LITERATURE CITED


SIMULATION STUDIES OF MAGNETIC SHIELDS

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The motion of charged particles in complex magnetic field configurations is studied by a γ-curve method. The magnetic field simulator is described, and experimental results are given for the motion of electrons in the field of a current loop. It is shown that a current loop has toroidally shaped forbidden volumes and can capture particles in periodic orbits.

Recently, a fairly large number of studies of magnetic shields have appeared [1–8]. The importance of the studies lies in the fact that the passive systems used at the present time do not satisfy the requirements for radiation shielding during long space flights or for shielding from highly energetic charged particles [1]. Calculations [2–4] indicate that in most cases superconducting shielding systems are considerably more effective than material systems.

One of the most important problems in the construction of magnetic shields is the study of the motion of charged particles in magnetic fields in order to find the forbidden volumes, where the particle flux below some assigned energy is equal to zero. Investigations in this direction were begun in [9] and continued in [2, 5, 10]. Forbidden volumes have been obtained for a dipole [9] and a current loop (approximately) [2]. However, forbidden volumes can be calculated for a broader class of fields, for example, fields having axial and translational symmetry, by means of the γ-curve method [5], which is a generalization of the approach of [9]. In this method the forbidden volumes (points) are calculated for a current loop, for example, by starting with the equations for γ curves:

\[
\gamma_{\pm} = r \left[ \pm 1 - \frac{J_{d} e v^{3}}{2 m v} \frac{C(x^{2})}{V r / a_{0}} \right],
\]


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Fig. 1. The $\gamma$ curves and the forbidden volumes for 1-MeV electrons and a loop current of $10^5$ A. Totally forbidden volume (cross hatching) and partially forbidden volume (single hatching) for a current loop.

where $e$, $m$, and $v$ are the charge, mass, and velocity of a particle, respectively; $a_0$ is the loop radius; $\mu_0 = 4\pi \times 10^{-7}$ G/m; $I$ is the loop current; $C(k^2)$ is a complete elliptical Emde integral with modulus $k^2$ [11]; $r$, $\Theta$, and $z$ are cylindrical coordinates. By choosing the value of $\gamma|_{z=const}$ and cutting off the $\gamma$ curves by the planes $\gamma = const$ we have a graphical method, shown in Fig. 1, of plotting the forbidden volumes. The $\gamma_+$ curves characterize the so-called totally forbidden volumes, which exist for particles with $-\infty \leq \gamma \leq +\infty$ and energies below the assigned energy.

The $\gamma_-$ curves describe the partially forbidden volumes, which vanish for some values of $\gamma$ as can be seen clearly in Fig. 1 (for $\gamma = -3.1$). The finite motion region is between these regions.

The shielding of real objects requires more complex magnetic field configurations, for which an analytic calculation of the forbidden volumes is very difficult and sometimes intractable. This problem can be solved in a simpler manner by studying the motion of low-energy particles in the fields of small-scale models of the magnetic systems. However, under realistic conditions the particle flux is generally almost isotropic, a situation difficult to realize in simulation studies. Therefore, the simulation may produce certain errors that require experimental verification. In this regard, the simplest and most thoroughly studied theoretically magnetic system, a current loop, is investigated in the present paper in order to determine the correlation between the theoretical and experimental results and to use the experimental technique to determine the forbidden volumes of more complex magnetic systems.

**EXPERIMENTAL**

The experimental investigation of a current loop was carried out on apparatus consisting of a vacuum chamber 120 cm in diameter and 75 cm long, a charged particle source, and a suspension system for the magnets. The lateral surface of the chamber contains seven identical pipes to support the electron guns.