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V.P.HAKOPIAN, I.P.KARABEKOV, V.D.KRAVTSOV,
M.Ya.VYRENKOVA

OPTIMIZATION OF THE SHAPE OF THE BENDING MAGNETS CROSS SECTION FOR ELECTRON ACCELERATORS AND STORAGE RINGS

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Ի.Պ. ԿԱՐԱԲԵԿՈՎ, Վ.Դ. ԿՐԱՎՑՈՎ, Վ.Պ. ՀԱԿՈԲՅԱՆ,
Մ.Յա. ՎԻՐԵՆԿՈՎԱ

ԷԼԵԿՏՐՈՆԱՅԻՆ ԱՐԱԳԱՑՈՒՑԻՉՆԵՐԻ ԵՎ ԿՈՒՏԱԿԻՉՆԵՐԻ ՃԿՈՂ ՄԱԳՆԻՍՆԵՐԻ ԼԱՅՆԱԿԻ ԿՏՐՎԱԾՔԻ ՁԵՎԻ ՕՊՏԻՄԱԼԱՑՈՒՄԸ

Մշակված են օպտիմալացման չափանիշ և հաշվարկման ծրագրեր, որոնց հիման վրա կարելի է ընտրել ճկող մագնիսի լայնակի կտրվածքի ձևը և նրա վրա փաթույթների տեղաբաշխումը, որոնց շնորհիվ մագնիսի բացվածքում համասեռ դաշտի տիրույթը կստացվի առավելագույնը: Հաշվարկների հիման վրա ստացվել են արագացուցչի, կուտակիչի և առածրգիչի մագնիսների փաթույթի և մագնիսատարի լայնակի կտրվածքի ուրվագծի առավել նպատակահարմար հարաբերակցությունները:

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В.П.АКОПЯН,М.Я.ВЫРЕНКОВА,И.П.КАРАБЕКОВ,
В.Д.КРАВЦОВ

ОПТИМИЗАЦИЯ ФОРМЫ ПОПЕРЕЧНОГО СЕЧЕНИЯ ЗАВОРАЧИВАЮЩЕГО МАГНИТА ЭЛЕКТРОННЫХ УСКОРИТЕЛЬНО-НАКОПИТЕЛЬНЫХ УСТАНОВОК

Представлены количественный критерий оптимизации и результаты машинного эксперимента по оптимизации формы поперечного сечения заворачивающего магнита для накопителя и ускорителя для разных значений индукции магнитного поля.

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V.P. HAKOPIAN, I.P. KARABEKOV, V.D. KRAVTSOV*,
M.Ya. VYRENKOVA

OPTIMIZATION OF THE SHAPE OF THE BENDING MAGNETS CROSS SECTION FOR ELECTRON ACCELERATORS AND STORAGE RINGS

The optimization criterion and programs of calculations for the choice of the form of the cross section of bending magnet's core and the disposition of its windings are worked out. On the basis of these calculations there are obtained the most efficient proportions for the dimensions of the magnetic core cross section contour and windings of the magnets for accelerators, storage rings and stretchers.

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[*] Moscow University

1. Introduction

The magnet system of charged particle accelerators and storage rings is one of the most labour-consuming, expensive and its essential parts determining most of the main parameters of the machine, such as the luminosity of colliders or brightness of SR sources, spatial and angular characteristics of the beams to be accelerated or stored up. In this connection, the optimization of the magnetic optics units, which will allow to improve the main physical and operating characteristics of accelerators and storage rings, is an urgent design problem.

In this paper there are considered some problems of optimization of the construction of warm dipole magnets which at present are a component of magnet systems of electron accelerators and storage rings.

2. The Criterion of Optimization

The possibility for a wide variation of the shape and dimensions of the magnetic core's cross section contour, disposition of excitation coils etc, requires a lot of machine computations to find correlations between the varying parameters of the construction and field intensity and its distribution in the gap. For a quantitative estimation of separate variants of construction, it is necessary to formulate the criterion of optimization. When constructing bending magnets, the following main goals are usually put.

