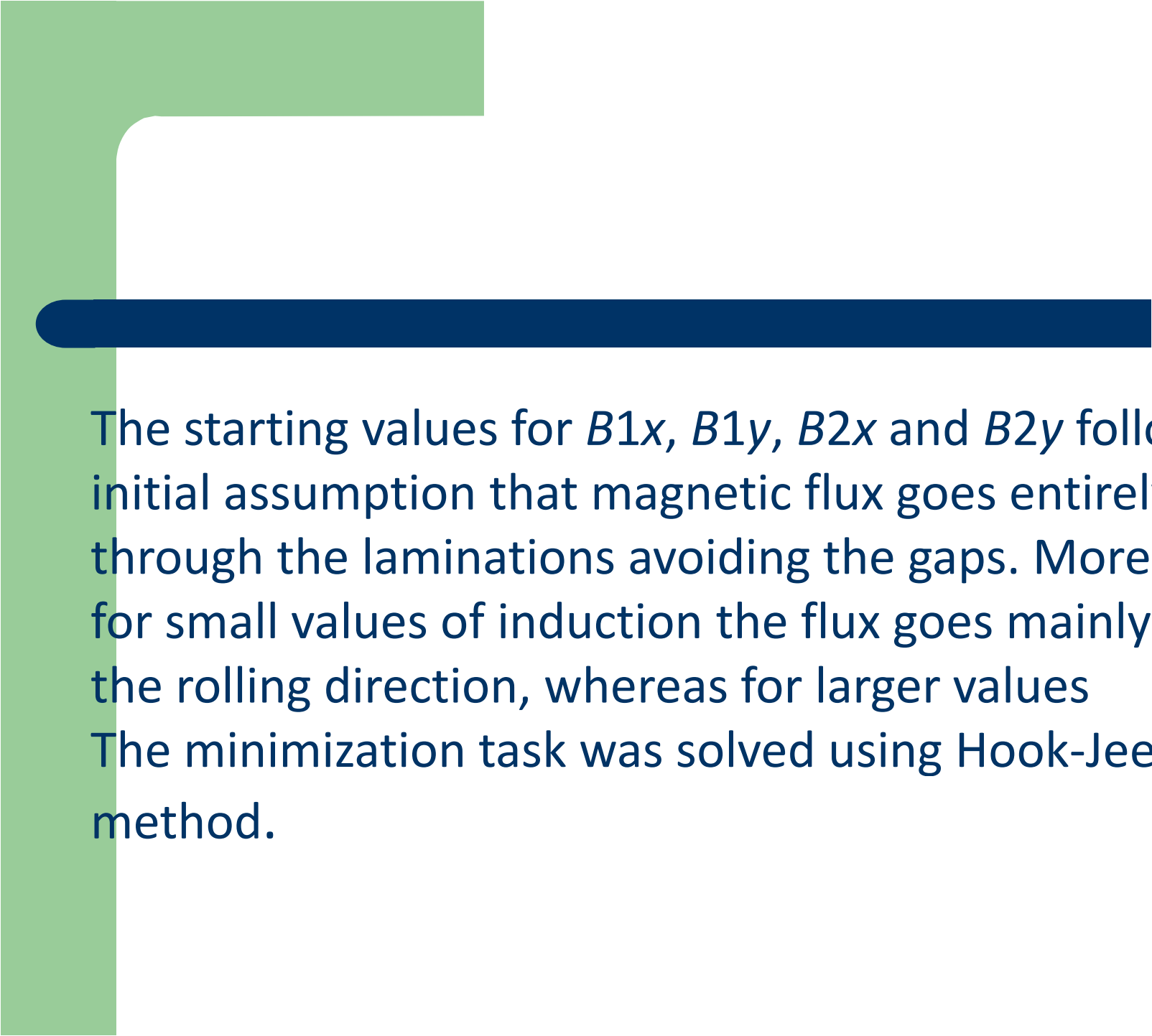
The total energy of the macrostructure results from the sum of the magnetic energy $W_{\mu i}$ stored in each volume V_i of the layer i

$$W_{\mu \min} = \sum W_{\mu i}(\mu_i, \vec{B}_i)$$

$$W_{\mu i} = \frac{V_{layi} \vec{B}_i \vec{H}_i}{2} = \frac{V_{layi} B_i^2 \nu_i(B_i^2, \alpha_i)}{2}$$

$$\nu(\vec{B}, W_{\mu \min}) = \frac{n_{Fe} \nu_{Fe} \vec{B}_{Fe}^2 + n_0 \nu_0 B_0^2}{n B^2}$$

The unknowns are flux densities vectors B_i in layers and the angles



The starting values for B_{1x} , B_{1y} , B_{2x} and B_{2y} follow an initial assumption that magnetic flux goes entirely through the laminations avoiding the gaps. Moreover, for small values of induction the flux goes mainly along the rolling direction, whereas for larger values

The minimization task was solved using Hook-Jeeves' method.

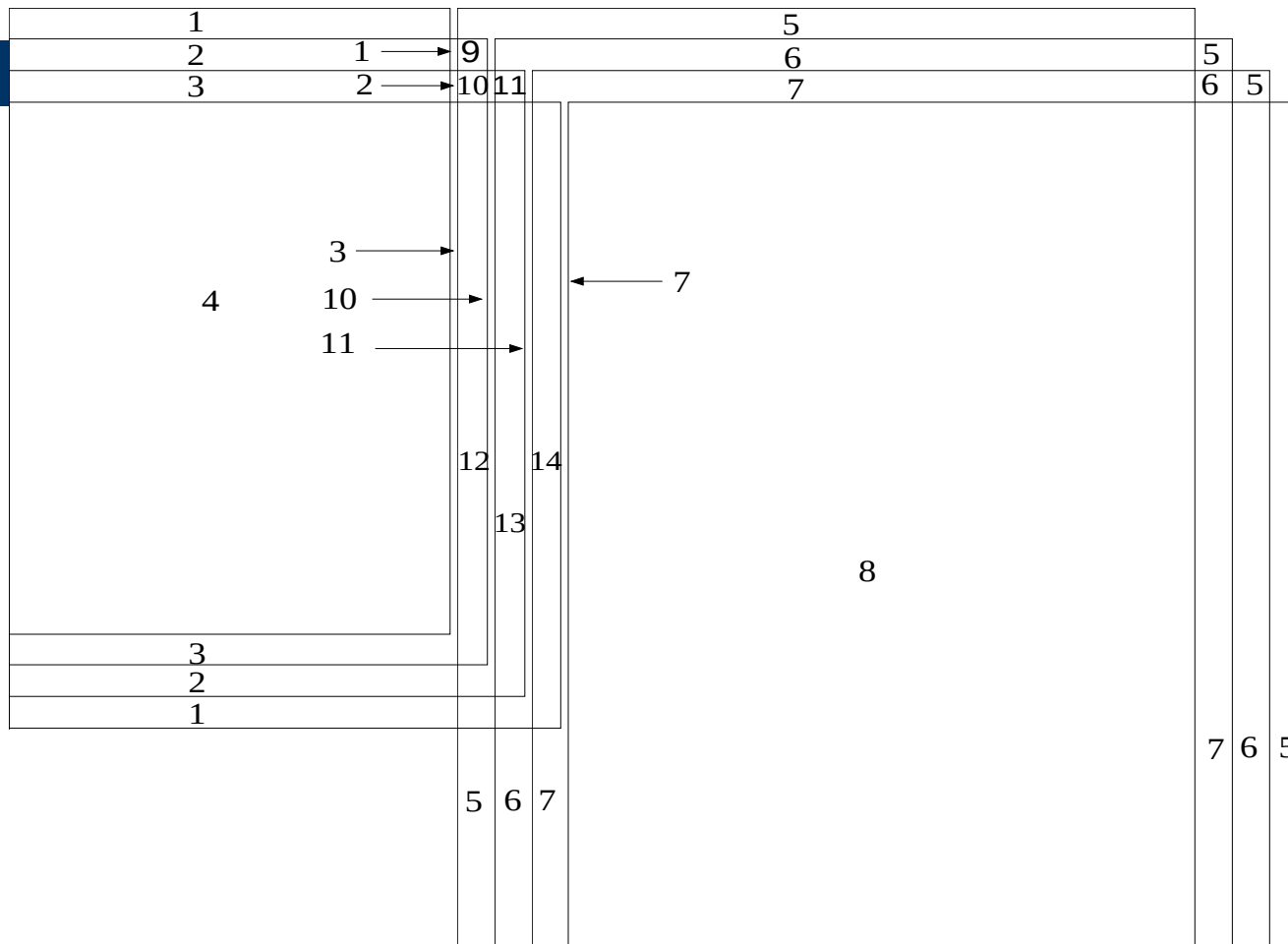
To calculate the equivalent curve $B-H$ the value of flux density B was changed in the interval $0-B_{sat}$
A single point of the curve $B-H$ was determined

- 1) To calculate $B_1, B_2, \alpha_1, \alpha_2$ from the minimization task
- 2) To calculate $\nu_1(B_1, \alpha_1)$, $\nu_2(B_2, \alpha_2)$
- 3) To calculate the homogenized reluctivity

