Finite Element Analysis of the Tagger

1. 2D magnetic analysis and forces calculation

1.1 Magnetic field in the magnet

To estimate magnetic forces in the yoke magnetostatic 2D analysis has been carried out using POISSON code from the program package of LANL.

Two runs have been done. The total number of Ampere-turns was 42.48 kA for the first run and 62 kA for the second one. In both cases material of the yoke was St 3. The finite element mesh contained ~90000 nodes. For these current loads the magnetic flux density in work region of the magnet was 1.5 T and 1.77 T correspondingly. In next pictures some results for the first case (B_0=1.5 T) are presented.

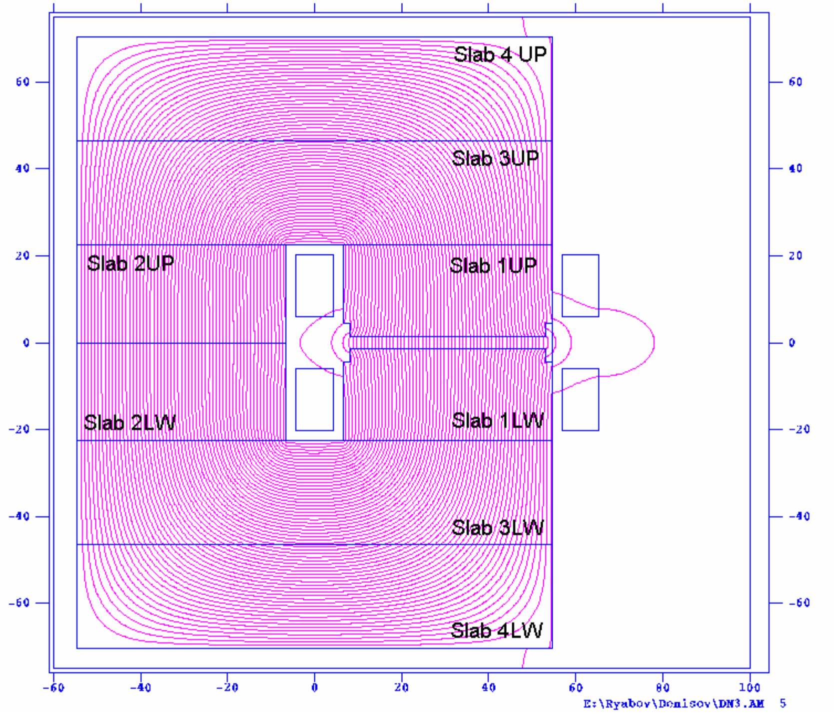

Fig. 1.1. Flux density distribution for NI=42.48 kA. B_0=1.5 T.

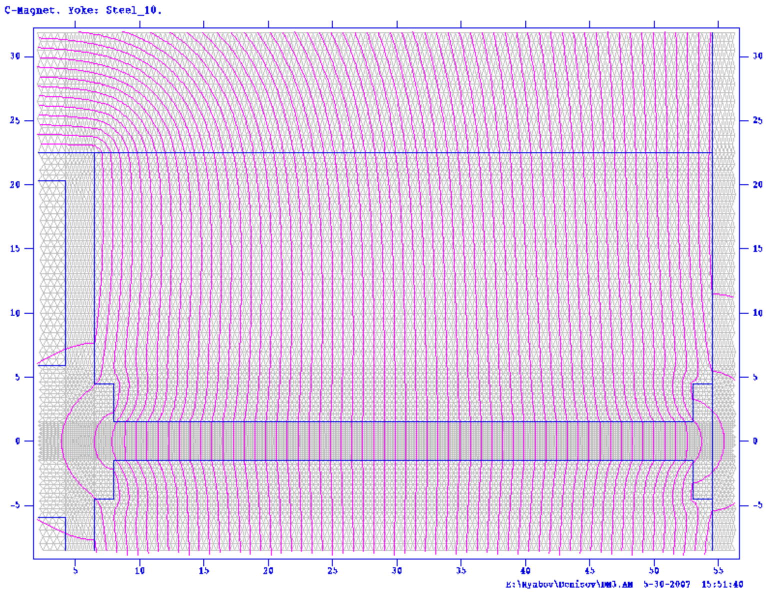

Fig. 1.2. Flux density distribution and finite element mesh (fragment).

