РАЗДЕЛ VII. ФИЗИКА

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The mathematical modeling of magnetic systems with rectangular structure for different experiments

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doi: 10.18411/sr-10-06-2021-21

Abstract

Design, construction and operation of the magnetic systems of some electrophysical setups require a preliminary mathematical modeling as well as a constant maintenance of mathematical modeling when debugging and operating the setups. While calculating the fields of the mentioned magnetic systems (on the base of solving a number of the direct problems of magnetostatics), we are concerned with the inverse problem of magnetostatics, namely, an optimal construction of the current elements and ferromagnetic yoke was found resulting in the expected distribution of the magnetic field. This work discusses the results on the numerical modeling of the distributing magnetic field for some modifications of the spectrometric magnet SP-94, SP-40 and the magnet of solenoid type, weach used in some experimental setups.

Аннотация

Проектирование и конструирование магнитных систем электрофизических установок требует предварительного математического моделирования. Математическое моделирование необходимо также и в процессе наладки и в последующей эксплуатации установки. Хотя расчеты магнитных полей магнитных систем проведены нами на основе решения ряда прямых задач магнитостатики, мы их все же относим к классу обратных задач магнитостатики, так как осуществляем фактически поиск оптимальной конструкции токовых элементов и железного ярма для наперед заданного распределения магнитного поля. В данной работе представлены результаты численного моделирования распределения магнитного поля некоторых модификаций спектрометрических магнитов СП-94, СП-40 и магнита соленоидального типа, используемых в ряде экспериментальных установок.

1. Introduction

The significance of numerical modeling at the investigating of magnetic systems is defined not the only known dignities of computational experiment, but also that, what measurement of magnetic field is labor-intensive and by expensive problem. The self process of the mathematical modeling of magnetic systems (see Fig. 1 and Fig. 2), as the authors of this work have presented, need to divide on two large stages.

Fig. 1 General view of spectrometric magnet ISP-40-4B

Fig. 2 Type of solenoidal magnet.

On the first stage of creation of new magnetic system, it is advisable to have possibility their quick and operative modeling with a help of program software, which have the properties of "logarithmic ruler", i.e. it have accessibility, simplicity of applications and the sufficient accuracy of numerical calculations. On the second stage, it study the chosen configuration of the magnetic system in more detail, i.e. it is making more accurate numerical calculations for two-dimensional and three-dimensional configurations. In the present work it is proposed a method of refinement of numerical solution of magnetostatic problem with piece wise smooth boundary in so - called "corner points". Using the stated above method it has done the numerical simulation of a whole number of magnetic systems. Lower (below) it is circumscribing (characterizing) the variants of mathematical models of magnetic system with the boundaries, containing the "corner points".

2. Geometry of magnet system (the two-dimensional case)

This coordinate system (the right-hand triplet) is chosen in such a way that Z axis is directed along the beam. The horizontal plain is XOZ . Fig. 3 shows a half of magnet core cross - section on the XOY plain (orthogonal to the beam), while Fig. 4 displays a 1/8 cross - section on the vertical plane YOZ . The domains Ω_f and Ω_c are filled with a ferromagnet and current sources respectively, $\Omega = \Omega_f \cap \Omega_c$. In the Table 1 given the linear sizes of the magnetic system (a basic version, without modifications).

The curve $\mu = \mu(B)$ corresponding to the steel used is given on Fig. 5.

Fig. 3. 1/2 of magnet core cross - section on the XOY plane

Fig. 4. 1/8 cross - section on the vertical plane YOZ

Table 1

The linear sizes of the magnetic system

x_1, m	x_2, m	x_3, m	x_4, m	x_5, m	x_6, m	z_1, m	z_2, m	z_3, m
0,15	0,3	0,36	0,49	0,605	1,175	0,65	0,62	0,81
y_1, m	y_2, m	y_3, m	y_4, m	y_5, m	y_6, m	y_7, m		
0,0645	0,114	0,144	0,302	0,46	0,49	1,06		

