APPLICATION OF MAGNETS WITH THE FIELD AZIMUTHAL VARIATION IN CHARGED PARTICLE OPTICS

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Abstract

The focusing properties of the magnet may be significantly improved due to strong sign alternating gradient focusing ($n>1$) by the field azimuthal variation. The improved focusing properties open the way of creating the compact magneto optical systems with high angular acceptance. In particular, field azimuthal variation permits to realize the beam achromatic bending by a single magnet. In the paper the examples of devices are given in which application of magnets with the field azimuthal variation is expedient. The problem of a guiding magnetic field formation is under discussion. Three-dimensional field of the magnets for a series of channels was numerically simulated taking into account the ferromagnetic materials saturation effects and the results are given. Besides, there is an experimental data on 270°-magnet, providing the beam transport in this paper.

1.Introduction.

Nowadays, bending magnets with the uniform field or with a weak non-uniform one ($n<1$), constant in azimuth, are widely applied in beam optics. To improve the focusing properties of the magnet the field index azimuthal variation is suggested to be used [1,2].

2.The main statements.

Charged particles being transported in a bending magnetsuccessively pass the sections where the fields provide either focusing or defocusing effect upon them. The total effect of these fields may be chosen (according to strong focusing principle) to be focusing simultaneously in two planes.

Along the axial circular trajectory $R=R_0$ the gap height - 2h between two pole pieces is constant and the magnetic induction is close to constant. The field index $n(\varphi)$ is varied, if necessary, by the pole pieces shaping. From the engineering viewpoint the law of the field index variation is most simply realized as the staircase function $n(\varphi)=n^{\pm}=\mathrm{const}$ which will be the landmark in our further statements.

Focusing properties of the magnet depend upon the number of local sections $\{\varphi_i \in [\varphi_i,\varphi_{i+1}], i=\overline{0,N}\}$ with n = const and amplitude of the field index variation between these different parts. Let us compare focusing properties of 90°-bending magnets providing simultaneous focusing both in horizontal and vertical planes. Magnet with $n=0.5$ and normal beam input and output as well as magnet with $n=0$ and edge bevel angles $\varphi_1=\varphi_2=26.5^{\circ}$are frequently used in opticalschemes for vertical focusing. For the first magnet the distance from its edge to co-focal points is $l_1=1.41R_0$, for the second magnet - $l_2=2R_0$. Magnet with the field index azimuthal variation (parameters: $\varphi_1=\varphi_2=\varphi_3=30^{\circ}$; $n_1=n_3=5.5$, $n_2=-5.5$) has $l_3=0.5R_0$. Magnet focusing power may be still increased due to larger number of local sections and more significant field index variation. In particular, magnet focusing power may be sufficient to realize the beam achromatic bending.

3. Suggested versions of applications.

3.1 Magnetooptical system (magnet mirror and bending focusing devices) of therapeutic accelerator LUER-40M [3] is shown in Fig.1 (a dotted line). Magnets with the uniform field and significantedge focusing are used. The main problem in tuning such small-scale systems can be attributed to the edge field and to stringent tolerances on the magnets relative position. The solid line on Fig.1 shows suggested devices with the field azimuthal variation. Bending-focusing device is a single magnet providing beam achromatic bending. It's parameters are: $\varphi_1=\varphi_5=0.28$ rad, $\varphi_2=\varphi_4=0.474$ rad, $\varphi_3=0.76$ rad; $n_1=n_3=n_5=-7$.. $n_2=n_4=7$. Fig.1 gives the beam envelopes taking into account the pulse spread. Magnet mirror uses also single magnet with the field azimuthal variation instead of magnets M2,M3,M2. This magnet parameters are: $\varphi_1=\varphi_5=50^{\circ}$, $\varphi_2=\varphi_4=34^{\circ}$, $\varphi_3=60^{\circ}$; $n_1=n_5=-0.55$, $n_2=n_4=3.58$, $n_3=-3.48$. Fig.1 illustrates optical characteristics of the magnet mirror. Thus, use of the magnets with the field azimuthal variation in this case permits on the one hand to reduce mass-overall dimensions, on the other hand - to attain significantly shorter start-up-tuning period being rather labor-intensive.

3.2 In optical schemes achromatic systems with 180°-bending angle comprising two and more magnets are used. Beam achromatic bending by a single magnet can be realized with the following parameters: $\varphi_1=\varphi_6=29^{\circ}$, $\varphi_2=\varphi_5=40^{\circ}$, $\varphi_3=\varphi_4=21^{\circ}$; $n_1=n_6=-4.98$, $n_2=n_5=4.43$, $n_3=n_4=-4.85$. Beam envelopes at symmetrical beam transport for $\mathcal{E}_x=\mathcal{E}=2\pi$ cm·mrad and dispersion function are given on Fig.2. Trajectory bending radius is $R_0=1$m.

