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# FOR ION SOURCE DECRIS

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# PERMANENT MAGNET HEXAPOLE FOR ION SOURCE DECRIS

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## I. INTRODUCTION

Electron Cyclotron Resonance Ion Sources (ECRIS) are now widely used for the production of high charge state ions [1]. Multicharged ions are produced in plasma with hot electrons and cold ions via electron impact ionization. Both electron heating by ECR and ion confinement depend strongly on the magnetic field distribution and take place in 3-dimensional "minimum B" magnetic trap. The "minimum B" magnetic field configuration is usually created by superposition of mirror axial magnetic field and hexapole field. For room temperature ECR ion sources, rare earth permanent magnets SmCo or NdFeB which have both high remanent field Br and intrinsic coercive force Hc is used to make hexapole. The value of the magnetic field on the hexapole surface must be at least more than that of the resonance field $B_{ec}$ for given microwave power frequency $\omega_{hf}$ ($B_{ec} = m\omega_{hf}/e$) to produce closed resonance surface for electron heating. But according to experimental results on the ion source CAPRICE [2] a hexapole field has to be maximized to improve an ion source performance. The following is the hexapole design for DECRIS (Dubna ECRIS) and results of magnetic field measurements.

## II. HEXAPOLE DESIGN

Constructions of hexapoles employed on different ECR ion sources are shown in Fig.1. The simplest construction which is used in many ECR sources

(Fig. 1a) consists of only 6 poles oriented to produce hexapolar field. This hexapole can be easily assembled or disassembled and allows the use of gaps between poles for hexapole cooling and vacuum pumping of discharge chamber. Unfortunately, there are two serious disadvantages in this simple construction:

- a total magnetic field in discharge region is nonuniform under constant radius and depends on azimuthal angle. So, for LBL ECR [3] the value of the magnetic field was 0.36 T on the pole and 0.26 T between poles. It leads to additional plasma losses on discharge chamber walls.

- the maximum value of hexapolar field is limited and doesn't usually exceed 0.4 T. The increase in hexapole thickness of more than 6 cm weakly influences on the field distribution because external magnets become situated far from the working area. For this reason the given hexapole construction only uses microwave power frequency up to 10 GHz.

To eliminate these disadvantages the magnetic flux concentration geometry was suggested [4]. Figure 1b shows cross section of the hexapole for MINIMAFIOS-16. The hexapole consists of 6 poles and additional permanent magnet pieces situated between poles with easy axis direction followed by magnetic force lines. This construction guarantees the same magnetic field value on poles and between poles and provides about 0.8 T for SmCo and 1 T for NdFeB magnets. Figure 1c



shows the hexapole for LBL AECR [5]. It produces a smaller magnetic field than the previous one but keeps advantages of the first construction. Gaps between poles can be used for vacuum pumping and investigations of source plasma.

The hexapole construction, the same that is usually used for permanent magnet lenses production [6], was chosen for our ECR ion source (Fig. 1d). The hexapole includes 12 identical NdFeB trapezoidal bars with corresponding easy axis directions. The hexapole has internal diameter of 7 cm defined by dimension of discharge chamber. A hexapole thickness must be sufficient enough to provide the needed magnetic field but minimize in order to decrease a weight and corresponding cost of hexapole. An increase of hexapole external diameter also significantly raises a power supply for solenoidal coils of ion source. Therefore to choose the hexapole thickness the magnetic field calculations for hexapole with different external diameters were carried out (Fig. 2). According to these calculations 6 cm thickness was used.

A radial and tangential components of the magnetic field in a multipole magnet can be expressed by Fourier series:

$$B_r(r,\theta)=\sum_{n=1}^{\infty} A_n r^{(n-1)}\sin(n\theta+\theta_n),$$

$$B_t(r,\theta)=\sum_{n=1}^{\infty} A_n r^{(n-1)}\sin(n\theta+\theta),$$

where $A_n$ is amplitude of harmonic with number n, r is radius and $\theta$ is azimuthal angle. For ideal hexapole only harmonics with numbers 3, 9, 15, 21 ... take place. In real hexapole many other harmonics are presented and when $A_3 >> A_n$ for all other n a total magnetic field is almost independent on azimuthal angle. According to [7], the two-dimensional field produced by a uniformly magnetized block can be described by equation:

$B(z_0)=\sum_{n=1}^{\infty} b_n \cdot z_0^{n-1}$, where $z = x + iy$. If easy axis direction $\beta$, remanent field $B_{rem}$, angle $\alpha$ or linear z position of some permanent magnet bar has small deviation from ideal case, undesirable harmonics appear: $\Delta b_n = \frac{\Delta B_{rem}}{B_{rem}} \cdot b_n$, $\Delta b_n = i \cdot \Delta\beta \cdot b_n$, $\Delta b_n = -n \cdot \Delta z \cdot b_{n+1}$,

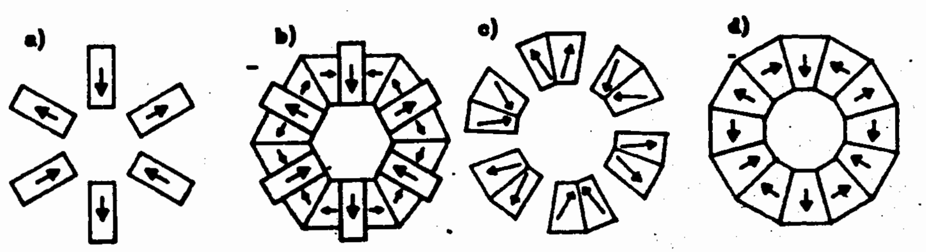
$\Delta b_n = -i \cdot n \cdot \Delta\alpha \cdot b_n$.

For this reason the careful control of magnetic characteristics and dimension precision for each magnet piece was needed.

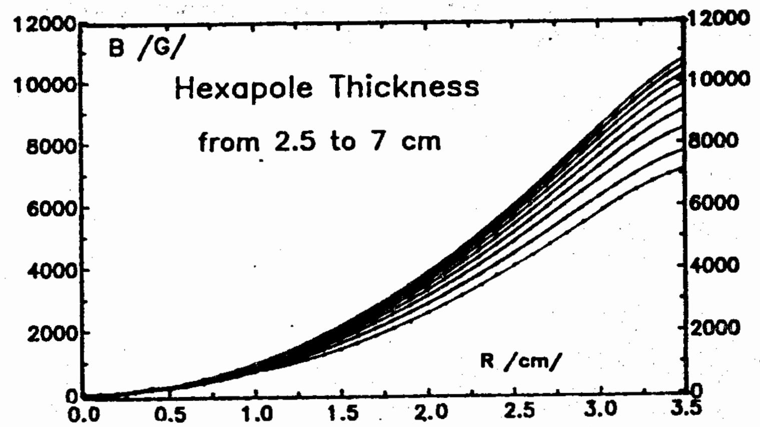
## III. THE HEXAPOLE PERFORMANCE

According to the source design the hexapole length is 35 cm. Because the maximum size of a permanent magnet piece is 5 cm it consists of 7 rings with a structure as in Fig. 1d. NdFeB with Br=1.05 T and Hcb=14000 kA•m was used to make 12 corresponding bars for each ring. At first 12 bars were connected to each other by a special compound and after all 7 rings were

