# ECR ION SOURCE TYPE NANOGUN HEXAPOLES[*]

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## *Abstract*

The paper presents an overview of research and development devoted to the construction of suitable hexapoles for NANOGUN type Electron Cyclotron Resonance Ion Sources (ECR IS). Permanent magnets are made from NdFeB magnetic material. The main attention is given to hexapoles with inner diameters of $\phi = (36 - 48)$ mm at different hexapole thicknesses of 14 – 90 mm.

## 1 INTRODUCTION

About 31-year history of Electron Cyclotron Resonance Ion Sources (ECR IS) has already shown that ECR IS is an ideal tool for the production of multicharged ions. ECR IS have improved continuously in many fields of science. They are very efficient tools for providing highly charged ions for atomic and nuclear research, material science, and surface physics. There have been various attempts to increase beam intensity and charge state of ions producing by ECR IS. The multi-frequency heating has proved an effective way to increase both the number and widths of the ECR zones. Wall coating in the inner wall of plasma chamber was used in order to supply the plasma chamber more electrons. Despite of these attempts, only a small fraction of the whole plasma of ECR IS is used at the resonance of microwaves and electrons. Of course, electrons can be accelerated only in this plasma zone. In order to produce more highly charged ions, the ECR zone would have be the utmost.

Recently a small ECR IS, so called ”Compact ECR IS”[1], based of permanent magnets has been developed at GANIL, for radioactive ion beams experiments. This type of ECR IS is very simple and easy for operation and maintenance without powerful electric supplies and cooling systems to get strong magnetic field not using of coils.

We should like to construct an ion irradiation system using ECR IS with permanent magnets so called ”NANOGUN-10B”. In order to understand suitable hexapole configuration we studied hexapoles with inner diameters of $\phi = (36 - 48)$ mm at hexapole thicknesses of 14 to 90 mm. Permanent magnets are designed of NdFeB material.

## 2 HEXAPOLES - RADIAL MAGNETIC FIELD CALCULATIONS

Single-frequency NANOGUN ECR IS consists of a longitudinal magnetic field, made by permanent magnets and a transversal one, made by hexapole compound of permanent magnets. The magnetic bottle is the region surrounded by a closed surface of constant magnetic field B so that $|\mathrm{B}|\mathrm{e} = \mathrm{m}_e\omega_{rf}$, where B is the average value of the magnetic field in the region where the plasma is, e the charge of the electron, $\mathrm{m}_e$ the mass of the electron and $\omega_{rf}$ the microwave frequency matching the electron cyclotron frequency $\omega_c$. For $\omega_c$ = 10 GHz we need $|\mathrm{B}| = 0.36$ T and $|\mathrm{B}| = 0.50$ T for $\omega_c = 14$ GHz. The magnetic field inside plasma region is lower than that on the surface of the magnetic bottle. The stronger is the magnetic field inside the magnetic bottle the higher is the rf frequency of resonance electrons. We thus obtain higher plasma density that results in higher ionization possibility.

The computer program PANDIRA[2] was used for calculations. It calculates magnetic field on a grid in a 2-dimensional space. Permanent magnets, iron, currents and other anisotropic and isotropic materials can be defined by the user in several regions.

We have investigated 26 hexapoles with thicknesses H = 14 – 90 mm and the inner radii $r \in \langle 18,\ 24\rangle$ mm. Hexapole magnets are made of NdFeB with a remanence of 1.1 T and a coercivity of 800 kA/m. Each calculated hexapole consists of 24 trapezoidal segments where the angle of magnetization varies by $60^\circ$ from one segment to the next one. Fig. 1 shows cross section view of hexapolar structures.

Magnetic field of 0.87 T is generated by hexapole at the inner radius of hexapole $r_H = 24$ mm (H = 14 mm). This corresponds to a ratio of $\mathrm{B}_{max}/\mathrm{B}_{ECR} = 2.42$ at resonance magnetic field of $\mathrm{B}_{ECR} = 0.36$ T corresponding to a cyclotron frequency of 10 GHz.

The calculations were done in one segment that is 1/12 of the total hexapole in which both the mirror and the rotational symmetries are assumed. The boundary conditions were fixed. The results of the calculations are summarized in Figs. 2 to 7, which show magnetic field B inside a hexapole as a function of a cylindrical coordinate $r$. These values correspond to the different cylindrical coordinates $r_0^{min}$ at which is the magnetic field B = 0. It is possible to show by extrapolation of calculated values B and $r$ that $r_0^{min} \in \langle 12,\ 18.5\rangle$ mm.