1. To achieve the maximum value of the good field region (GFR) ΔA in tha gap, where the field non-uniformity is less than the given value at the chosen pole width A, height of the gap h and the maximum field intensity H .

2. To achieve maximum intensities of field in the centre of the gap at the given number of ampere-turns, height of the gap and width of the pole piece. These requirements can be combined into a single criterion:

$$K = \frac{H \Delta A \delta}{j S_w A} \qquad (1)$$

where S_w is the area of the winding's cross section, j is the current density in the windings, δ is the unit length along the azimuthal axis of the magnet.

In this paper there is studied the dependence of criterion (1) on the change of dimensions of the main parts of the cross section contour of the C-shaped magnetic core with non-shimmed parallel poles. These main parts are: the pole width A; the pole height E; height of the yoke D, height of the gap h and geometric dimensions of the coil - the width a and the height b (see fig.1).

The work has been carried out to optimize the cunstruction of bending magnets of storage rings for generation of SR beams [1] and of the beam stretcher [2] of the Yerevan Physics Institute electron synchrotron.

3. Calculation Programs

Programmes using the method of three-dimensional integral equations in a two-dimensional approximation described in ref.[3] have been elaborated for computations. The essence of the method is the following. Let $\vec{B}(\vec{x})$, $\vec{H}(\vec{x})$, $\vec{M}(\vec{x})$ correspondingly be the magnetic field inductance, strength and moment in the point x: $\mu = \mu(|\vec{B}(\vec{x})|)$ is the permeability, $\vec{H}(\vec{x})$ is the field induced by the current elements calculated according to Biot-Savart law. Let G be the iron-filled region. The integral formulation of magnetostatics in a two-dimensional case has the form [4] :

$$\vec{H}(\vec{a}) = \vec{H}^{s}(\vec{a}) - \frac{\nabla\vec{a}}{2\pi}\int_{G} \left(\vec{M}(\vec{x}),\ \nabla\vec{a}\, \ln(|\vec{x}-\vec{a}|)\, ds\vec{x}\right. . \qquad (2)$$

$\vec{H}$, $\vec{M}$ and $\vec{B}$ are connected as follows:

$$\vec{H}(\vec{x}) = \frac{\vec{B}(\vec{x})}{\mu_0 \mu(|\vec{B}(\vec{x})|)} , \qquad (3)$$

$$\vec{M}(\vec{x}) = \frac{\vec{B}(\vec{x})}{\mu_0} - \vec{H}(\vec{x}) . \qquad (4)$$

Let G be divided into triangles $\{G_i\}$, $G = \bigcup_{i=1}^{N} G_i$, the division satisfying the following conditions:

a) measure of intersection of G_i and G_j is equal to zero at $i \neq j$.

b) at $i \neq j$ the triangles G_i and G_j can be in contact only by a whole side.

Determine a_i as follows:

$$a_i = \frac{\int_{G_i} \vec{x}\, ds\vec{x}}{ds\vec{x}}, \quad i = 1,2 \ldots N \tag{5}$$

To solve (2) discretization from [4] has benn used

$$\vec{H}_i = \vec{H}^s(\vec{a}_i) - \frac{\nabla \vec{a}}{2\pi} \sum_{j=1}^{N} \int_{G_j} (\vec{M}_j \, \nabla \vec{a} \, \ln|\vec{x} - \vec{a}|) \, dS\vec{x} \Big|_{\vec{a} = \vec{a}_i} . \tag{6}$$

$\{\vec{H}_i\}$ and $\{M_i\}$ are connected by eqs.(3),(4). The optimization method from ref. [3] has been used when calculating the coefficients of the discretized equations (6).

Fedorenko's method of successive lattices [5] was used to solve the set of discretized equations.

4. Results

In the analysis of results of numerical calculations using the optimization criterion (1) the GFR was limitted by the field non-uniformity tolerance $\frac{\Delta H}{H} = 10^{-3}$. For each type of construction considered, calculations have been carried out for low ($H < 1000$ oersted, $j = 0.126 \text{A mm}^{-2}$), medium ($H = 10000$ oersted, $j = 2.49 \text{A mm}^{-2}$) and high fields ($H > 10000$ oersted, $j = 5.09 \text{A mm}^{-2}$).

