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COMPUTER STUDIES OF THE FIELD FOR THE SUPERCONDUCTING MAGNETIC SYSTEM OF THE DEUTERON CYCLOTRON DC-1

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INTRODUCTION

The deuteron complex[1] with the beam intensity 10-100 mA consists of the 15 MeV linac and two cyclotrons with the extraction energy 90 MeV and 2000 MeV, respectively.

The calculations have been based on the following prerequisites:

(i) the necessary dynamic characteristics of the system's magnetic field chould be provided;

(ii) each of the system's four magnets is placed within the 60° sector free of accelerating Δ-electrodes;

(iii) the allowable current density in the superconducting cable should be in accordance with the empiric relationship[2]:

$$Wj^2 < 10^{23}\,J \cdot A^2 \cdot m^{-4},$$

where W is the store of energy, j is the current density in the cross section of the superconducting cable. For DC-1 at $W = 5$ MJ we have $j < 140$ A/mm^2.

CALCULATION OF THE MAGNET WITH A FLAT GAP

Parameters of the DC-1 magnetic system were preliminary selected with the help of calculations carried out by the uniform magnetization method using the programme MAFCOD based on ref.[3].

The computer studies of the required magnetic field were performed by choosing the curvature of the separate coil fragments and the configuration of the external contour and the contour of cavities in pole ends, the axial gap being unchangeable (a flat gap, $2h_1$ = 20 cm).

In fig.1 one can see a schematical drawing of the sector magnet with convex superconducting coils. Its basic parameters are listed in Tables 1 and 2.

In figs. 2 and 3 the mean magnetic field is plotted against the radius, and the dynamic characteristics are plotted as a function of energy. Figure 2 shows that in the given energy range (15-90 MeV) stability of the circulation frequency (isochronism) f_0 = 12.375 MHz is maintained with the accuracy of 9×10^{-3}. The axial oscillation frequency (fig.3) $Q_z > 1.13$, starting from $E \geq 21$ MeV. One can see that after certain changes

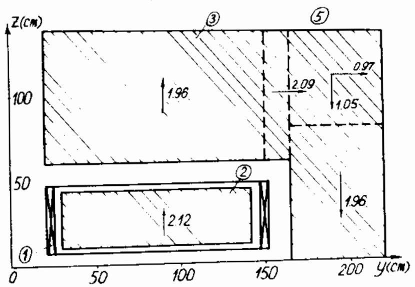
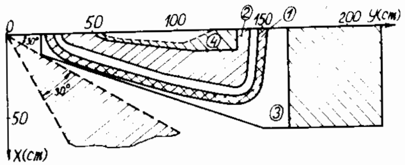


Fig.1. Flat gap. 1 - coil, 2 - pole, 3 - yoke, 4 - pole shape correction. Figures near arrows are μ_0 M(T).



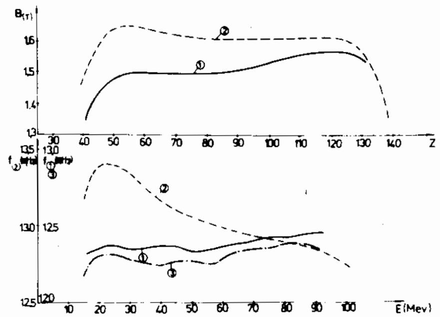


Fig.2. Flat gap. 1 - MAFCOD, 2 - MAGSYS, 3 - pole shape correction.

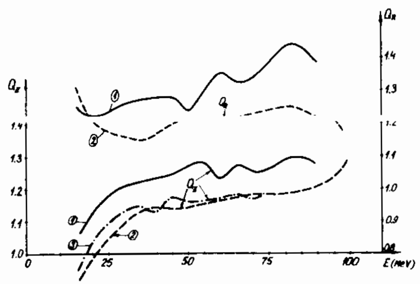


Fig.3. Flat gap. 1 - MAFCOD, 2 - MAGSYS, 3 - pole shape correction.

in the system (e.g., in order to eliminate the resonance $Q_z - Q_r = 0$ at $E \approx 46$ MeV and $3Q_r = 4$ at $E \approx 70$ MeV) the dynamic characteristics of the field meet the set requirements ($1.13 < Q_z < 1.32$; $1.22 < Q_r < 1.25$).