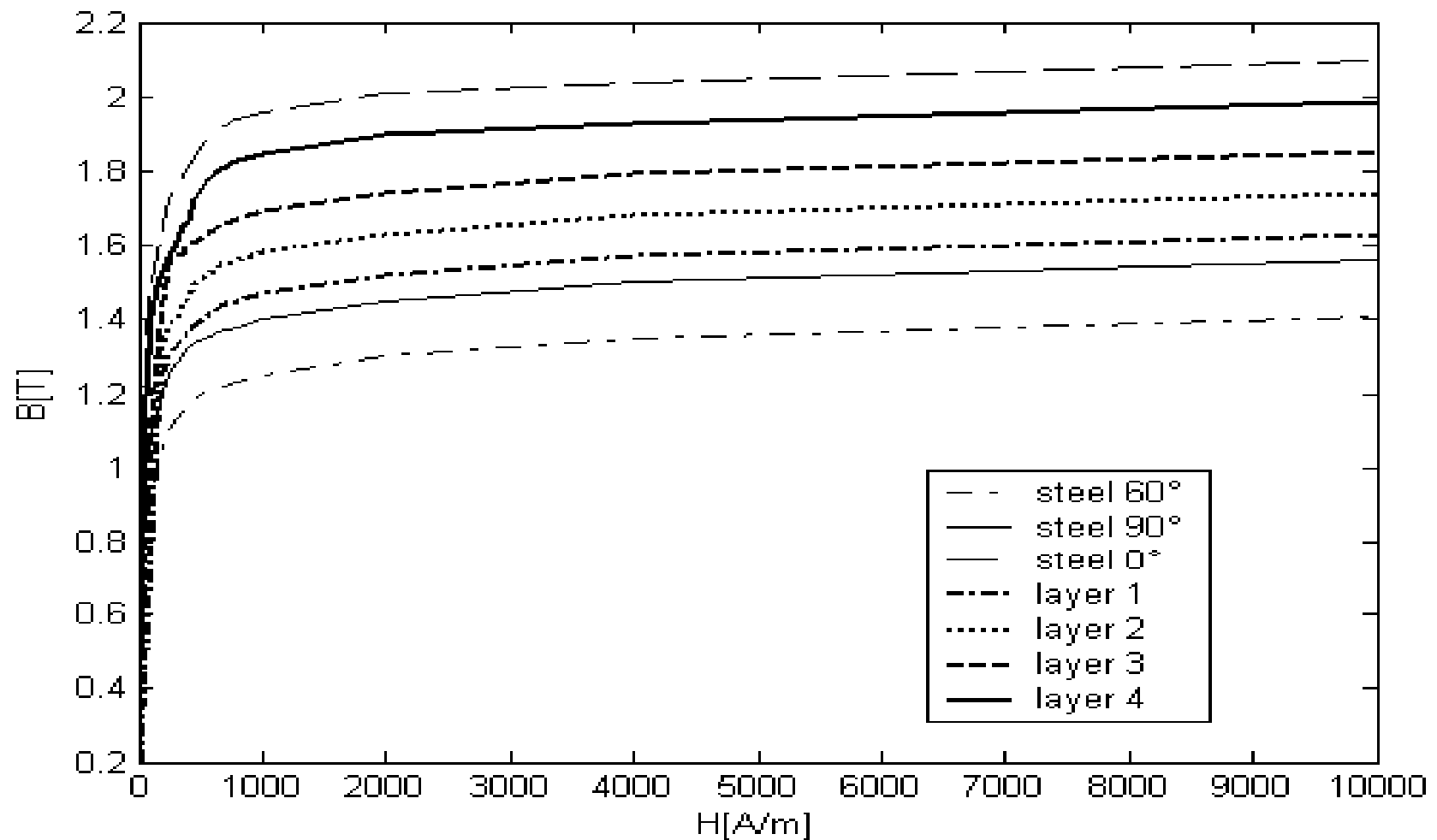
$$\nu(\vec{B}, W_{\mu \min}) = \frac{[\nu_1(B_1^2, \alpha_1) \cdot B_1^2 n_1 + \nu_2(B_2^2, \alpha_2) \cdot B_2^2 n_2]_{\min}}{(n_1 + n_2) B^2}$$

- 4) To calculate field intensity.

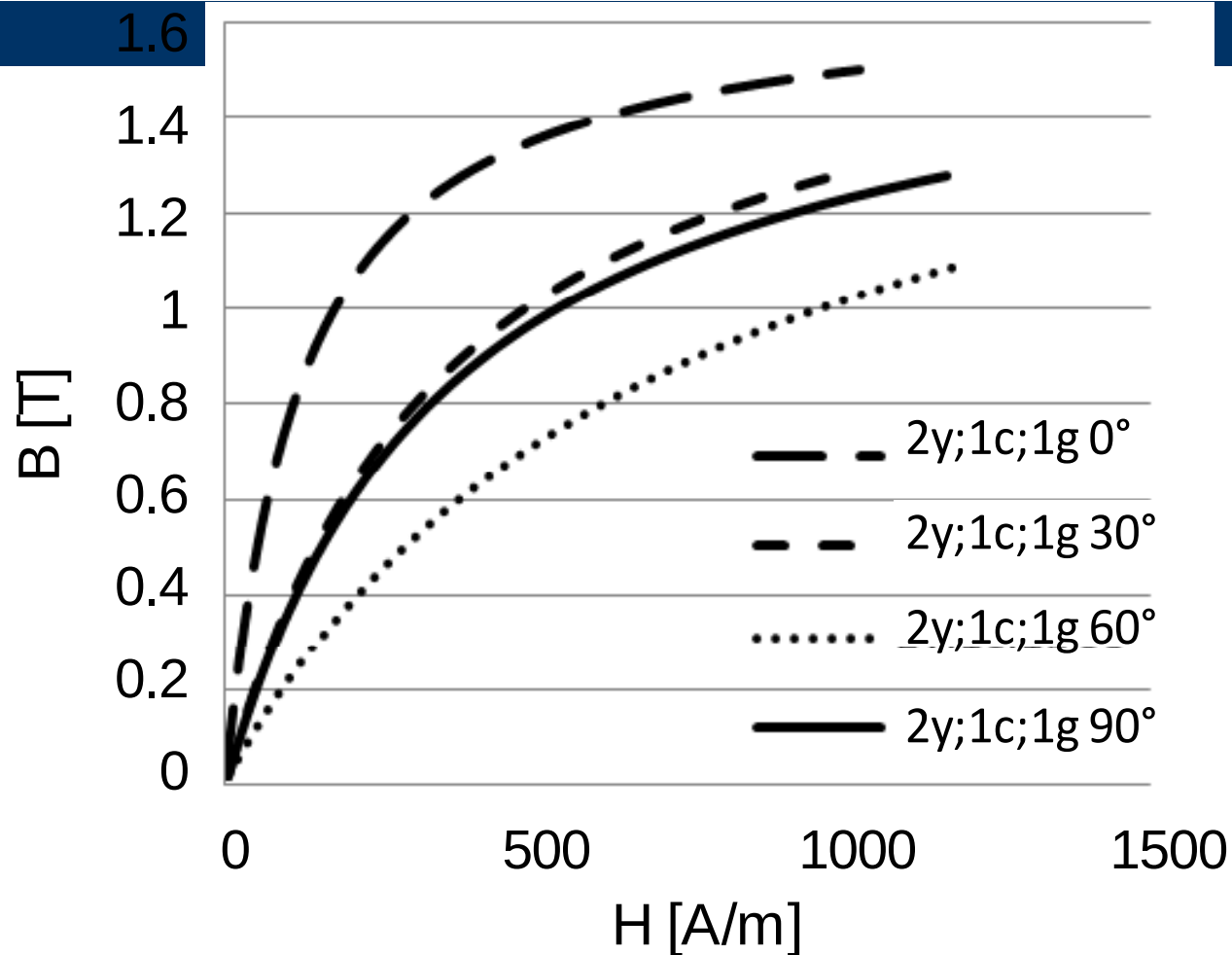
2D model of the core corner



Family of characteristic B-H for the directions 0° for the 4 layers



• Equivalent static B/H curves for the air-gap (2y;1c;1g) at four different anisotropy angles