Results of calculations of construction parameters are given in Tables 1-3 and on the corresponding diagrams. Values of the coefficient K presented in the Tables are normalized to the constant value $\delta S_W^{-1} A^{-1}$

In Table 1 and figs.2 and 3 is presented the optimization criterion (1) versus the ratio of the width of the winding to its height within 0.2 ÷ 5 . It is seen from the presented results that the maximum value of K corresponds to a/b=0.197 . However, for this magnet construction at the same current density in the winding cross section, the field intensity in the centre of GFR is by 22% lower than for the construction with a/b=5 . The growth of K takes place due to more than twice expansion of GFR. That is why for storage rings where GFR determines the beam life time, the achievable value for the current stored, the beam emittance and, correspondingly, the luminosity or the brightness of SR sources, in stretcher ring electromagnets demanding a wide and homogeneous working region for a continuous and uniform extraction of particles, the magnets with high pole pieces and windings with the ratio a/b=0.2 are preferable.

Magnets with windings having the ratio a/b=5 are preferable for accelerators where the beam acceleration and extraction time is measured in seconds or in fractions of a second and the beam transverse cross section must be large enough to provide an extended extraction. And what is more, the achievement of a higher field in magnets with a/b=5 at the given power of the supply system and the radius of accelerator, determines the energy of particles and hence, it affects the cost of the machine and the effectiveness of its operation.

In Table 2 the values of GFR, magnetic field intensity in the centre of that region and the optimization criteria for low, medium and high fields are given for three types of windings constructions and hence, the magnetic core for the ratios a/b=0.197; 1.72 and 5.09 . It follows from the Table and fig.4 that for low fields most effective is the construction with a flat winding ($a/b=5.09$); for medium fields a construction with $a/b=1+2$ is most effective as well as vertical windings for high fields.

The dependence of the optimization parameter K on the pole width A for a construction having $a/b=1.72$ at the constant yoke width at high fields is presented in Table 3 and figs.5 and 6 . The pole width A is changed within $160+240$mm at the yoke width of 240 mm. The maximum value of K is obtained at the pole width $A=220$. The further extension of A results in a sharp decrease of field in the centre of GFR, while its size increases only by 10%. Hence, the ratio of the pole width to the yoke width for a construction with a/b 2 in a chosen range of A must be 0.9 . In the same Table K versus the yoke width is given at $A = 160$mm. The width of GFR is in strong dependence with the width of the yoke. For $a/b=1.72$ and 5.122 A/mm^2 the deminition of the yoke width from 240mm to 140mm leads to the decrease of H_{max} by 8.9% and to the increase of ΔA by 27%. That is why it is not reasonable to have magnets with wide yokes for storage rings. A more detailed optimization of the yoke width must be done during each particular design, for the chosen material for the magnetic core and at the required values of ΔA and j .

In conclusion the authors express their gratitude to E.P. Zhidkov and P.G. Akishin for the help in calculation programming and calculations.

Table 1

K versus a/b at the pole width A=160mm and yoke width D=240mm

A a (mm)	b (mm)	a/b	j (A/mm^2)	H (T)	ΔA (mm)	K
40	203.5	0.197	5.09	1.36	41	10.97
46	176.5	0.26	5.1	1.41	37	10.24
59.5	136	0.44	5.12	1.50	30	8.75
68.5	113	0.58	5.12	1.53	27	8.06
118	68.5	1.72	5.12	1.69	24	7.90
136	59.5	2.286	5.12	1.71	23	7.70
176.5	46	3.837	5.10	1.744	21	7.31
180	45	4.0	5.11	1.746	21	7.17
203.5	40	5.09	5.09	1.75	20	6.88

Table 2

ΔA versus H for three values of a/b at the pole width A=160mm, yoke width D = 240mm

a (mm)	b (mm)	a/b	j (A/mm^2)	H(T)	ΔA (mm)	K
40	203.5	0.197	0.124	0.058	78	36.3
			0.48	1.05	62	26.36
			5.09	1.36	41	10.97
118	68.5	1.72	0.125	0.061	76	37.0
			2.494	1.18	53	25.1
			5.122	1.69	25	7.91
203.5	40	5.09	0.124	0.0615	84	41.7
			2.477	1.21	56	27.4
			5.09	1.75	20	6.88