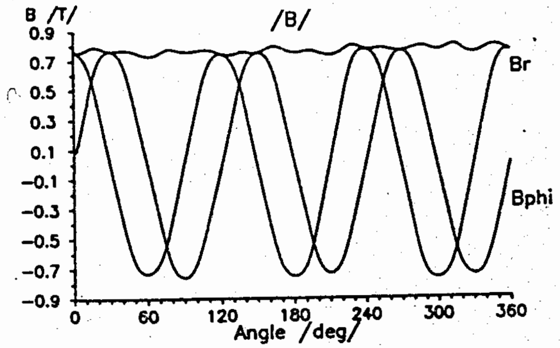




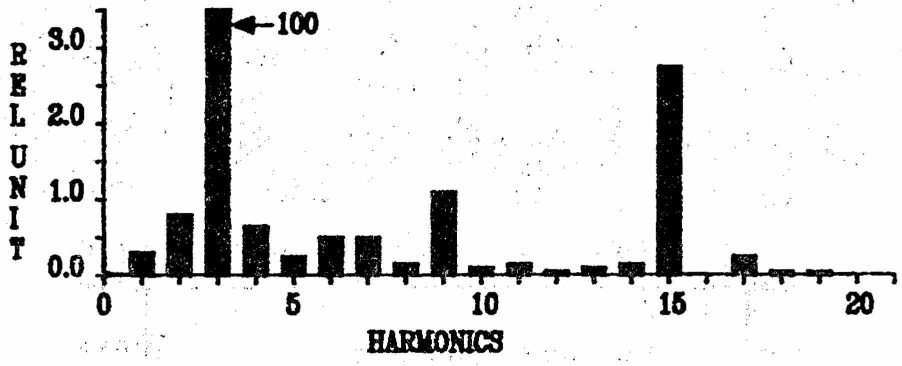

1. Hexapoles for different ECR ion sources.



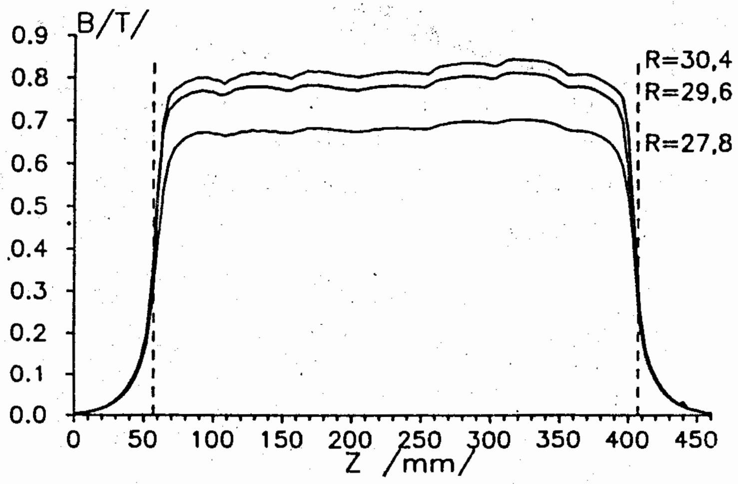

2. Calculated magnetic field distribution in front of pole for different thickness of hexapole. Internal radius 3.5 cm.




3. Measured radial $B_r$ and tangential $B_\theta$ components of the magnetic field and total field B in mid plane of the hexapole.




4. Fourier transformation of the measured magnetic field.




5. Magnetic field distribution in front of pole along the hexapole axis on different radii.



prepared they were coupled the same way to produce whole hexapole. The result is that the hexapole represents one whole body without any additional supporting arrangement. The use of NdFeB material is subjected to problems dealing with their extreme sensitivity to corrosion. To protect a material, the hexapole was surrounded by thin stainless steel screen and the spaces were filled up by the same compound which was used for bars coupling. Therefore NdFeB magnets do not have any interaction with air or cooling water.

For the magnetic field investigation of the hexapole, automatical measurement system driven by PC was used [8]. Results of measurements $B_r$ and $B_\theta$ component of hexapolar field and total field $B = (B_r^2+B_\theta^2)^{1/2}$ in the hexapole middle plane are presented in Fig. 3. The total magnetic field has a scattering of less than 2% on the given radius. Figure 4 shows the Fourier transformation for one component of the measured field. The amplitude of the main harmonic $A_3$ was assumed to be 100 arbitrary units and amplitudes of each undesirable harmonic are less than 1 in this case. For this reason they exert insignificant influence on field distribution. Radial field component measured in front of the pole along the hexapole axis on different radii is presented in Fig.5. For high radii it is possible to observe small field falls situated between different rings, but at less radii field distribution becomes smooth. After these measurements the magnetic field value on the hexapole surface was estimated in range of 1.05-1.1 T.

## IV. CONCLUSION

The hexapole for ion source DECRIS described above has two main features:

- it consist of 12 identically shaped permanent magnet bars to create magnetic flux concentration geometry;
- all magnet pieces are coupled by special compound without additional supporting arrangement. It has a reliable protection against corrosion.

Using a permanent magnets with middle characteristics, the more than 1 T magnetic field was obtained on the hexapole surface.

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Гексаполь из постоянных магнитов для источника многозарядных ионов DECRIS


Для источника многозарядных ионов DECRIS-14 разработан и изготовлен гексаполь из постоянных магнитов типа NdFeB. Гексаполь имеет внутренний диаметр 7 см и внешний диаметр 19 см. На основании проведенных измерений магнитного поля в рабочей области можно заключить, что величина магнитной индукции на поверхности полюса гексаполя составляет 1,05 — 1,1 Т.

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Перевод авторов


Efremov A. et al. E9-92-495


Permanent Magnet Hexapole for Ion Source DECRIS


The hexapole design for ECR - type ion source DECRIS-14 and results of magnetic field measurements are presented. NdFeB permanent magnets were used to produce hexapole. It has internal diameter 7 cm and external diameter 19 cm. According to measurements the value of magnetic induction on the pole surface is about 1.05 — 1.1 T.

The investigation has been performed at the Laboratory of Nuclear Reactions, JINR.



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