3. The description of the program software and the some algorithms

3.1 The program software

On first stage for the solution of magnetostatic tasks was created the complex of programs CPMMS -1.0 [1] for the numerical modelling of magnetic systems, witch including such known the program software, as POISSON [2] - the numerical modeling of two-dimensional magnetic fields, the package of graphic programs, so as GRAPHER, SURFER, PAW [3]. Into the complex of programs (CPMMS) is included the program of expert systems for optimal choice of the configuration of magnetic system and the program of polinomial representation of the components of magnetic field, weach is used in the tasks of the dynamics of charge particles. The suggested complex of programs CPMMS is formed in the

form the library of programs, which you may constantly, complete or replacement of been used programs. Authors those works stopped its choice on the package of programs POISSON for the numerical research of magnetostatic tasks. How shown the experience, this system of programs is the moust many usable from the entire known programs of such class, and have the high computational characteristics.

The complex of programs CPMMS-1. 0 [1] contains the accumulation of the data base of investigated the configurations of magnetic systems for further graphic study of the numerical results, therefore the process of the selection of the configuration of magnetic system for him technical realization is enough ease and accelerate. For mathematical modeling of three dimensional magnetic system was created by complex MFC programs. TOSCA software package was also used. The suggested numerical algorithms and the complexes of programs made the mathematical modeling of magnetic systems with enough high accuracy. The main criterion of the good results of modeling is the concurrence of numerical calculations with experimental data with the high accuracy. Follows to note, that the results of numerical calculation consisting with available experimental data not less, than $10^{-3} - 10^{-4}$.

Fig. 5 The curve $\mu = \mu(B)$

Fig. 6. The domain with the corner point

3.2 Numerical calculation in corner points

Very often in the calculation of particular magnetic system the domain (region) where is solving the boundary - value problem has smooth boundary everywhere with the exception of finite number of "corner points", in the vicinity (neighborhood) of which the boundary is formed by the intersection of two smooth curves. In those cases the solution of the problem or the derivatives of the solution may have singularity. It may be used for example the Dirichlet boundary problem for the laplace equation in the region represented on fig.6

$$\begin{cases} \Delta u(p) = 0, p \in \Omega \\ u|_{\Gamma_1} = 0 \\ u|_{\Gamma_2} = \sin(2\phi/3) \end{cases} \quad (1)$$

(r, ϕ) - polar coordinate system; region $\Omega = \{(r, \phi) : 0 < r < 1, 0 < \phi < 3\pi/2\}$ boundary $\Gamma_1 = \Gamma' \cup \Gamma''$ where $\Gamma' = \{(r, \phi) : 0 \leq r \leq 1, \phi = 0\}$, $\Gamma'' = \{(r, \phi) : 0 \leq r \leq 1, \phi = 3\pi/2\}$ while the boundary $\Gamma_2 = \{(r, \phi) : r = 1, 0 < \phi < 3\pi/2\}$

The problem (1) has solution $u = r^{2/3} \sin(3\phi/2)$. Let us write the derivatives u_x, u_y and will get $u_x = -(2/3)r^{-1/3} \sin(2\phi/3)$, $u_y = (2/3)r^{-1/3} \cos(2\phi/3)$. For the derivatives u_x and u_y grow

with no limit (indefinitely). Therefore, at the solution of those problems by numerical methods it is necessary to take into account the nature of its solution behavior in the vicinity of the corner point.

In the present work it is conducted the study of the question about the behavior of magnetic field in the vicinity of the corner points with the application of effective algorithms which give the improvement of the accuracy at the numerical solution of magnetostatics problem.

In the work [4] it is conducted the investigation of nonlinear differential equation $\operatorname{div}[\mu(|\nabla u|)] = 0$, entering the setting of the magnetostatics problem on the presence of its solution with unlimited growing $|\nabla u|$. It is constructed the difference scheme for the Dirichlet boundary problem with the equation $\operatorname{div}[\mu(|\nabla u|)] = 0$ in the region with corner. It is considered the question about the possibility of the construction of the solution with unlimited $|\nabla u|$ of the magnetostatics problem from solutions which are obtained for the equation $\operatorname{div}[\mu(|\nabla u|)] = 0$ and from solutions which are well - known for the equation with unlimited $|\nabla u|$. Starting from the integral selling of the magnetostatics problem it was done the upper bound of admissible magnetic field growth near the corner point of ferromagnet. It is proposed the method of concentration of difference frame (net, mesh, grid, lattice) in the vicinity of the corner point. The obtained results may be used at the solution of various (different) nonlinear physical problems containing into its formulation of the equation type $\operatorname{div}[\mu(|\nabla u|)] = 0$ in particular at the determination of magnetic field in the magnetostatics problem when the boundary of region of ferromagnet contains corner points, as in our particular (concrete) case. At the numerical calculation such method gives results by accuracy, obtained only in frames with 4-5 times large number of nodes along every axis than the initial frame (net). With the utilization of above statid method it is performed (produced) the simulation of the configuration of the spectrometric magnet SP-94 being used in the experiment DELTA - SIGMA (LHE, JINR).