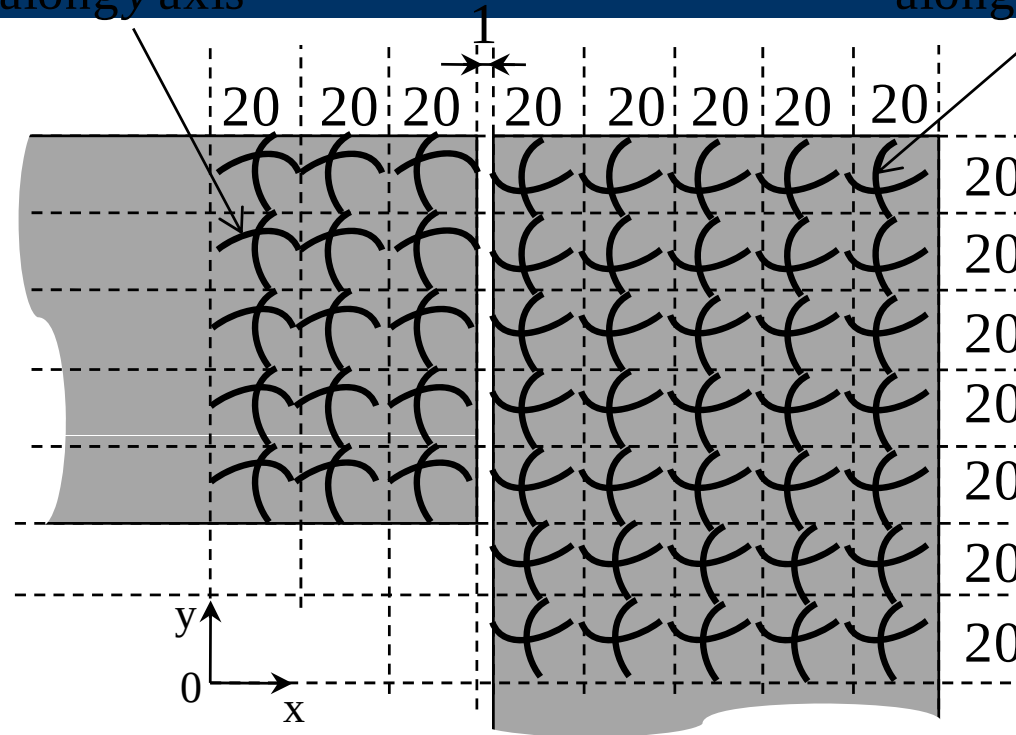
The experimental set up

A two-turn search coil for
measuring magnetic flux

A two-turn search coil for
measuring magnetic flux

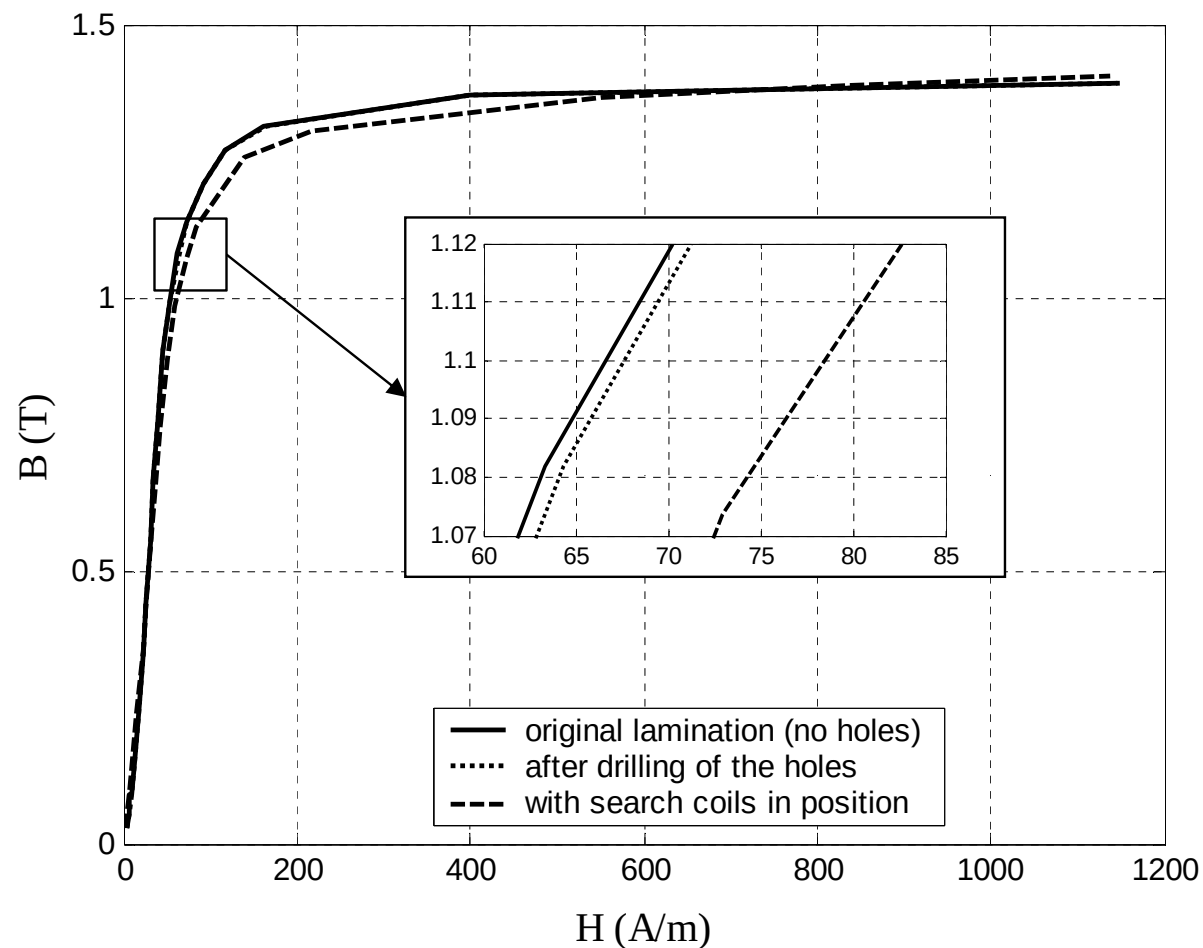
along y axis

along x axis

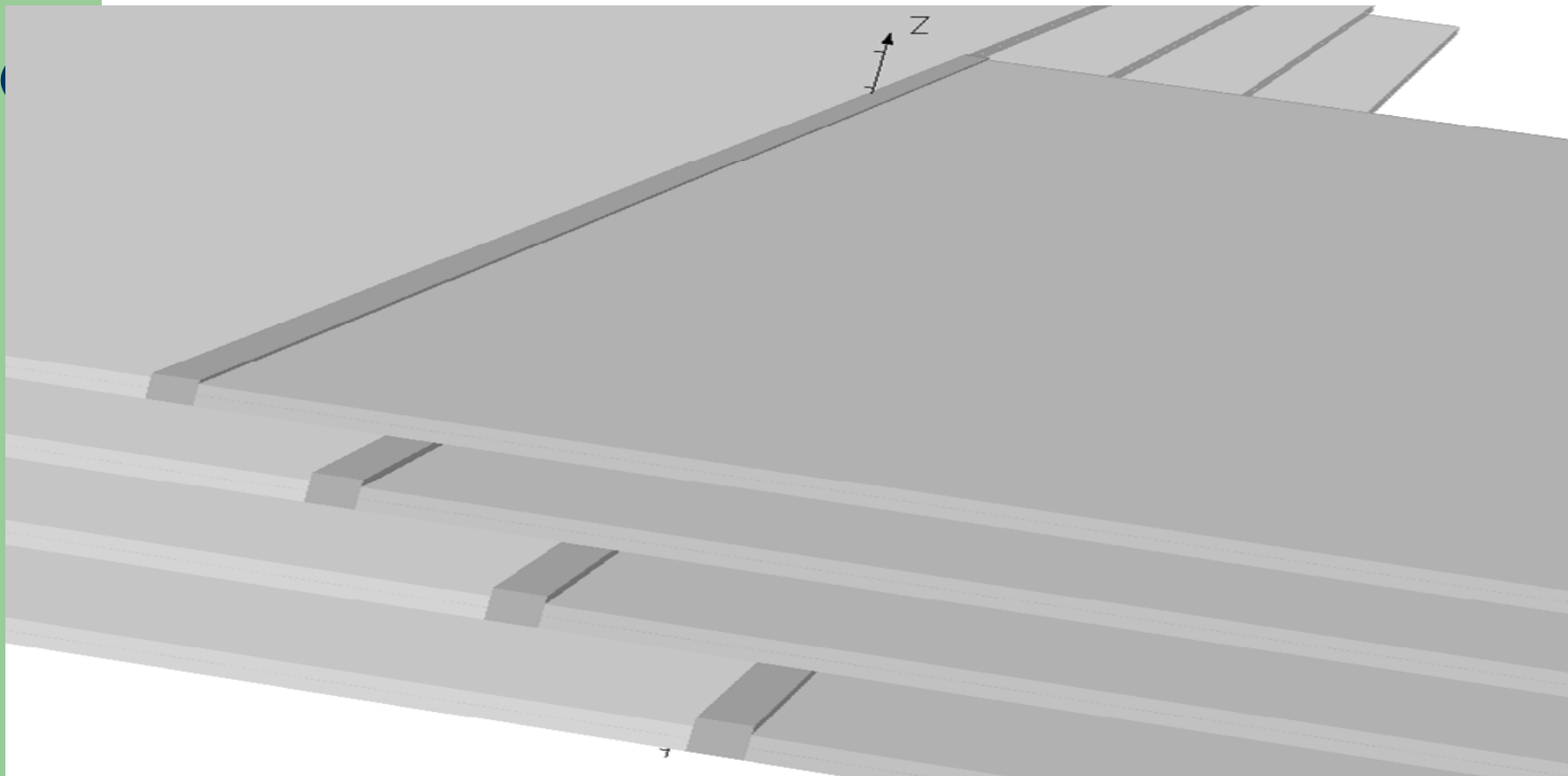


Layer 1

Measured characteristics for the whole structure (before and after drilling of the holes and installation of the search coils).

