EFFECT OF DEFORMATIONS CAUSED BY THE PONDEROMOTIVE FORCE ON MAGNET SYSTEM QUALITY IN CYCLOTRON DC60

Abstract

An impact of deformation associated with the ponderomotive force on a field produced by the magnet system of the cyclotron DC60 (Kazakhstan) was analysed. The analysis was based on coupled calculations of electromagnetic and mechanical loads on components of the magnet system. Deformations estimates were then applied to correct the field configuration. Distributed electromagnetic loads, calculated with the use of software package KOMPOT, were transformed into equivalent nodal forces using the program NFORCE and served as the inputs suitable for ANSYS stress-strain state calculations.

The mechanical stresses due to electromagnetic loads and their effect on field quality were analysed for the cyclotron DC60 designed for the Gumilyev University in Astana, Kazakhstan. Based on the analysis, actions were proposed to compensate for the stress effects. Mathematical models used to simulate the field distribution and ponderomotive forces in DC60 in order to optimise the magnet system performance were described in details in Ref.[1-3]. This paper presents a method of stress assessment based on coupled calculations of electromagnetic and mechanical loads on components of the magnet system. The main steps in the DC60 stress analysis were:

1. A 3D field simulation at given coil currents. The calculation region was taken as a part of the space R^3. The simulation was made with the use of the program package KOMPOT [4]. A detailed finite-element (FE) model of the DC60 magnet system was developed so as to provide realistic geometry description and take into consideration the $\mu(|\vec{H}|)$ curve , where μ is permeability, $\vec{H}$ is the field strength vector.
2. The magnet FE model was used as a basis to built an ANSYS model for the stress-strain analysis. Both models had the same reference mesh used to define distributed loads associated with ponderomotive forces.
3. The magnet FE model was applied to calculate the volume force density on ferromagnetic and conducting components of DC60. Distributed ponderomotive loads were transformed into their nodal equivalents with the use of the program NFORCE [5]. The results were presented in a format suitable for ANSYS calculations. The calculation of nodal loads was implemented as integration of the finite elements over a volume: $\int_{V_{(e)}} \vec{f} \cdot N_i \cdot dV$, where $\vec{f}$ is the ponderomotive force density vector, N_i is the shape function, $V_{(e)}$ is the volume of finite element (e). An allowance was made for the specifics of the FE meshes for the magnetostatic and stress calculations.
4. Results of the stress analysis were used to correct the magnet model with regard to the predicted deformations and re-calculate the magnetic field distribution.
5. To finalise the analysis, possible compensation for the strain effects in the magnet working zone was studied. As the compensation actions, variations of coil currents and shaping of the ferromagnetic components were proposed. Fig.1 illustrates a field distribution calculated in a representative magnet cross-section at the normal operation, assuming the maximum field level B=1.65 T on the

ejection radius (the coil current is 372 A). In the calculation nonlinear steel properties were taken into account for the magnet components.

The FE model of DC60 developed in order to calculate magnetic field is presented in Fig.2. The FE model consists of one eighth of the magnet core – a half of height and one quadrant. A magnet yoke beam is considered without slits in the FE model. The sectors symmetry relative to the horizontal beam is assumed. The magnet FE model with calculated nodal forces was used to develop the model for the stress analysis. FE model of the magnetic core used for stress-strain calculations was developed taking into account an "E"-shape of the core. The model consists of the magnet yoke, poles, sectors, holders and fasteners. The magnet yoke consists of two horizontal beams and two vertical stands. Each horizontal beam is connected to the yoke stands with 6 pins M42. Two poles 1.62 m in diameter are oppositely oriented and connected to the horizontal beams. The upper pole is fixed to the horizontal beam by 6 tie-rods M42, the lower pole is connected to the lower horizontal beam by 6 bolts M36. The gap between upper pole and horizontal beam is fixed by special shims to be 2 mm. Each sector is connected to a pole by 3 M12 bolts. The gap between the pole and sectors is fixed by 5 bushes with the inner diameter of 17mm and the outer diameter of 36 mm. The distance between poles is 176 mm, the gap between sectors is 33 mm. All elements of the magnetic core and fasteners are made of steel 10 having the followings mechanical properties: Young's modulus is 200 GPa, Poisson's ratio is 0.3, ultimate tensile strength Su is 333 MPa, Yield strength Sy is 186 MPa. The nominal allowable stress in the steel is Sm= min{Su/nu; Sy/ny}, where nu = 2.6, ny=1.5. The allowable primary bending stress is 1.3*Sm = 161 MPa [6]. In order to take into account the yoke beam-stand mechanical contact, a horizontal cut was inserted in the FE model. Surface-to-surface contact elements are used.