To check the conclusions on the system's parameters the configuration of the flat gap magnet was calculated by the programme MAGSYS[4]. In this programme the field is calculated on the basis of the volume integral equations method.

The dashed lines in figs.2 and 3 show the calculation results for the flat gap magnet. One can see that the mean field differs by 0.14 T (or 9%), isochronism is almost an order of magnitude worse ($\Delta f/f = 5\times10^{-2}$), the axial oscillation frequency $Q_z > 1.13$, starting from $E \simeq 35$ MeV. The results of the correction of the system's parameters (number of ampere-turns decreased by 14%, the cavity contour changed as in fig.1) show

Table 1

Basic parameters of the magnetic system

No.	Parameter	Ref./1/	More accurate flat gap variant	Shaping of the pole as to its height
1.	Magnet dimensions (m)	2x1.2x2.8	2x1.2x2.8	2.4x1.2x2.8
2.	Weight of the magnet iron (t)	30	35	35
3.	Angular length of the pole (degrees)	17.8-30.4	17.8-30.4	19-27.8
4.	Minimal gap between poles (cm)	20	20	10
5.	Cross section of the coil (cm^2)	5x40=200	5x40	2x(5x18)=180
6.	Angular length of the coil (degrees)	47.5-40.2	47.5-40.2	43.2-34.6
7.	Gap between coils (cm)	14	14	14
8.	Superconductor NbTi	I_{max} = 2000 A at B = 5 T, (3.5x2) mm^2		
9.	Mean current density with respect to the area of the coil (A/mm^2)	85	95	102
10.	Ampere-turns per one magnet (MA·turn)	3.4	3.8	3.668
11.	Maximum field in the magnet gap (T)	4.3	4.4	4.6
12.	Store of energy (MJ)	5	5	-
13.	Maximum linear density of the normal force per coil (MN/m)	2	-	3
14.	Maximum linear density of axial forces (MN/m)	1	-	0.8

Table 2

Parameters of the internal contour of the coil

Shaping with respect to the height	No. of fragments	1	2	3	4	
	α°	66.8769	13.8	86.8226	12.5	angular length
	X(cm)	0	415.9829	-29.6522	0	coordinates of the curvature centre (X,Y)
	Y(cm)	39.279	216.9093	143.75	10	
	R_c(cm)	9.279	461.6	10	147	curvature radius
flat gap	R_c(cm)	11	462.7	10	147.5	

Table 3

The pole shape h_1 (r)

r (cm)	35	44.5	50	62.5	75	90	110	140	152.5
h_1(cm)	5	5	10	17	19.6	19	16	10	10

h_2 = 48 cm, where the pole height is $h_2 - h_1$.

that the injection energy E = 21 MeV (the position of the point $\partial f/\partial E = 0$ in fig.2) is possible. The condition $Q_z > 1.13$ is satisfied at E ≈ 30 MeV.

SHAPING OF THE POLE AS TO ITS HEIGHT

Further computer studies of the field were carried out by the programme MAGSYS. Comparison of the method of the field generation by shaping the pole as to its height with the flat gap variant showed the pole shaping reduces the injection energy by (2-3) MeV.

Later on it was found that the minimal gap between the poles should be reduced from 20 cm to 10 cm. At the same time we managed to get the configuration of the magnet which is considered to be the basic one now (fig.4).Parameters of this magnetic system are given in Tables 1-3.