The flux density distribution and its quality $\Delta B / B_0$ [%] in median plane of the pole gap are shown in next pictures. Region of “good” field quality is defined as $|\Delta B / B_0| \leq 2 \cdot 10^{-3}$.

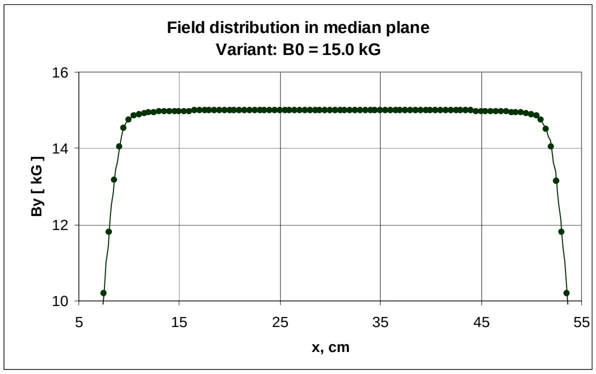

Fig.1.3a. B_0=1.5 T. Flux density distribution in the magnet median plane along X-axis.

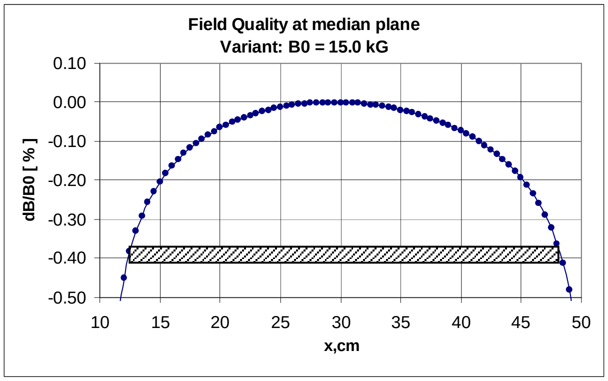

Fig.1.3b. Field quality. Width of the region of good field quality is about 35 cm

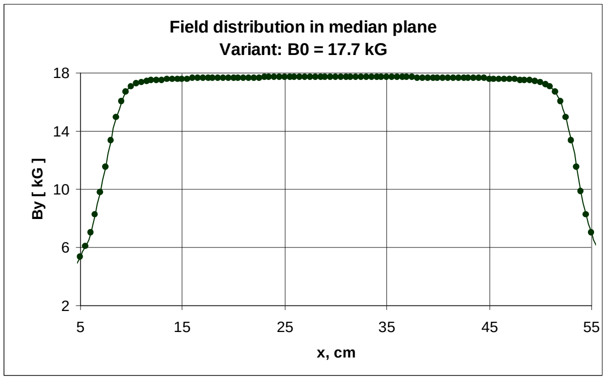

Fig.1.4a. B_0=1.77 T. Flux density distribution in the magnet median plane along X-axis.

