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CONSTRUCTIVE ELEMENTS STRESS ANALYSIS OF DEUTERON CYCLOTRON DC-1 MAGNETIC SYSTEM

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The magnetic system of the cyclotron DC-1 is a 4-sector structure with superconducting coils /1/. Parameters of current and ferromagnetic elements of the sector magnet were chosen by calculation using the programme for calculation of 3-dimensional magnetic systems by the method of integral equations /2/.

The stress analysis of the magnetic system elements was carried out on the computer realizing the method of FE on a 2-dimensional triangular mesh /3/. The edge problem of the stress theory is solved for the flat stressed state. This problem consists in determination of the displacement field U_i, deformation field $\mathcal{E}_{ij}$ and stress field σ_{ij} by the given properties of materials and distribution of forces.

The problem is solved by finding the minimum of the integral value related to work of stresses and the applied external load.

The following equation is solved in the programme:

$$\sum_{e}([K^e]\{U\}+\{f^e\})=0$$

where a sum is calculated by elements of quantities

$$[K^e]=[B^e]^T[D^e][B^e]\cdot t\cdot S$$

where $[B^e]$ is the form matrix, $[D^e]$ contains elastic constants of the material, t and S are the thickness and area of the element, $\{U\}$ is the tensor of node displacements.

$$\{f^e\}=[B^e]^T[D]\{\mathcal{E}_0\}\cdot t\cdot S-\{P^e\}$$

where $\mathcal{E}_0=\alpha\cdot\Delta T\left\{\begin{smallmatrix}1\\1\\0\end{smallmatrix}\right\}$, is the coefficient of temperature deformations, ΔT is the temperature difference, P^e are the forces in the nodes of mesh.

The structure of the electromagnet sector is schematically drawn in Fig. 1. The sector electromagnet consists of a C-shaped yoke made of CT-10 steel. In the magnetostatic calculations the current coil is divided into the elements. Distribution of pondermotive forces along circuit A (Fig. 1) for all four elements of the current coils is almost the same, therefore the pressure of magnetic forces is taken uniform and equal to 7.5 MN/M^2, which maximally exceeds the calculated force by 20 per cent.

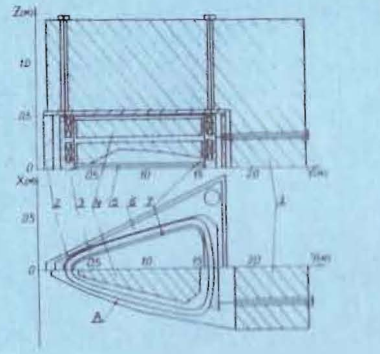

Fig. 1. The DC-1 electromagnet layout. 1 - yoke, 2 - cryostat vacuum chamber, 3 - estimated configuration of superconducting current elements, 4 - cold pole, 5 - vacuum region for the accelerated beam, 6 - cryostat vacuum region, 7 - heavy-duty nonmagnet element of the construction.

Table I.

Material	E, MN/M^2	Poisson's ratio	Temperature coefficient
Stainless steel 12X18H10T	$2\cdot10^5$	0.25	$0.11\cdot10^{-4}$
AMr5	$0.7\cdot10^5$	0.3	$0.138\cdot10^{-4}$
Copper M1	$0.125\cdot10^5$	0.35	$0.115\cdot10^{-4}$
Nb Ti /cu /5/ 0.3/0.7	$(0.11-0.2)\cdot10^5$	0.33	$0.083\cdot10^{-4}$

After a preliminary design analysis of the current coils attachment it was suggested that the coil should be divided vertically into 7 sections. Stresses in structure elements of a coil section were analysed for two cross sections. A possibility to use stainless steel 12X18H10T and aluminium alloy AMr5 as construction materials was analysed. The properties of those materials are given in Table 1 /4/. The thermal deformation coefficient is given for temperature changing by -300°K.

a) <u>Cross section of a Section</u>

The shape of the cross section of a current section is shown in Fig. 2. The current region I is a dense winding 50 mm wide wound as a superconducting 3.5*2.0 mm^2 bus, isolated by fiber glass braiding with epoxy resin empregnation. The coil is wound by two-layer wafers on the holder II with a thin membrane III over the whole internal region of the section. The external loop of the coil is closely embraced by the band IV fastened to the holder by plates V. In the analysis we took into account cooling by -300°K and pondermotive forces uniformly distributed over the current coil

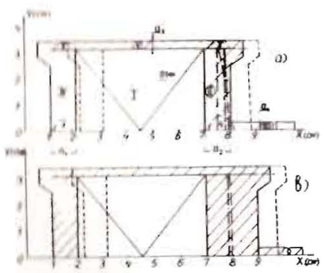

Fig. 2. Shifts of the cross section of the current section (the scale is given in the Fig.). The common boundary of regions I and II for materials:

—·—·— AMr5 ,

——— 12X18H10T.