3.3 Richardson's method of approximating conditions $u(\infty) = 0$

In the process of the numerical calculations of the spectrometric magnet field (Fig. 7) the complementary monitoring of the approximation accuracy of the $u(\infty) = 0$ condition is performed on the base of methods, using by analogy with [5], an extrapolation according to the parameter R^{-1} , where $R = \max(l_x, l_y)$ and l_x and l_y are the lengths of the sides of rectangle limiting computative region Ω . Using this numerical algorithm the all variants of the configurations of magnetic systems SP-40 and SP-94 calculated for two radii R_1 and R_2 . Then linear combination

$$\bar{u}(p) = \gamma_1 u_{R_1}(p) + \gamma_2 u_{R_2}(p) \quad (2)$$

satisfies the condition $\|u(p) - \bar{u}(p)\| \leq O(R^{-\beta})$, i.e. condition $u(\infty) = 0$ with larger accuracy, than each from u_{R_1} and u_{R_2} , and parameter γ is equal to 2. The graphs of the function $|\bar{B} - B(R_i)|$, $i = 1, 3$; $\bar{B}$ corresponds to $\bar{u}$ are presented on Fig. 7. It is seen, that the accuracy of the numerical results in the region, close to magnetic pole where are produced higher requirements to the accuracy of computation is enough high. Complex programs CPMMS - 1. 0 [1] contains the accumulation of the data base of investigated the configurations of magnetic systems for further graphic study of the numerical results, therefore the process of the selection of the configuration of magnetic system for him technical realization is enough ease and accelerate. The suggested numerical algorithms and the complex of programs made

the mathematical modeling of magnetic systems with enough high accuracy. The main criterion of the good results of modeling is the comparison of numerical calculations with experimental data with the high accuracy. Follows to note, that the results of numerical calculation consisting with available experimental data not less, than $10^{-3} - 10^{-4}$.

4. Results numerical modeling of magnet system SP-94 and SP-40

4.1 Magnet SP-94, IHEP

The computational results show (see Fig. 8) that the inhomogeneity of the magnetic field (of the 1 T level) in the air-gap of 13 cm is the highest at the edge of the pole (the pole size is of $xy = 30\text{cm} \times 130\text{cm}$). In the vicinity of the edge it can be more than 5 percent for $y = 5.2\text{cm}$

Рис. 7. Результаты уточнения решений с использованием аппроксимации условия $u(\infty) = 0$

Fig. 8. Distribution of the magnetic field induction at the edge of the pole: 1- $y=0\text{cm}$, 2- $y=1.3\text{cm}$, 3- $y=3.9\text{cm}$, 4- $y=5.2\text{cm}$

On the other hand, the same extension of inhomogeneity is observed also for the median plane ($y = 0$) when the coordinate x is such that $x > 10\text{cm}$, i.e. at the edge of the pole for $x = 15\text{cm}$. In order to increase the area of the homogenous field, it is naturally to set up (in a reasonable way) the ferromagnetic brackets at the edge of the pole. Such brackets (see Fig. 9, Table 2) were made of steel which is close to steel - core by magnetic characteristics on the pole of spectrometric magnet SP-94 of the experiment EXCHARM-II on the 5H channel of the U70 IPHVE accelerator (Protvino). On Fig. 10 for the median plane $y = 0$, given the graphs for the basic (without brackets) and two versions with ferromagnetic brackets. One can certify that really we observe the significant increase in the size of the area with the homogenous field inside the inter - pole gap of 13 cm.