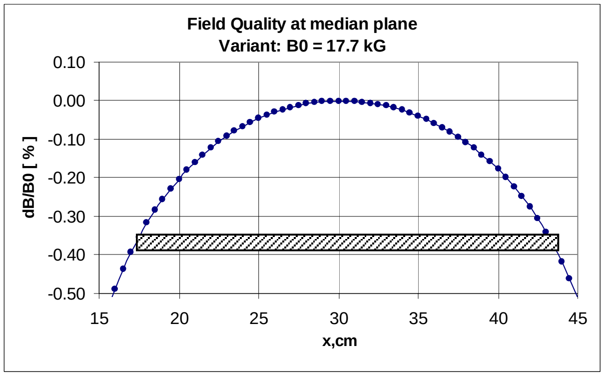

Fig.1.4b. Field quality. Width of the region of good field quality is about 28 cm

1.2 Magnetic forces on yoke slabs

POISSON gives the following values of forces and moments (calculated relative to the slab centre of gravity) for each slab:

Table 1: B_0=1.5 T

Slab	F_x, kg/m	F_y, kg/m	Mc, kg
1UP	-290.	+7 570	+500
2UP	+130.	+1 320	-100
3UP	+10.	-73 440	+150
4UP	0.	-25 890	+30
SUM:	-150.	-90 440	+580

Table 2: B_0 = 1.77 T

Slab	F_x, kg/m	F_y, kg/m	M_c, kg
1UP	-220.	+9 170	+430
2UP	+50.	+1 070	-100
3UP	+10.	-96 090	+280
4UP	0.	-37 670	+60
SUM:	-160.	-123 520	+670

To obtain the total forces for each slab one should multiply values shown in the tables by factor of ~3m (magnet length).

2 Magnetic-Structural Analysis

Magnetic-structural analysis of the magnet has been carried out using ANSYS code.
Four load cases have been considered:

Case	Load	Constrains and support
1	Magnetic forces only	Symmetric plane Y=0; minimal restrictions on X and Z-directions rigid movement
2	Vacuum pressure only	as for Case 1
3	Magnet dead weight only	Support from 3 points; minimal restrictions on X and Z-directions rigid movement
combi	Combined all above	As for Case 3

The finite element model of the magnet contains independent meshes of all slabs, but it does not contain tightening bolts and clamps which are shown in the magnet drawings. But coupling between degrees of freedom at common interface surfaces of adjusting slabs allow one to simulate behavior of the magnet model with all bolts and clamps working as designed. Analysis of nodal forces and normal stresses at common surfaces of adjusting slabs allow one to make conclusions on specific characteristics of interactions between the slabs.
In next picture all boundary conditions used in the analysis are presented.

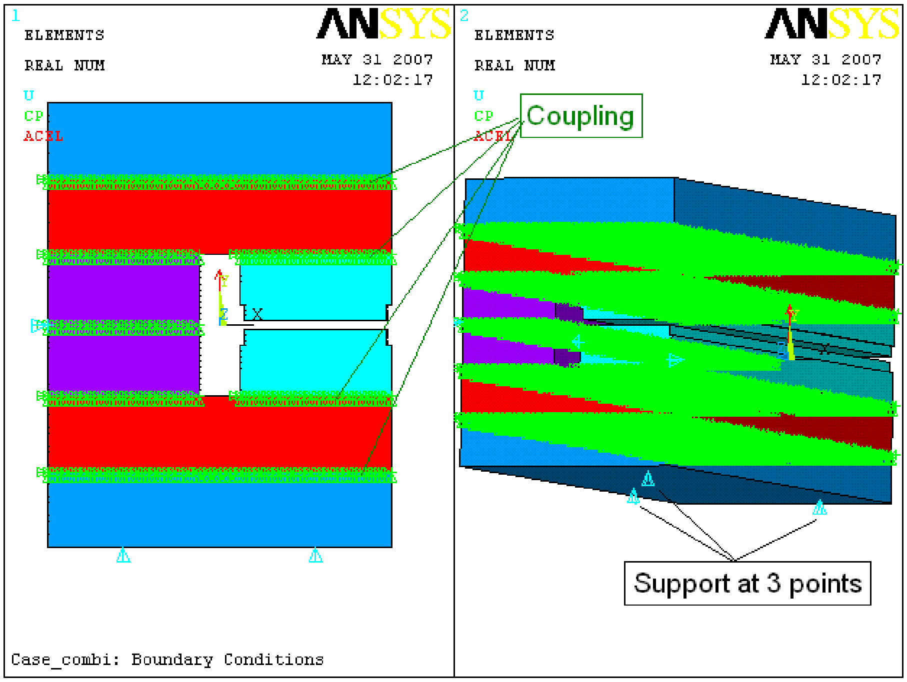

Fig. 2.0: Boundary conditions used in the FE analysis

2.1 Displacements

Results of displacement calculations are presented in figures 2.1–2.4 and summarized in next table:

Load Case	Maximal displacement [microns]	Loss of poles clearance [microns]
1	82	140
2	8	14
3	27	10
combi	198	**164**

The main result: the loss of clearance between the magnet poles does not exceed 164 microns under all three load factors considered!

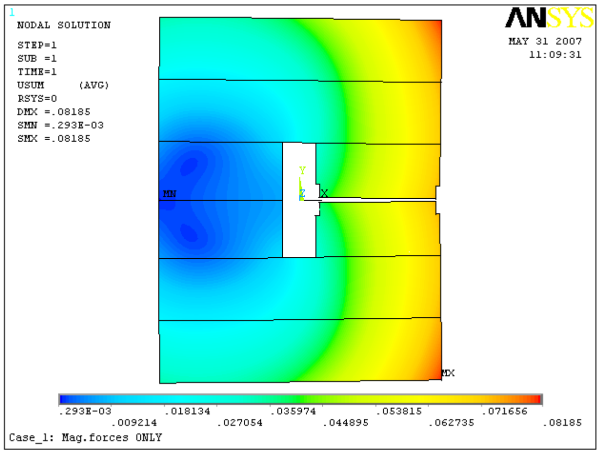

Fig. 2.1: Case 1. Overall displacements [mm]

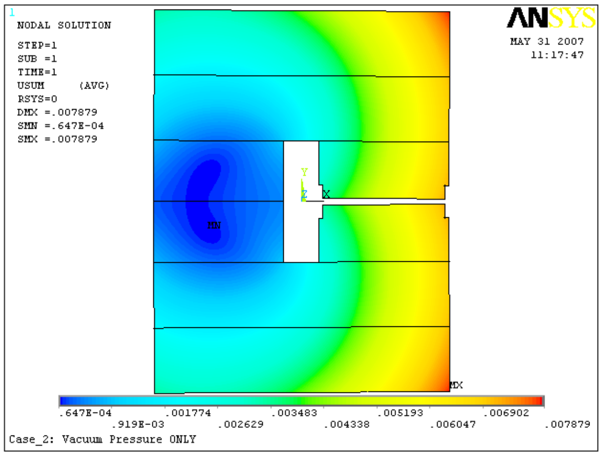

Fig. 2.2: Case 2. Overall displacements [mm]

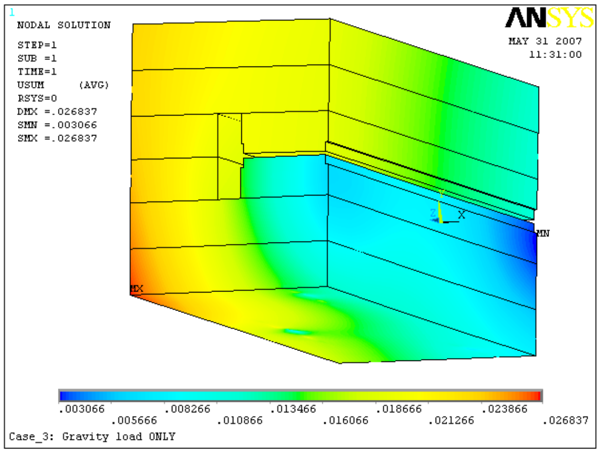

Fig. 2.3: Case 3. Overall displacements [mm]