Table II.

Number of configuration parameter	I	II	III	IV
a_1 (mm)	30	10	10	10
a_2 (mm)	30	10	20	20
a_3 (mm)	3	3	3	4
a_4 (mm)	6	6	6	6

and directed against the X-axis. There is a cross section through the common boundaries of regions I-V and I-II. The calculated dimensions of the construction elements are given in Table II.

Analysis of configuration I have shown that dimensions a_1 and a_2 are large, because deformation of the band and the holder are insignificant and the main stresses in them do not exceed 80 MN/M^2. At the same time at the boundary of regions I-II a 0.05 mm gap is possible due to tension of the connecting plate V. Reducing a_1 and a_2 to 10 mm (configuration II) leads to the fact that the holder, affected by forces, is deformed, as is shown in Fig. 2a. The use of the alloy AMr5 as a construction material results in worse deformation, and the gap between the current region and the holder reaches 0.18 mm. Note that the band bending does not exceed 0.01 mm for the materials mentioned. Increasing a_2 to 20 mm leads to a significant decrease of the band bending (Fig. 2b), and increasing a_3 to 4 mm decreases lenghtening of the plate V. As is seen in Fig. 3b, the gap for the current region and the holder is 0.03 mm for the alloy AMr5, and there is practically no gap for stainless steel. Since the current coil is covered with epoxy resin and glued to the surrounding material, there is no calculated gap, but insignificant stresses appear in epoxy resin.

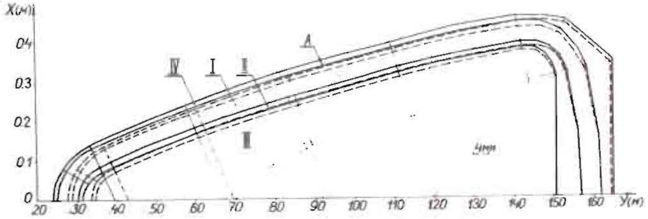

Fig. 3. Longitudinal section of the current section, shifts of points of contours of the estimated division into elements.

Table III. The main stresses σ_1 (MN/M^2) in the regions marked by figures in Fig. 2a.

	Configuration II		Configuration IV	
No	AMr5	12X18H10T	AMr5	12X18H10T
1.	103	100	100	99
2.	102	98	98	96
3.	185	185	100	105
4.	158	155	70	75

The maximum calculated main stresses in the construction regions marked by 1-4 in Fig. 2a, are given in Table III. One can see that the main stresses do not exceed the permissible range for configuration IV.

b) Longitudinal Section of a Section

The analysis region of the longitudinal section is shown in Fig. 3. The dashed line is the scaled-up configuration after cooling. The figures mark the subregions with different properties of materials; analogous ones are shown in Fig. 2. The construction will be analysed by the graphs of the main stress dependence on the length along the following contours: (i) the middle line of the band; (ii) the middle line of the current coil; (iii) the middle line of the holder. Pondermotive are normal to circuit A. Fig. 4 represents distribution of the main stress which occurs under the effect of magnetic forces and temperature deformations in configurations I and IV when stainless

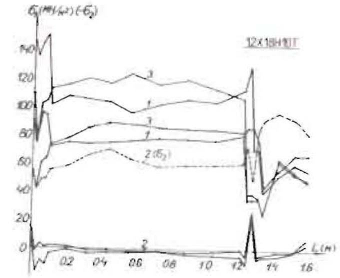

Fig. 4. Distribution of the main stress σ_1, along lines 1,2,3 for configurations I —x—x— and IV —·—·— . The dashed line is the compressing stress for configuration IV (σ_2).