Four variants of calculations were performed in order to study the influence of tie-rods and bolts initial pre-tension on vertical displacements in the magnet core due to electromagnetic forces (see Table 1). Variant 1: no initial preload to model the case of the maximum flexure. Variant 2: yoke bolts and tie-rods preload up to 15 MPa models the assembling of the yoke structure; tie-rods and bolts at the pole and the sector are initially tightened up to 150 MPa to model the case of strong fixed pole and sectors. Variant 3: all tie-rods and bolts are initially tightened up to 90 MPa. It corresponds to the case of realistic pre-tension up to a half yield stress of the steel. Variant 4: all tie-rods and bolts are initially tightened up to 150 MPa, this case models a strong structure pre-tension to provide no gaps under electromagnetic loading. Main results are presented in Table 2. The emphasis is on variant 3 as the most realistic case.

Yoke beams. The calculations for variants 1 and 2 showed that the gap between the beam and the stands is partly open, stress in the tie-rods increases under electromagnetic loads. Variant 1 shows the highest beam flexure. Variant 3 shows a partial gap opening, the maximum deflection of the beam is U_z^b = 0.147 mm (Fig. 3). Mutual closure of the magnet core elements can be estimated as doubled values from Table 2: the maximal closure of the beams is ΔU_z^b=2*U_z^b=0.294 mm. Stress in the tie-rods due to electromagnetic loads increases by 3 MPa and remains within a half yield stress. The maximum of the stress intensity in the yoke amounts to 44 MPa. The calculation for variant 4 showed no gap opening and no increase of stress in the tie-rods. It corresponds to the most rigid connection and minimal flexure. In this case, strong steel should be used for the tie-rods and bolts.

Poles. The calculation showed that the poles would pull the beams under electromagnetic loads. The maximal vertical displacement in the pole is 0.149 mm, the maximal closing is 0.298 mm (variant 1, Table 2). The maximal vertical displacement at the bottom part of the pole (facing the sectors) for variant 3 is calculated as 0.111 mm, thus the maximum closure of the poles is 0.222 mm. Stress in the tie-rods stays within the initial pre-tension value.

Sectors. The calculations showed that the sectors would pull each other due to electromagnetic forces. For variant 3, the maximal deflection achieves 0.127 mm in the central tap area, the minimal vertical displacement occurs on the outer radius. The maximal closure of the sectors for variant 3 is 0.254 mm. The calculation for variant 1 gives the maximal closure of 0.472 mm. Stress in the bolts arises up to 100 MPa due to electromagnetic forces. The calculations for variants 1 and 2 showed that the shims between the pole and sectors lose the initial contact (the sectors pull each other). This phenomenon was taken into account for variants 1 and 2. The pressure-free bushes were removed from the model, and re-calculations were carried out by several iterations.

Summarizing up obtained results, the stress-strain state calculations of DC60 under electromagnetic loads has shown:

- Initial preload of tie-rods, connecting beams and stands, has essential impact on vertical displacements of the beam, poles and sectors. Insufficient initial preload leads to increasing the maximal downward deflection of the beams and closing of the poles.
- The upper sectors are pulled towards the lower sectors under electromagnetic loads. It is necessary to take into account the attraction of the sectors at magnet core elements fixing the gap between sectors and the pole.
- Stresses in the magnet core elements do not exceed allowable values.

