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# DESIGN OF A NEW 10 GHz ECRIS WITH A HEXAPOLE OF CONTINUOUS EASY AXIS ORIENTATION

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# 1 Introduction

Development of Electron Cyclotron Resonance Ion Sources has grown a great deal in the last decades. Because of the desirable characteristics of ECR sources including high charge state production, high intensity, stability, wide range of ion species, relatively longevity and ease of operation, the sources have found application in heavy ion cyclotrons, heavy ion linacs, synchrotrons, storage rings, radioactive beam facility, atomic physics, and ion implanters. The other application is being planned and being developed. Although the number of ECR sources used for the production of high charge state ions continues to expand with more than 40 now in operation[1], there are still so many laboratories from different areas all over the world who are anxious to be waiting for the use of ECR sources. It is the relatively high price of ECR source that prevents them from using it. Particularly, the ECR sources for the production of high beam current and high charge state are expensive for most of groups. The main cost of such ECR source comes from expensive hexapole with high enough magnetic field on the wall, rf generator with high frequency and enough output power, high electric power consumption, and expensive insulator with complicated structure. It would be exciting and promising for the application of the ECRIS if we could provide a source with relatively low costs and good performances. A new hexapole with continuous easy axis orientation and a small 10GHz rf generator with relatively low price in Russia make such thing to be possible.

# 2 General Description of the Source Design

## 2.1 Source Structure

Figure.1 illustrates the design of this source. The main parameters are listed in Table 1.

This source shares many common features with other ECRIS, such as plasma chamber with double wall for cooling, 6.5 cm in diameter, 16 cm in length; the coaxial line for the rf coupling and gas feeding; the cone-shape ring around the first stage used for raising the axial magnetic field peak and defining the peak position; the two solenoids shielded by iron rings; the iron ring between the two solenoids dedicated to the reduction of the axial field in the center to achieve a required mirror ratio.

What is more important about this source is that it is equipped with a new hexapole and a very simple insulator. As shown in Fig.1, two different extraction systems corresponding to two different magnetic field configurations are employed. On the other hand, the magnetic coils, the double plasma chamber and the other elements in the beam line will share with the same cooling system. In this case, the cooling water pressure should be very low, and the detailed calculations for the cooling water pressure is essential.

## 2.2 Hexapole with Continuous Easy Axis Orientation

In most of ECR sources hexapole is used to confine the plasma radially. Generally speaking, the thickness of hexapole is very important to the magnetic field configuration and electric power consumption. One wants to make the hexapole as thin as possible in order to leave more space for the magnetic coils. In recent years, although various constructions of hexapole were employed