The results of the field generation in the selected version are given in fig.5, where the sinusoid show the position of equilibrium orbits for the injection radius (r_i = 46.7 cm) and the particle extraction radius (r_e = 116.6 cm). For the magnet version under consideration the density of the reverse flux between the sectors is at the level of 0.26 T (6% of the field in the hill). Contribution to the mean field due to the coil is 0.75 T (≈50%). About 42% of the mean field are due to the yoke field and, 8% are due to the pole (curves 1,2,3 on fig.5 consequently). Deviation of the mean field from the required one does not exceed ±3 mT, which is close to the given generation accuracy ±1 mT. At this accuracy the phase shift of particles with respect to the accelerating field does not exceed ±10°.

Dynamic characteristics of the equilibrium orbits were calculated by the programme CYCLOPS. It is shown that stability of the circulation frequency in the 15-103 MeV energy range is maintained with the accuracy $\pm 2 \times 10^{-3}$ (or ±0.03 MHz). In the diagram of free oscillation frequencies (fig.6) one can see that the operational point is far from dangerous resonances, apart from the non-linear internal resonance $3Q_r = 4$.

Calculations of the pondermotive forces affecting the coil showed that the maximum density of normal and axial forces is of the order of 2.7 MN/m and 0.5 MH/m, respectively. The resultant of the forces attracting the upper and lower magnet coils is F_z = 1.7 MN. The similar force for the poles F_z = 0.65 MN. The resultant of the normal forces per a coil is directed along the Y-axis and to the magnet centre (F = 0.15 MN). For the pole F = 0.40 MN.

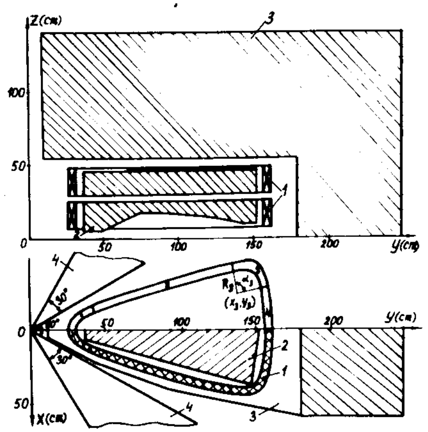


Fig.4. Profile gap. 1 - coil, 2 - pole, 3 - yoke, 4 - place for RF system.

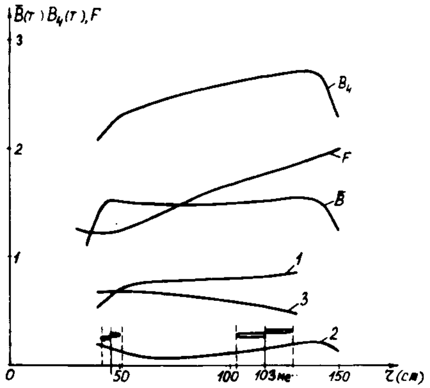


Fig.5. 1 - coil field, 2 - pole field, 3 - yoke field, B - mean field, F - flutter, B_4 - main garmonic amplitude.

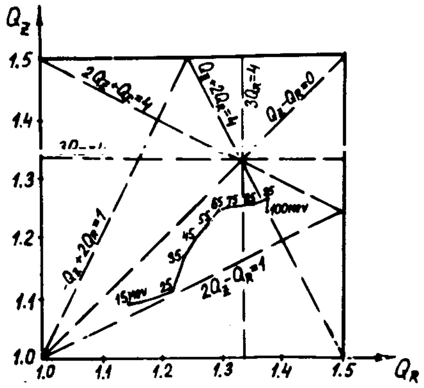


Fig.6. Working point on frequency diagram.

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Ворожцов С.Б. и др. E9-83-608

Расчетное формирование поля сверхпроводящей магнитной системы дейтронного циклотрона ДЦ-1

В работе представлены результаты расчетов параметров магнитной системы дейтронного циклотрона с энергией 90 МэВ /ДЦ-1/.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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Vorozhtsov S.B. et al. E9-83-608

Computer Studies of the Field for the Superconducting Magnetic System of the Deuteron Cyclotron DC-1

In this paper the calculation results are presented concerning the magnetic system parameters for the 90 MeV cyclotron (DC-1).

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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