4. Specific features of guiding magnetic field formation

Necessary azimuthal field index distribution is achieved by choosing the shape of pole pieces. At abs(n)<1 the pole pieces can be made as conical surfaces with the rectilinear generatrix. In this case the magnetic field second derivative appears; it's generalized index $b=(R_o^2/2B)\cdot(\partial^2B/\partial X^2)$ approximately equals to n^2. Taking into account the azimuthal coordinate φ curvature the angle of the pole pieces inclination - α to the azimuthal plane is defined in the following way:

$$\mathrm{tg}\,\alpha = \frac{\bar{n}_1 h}{R_o}\left[1 - \frac{4h^2}{R_o^2}\left(\bar{n}_1 + \frac{b}{2}\right)\right] \qquad (1)$$

where $\bar{n}_1$ is the field index defined from the plane-parallel case. At abs(n)<1 the field second derivative influence upon the particles motion results in partial compensation of the second order aberration effects and in some cases this compensation may be sufficient. At abs(n)>1 "b"-magnitude rises abruptly and aberration effects appear to be dominant. In this case the pole pieces surfaces should be of confocal hyperbola shape resulting in b=0. Required aberration compensation can be realized by the pole pieces shimming. In real magnets there is some transit region D_{tr}, where $n(\varphi)$ continuously changes from n^+ to n^- between the sections with the different field indices. Such section length (≈2h) depends upon the magnet geometrical parameters and the degree of the pole pieces saturation. Besides, in D_{tr}-region the field second derivative appears which may be rather high. These factors should be allowed for calculating the particles motion to take the necessary measures for the field index correction.

For the case of negligible saturation of iron core steel and abs(n)<1, an approximate single-parametric model can be constructed permitting to evaluate the character of the magnetic field induction distribution B(R) in a transit region and, in particular, the magnitude of the magnetic field second derivative. Setting the difference of the magnetic scalar potential between two poles - 2V, the following system of equations can be obtained:

$$\delta=\delta(R);\; h=h(R);\; j=B(S)/B^-;$$

$$B^-=V/h;\; B^+=B^-/(1+\delta);$$

$$\gamma\in\left[(1+\delta)^{-1},1\right]; \qquad (2)$$

$$S(\gamma)=\frac{h}{\pi}\ln\frac{(1+\gamma)^2[(1+\delta)^2j^2-1]^{(1+\delta)}}{(1-\gamma^2)[1+\gamma(1+\delta)]^{2(1+\delta)}},$$

where S - is the coordinate calculated along $R=R_o$ arc in azimuthal direction corresponding to jump-like variation of the gap height from the value in the region n^+ - 2h(1+δ) to the value in the region n^- - 2h. For $\Delta B^{\pm}$-derivation from the average magnetic field induction $B_o=0.5(B^++B^-)$ along the $R=R_o$ trajectory the following evaluation is obtained, when there are no ferromagnetic saturation effects:

$$\Delta B^{\pm} = \mp(B_o h\cdot \mathrm{tg}\alpha)/(6R_o). \qquad (3)$$

The spatial field actual distribution was calculated using KOMPOT package [4].

5. Example of a particular applications.

5.1 The magnet for linear accelerator "Electronika 4-003" has been manufactured and experimentally studied. It provides 270°-achromatic bending of 10 MeV electron beam. Fig.3 shows the pole pieces forming the required azimuthal distribution of the field index. The main magnet parameters are : $\varphi_1=\varphi_3=67.5°$, $\varphi_2=135°$; $n_1=n_3=0.7$, $n_2=-0.63$; $R_o=12$cm, $B_o=0.29$T. The results of the magnetic field numerical simulation for the different radii near the median plane (z=0.0625cm) are presented on Fig.4; ΔR - magnitude corresponds to deviation from the the equilibrium orbit. Fig.5 gives variation of dependency upon azimuthal bending angle of the magnetic field first, second and third derivatives. Required n_1 and n_2 were obtained due to correction of the pole pieces inclination angle and poles shimming.

Magnetic measurements results coincided completely with the calculations (within the limits of the field measurements accuracy $\approx 10^{-3}$) and correlated well with the calculational model of p.4. Magnet achromatic properties were studied on the base of magnet supply current variation what was equivalent to the electrons mean energy variation. At current ±1.5% deviation from the calculated values, the beam transverse dimensions changes were not observed.

5.2 Numerical simulation of the bending magnets for the extraction from the Moscow meson facility proton storage ring has been made [5]. Magnets are characterized by relatively high field indices. The M4 main parameters are : $\varphi_1=\varphi_2=15°$; $n_1=-7$, $n_2=7$; $R_o=340$cm; $B_o=1.2$T. The M5 main parameters are : $\varphi_1=30°$, $\varphi_2=15°$; $n_1=-4$, $n_2=4$; $R_o=280$cm; $B_o=1.45$T. Fig.6,7 give the field distributions along $R=R_o$ trajectory for M4 and M5 magnets, respectively. In the first case the calculation was performed on the assumption that $\mu=\infty$, in the second case - the ferromagnetic saturation effects were taken into account. Discrepancy in evaluations of $\eta=(\Delta B^++\Delta B^-)/B_o$ magnitude for M4 magnet, obtained basing upon analytical solution ($\eta=7.26\cdot10^{-4}$) using equation (3) and by the results of numerical simulation of the spatial magnetic field was not more than 2%.