Table 2

The linear sizes of the ferromagnetic brackets

x_1, m	x_2, m	x_3, m	x_4, m	y_1, m	y_2, m	y_3, m	y_4, m
0,108	0,1235	0,1345	0,15	0,053	0,05587	0,06162	0,0645

4.2 A magnet SP-94, LHE, JINR

4.2.1 A dependence of the inter-poles air-gap with the pole width of 30 cm for different values of h

The Fig. 11 gives the results of numerical modeling of the magnetic field distribution for the air-gap (for the full current at the half coil $I = 0.73 \times 10^5 \text{ A}$, generating a field of 1T in the 13 cm air-gap) with the values of inter - pole air - gaps $h = 7, 8, 9, 10$ and 13 cm. The

constructed dependencies allow one to compute the field for other configurations close to the presented ones. The nominal working current in a loop is equal to 635A while the full current in the half coil is $I = 1.016 \times 10^5$ A. Such a current creates a field distribution for the given configurations of the magnet with air-gaps $h=7, 8, 9, 10$ and 13 cm, which is shown on Fig. 12. The numerical results of 3-dimensional computation ($h=9$ cm, $s=30$ cm) are shown on Fig.13. Here one can see the dependence of B_y on x for $z=0$ and for various values of y : $y=0$, $y=0.09$, $y=1.8$ cm, $y=2.7$ cm .

Fig. 9. 1/8 cross - section on the vertical plane YOZ

Fig. 10. 1- without brackets, 2- with ferromagnet brackets (variant A), 3- with ferromagnet brackets (variant B).

Fig. 11. 1- $h=13$ cm, 2- $h=10$ cm, 3- $h=9$ cm, 4- $h=8$ cm, 5- $h=7$ cm

Fig. 12. The distribution of the magnetic field with air-gaps: 1- $h=7$ cm, 2- $h=8$ cm, 3- $h=9$ cm, 4- $h=10$ cm, 5- $h=13$ cm

At present the working version of the magnet SP-94 at LHE, JINR, at the "Delta-Sigma" experiment is the inter-pole air-gap with $h=9$ cm and pole - width $s=30$ cm . A nominal field is the field at the center $B_y(0,0,0)=1.75T$. A 3 - dimensional distribution of the magnetic field for this working version with the nominal current $I=1.016 \times 10^5$ A is given on Fig. 14 - Fig. 15 shows the dependence $B_y = B_y(x,0,0)$, while the dependence of the field along the Z axis, i.e. $B_y(0,0,z)$ is given on Fig. 15. The quantity of $\int_{-L}^L B_y(0,0,z)dz$ is equal to $2.4T \cdot m$. Here $B_y(0,0,0)=1.751T$, $L=1.5m$ is the size (along the Z axis) of the region where the computations of the magnetic field were performed. The existence curve is shown on Fig. 16 for this magnetic configuration.

Fig. 13. The dependence of B_y on x for various values of y : 1- $y=0$, 2- $y=0.09\text{cm}$, 3- $y=1.8\text{cm}$, 4- $y=2.7\text{cm}$

Fig. 14. 3-D the magnetic field

Fig. 15. The dependencies the field on corresponding coordinates the X axis and Z axis

4.2.2 Dependence of the field for the different values of pole - width s with the same inter-poles air-gap $h = 13\text{cm}$

On Fig.17 we give a dependence of the magnetic field $B_y = B_y(0,0,0)$ computed (with $h = 13\text{cm}$, $I = 1.016 \cdot 10^5 \text{ A}$) for different values of s (the width of the pole), equal to 20 cm, 25 cm, 30 cm, 35 cm, 60 cm. These graphs show a stringent dependence of the width of the homogeneous field region on the width of the pole. The width of the homogeneous field is always slightly less than the width of the pole.