Table 3

ΔA and K versus the yoke width D and the pole width A for
$j = 5.12\ A/mm^2$ and $a/b = 1.72$

D (mm) (yoke)	A (mm) (pole)	H (T)	ΔA (mm)	K
240	160	1.69	24	7.9
200		1.67	26	8.5
180		1.65	27	8.68
160		1.60	28	8.74
140		1.54	30	9.01
240	160	1.69	24	25.3
	180	1.705	29	27.5
	200	1.71	34	29.0
	220	1.70	40	30.9
	240	1.677	44	30.7

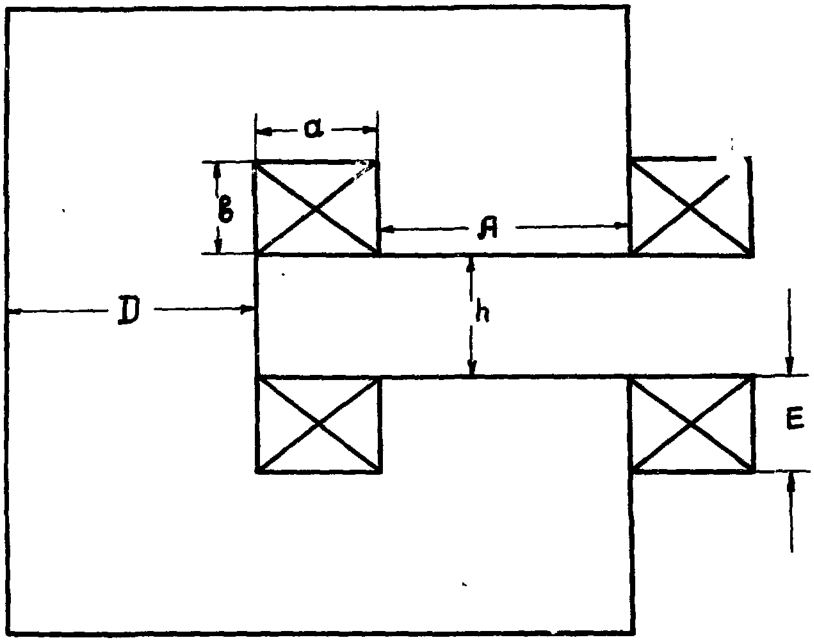

Fig.1

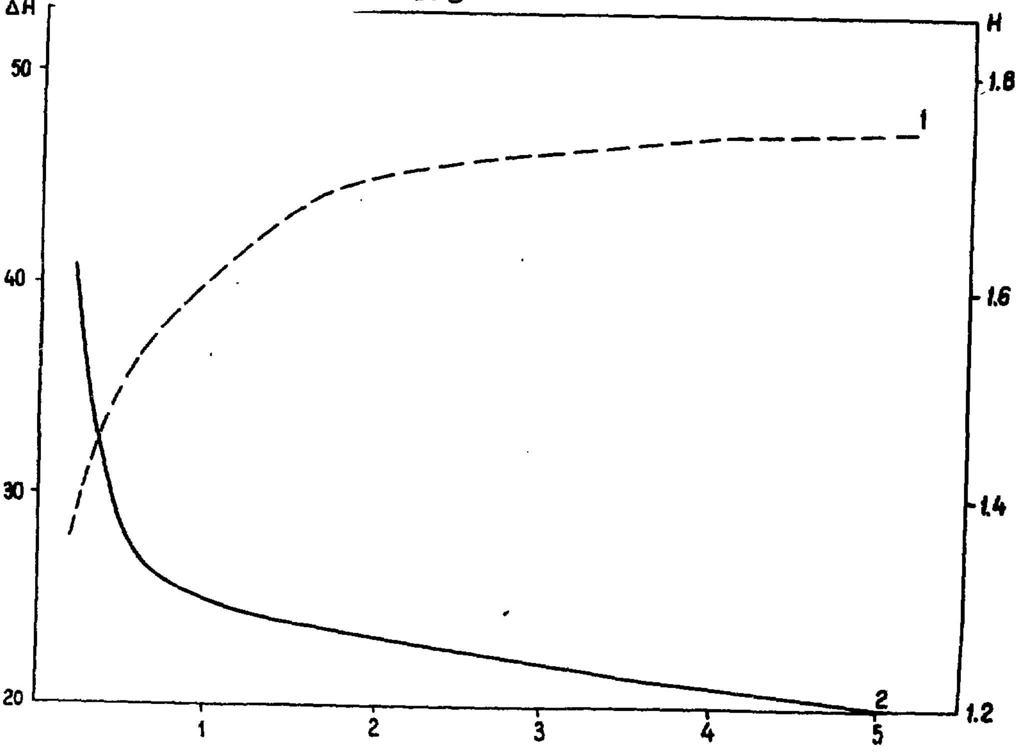