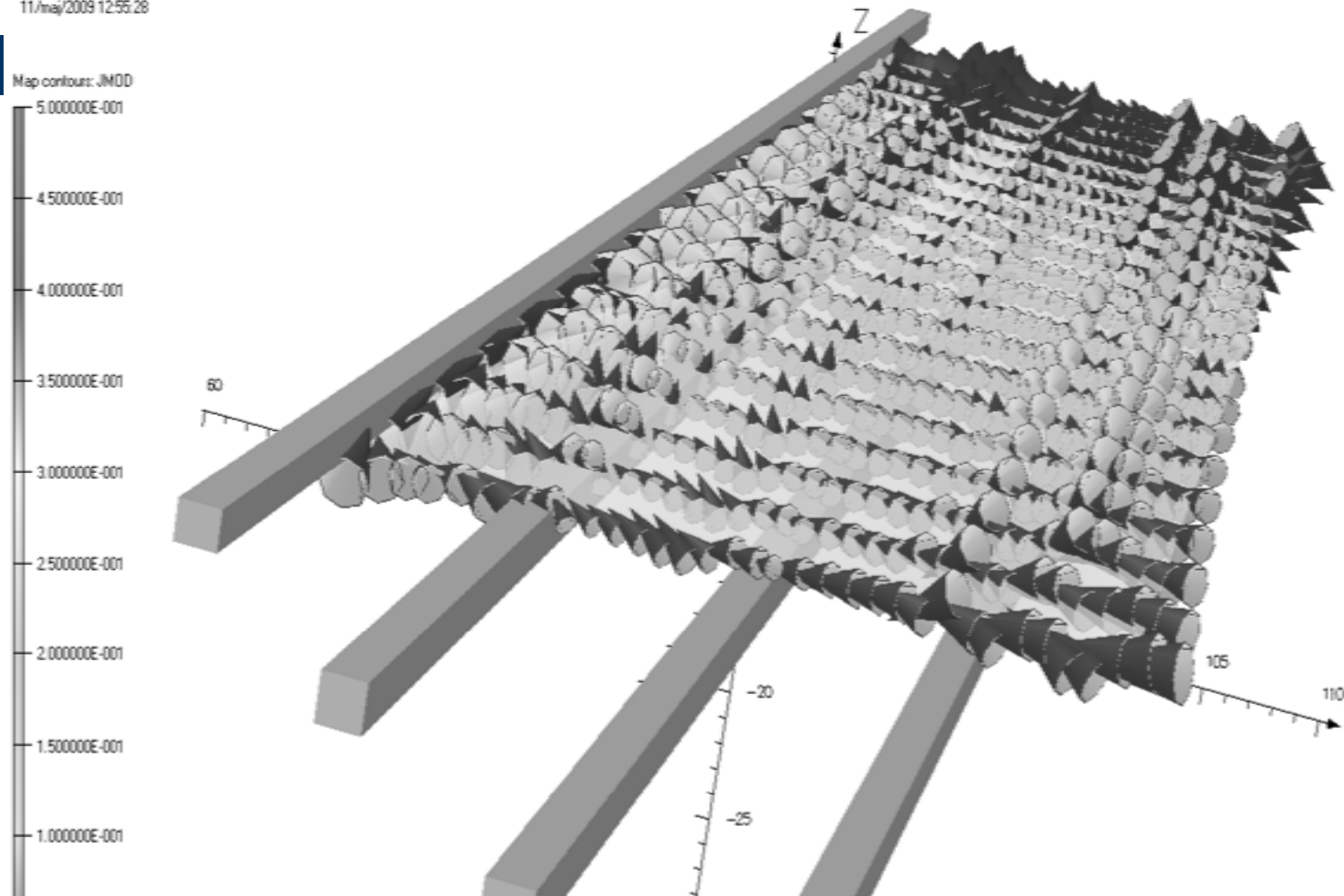


3D simulation

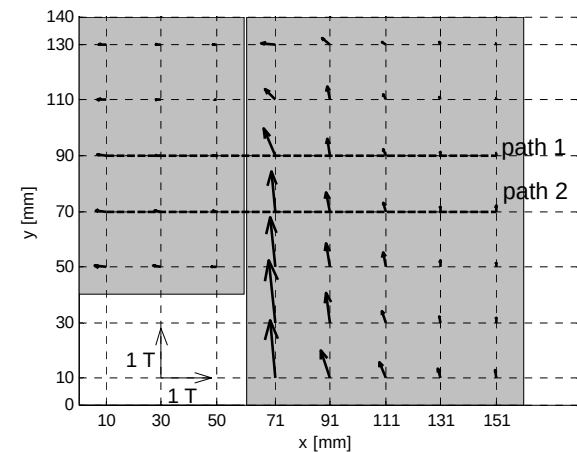
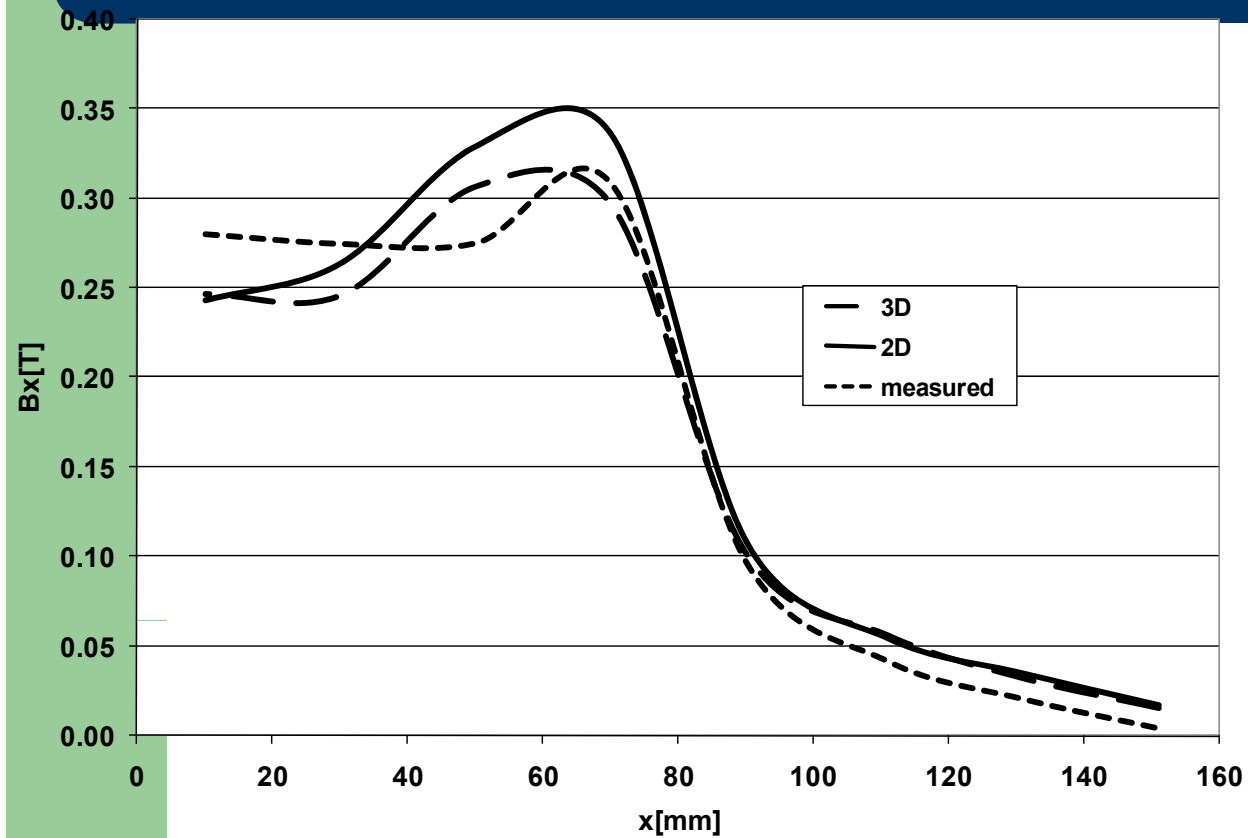