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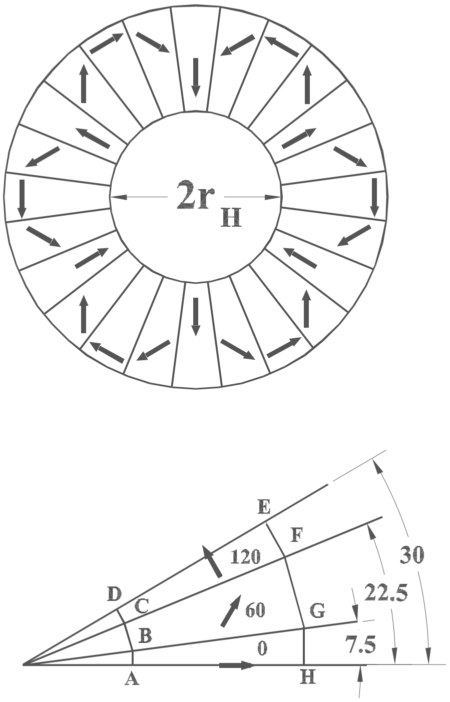

Figure 1: Cross section view of the hexapolar structures. Here, $r_H$ is radius and ABCDEFGH the characteristic segment of hexapole.

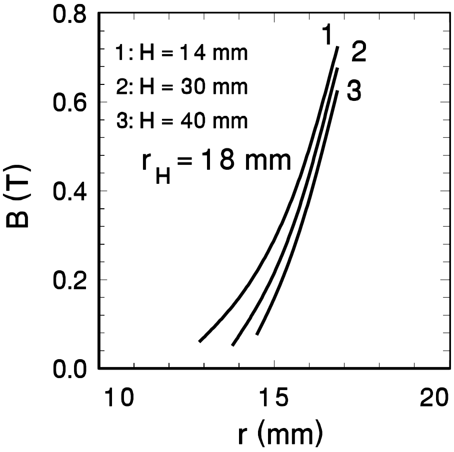

Figure 2: Magnetic field B inside hexapole of $B_{max} = 0.72$ T for H $= 14$ mm. Here, $r_H$, H and $r$ are inner radius, thickness and cylindrical coordinate of hexapole, respectively.

## 3 RESULTS

We have chosen the thicknesses of hexapoles H $= 14$, 30, 40, 50, 60 and 90 mm for our investigations. The calculations showed that differences ΔB between magnetic fields at the surfaces of hexapoles decrease with increas of the hexapole radius. An increas of magnetic field at the surface of hexapole was found to be $\Delta B = 0.1$, 0.06, and 0.01 T in the regions of $r_H \in \langle 18,\ 24\rangle$ mm, H $\in \langle 14,\ 40\rangle$ mm, and $\Delta B = 0.23$, 0.21, and 0.17 T in the regions of $r_H \in \langle 18,\ 24\rangle$ mm, H $\in \langle 50,\ 90\rangle$ mm, respectively. It has been confirmed that the suitable radius of hexapole for the ECR IS NANOGUN-10B can also be taken from the region $r_H \in \langle 18,\ 24\rangle$ mm.

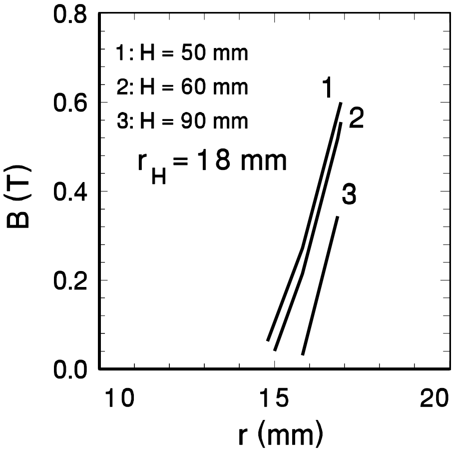

Figure 3: Magnetic field B inside hexapole of $B_{max} = 0.57$ T for H $= 50$ mm. Here, $r_H$, H and $r$ are inner radius, thickness and cylindrical coordinate of hexapole, respectively.

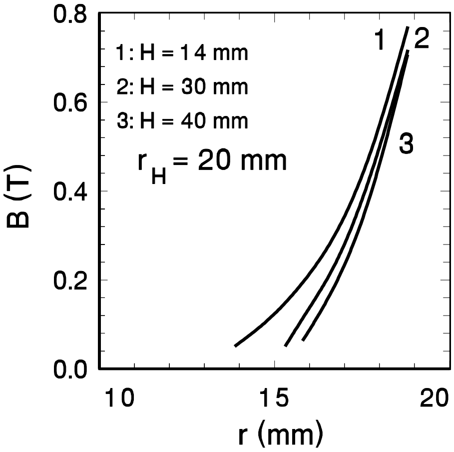

Figure 4: Magnetic field B inside hexapole of $B_{max} = 0.77$ T for H = 14 mm. Here, $r_H$, H and $r$ are inner radius, thickness and cylindrical coordinate of hexapole, respectively.