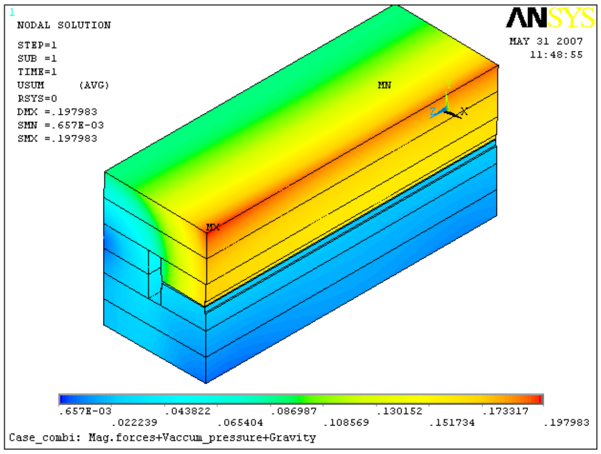

Fig. 2.4: Case combi. Overall displacements [mm]

One can see that solution is symmetric relative to symmetry planes of the magnet for load cases 1 and 2 as it is expected. Asymmetry in solution for the load case 3 is explained by asymmetrical position of one of the three magnet supports (see drawings). A maximal overall displacement does not exceed 200 microns.

The main displacement component is the vertical one.

2.2 Interaction between slabs

Pictures 2.5–2.8 demonstrate features of interaction between adjusting slabs. In these pictures the distribution of interaction forces and isolines of SY stress (close to pressure) on the interface surfaces of the slabs are shown. Results are presented for the upper slabs only. Results for the lower slabs have similar features.

As it can be seen from the Figs there are forces at the slab edges (red regions in the Figs). To compensate these forces and to minimize the magnet deformations and tension of the inner bolts (see magnet drawings) the clamps around side yoke walls are used.

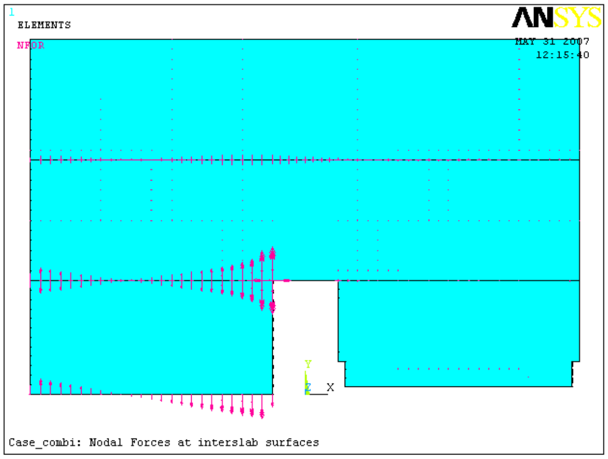

Fig. 2.5: Interaction force distribution in upper part of the magnet model

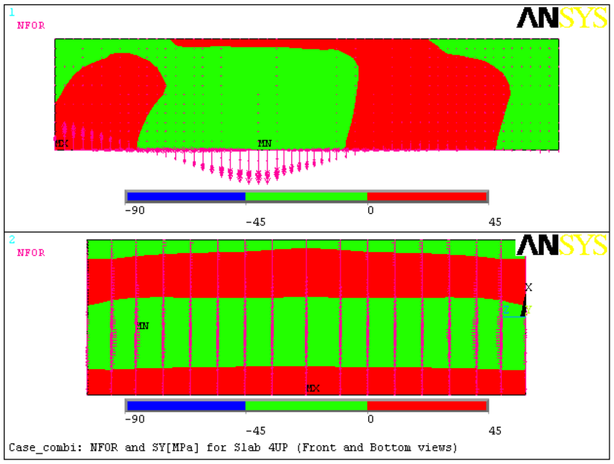

Fig. 2.6: Interaction force distribution and isolines of SY stress component for Slab 4UP