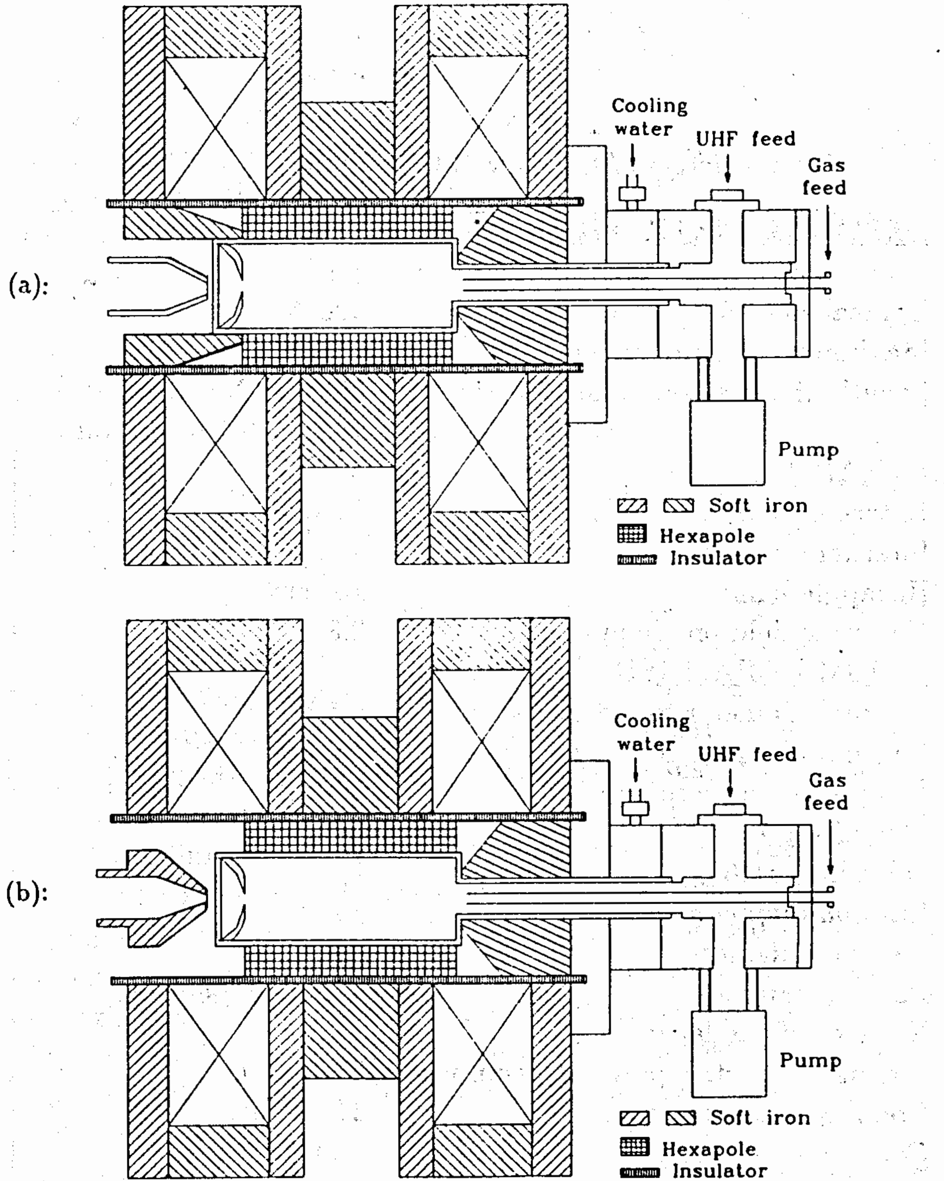

Figure 1: The source structure. (a): Without iron puller. (b): With iron puller.

TABLE 1

Parameters of the New 10GHz ECRIS

| | |
|---|---|
| AXIAL MAGNETIC FIELD | |
| Peak on axis | 1.2 T |
| Typical solenoid current | 900 A |
| Maximum solenoid current | 950 A |
| Length of the second stage mirror | 15.5 cm No iron puller |
| | 18. cm With iron puller |
| HEXAPOLE | |
| External diameter | 12. cm |
| Internal diameter | 7. cm |
| Hexapole length | 16. cm |
| Hexapole field on chamber wall | 0.8 T |
| PLASMA CHAMBER | |
| Internal diameter for second stage | 6.5 cm |
| Internal diameter for first stage | 2.5 cm |
| Length for the second stage | 16. cm |
| SOLENOID | |
| Solenoid number | 2 |
| Internal diameter | 13. cm |
| External diameter | 34. cm |
| Pancake number | 4 Double pancake |
| Number of the layers | 11 |
| Maximum electric power consumption | 40 Kw |
| Cooling water flow rate | 11. l/min |
| Cooling water pressure | 4 atm |
| Length of the wire for two solenoids | 130 m |

by different ECR sources, it turns out that Halbatch construction has been adopted in more and more ECR sources. The hexapole with a Halbatch construction[2] consists of $M$ geometrically identical pieces. The structure is invariant to rotation by the angle $2\pi/M$. Throughout each piece, the easy axis points in the same direction, but that direction advances by $8\pi/M$ from one piece to the next. The hexapole component of the magnetic field within the aperture ($r \leq r_1$) is given analytically as :

$$| B | = \frac{3}{2} B_r (\frac{r}{r_1})^2 [1 - (\frac{r_1}{r_2})^2] K \qquad (1)$$

where $K = \cos^3(\varepsilon\pi/M) \frac{\sin(3\pi\varepsilon/M)}{3\pi/M}$, $r_1$ and $r_2$ is internal and external radius of the hexapole respectively. $\varepsilon$ is volume filling factor, $B_r$ is the remanent field of the material.

Eventhough the Halbatch construction both maximizes the strength of hexapole component and minimizes all the other components in comparison with other hexopole constructions for a given amount of hexapole materials, such construction causes a loss of magnetic field within the aperture because it is formed by segmented pieces and the easy axis orientation is not continuous. It is also difficult to get a maximum exploitation of the magnetic material for such construction. In order to produce strong fields of high quality, one wishes the number of segmented pieces is as much as possible, with $M/3 \geq 8$ easy axis orientation per period being a good guide number[2]. On the other hand, the segmented pieces should be placed, with the largest possible volume filling factor, as closely as possible to the "business" region, and the easy axis throughout each piece should point precisely to the desired direction. All of them add the difficulties for machining and cause a high price.

In fact, an ideal hexapole should be with continuous easy axis orientation. That is an upper limit for $M \rightarrow \infty$ in formula (1). Halbach construction is just a reasonable approximation to such ideal hexapole. The magnetic field within the aperture is:

$$|B| = \frac{3}{2}B_r\left(\frac{r}{r_1}\right)^2\left[1-\left(\frac{r_1}{r_2}\right)^2\right] \tag{2}$$

