Choice of Hexapole Parameters for ECR Ion Source

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Abstract

Some results of optimization of *Nd Fe B* hexapole parameters, carried out on the base of analytical and numerical calculations for a 14 GHz compact ECR ion source are presented. On providing the required value and distribution of magnetic field it has been enabled to minimize the magnetized volume of the hexapole. The number of bars and outer radii of Halbach hexapole magnetic rings at fixed inner radius, defined by outer radius of the plasma chamber, have been varied.

I. INTRODUCTION

At present, in ion beam physics a considerable progress is seen. It is directly attributed to the development and construction of ECR ion sources with the operational principle based on ions extraction from hot electron plasma heated by electron-cyclotron resonance to the temperature necessary for the generation of multicharged ions of the working substance.

For stable plasma confinement a magnetic field of "minimum B" configuration, increasing to all sides from the region occupied by the plasma, is used. Such field configuration in the ion source results from the superposition of the fields produced by coaxial coils and a multipole structure. Usually, a hexapole, made of permanent *Sm Co* or *Nd Fe B* magnets, is employed as a multipole structure. The hexapole produces magnetic field increasing in radial direction. A coil system is a simple mirror trap with the mirror ratio of 1.5–2 and provides field increase in the axial direction.

Lack of the axial symmetry in the magnet system necessiates the 3-dimensional calculations of the hexapole field, in particular, the identification of the character of edge fields distribution because of probable appearance of the spurious resonances in the area of the ion beam extraction and RF power input.

This paper presents the investigation and optimization results for the permanent magnet hexapole for the ECR source of multicharged ions at 14 GHz microwave frequency, corresponding to the 0.5 T resonance magnetic field.

II. OPTIMIZATION OF HEXAPOLE PARAMETERS

The hexapole represents a set of segmented magnet rings, whose magnetization vector $\mathbf{M}$ lies in the plane perpendicular to the longitudinal axis. Continuous law of the magnetization distribution over the ring in the azimuthal direction, corresponding to the ideal hexapole case, is defined as

$$\mathbf{M} = M_0 \left(\mathbf{e}_\phi \cos 3\phi - \mathbf{e}_r \sin 3\phi\right) \ ,$$

where $\mathbf{e}_\phi$, $\mathbf{e}_r$ are the orts of the polar system of coordinates. In an actual construction it is approximated with a polyline in accordance with the number of segments assembled of a homogeniously textured material.

For the case of an ideal hexapole with a given inner radius R_1 and outer radius R_2, magnetic induction dependency upon the coordinates in presentation $\mathbf{B} = \mathbf{H} + 4\pi\,\mathbf{M}$, where $\mathbf{H}$ is the magnetic field strength, is the following:

$$\mathbf{B} = \begin{cases} \dfrac{6\pi M_0 (R_1^2 - R_2^2) r^2}{R_1^2 R_2^2} (e_r \sin 3\phi + e_\phi \cos 3\phi) \ , & 0 \le r < R_1 \\ 2\pi M_0 \left[3 \left(\frac{r^2}{R_2^2 - 1} \right) e_r \sin 3\phi + \left(\frac{3r^2}{R_2^2} - 1 \right) e_\phi \cos 3\phi \right] \ , & R_1 \le r \le R_2 \\ 0 \ , R_2 < r \end{cases}$$

Simple analysis of these expressions permits to make the following conclusions:

- Magnetic induction in the hexapole aperture ($r < R_1$) is $B \sim r^2$;
- In the case of $R_2 > \sqrt{3} R_1$, near to the points $r = R_1$, $\phi = \frac{\pi k}{3}$, $k = 0, 1, \ldots, 5$, a working point on the magnetization curve $B = B(H)$ lies in the 3-rd quadrant. For the contemporary magnet materials it can produce the unwanted effects of the hexapole inner layers demagnitization by outer layers.
- Neglecting the demagnetization effects, maximum probable induction in the hexapole aperture on its inner surface is $B_S = B_{\max} = 1.5\, B_0$, where $B_0 = 4\pi M_0$ is the residual induction. In a particular case at $R_2 = \sqrt{3} R_1$, $B_S = B_0$.

For the analysis of the hexapole edge fields, the 3-dimensional calculations have been done. The programm complex DIAMOND has been developed for the calculation of permanent magnet systems.

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Table 1: Dependency of the magnetic field on the number of segments

Number of sectors, N	12	18	24	2400
B_S/B_0	0.8696	0.9404	0.9662	1.0000

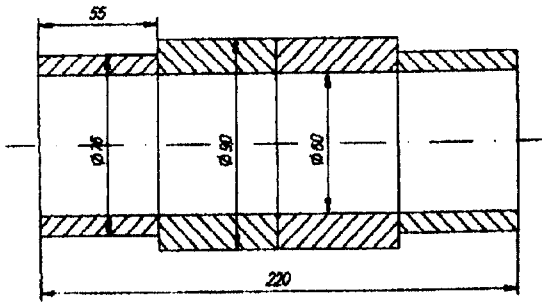

Figure 1: The longitudinal cross-section of the hexapole for the ECR ion source

Design optimization of the hexapole with the specified length and radius R_1, determined by the ionization chamber outer radius and length, consists in the variation of R_2-radii and the number of magnet rings segments. As a criterion, the efficiency of the permanent magnet material use was considered on condition that the requirements for the magnetic field magnitude and profile distribution were kept. The table 1 gives the dependency on the number of segments of the magnetic field value, reduced to the surface value $B_S = \left(\frac{R_1}{r_*}\right)^2 B_*$, for the ratio $R_2 = \sqrt{3}R_1$ and $r_* = 0.75\,R_1$.

The number of segments $N = 18$ seems to be optimal in technological aspect. Fig.1 shows schematically the longitudinal cross-section of the accepted hexapole construction for the ECR source of multicharged ions. The hexapole is composed of 4 rings of equal length with the $N = 18$ segments made of $NdFeB$ magnets with the residual induction of $B_0 = 10.5$ kGs. The outer diameter of the extreme rings can be reduced proceeding from the plasma stability conditions. The magnetic field distribution for the hexapole aperture in the longitudinal direction is shown in Fig.2 as a function of radius.

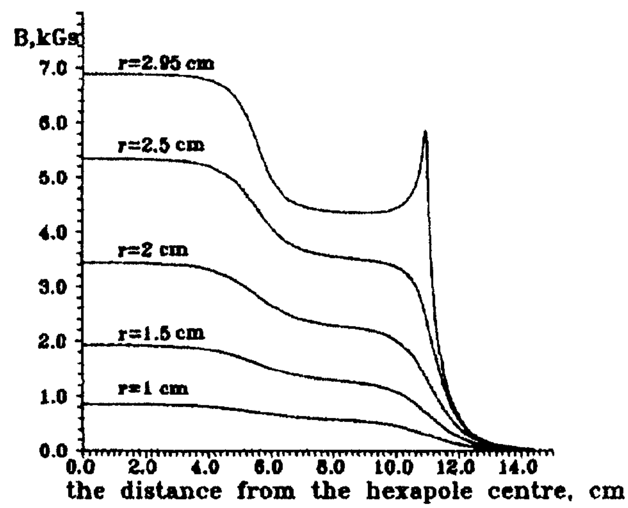

Figure 2: The magnetic field distribution in the longitudinal direction