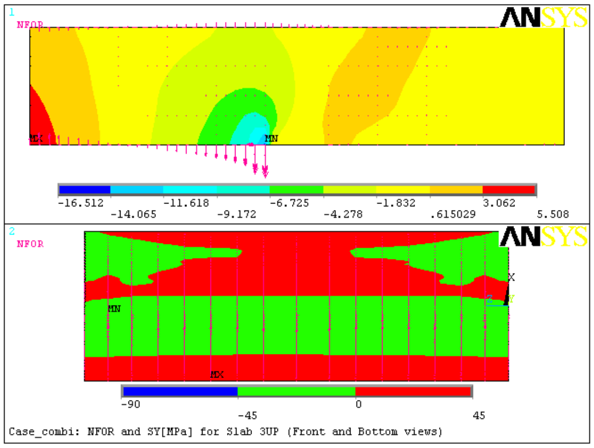

Fig. 2.7: Interaction force distribution and isolines of SY stress component for Slab 3UP

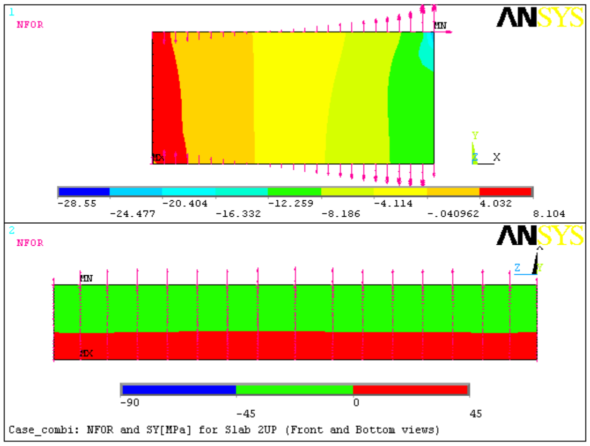

Fig. 2.8: Interaction force distribution and isolines of SY stress component for Slab 2UP

3 Clamps

It was proposed to use three clamps tightening the slabs 2UP and 2LW, 3UP and 2UP, 3LW and 2LW. Calculations were performed to understand the behavior of such clamps. Sliding between different parts of the model was taken into account (so called nonlinear contact problem). Using symmetry and periodical conditions only a half of the period (103mm pitch in Z-direction) and a half of the height of the clamp were taken into account. General and detailed views of the FE model with some definitions are shown in the next two Figs.