Eddy current distributions in the x-y cross-section of the lamination

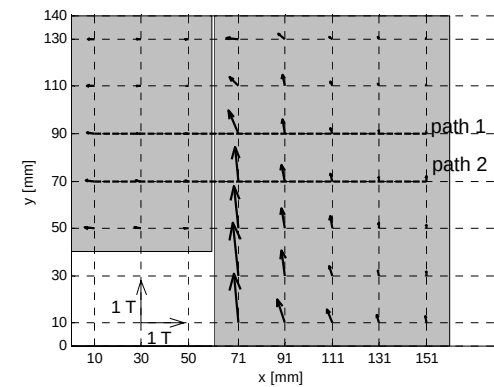
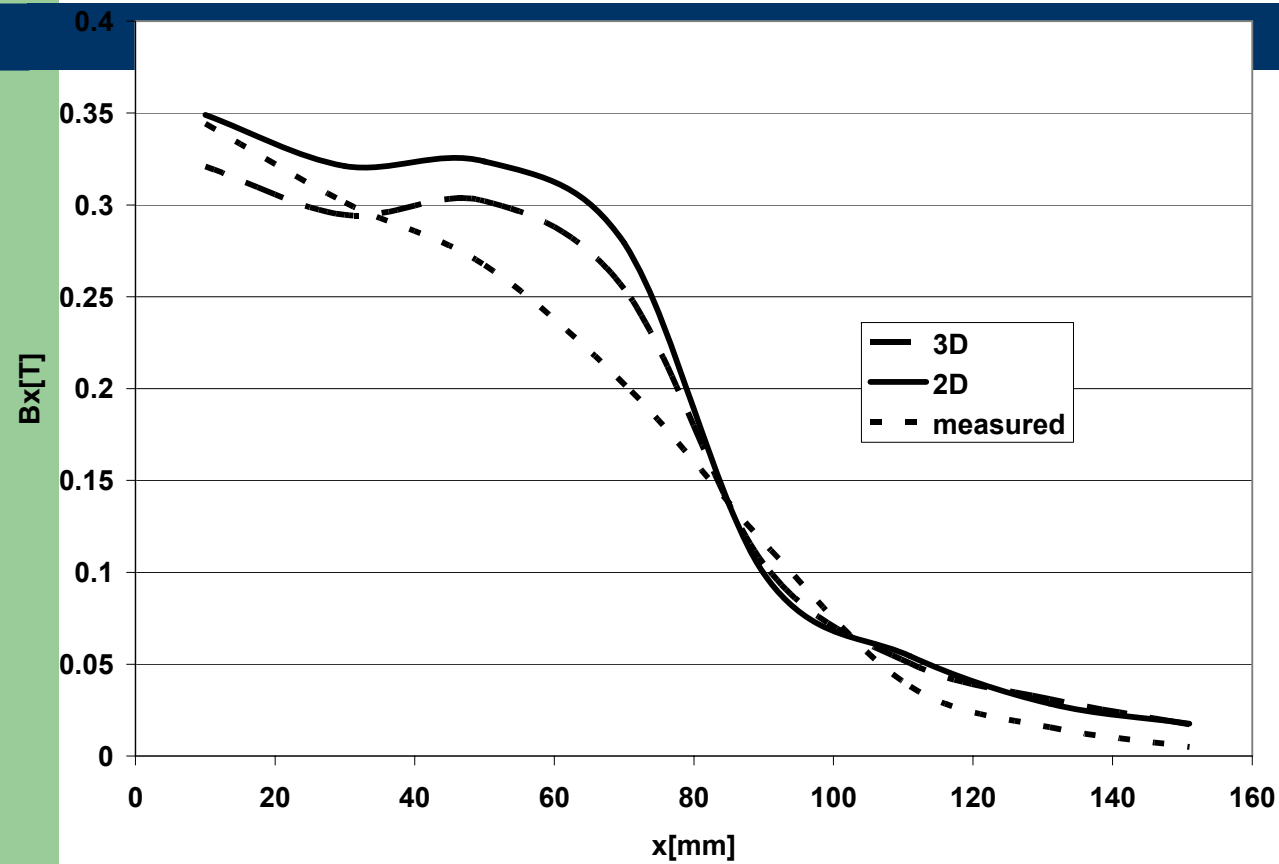
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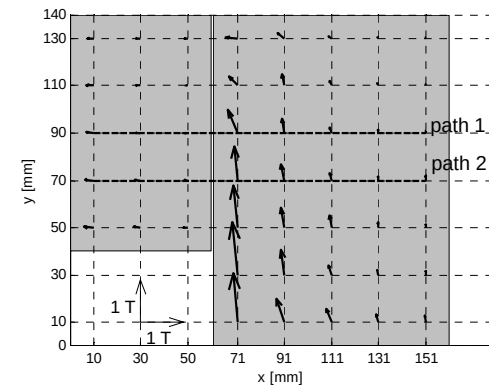
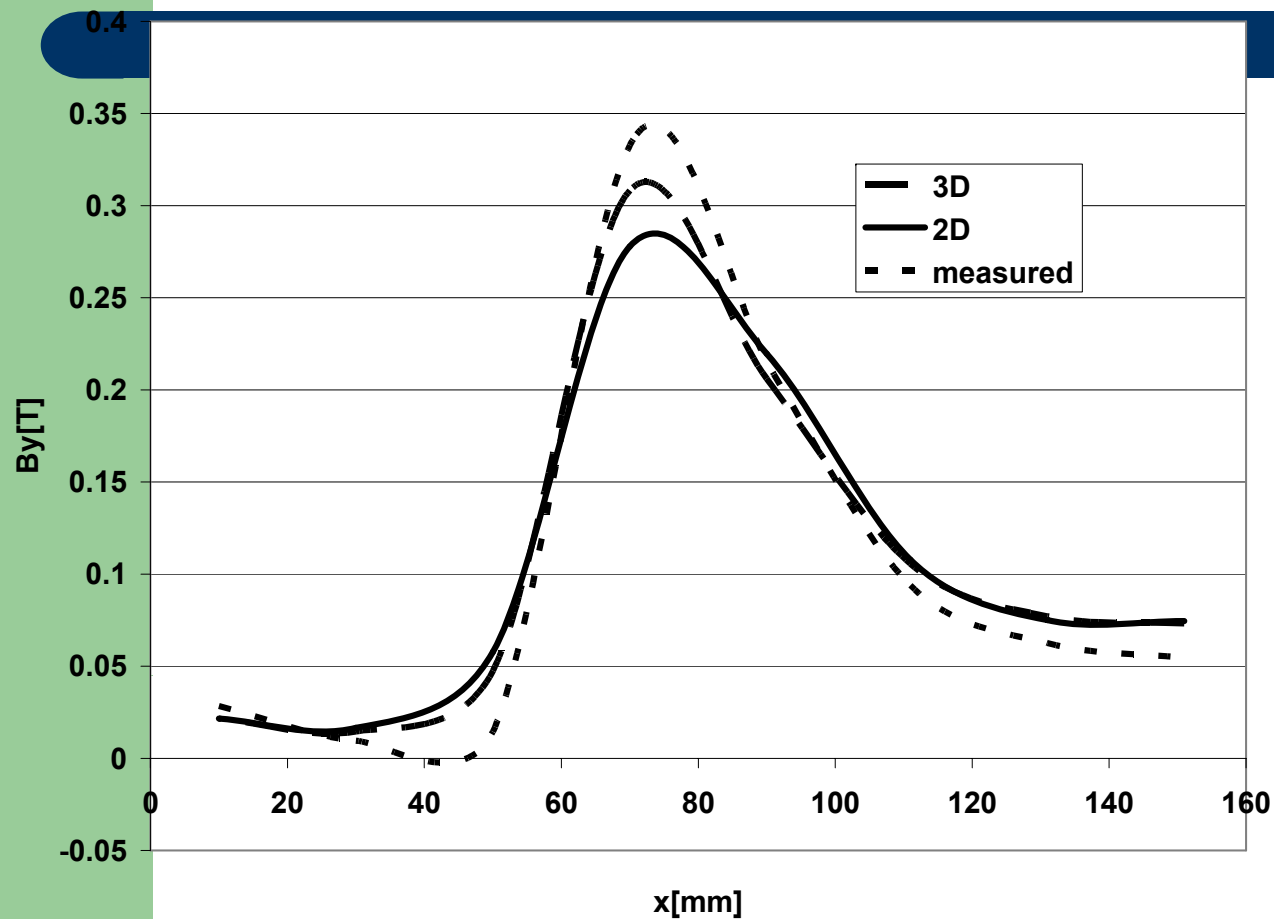
Distribution of B_x along path 1



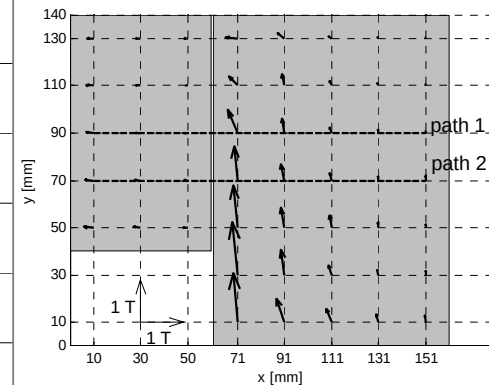
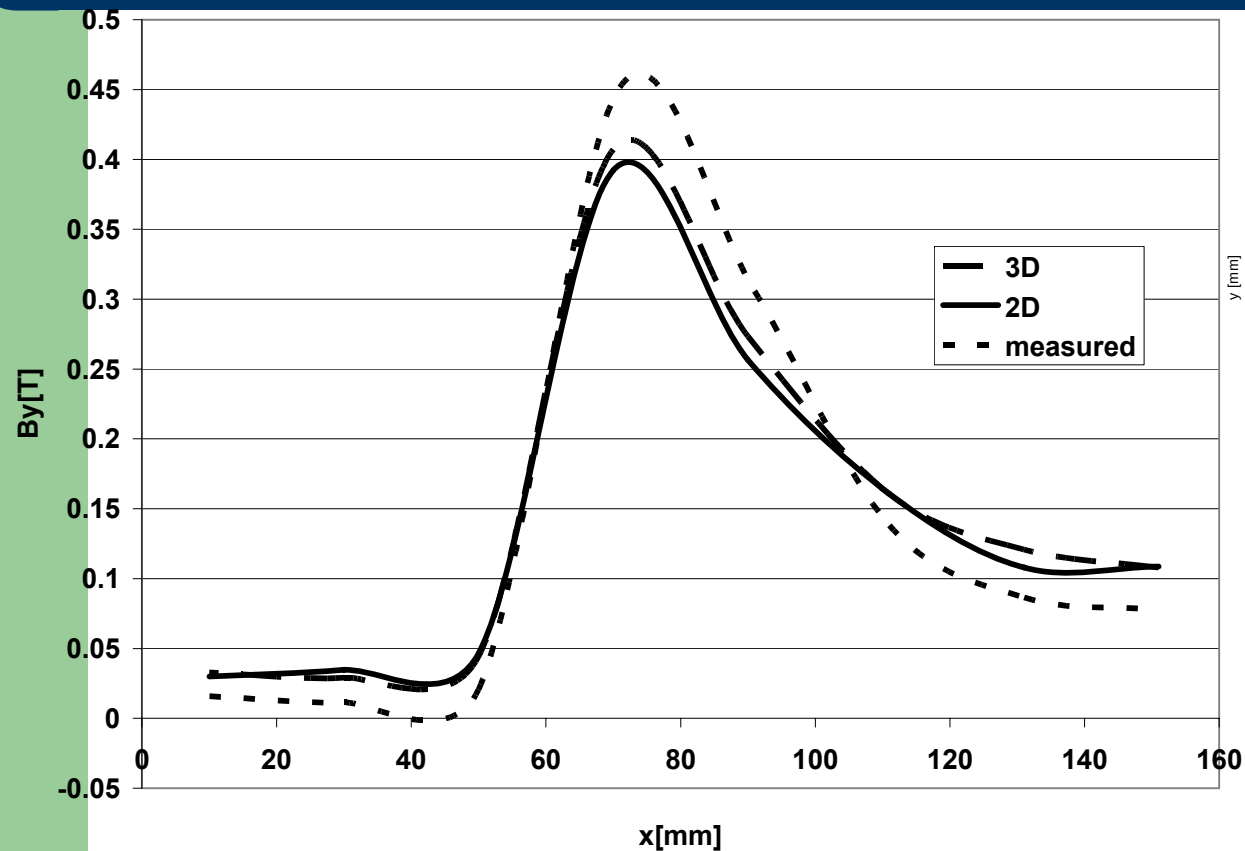
Distribution of B_x along path 2