Fig. 16. The existence curve for this magnet configuration

Fig. 17. A dependence of the magnetic field for different values of the pole-width

4.3 Magnet SP-94 with three coils

Further researches were directed toward the solving of the following inverse problem in magnetostatics. We were interested in finding out a magnet configuration which would provide a larger value of the working magnetic field inside the aperture as well as a larger value of the field integral and with a possibly larger width of the pole. A technological possibility exist in the form of placement an extra, a third coil, exactly the same in size as for example, the first (the upper) one or the second (the lower) half coil in the basic version of the magnet SP-94. The height of the ferromagnet core increases for 4 cm in this case. The nominal current in a loop would be, naturally kept the same and is equal to 635 A. The full current in such a loop consisting of three mentioned parts, increases 1.5 times. The suggested configuration (half a section of the XOY plane) of the magnet is given on Fig. 18. The results shown on graphs Fig. 19-20 were obtained by a numerical modeling. Fig.19 demonstrates the distribution of the component of the field B_y along the X axis for $h = 7, 8, 9, 10, 13$ cm. Fig.20a shows the distribution of B_y along the X axis for $y = z = 0$ and $h = 9$ cm, while fig.20b shows the distribution of B_y along the Z axis for $x = y = 0$ and $h = 9$ cm. The value of $\int_{-L}^L B_y(0,0,z)dz$ is equal to 3.019Txm. Here $B_y(0,0,0) = 2.21$ T, $L = 1.5$ m is the size (along the Z axis) of the region, where the computation of the magnetic field was made. Thus, the value of the field integral for this configuration increases 1.3 times against its value for the configuration of the version of the magnet ($h = 9$ cm) with two half coils.

Fig. 18. The magnet with three mentioned parts **Fig. 19.** The distribution of the component of the field B_y along the X axis for 1- $h = 13$ cm, 2- $h = 10$ cm, 3- $h = 9$ cm, 4- $h = 8$ cm, 5- $h = 7$ cm.

Fig. 20 a,b. The distribution of B_y along the X axis for $y = z = 0$ and $h = 9$ cm.

4.4 Magnet SP-40A for NIS-experiment

In this work are presented the results of the modelling of the magnetic systems SP-40A

(Fig. 21) for the setup EXCHARM [6], which are received in last 2 years by means of above described of the complex programs. The configurations of magnet SP-40A (accordingly var. a, b, c) are presented on the Fig. 22(a, b, c), for which were spent the numerical calculations of the magnetic fields, i.e. was decided actually nonlinear inverse magnetostatic task. The modelling purpose is calculated of the geometry of magnet, for which increased the region of the uniformity of magnetic field compared with the real configuration of magnet. In the process of computer modelling it is necessary to chose the location of additional iron bars for the increase the uniformity region of the magnetic field for magnet SP-40A, and to create the configuration of magnet with the least expenditure of the material resources. The choice of the configuration of magnet SP-40A with the most wide area of the uniformity of magnetic field was conducted on the basis of the investigations of the field of magnetic systems by means of the graphic comparisons. So from graphs on fig. 23(a, b) it is clearly, that the pattern of the magnet of variant (Fig.22c) replies to the main demands supplied task. The Fig. 24a, b are presented the distributions of magnetic field for the magnet of configurations c (Fig. 22c) in the region close to iron pole, i.e. for $y = 0$ and $y = 0.2025$. From these pictures it is clearly that the magnetic field have the enough high degree uniformitie in this area. The problem of using the obtained map of the measured field for physical data processing in other sessions of the experiment EXCHARM, where winding current differed from its value in carrying out measurements, is topical. Let us investigate a mode with the field in the center of the magnet $B_0^{(2)} = \alpha \cdot B_0^{(\text{exp})}$ where $\alpha = 0.85$ in our case. The received calculation values of the magnetic field components for this mode are designated as $B_x^{(2)}(x, y, z)$ and $B_y^{(2)}(x, y, z)$. Further, we determine the differences as

$$\begin{cases} \Delta B_x(x, y, z) = B_x^{(2)}(x, y, z) - \alpha B_x^{(1)}(x, y, z) \\ \Delta B_y(x, y, z) = B_y^{(2)}(x, y, z) - \alpha B_y^{(1)}(x, y, z) \end{cases} \quad (3)$$

For experimental physical data processing received under the conditions of the second work mode, one can suggest the following computed map of the magnet field:

$$\begin{cases} B_x(x, y, z) = \alpha B_x^{(\text{exp})}(x, y, z) + \Delta B_x(x, y, z) \\ B_y(x, y, z) = \alpha B_y^{(\text{exp})}(x, y, z) + \Delta B_y(x, y, z) \end{cases} \quad (4)$$

where $\alpha = 0.85$, and $\Delta B_x(x, y, z)$ and $\Delta B_y(x, y, z)$ are determined from (4).