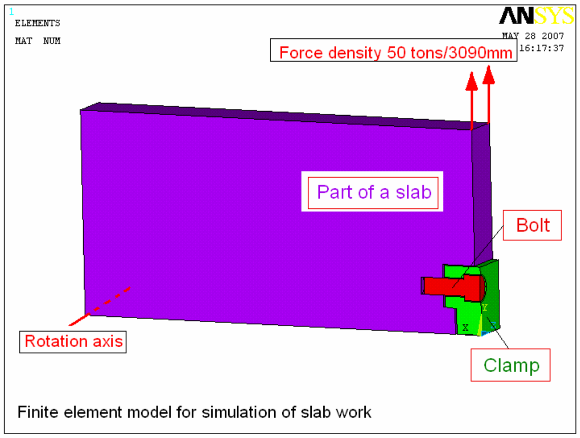

Fig. 3.1: Definition of the model parts; load and boundary conditions

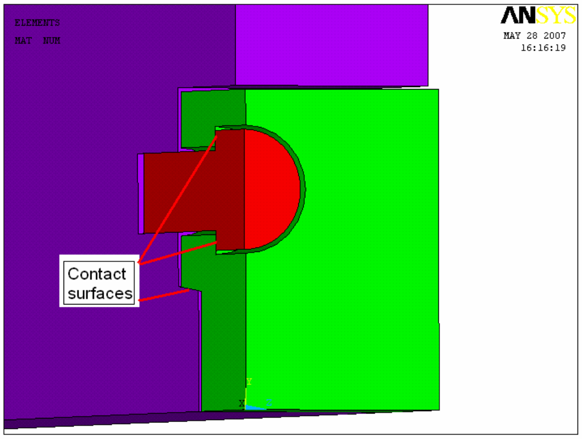

Fig. 3.2: Definition of contact surfaces bolt–clamp and clamp–slab

A force of 50 tons used in calculations is too high. One can expect it at the level of 30–40 tons. Results of the analysis are presented in Figs 3.3-3.8. Stresses in all parts of the model do not exceed 40 MPa and significantly less than the critical value of 200 MPa for steel. Contact is very good for all contact surfaces. Stresses in bolts appeared to be rather small: they are less than 20 MPa.

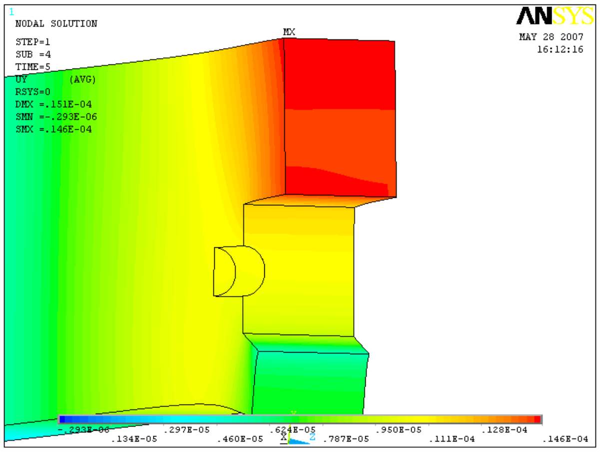

Fig. 3.3: Vertical (Y) displacements of a slab [m]. Max. opening of adjusting slabs is ~ 20 microns.

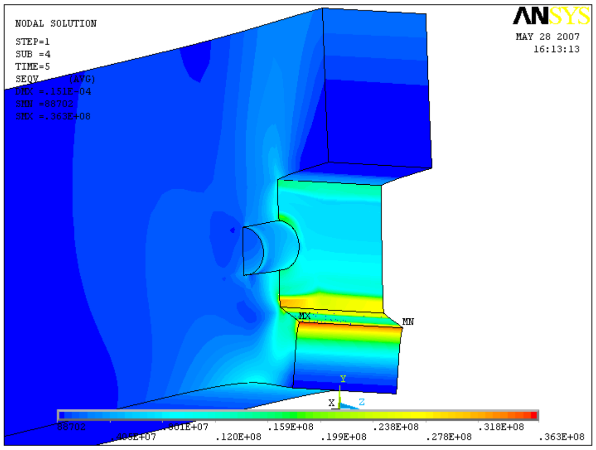

Fig. 3.4: Von Mises Stress in a slab. Max. stress is achieved at the slab–clamp contact surface.

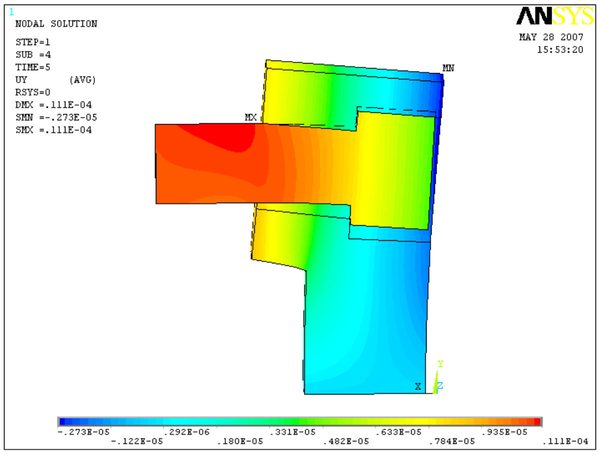

Fig. 3.5: Vertical displacements [m] of the clamp and bolt. Maximal displacement is 11 microns.