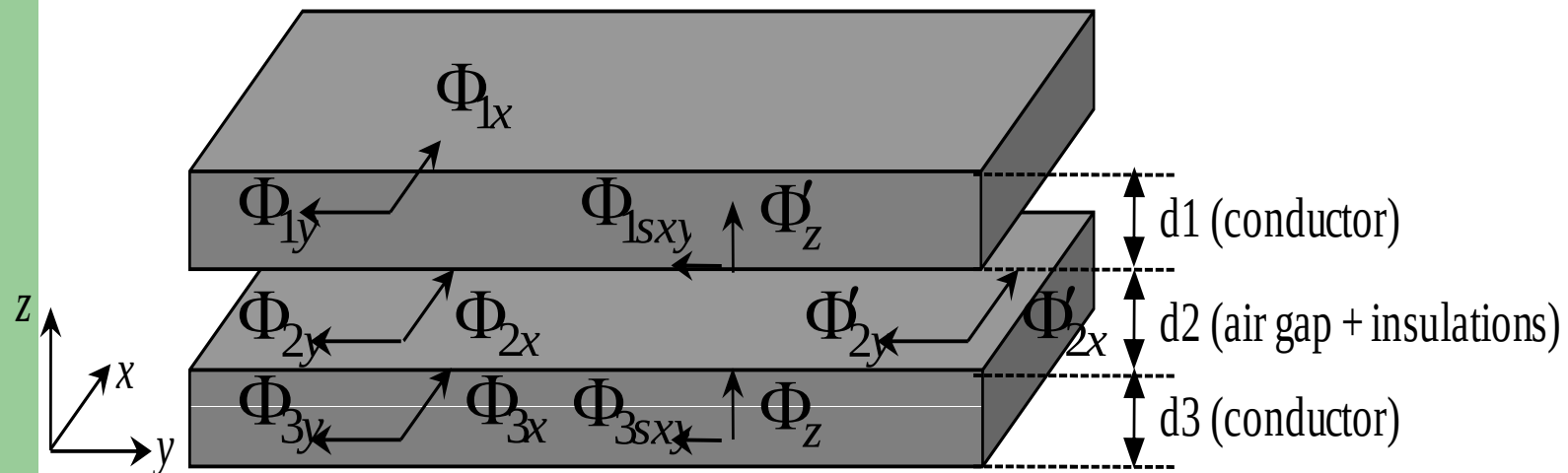
Distribution of B_y along path 1



Distribution of B_y along path 2



Fluxes in three consecutive layers



The flux density components in a sample of dimensions $\delta x \times \delta y \times \delta z$ may be found as:

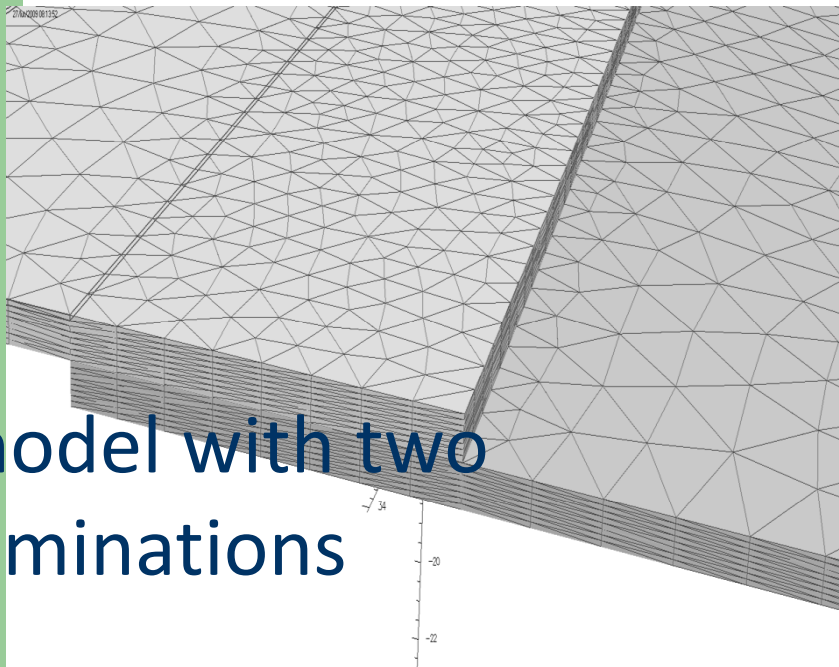
$$B_{ix} = \frac{1}{2} \frac{\phi'_{ix} + \phi''_{ix}}{\delta y \delta z};$$

$$B_{iy} = \frac{1}{2} \frac{\phi'_{iy} + \phi''_{iy}}{\delta x \delta z};$$

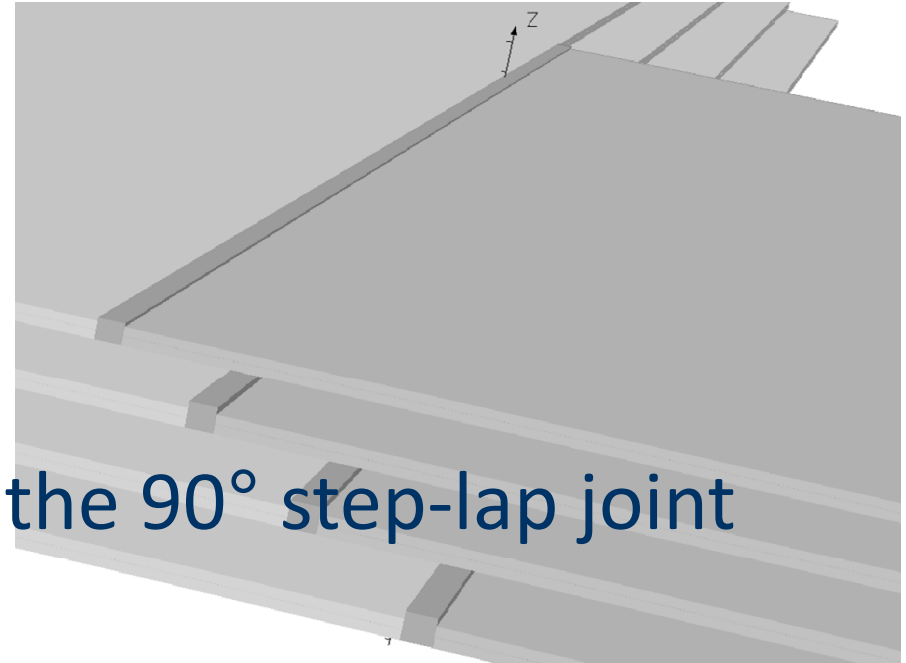
$$B_{iz} = \frac{1}{2} \frac{\phi'_{iz} + \phi''_{iz}}{\delta y \delta x};$$