Fig.2

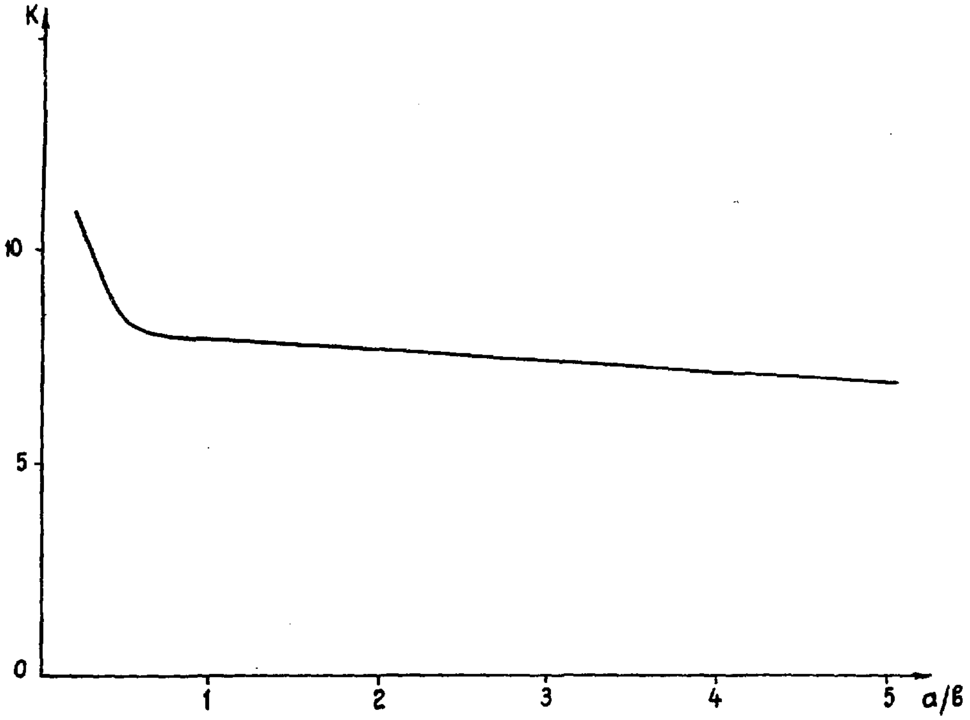

Fig.3

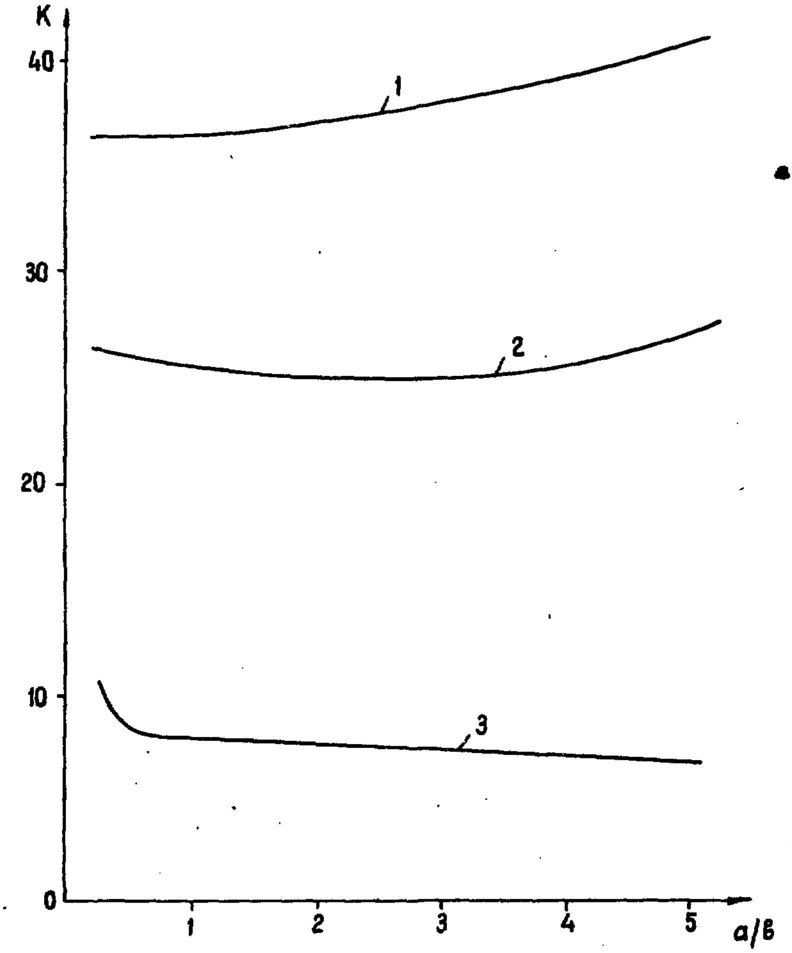

Fig.4

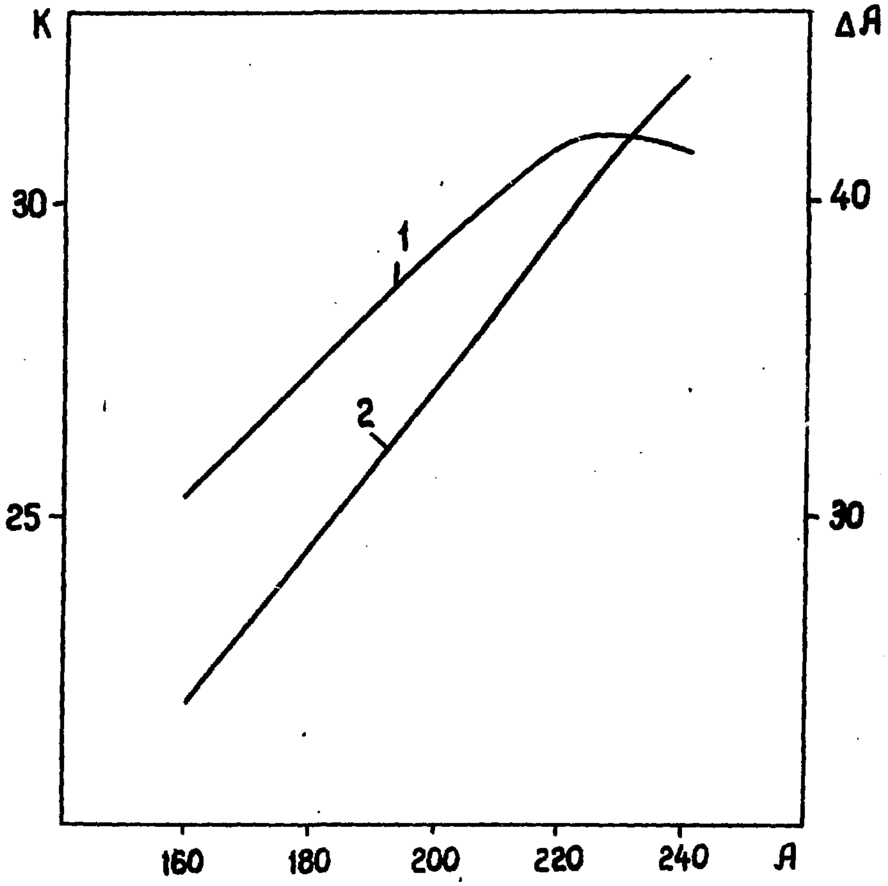

Fig.5

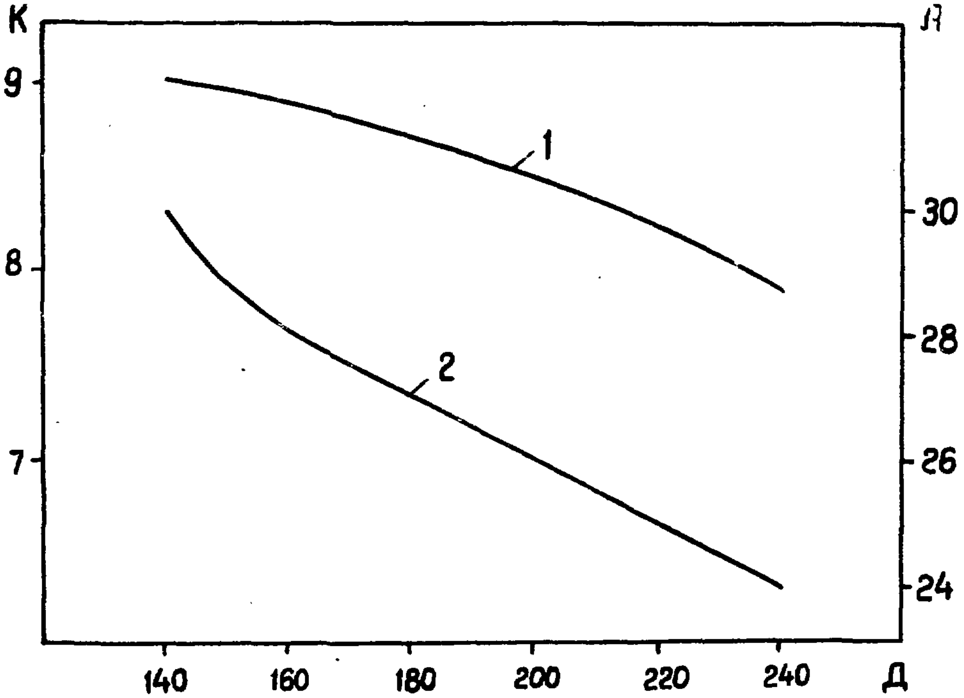

Fig.6

Figure Captions

Fig.1 ~~No caption~~ .

Fig.2 1. GFR versus a/b for $j=5.0$ A/mm^2;

2. H_{max} versus a/b in the centre for j 5.0 A/mm^2.

Fig.3 The optimization criterion K versus a/b for $j = 5$ A/mm^2.

Fig.4 K versus a/b for three levels of j:

1. $j = 0.124$ A/mm^2;
2. $j = 2.48$ A/mm^2;
3. $j = 5.03$ A/mm^2.

Fig.5 1. K versus the pole width A at the yoke width $D = 240$mm and $j = 5.122$ A/mm^2, $a/b = 1.72$.

2. ΔA versus the pole width at the same values of D, j and a/b .

Fig.6 1. K versus the yoke width D at the pole width $A = 160$mm, $j = 5.122$ A/mm^2 and $a/b = 1.72$.

2. ΔA versus the yoke width D at the same values of A , j and a/b .

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The address for requests:
Information Department
Yerevan Physics Institute
Markaryan St., 2
Yerevan, 375036
Armenia, USSR

Г.АКОПЯН, Я.ВЫРЕНКОВА, И.П.КАРАПЕКОВ, В.Д.КРАВЦОВ

ОПТИМИЗАЦИЯ ФОРМЫ ПОПЕРЕЧНОГО СЕЧЕНИЯ ЗАВОРАЧИВАЮЩЕГО МАГНИТА

ЭЛЕКТРОННЫХ УСКОРИТЕЛЬНО-НАКОПИТЕЛЬНЫХ УСТАНОВОК

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