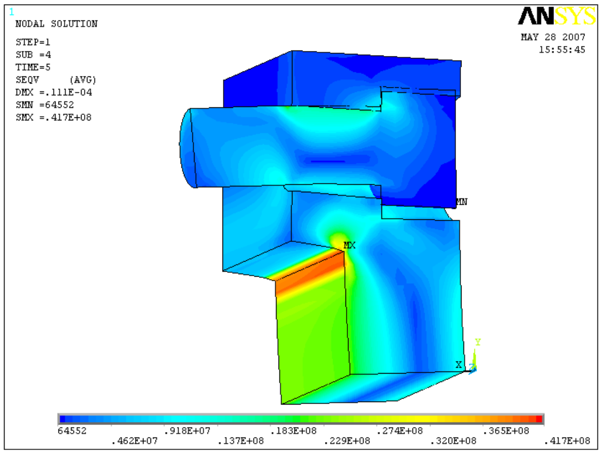

Fig. 3.6: Von Mises Stress in a slab. Max. stress is at the slab–clamp contact surface. S_{max}=42 MPa

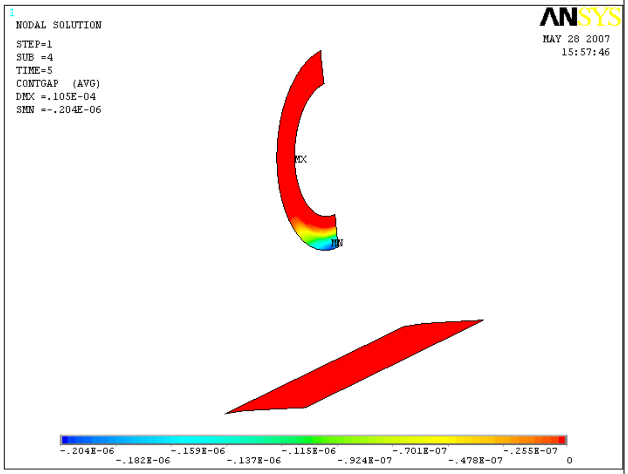

Fig. 3.7: Contact gaps at contact surfaces. Regions in red – full contact, in blue – no contact.

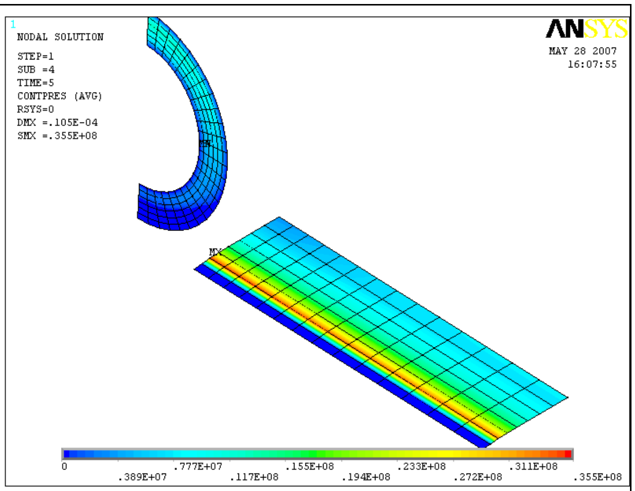

Fig. 3.8: Pressure on contact surfaces. Maximal pressure is 35 MPa.

4 Conclusions

From the performed analysis one can conclude:

- The loss of clearance between the magnet poles is 164 microns under all loads (magnetic forces, vacuum pressure and dead weight of the magnet) assuming the ideal contacts between slabs.
- If only clamps are used to connect the slabs together the loss of the poles clearance increases and becomes 164+2*20+20=224 microns. In fact when the inner bolts are used an opening between slabs will be less. Also the forces will be less than 50 tons.
- More accurate and intensive simulations with more sophisticated FE model should be done for the final engineering design.