Fig. 21 1/4 of magnet SP-40A on the XOY plane

Fig. 22a

Fig. 22b

Fig. 22c

The computed map lets to use measured magnet field, and also take into account nonlinear effects of the real magnet field.

The Fig. 25 is presented of the meaning of deviations $\Delta B_x(x, y, z)$ and $\Delta B_y(x, y, z)$ for the real magnet SP-40A (variant I: Fig. 21) and his modification (variant II: Fig. 22c). From this figure it is clearly, that meanings of these values for the configuration c (Fig. 22c) are essentially less, than for the really existent magnet.

Fig. 23(a,b) According $B_x(x), B_y(x)$ for $y = 0$ to current 1100 A and the difference calculated fields for 2-piece magnet configuration options

Fig. 24(a,b) According $B_x(x), B_y(x)$ for $y=0.2$ to current 1100 A and the difference calculated fields for 2-piece magnet configuration options

Fig. 25 According $B_x(x), B_y(x)$ for $y=0.32$ to current 1100 A and the difference calculated fields for 2-piece magnet configuration options

The above circumscribed procedure resolves a practical problem for a spectrometric magnet SP-40A, figured on a Fig. 21. In a Fig. 26 the allocation, obtained in computing experiment, the distribution $B_y(x,0)$ along a line $y=0$ is given. A field at centre $B_y(0,0)=0.62$ T at a current in a coil of a winding $I=1100$ A. Quantities a builder $B_x(x,0)$ and $B_y(x,0)$ along a line $y=0.30$ m we give in a Fig. 27. The crupion outbursts on edges of poles ($x=0.50$ m) are visible. The obtained effects(results) are indispensable for conducting model operation of setting of experiment on measuring section pp - collisions in a gamut of energies 1-4 Gev on the accelerator Nuclotron LHE JINR, DUBNA.

Fig. 26. The distribution of the component of the field B_y along a line $y = 0.30$ m.

Fig. 27. A distributions of $B_x(x,0)$ and $B_y(x,0)$ along a line $y = 0.30$ m.

In Figure 28-29 shows the distribution of the magnetic field component for our two options for magnet configuration in the three-dimensional case. It can be seen that option II field component allocation has become smoother. For approximate calculations use a homogeneous field, induction of induction into the center of the magnet (B_c) and effective length (L_{eff}) is calculated by the formula: $L_{eff} = \Sigma / B_c$, where $\Sigma(x, y) = \int_{-L_1}^{+L_2} B_y(x, y, z) dz$ is the integral of the fields along the central trajectory from a distance $-L_1$ - the beginning of the action of magnetic field to the distance $+L_2$ - the end of the field. The relevant results of the calculations of the main characteristics of a magnet for two configurations are given in tables 3-6 for four lines: (0, 0, Z), (0, 0.30 m, Z) (0.5 m, 0, Z) (0.5 m, 0.30 m, Z).

Table 3.

The main characteristics of the magnet for the line (0, 0, Z) for approximate calculations.

I (A)	B_c (T)		Σ (T*m)		L_{eff} (m)	
	variant I	variant II	variant I	variant II	variant I	variant II
1100	0.5720	0.5747	1.004	1.006	1.755	1.751
700	0.3980	0.4005	0.708	0.710	1.778	1.774
350	0.1992	0.2004	0.356	0.358	1.785	1.784

Table 4.

The main characteristics of the magnet for the line (0, 0.30m, Z) for approximate calculations.

I (A)	B_c (T)		Σ (T*m)		L_{eff} (m)	
	variant I	variant II	variant I	variant II	variant I	variant II
1100	0.5782	0.5784	1.009	1.016	1.751	1.756
700	0.4058	0.4063	0.715	0.719	1.764	1.769
350	0.2011	0.2019	0.358	0.364	1.784	1.789

Table 5.

The main characteristics of the magnet for the line (0.5m, 0, Z) for approximate calculations.