Models geometry

model with two
laminations



the 90° step-lap joint

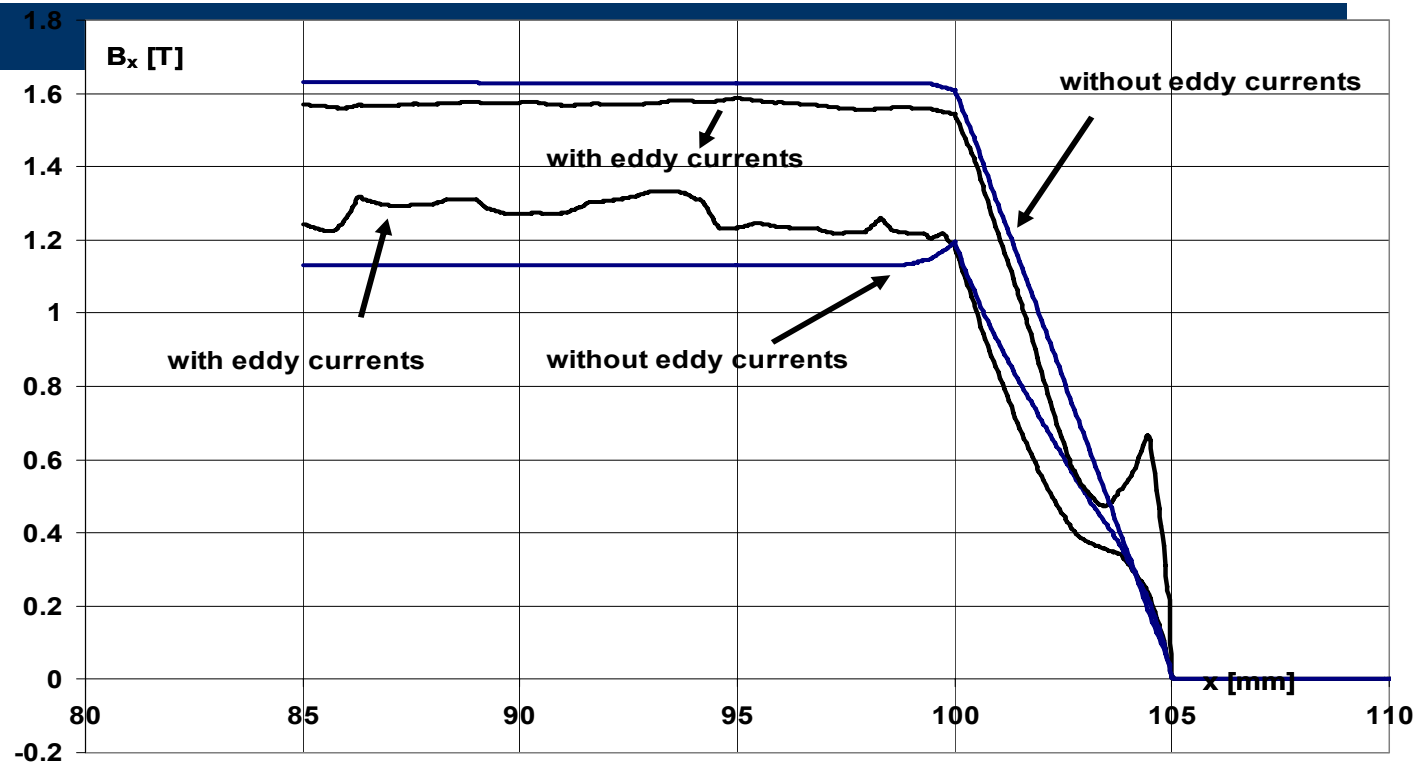


Model 1

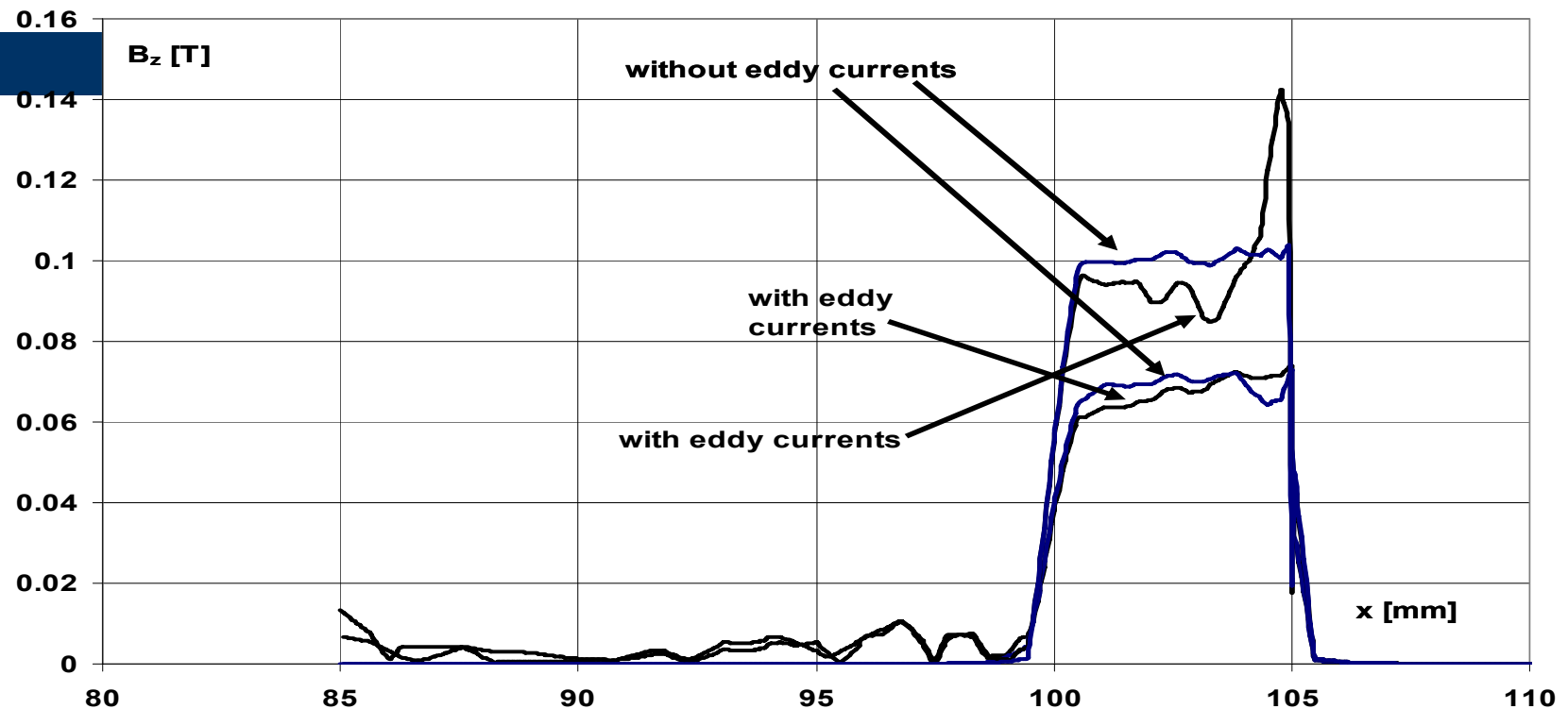
A series of simulations were executed:

- For excitations with the flux 42e-6 Wb (excitation 2) and 35e-6 Wb (excitation 1) the repartitions of the flux density and of the eddy currents were simulated. The real conductivity was taken into account.
- For the excitation with the flux 42e-6 Wb and 35e-6 Wb the simulations neglecting the eddy currents were executed.
- For excitations with the flux 42e-6 Wb and 35e-6WB the anisotropic conductivity was applied. Zero conductivity in the normal direction. It permits the analysis of the eddy currents induced by the normal flux.
- For excitations with the flux 42e-6 Wb and 35e-6WB the anisotropic conductivity was applied. Zero conductivity in the tangential direction. It permits the analysis of the eddy currents induced by the longitudinal flux.
- The same simulations were executed for isotropic materials (ThyssenKrupp Electrical Steel Company NO 0.35 mm).

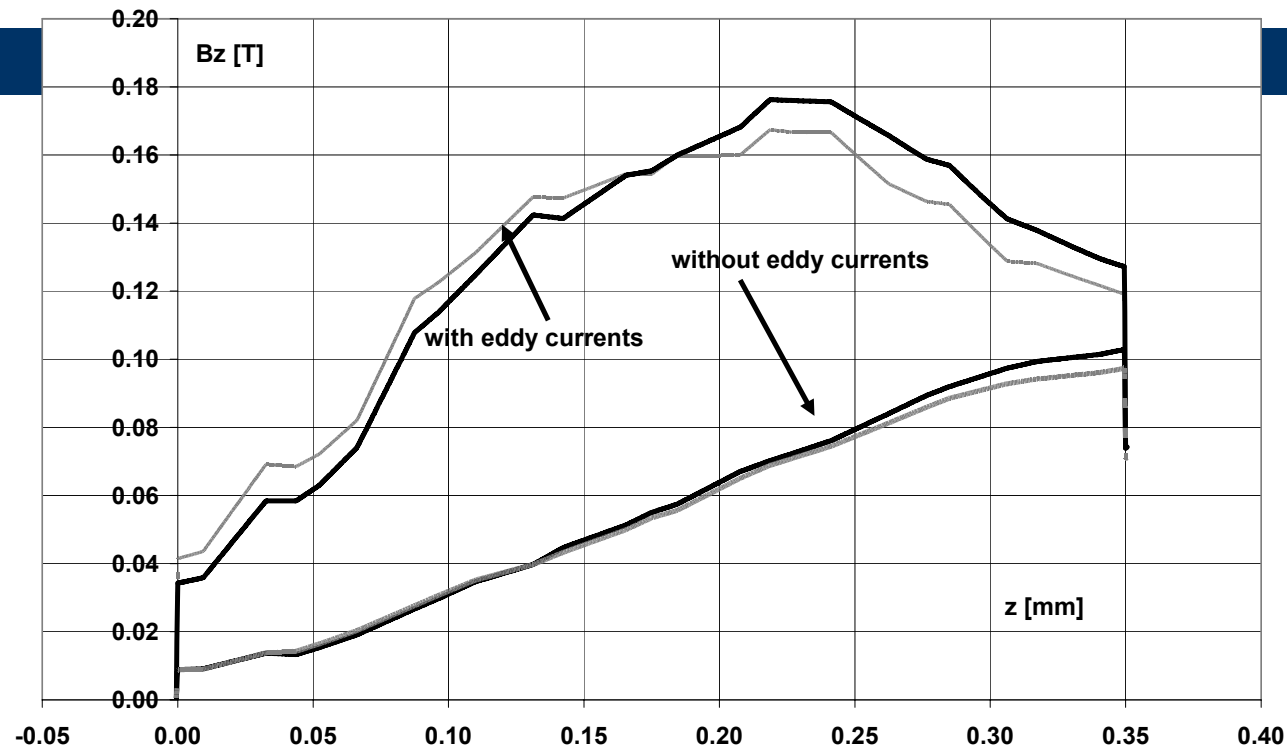
Variation of B_x along x in the area of the lamination (excitation 1 and 2)