6. Conclusion.

The results of numerical simulation and experimental studies testify to the feasibility of development and manufacture of the compact magnetooptical systems on the base of magnets with the field azimuthal variation providing the necessary characteristics of output charged particles beams.

References

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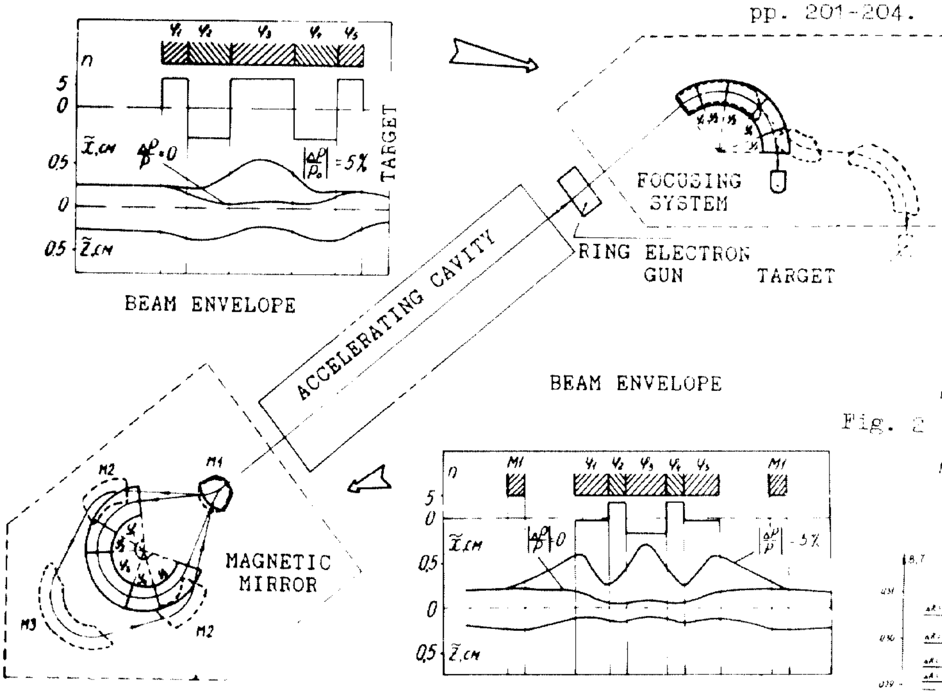


Fig. 1

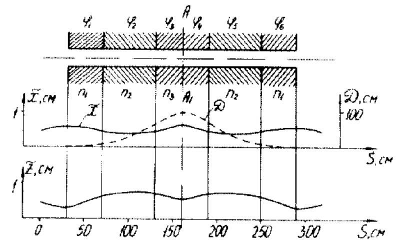


Fig. 2

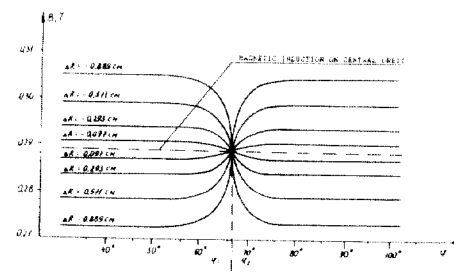
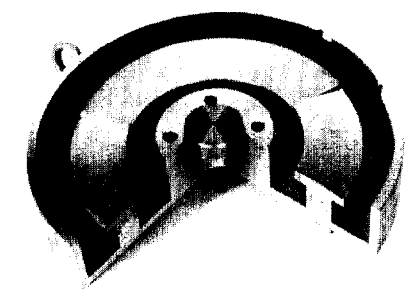


Fig. 4

Fig. 3



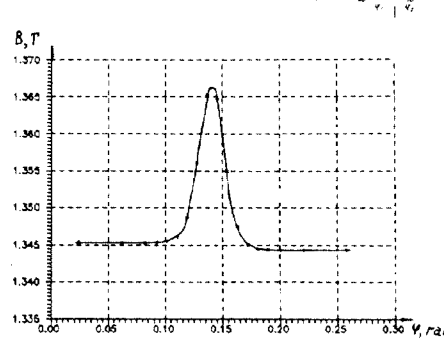


Fig. 6

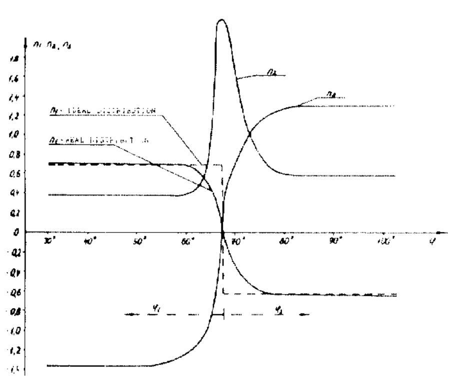


Fig. 5

Fig. 7