I (A)	B_c (T)		Σ (T*m)		L_{eff} (m)	
	variant I	variant II	variant I	variant II	variant I	variant II
1100	0.4885	0.5533	0.861	0.957	1.764	1.731
700	0.3453	0.3887	0.614	0.678	1.778	1.744
350	0.1742	0.1928	0.315	0.343	1.808	1.776

Table 6.

The main characteristics of the magnet for the line (0.5m, 0.3m, Z) for approximate calculations.

I (A)	B_c (T)		Σ (T*m)		L_{eff} (m)	
	variant I	variant II	variant I	variant II	variant I	variant II
1100	0.6742	0.5989	1.112	1.040	1.650	1.736
700	0.4621	0.4607	0.777	0.763	1.682	1.676
350	0.2250	0.2137	0.389	0.373	1.729	1.745

Fig. 28. According $B_y(x, 0.3, z)$ to two current magnet configurations and 1100A.

Fig. 29. According $B_x(x, 0.3, z)$ to two current magnet configurations and 1100A.

1. The solenoid type magnetic field detector modeling

Fig.31 Mesh

Fig.30 Magnet geometry

Magnetic systems are very important parts [7-8]. To create the necessary configuration of magnetic field, the repeated solution of nonlinear boundary value problem of magnetostatics is needed. In the present work, we consider the problem of creation of homogeneous map of magnetic system of solenoidal type (see Fig. 30). As a result of optimization, the geometric parameters of magnetic system were chosen in such a way so as to get maximal size of the domain of homogeneity of the magnetic field.

Fig.32 Field distribution

Due to symmetry, in the modeling only 1/24 part of the geometry with corresponding boundary conditions. The calculations were performed (using two software products: TOSCA and native MFC) by the method of finite elements on tetrahedral mesh with 5 000 000 elements (see Fig. 31).

The distribution of the module of magnetic field on the surface of ferromagnetic is shown in Fig. 32. It is seen that maximal value of magnetic field is reached in the corner points (1.3 T). The density of the current in winding $J = 9.956410099 \cdot 10^6 \text{ A/m}^2$. The cross-section of coil $S = 0.04 \times 4.7 \text{ m}^2$. The total current $I = 1.871805098 \cdot 10^6 \text{ A}$. The field in the center of magnetic system $B_{center} = 0.5 \text{ T}$.

On Fig. 33 and 34 the domains with the degrees of homogeneity of magnetic field of 0.1 % and 0.5% correspondingly. The black continuous line shows the homogeneity 0.1 % is needed. On Fig. 33, the scale of magnetic field has site from 0.99 – 1.001 T, on Fig. 34 from 0.998 – 1.002 T.

Fig. 33 Field homogeneity is $\pm 0.1 \%$

Fig.34 Field homogeneity is $\pm 0.5 \%$

2. Results of the numerical simulation of the magnetic system of installation MARUSYA, VBLHE, JINR

Works [9-10] presents the results of mathematical simulation and comparison of a computer distribution of the magnetic field with the conducted measurements of the field of the modified magnet SP-40 of installation MARUSYA (JINR). As an example, this work shows part of the results of numerical simulation of the mentioned above magnetic system. Fig. 35 shows the dependences $B_y(x, 0, z)$, $B_x(x, 0.05m, z)$, $B_x(x, 0.05m, z)$, $B_z(x, 0.05m, z)$ for 600 A current. Fig. 35a gives a distribution of the basic component of field $B_y(x, 0, z)$ on the median planes ($y = 0$). The area of a homogeneous field at the level 1.21 Tl is located entirely under the magnet's pole falling down on the edges of the pole (both in a cross direction and on the beam) up to sizes of the order of 8 Gs for $z = 2.50m$ ($x = y = 0$) and up to 0 Gs in a cross direction for $x = 1.35m$ ($y = z = 0$). Fig. 35b shows a distribution the basic component of field $B_y(x, 0.05m, z)$ on plane $y = 0.05m$. The area of the homogeneous field at the level of 1.21 Tl is also located under the magnet pole. Further the field also falls down at the edges of the pole (both in a cross direction and on the beam) up to sizes of the order of 5 Gs for $z = 2.50m$ ($x = y = 0$) and up to 0 in a cross-direction for $x = 1.35m$ ($y = z = 0$). Figs. 35c, 35d give distribution of cross and longitudinal components of field $B_x(x, 0.05m, z)$ and $B_z(x, 0.05m, z)$ on plane $y = 0.05m$. As shown on fig.1, the proposed procedure of numerical modeling of the magnetic system under consideration adequately describes the nonlinear measurements of the form of the magnetic field depending on the current in winding.