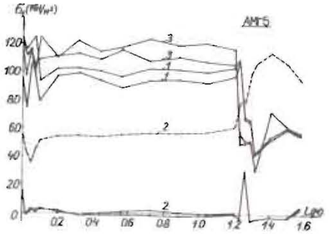

Fig. 5. The same for the aluminium alloy AMr5. —x—x— configuration II, —·—·— configuration IV.

steel 12X18H10T is used as a construction material. The value of the stress does not exceed 120 MN/M^2 over the whole length of the winding, and grows to 150 MN/M^2 only in the central zone. In Fig. 5 one can see the analogous curves for the aluminium alloy for configurations II and IV; in this case $\sigma_1 < 120$ MN/M^2. The dashed lines are compressing stresses (σ_2) in the current regions in both cases.

Fig. 6,7 show distributions of the main stresses produced by temperature deformations in configuration IV for 12X18H10T and AMг5 respectively. Concentration of stresses occures in the central zone; however, they do not exceed the permissible range.

It follows from the analysis that the section of the coil must be made according to dimensions in Fig. 2b; both stainless steel and the alloy AMг5 may be used.

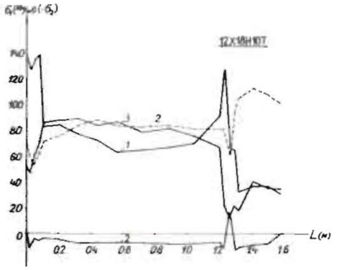

Fig. 6. The main stress in configuration IV without allowance for pondermotice forces. The dashed line is the compressive stress (σ_2).

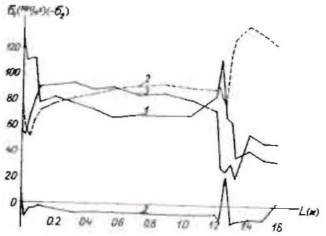

Fig. 7. The same for the aluminium alloy AMг5.

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Прочностной расчет конструктивных элементов магнитной системы
дейтронного циклотрона ДЦ-1

Приводятся результаты расчета задачи упругости для элементов конструкции магнитной системы четырехсекторного дейтронного циклотрона со сверхпроводящими токовыми обмотками. Анализируются возможности использования в качестве конструкционных материалов нержавеющей стали и алюминиевого сплава. Выбраны размеры бондажа и обоймы и других элементов исходя из предварительно разработанной схемы разбиения токовой обмотки на секции и конструкции каждой секции. Расчеты проводились по программе на ЭВМ, реализующей метод конечных элементов на двумерной треугольной сетке. Решается задача теории упругости для плоского напряженного состояния с учетом распределения пондеромоторных сил по узлам сетки и напряжений, возникающих в результате тепловых деформаций. Для двух взаимно перпендикулярных сечений секции токовой катушки рассчитаны распределения перемещений и главных напряжений по области задачи. Размеры элементов конструкции выбраны таким образом, что изгибы их не превышают 0,03 мм для алюминиевого сплава и незначительны для нержавеющей стали. При этом главные напряжения не превышают допустимых, следовательно, в рамках данной конструкции магнита возможно использовать оба указанных конструкционных материала и конкретный выбор необходимо делать исходя из других соображений.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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Alenitsky Y.G. et al. E9-85-608
Constructive Elements Stress Analysis of Deuteron Cyclotron
DC-1 Magnetic System

The stress problem is calculated for structural elements of the magnetic system of the four-sector deuteron cyclotron with superconducting current coils. Possibilities to use stainless steel and aluminium alloy as constructive materials are analysed. The size for bandage, yoke and other elements is chosen on the basis of the preliminary developed scheme for division of the current coil into sections and design of each section. The calculations have been made on the computer which realizes the method of finite elements on the two-dimensional triangle net. The problem of stress theory is solved for the flat stressed state with allowance for distribution of pondermotive forces over the knots of the net, and stresses occuring due to thermal deformations. Distributions of displacements and the main stresses over the problem region are calculated for two mutually perpendicular cross sections of the current coil section. The size of structural elements are chosen in the way that their bends do not exceed 0.03 mm for aluminium alloy and are insignificant for stainless steel. The main stresses are within the permissible limit; hence the given magnet design allows one to use both constructive materials. Some other reasons should determine the choice of the material.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR. **Preprint of the Joint Institute for Nuclear Research. Dubna 1985**