We have also shown that the higher is the thickness H the lower is the magnetic field B for the given coordinate $r$ and at given hexapole radius $r_H$. The magnetic field at the ECR IS plasma chamber surface is 0.45 T for hexapole of $r_H$ = 1.8 cm and for the plasma chamber thickness of 1.77 mm. It is also seen that the highest magnetic field B is for the least thickness H at given radius of hexapole $r_H$. It is also possible to show by extrapolation of calutated values that the magnetic field $B = 0$ is for the coordinates $r_0 \in \langle 12,\ 18.5\rangle$ mm.

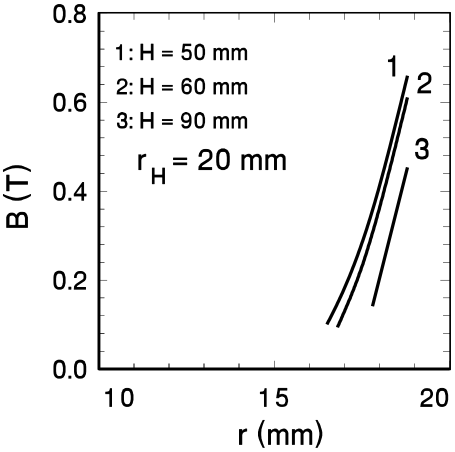

Figure 5: Magnetic field B inside hexapole of B$_{max}$ $=$ $0.66$ T for H $=$ $50$ mm. Here, $r_H$, H and $r$ are inner radius, thickness and cylindrical coordinate of hexapole, respectively.

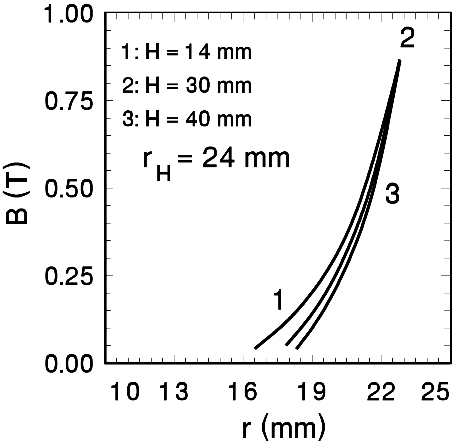

Figure 6: Magnetic field B inside hexapole of B$_{max}$ $=$ $0.87$ T for H $=$ $14$ mm. Here, $r_H$, H and $r$ are inner radius, thickness and cylindrical coordinate of hexapole, respectively.

## 4 CONCLUSIONS

This results complete permanent magnet technology for design of new small prototypes ECR IS. It would be possible to build very rapidly a new ECR IS and test it for production multicharged ions. By reduction of dimensions of ECR IS, it is possible to show that the plasma volume is not a critical parameter for source performances. We can build ECR IS with performances relatively similar to the classical one but for a total cost 5 to 10 times smaller.

The results obtained here show that the magnetic fields B$(r)$ inside hexapole with thicknesses of H $=$ $14$ to 90 mm have the highest value for the least hexapole thickness H at given radius $r_H$. On the other hand, the larger the radius of hexapole is the larger is the distance from the centre of hexapole to the point with the least magnetic field B $=$ $0$.

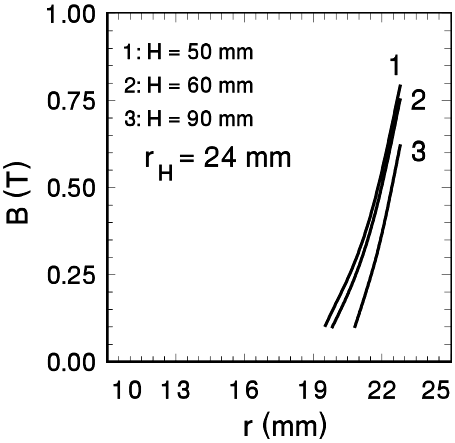

Figure 7: Magnetic field B inside hexapole of B$_{max}$ $=$ $0.8$ T for H $=$ $50$ mm. Here, $r_H$, H and $r$ are inner radius, thickness and cylindrical coordinate of hexapole, respectively.

According to our results, the thickness of hexapole H $=$ $1.4$ cm[3] for NANOGUN-10B is sufficient for all designed radii of hexapoles $r_H$.

## ACKNOWLEDGEMENTS

The authors wish to thank E. Běták for his understanding in this work and for his help concerning the language correction of the paper. They are also indebted to V. Matoušek and J. Zrubcová for helpful discussions. The work has been partially supported by VEGA grant No. 2/5122.

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