The obtained numerical results are used for carrying out the computer modeling of installation MARUSYA and experiment on this installation and, after carrying out physical data gathering sessions, are used for processing those data.

Fig.35(a,b,c,d) Spatial distribution of B_x, B_y, B_z magnetic field SP-40 for $I=600A$.

Main conclusions

1. The software complex KPMMS has been created that allows one to solve a wide class of magnetostatic problems in a 2-dimentional case in the cartesian and cylindrical systems of coordinates. It also allows one to accumulate a

databank of numerical models of magnetic systems that enables to facilitate and accelerate considerably the process of creation and reconstruction of magnetic installations. A software complex for calculation of 3D-distribution of a field of magnetic systems has been developed.

2. Numerous calculations of magnetic systems and comparison of numerical calculations with experimental data have shown that the computer distribution of the magnetic field in most cases with 1% accuracy (or less) coincides with experimental data. It seems sufficient for carrying out a numerical research on the influence of various parameters of the magnetic system on the size and the form of the magnetic field.
3. Two and three - dimensional distributions of the magnetic field for some modifications of the spectrometric magnet SP-94, that is in wide use in various nuclear-physical experiments, are obtained through the numerical modeling. The optimal configuration for the magnet, well suitable to the implementation of different experiments, has been found.
4. Using this program package, a set of practical problems have been solved the results of which were used in the reconstruction and design of the magnetic system for the EXCHARM setup. By the numerical modelling it is constructed the configuration of magnet SP-40A, its uniformity of the magnetic field is increased on 60% compared with the really existent configuration of the magnet.
5. As a result of optimization, the geometric parameters of the solenoid type magnetic field detector were chosen in such a way so as to get maximal size of the domain of homogeneity of the magnetic field.
6. With the help of the suggested procedure, a lot of important practical problems have been solved. The results of which have been put as a basis for reconstruction and creation of magnetic systems of NIS, EXCHARM, DELTA-SIGMA, MARUSYA installations (JINR) and EXCHARM-II on the 5H channel of U70 IPHVE accelerator (PROTVINO).

1. Zhidkov E.P., Lima S., Polyakova R.V., Fernandes Nodarse F., Yudin I.P. The complex of programs for the modelling of magnetic systems, Ъ11-93-256, Dubna, 1993.
2. Holsinger R. F., Iselin C., POISCR, User Guide, CERN, SPS/EMA, 1982.
3. Brun R. et.al. PAW, CERN Program Library Entry Q121, Geneva, 1989.
4. Zhidkov E.P., Perepelkin E.E. //An analytical approach for quasi-linear equation in secondary order" CMAM, vol 1(2001), No.3 pp. 285-297.
5. Zhidkov E.P., Khoromsky B.N. Preprint OVM AN USSR, n 137, M., 1987, p.40.
6. Potrebenikov Yu.K., Yudin I.P. et al. Measurements of the magnet field of spectrometer EXCHARM.-In Proceedings of XV.
7. Perepelkin E. and ATLAS collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, Aad, JINST 2008, S08003, vol.3, p.437
8. Perepelkin E. and ATLAS collaboration, Commissioning of the magnetic field in the ATLAS muon spectrometer, Nucl.Phys.Proc.Suppl., ISSN:0920-5632, vol. 177-178, pp. 265-266, 2008.
9. Baldin A.A., Yuudin I.P. Numerical modelling of distribution of the magnetic field of magnet SP-40 of installation MARUSYA and comparison of results with experimental data. JINR Pre- TOSCA print P11-2006-99. Dubna, 2006.
10. Polyakova R.V., Perepelkin E.E., Shavrina T.V., Yudin I.P.. Calculation of distribution of the spectrometer magnet field // Part. Nucl. Letters, (2006), v.3, issue 7, pp.74-77. (Proceedings of the Conference devoted to the memory of Prof. V.P.Sarantsev, Alushta, 8-10 Sept. 2005)