Machining imperfections and initial gaps between magnet core elements as well as temperature gradients are able to influent essentially the final magnet core shape. It is recommended to use initial preload of at least 90 MPa on the fastening elements (that is a half yield stress of the steel) in order to decrease influence of the initial gaps and machining imperfections as well as to avoid gapping due to electromagnetic loads.

The actual (deformed) mesh was produced based on the stress-strain analysis in order to calculate electromagnetic field in the deformed magnet core. Then the effect of the deformed magnet core on the field configuration was calculated at the maximal induction level. The model was modified by means of approaching all nodes (related to the sectors, central tap, central shim, pole and beam) to the median plane by 0.1 mm. The total closure of the nodes located symmetrically relative to the median plane amounted to 0.2 mm. This value was chosen according to the stress-strain calculation results to fit average pole and sectors displacements under an initial preload of 90 MPa.

The numerical modelling demonstrates that displacement is near constant in the pole regions, which are important for field formation, but is essentially variable in the sectors. The main reason is that the force pushing the sector end to the central tap was not considered. This force appears when there is a gap between the sectors and the tap, which omitted in the original FE model. So, the constant displacement of 0.1 mm was taken in the calculated area. Fig.4. shows an average field for the original and modified models. It is clear that the new curve is parallel to the old one, merely higher by about 12-15 G over the radius range. The difference is shown in Fig. 5. It is described by a smooth curve near value of 14 G with variations of about $\pm(2\div3)$ G.

The result obtained demonstrate that it is possible to compensate for the DC 60 field distortion due to magnet core deformation under electromagnetic loads only by varying the coil currents. No adjustment of the shape of the ferromagnetic core elements are needed.

Table 1. Variants of bolts and pins preload.

	Variant			
	1	2	3	4
Yoke pins preload, MPa	0	15	90	150
Pole – beam pins preload, MPa	0	150	90	150
Sector-pole bolts preload, MPa	0	150	90	150

Table 2. Downward deflection of the magnet core, mm.

Facility element	Variant							
	1		2		3		4	
	min	max	min	max	min	max	min	max
Beam	-0.183	0.073	-0.174	0.062	-0.147	0.028	-0.137	0.019
Pole bottom	-0.149	-0.131	-0.129	-0.106	-0.111	-0.093	-0.098	-0.081
Sectors	-0.236	-0.099	-0.141	-0.091	-0.127	-0.079	-0.112	-0.064

References

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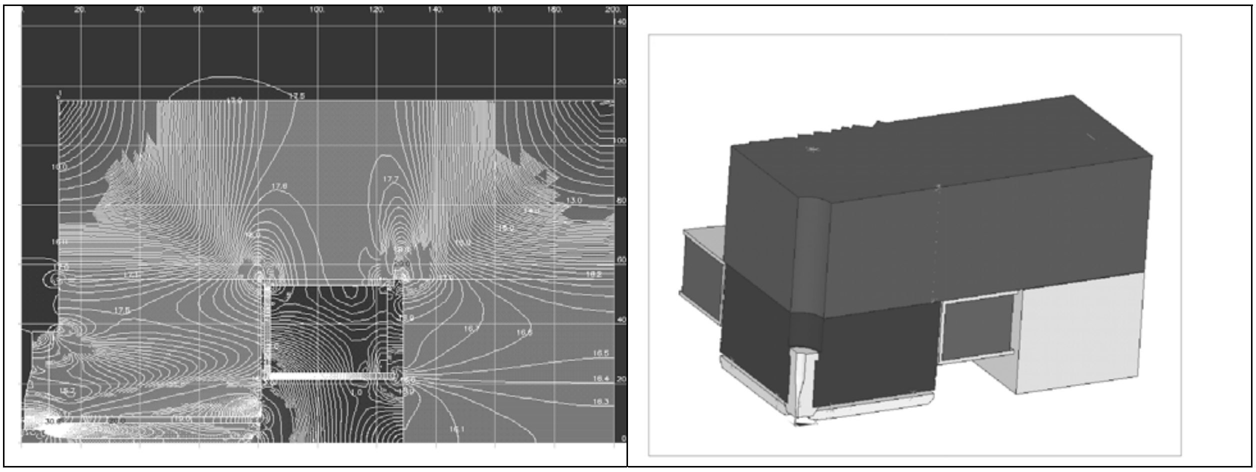
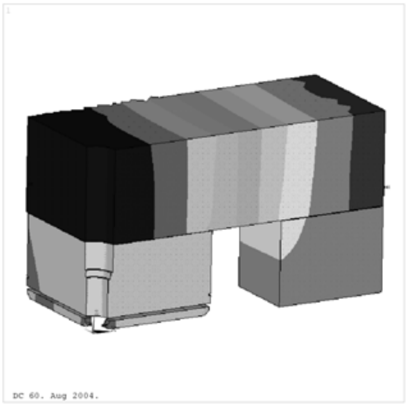