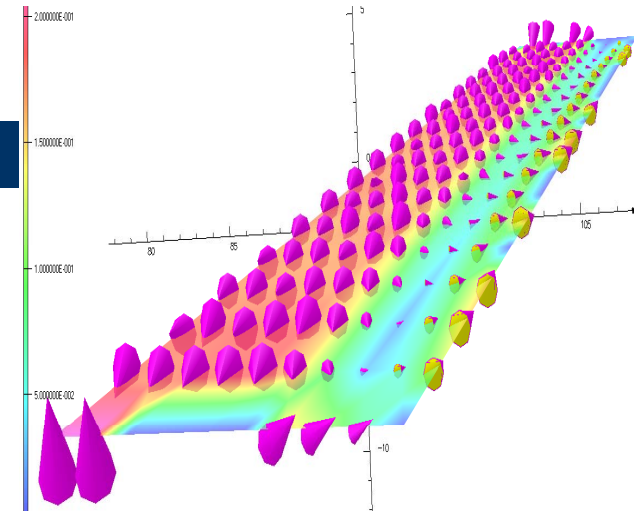
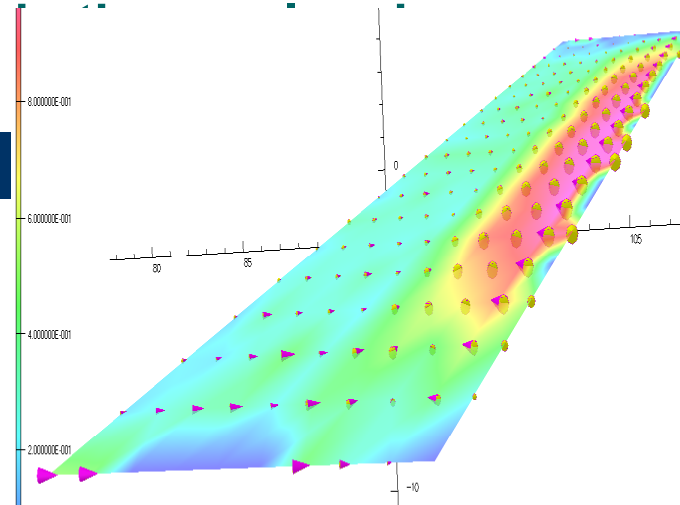
Variation of B_z along x in the area of the lamination (excitation 35e-6 Wb and 42e-6 Wb .)



Variation of B_x along z in the area of the lamination

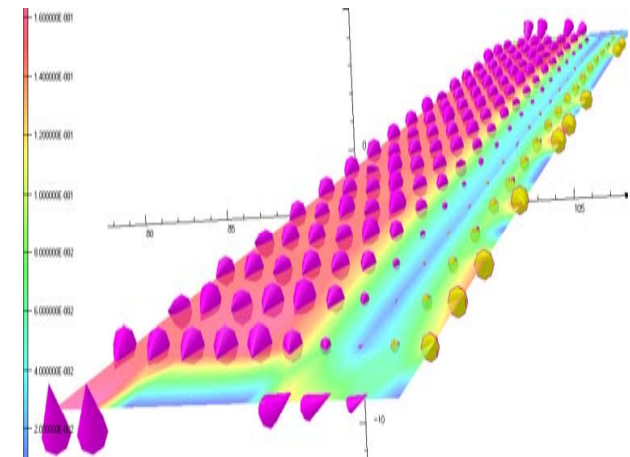
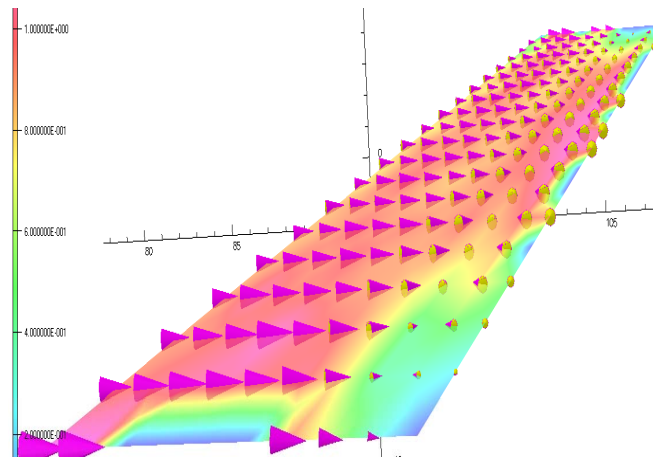


The repartition of the flux density (left) and eddy currents (right)

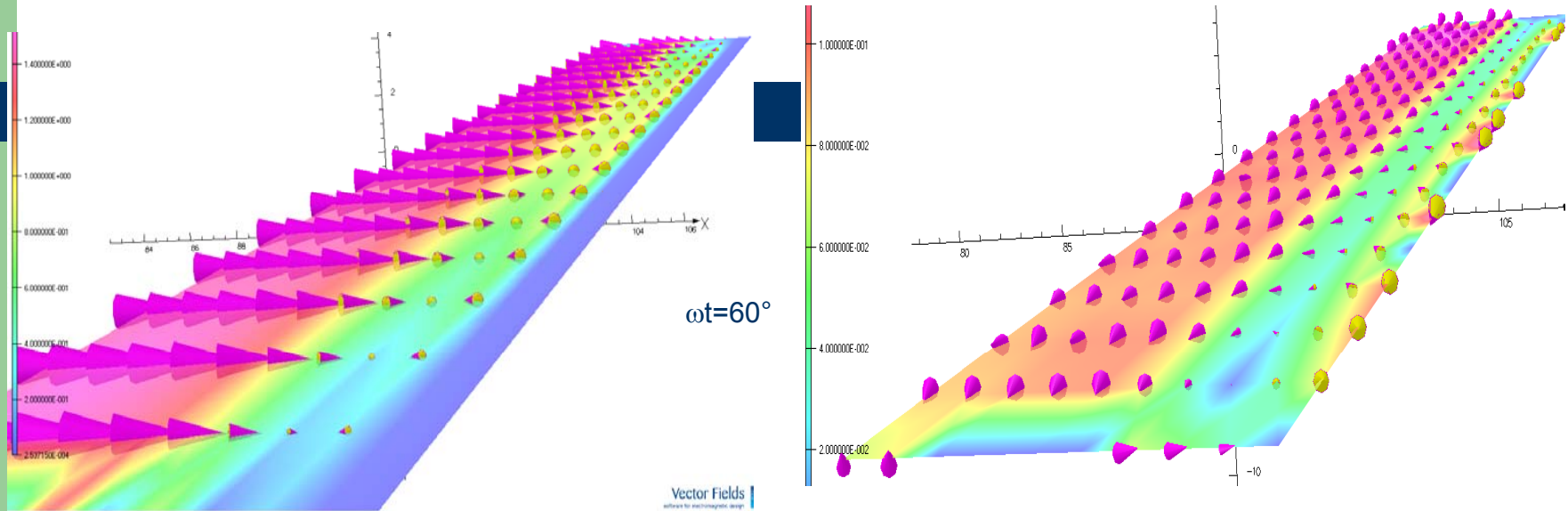


$\omega t = 0^\circ$

$\omega t = 30^\circ$



The repartition of the flux density (left) and eddy currents (right) in the overlapping area



- The repartition of the flux density vectors (left) and eddy currents (right) for the different time instants make it possible to analyze the comportment of the phenomena's in the overlapping area. All the flux passes there from one lamination to another. This results in a significant normal flux in addition to the longitudinal flux. Both cause the eddy currents in the x-y and y-z plans.

- The inducted eddy currents are sources of own fluxes. The result is the existence of the flux density components in the y direction and eddy currents in x direction. Before the overlapping in the lamination only the longitudinal flux exists. Inside the overlapping area longitudinal flux decreases and the normal increases or eddy currents will decrease in the y-z plane and increase in the x-y plane. This results in an excitation of the significant x component of the eddy currents and of the turning of the flux in y direction (Fig. 9). The simulations with the assumption of zero conductivity values in x direction those with zero conductivity in z direction (fig 9) confirms the presented conclusions. Eddy current is shifted in phase relative to the flux density of a little less than 90° .

Conclusions

- Existence of both normal and longitudinal fluxes
- should be taken into account in the regions where the flux passes from one lamination to another.
- The eddy currents induced by the fluxes modify the field distribution in the structure and should be taken into account.
- The internal air-gaps greater than 0.1 mm have a powerful impact on the field distribution, the insulation between the laminations of 0.01mm have a negligible effect on the passing of the flux.
-

- The normal flux passing of the one sheet to another does not change direction immediately after the entrance to the lamination, the transition is progressively.

- The main purpose of these 3D simulations was to prepare a mathematical model that makes possible calculation of eddy currents distribution in thin ferromagnetic sheet with given flux. The estimation of eddy currents distribution and their influence on electromagnetic field distribution, for both the longitudinal and normal fluxes, have been done.

- We remark that the normal and longitudinal fluxes induce eddy currents. The induced eddy currents modify the field distribution in the structure and should be taken into account. In the prepared model

- existence of both normal and longitudinal fluxes should be taken into the consideration.
- The analysis of the step-lap structure (model 2) permits to conclude that the internal air-gaps higher than 0.1mm have an important influence on the field distribution. On the contrary the isolation between the laminations of 0.01mm has a negligible effect and can be omitted in the mathematical model.

- Very important fact was concluded, the direction of the normal flux from one sheet to another one does not change immediately after the entrance

- of the lamination, and the transition is progressive. Therefore is not possible to introduce a simple boundary condition stated that flux turns immediately after entering into sheet.
- To take into account the eddy currents the superposition of 2D and 1D problem is needed