Fig.1 Field map in the DC60 vertical plane, kG

Fig.2. FE model of DC60.



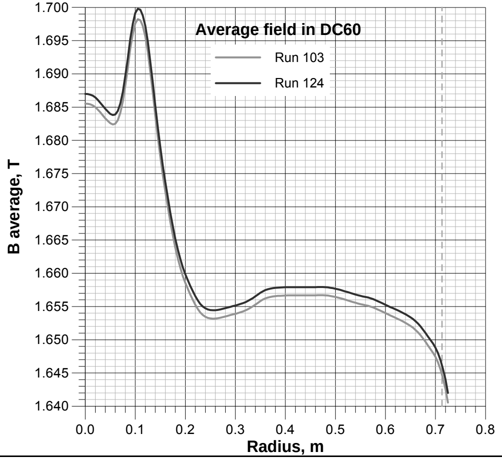


Fig. 3 Vertical displacements due to electromagnetic loads, m. Variant 3.

Fig. 4 Average field vs radius for deformed and initial states at current of 372 A

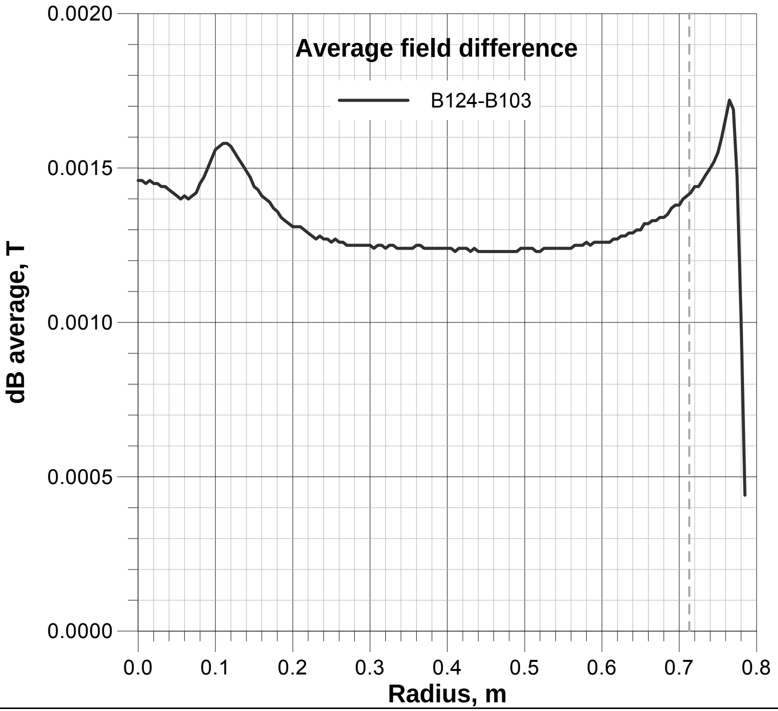


Fig. 5 Impact of deformation on field configuration at current of 372 A.