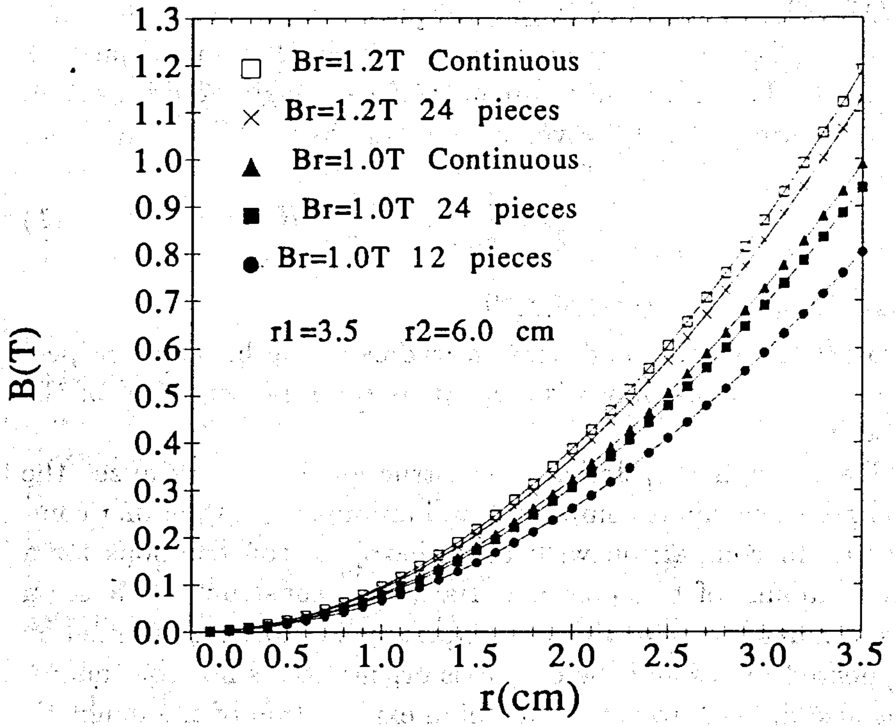

Figure 2: The radial magnetic field for the hexapole with continuous easy axis orientation and the hexapole with Halbatch construction consisting of 12 and 24 pieces.

In comparison with Halbatch construction, the same size hexapole with continuous easy axis orientation can produce stronger field. In other words, the same magnetic field on the wall can be available by a smaller hexapole. Fig.2 shows the radial magnetic field for the hexapole with continuous easy axis orientation and the hexapole with Halbatch construction consisting of 12 and 24 pieces, the internal and external diameter for both of them being 7.0 *cm* and 12.0 *cm* respectively. Such hexapole overcomes those disadvantages of the Halbatch construction. It is obvious that there is more space to leave for magnetic coils if an ECR source is equipped with such hexapole. The technology to produce such hexapole with external diameter up to 12.0 *cm* has already matured in Russia. The price is much more less than that of the usual segmented hexapole.

Considering the costs, the compact structure, the radial confinement to the plasma, and the restraint to the interference between the coils and the hexapole[3], we make the hexapole to be with the same length as the chamber and just beyond the mirror in the second field configuration. That is 7.0 *cm* in internal diameter, 12.0 *cm* in external diameter, and 16.0 *cm* in length.

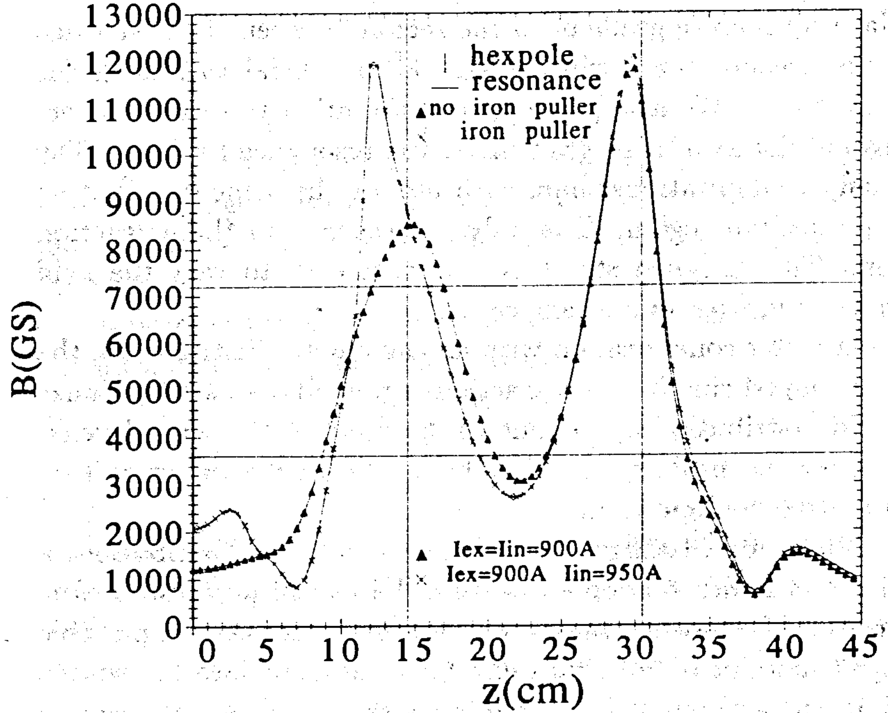

Figure 3: The axial magnetic field distribution.

## 2.3 Configuration of the Axial Magnetic Field

In the design of this source, a particular emphasis has been laid on the optimization of the axial magnetic field configuration, shown in Fig.3 . We have to get a compromise among the reasonable magnetic field configuration, the minimum electric power consumption and the minimum size of the source body. It is very important to optimize the coil arrangement (pancakes and turns) and the relative position of the coils in order to minimize the magnetized volume. The exciting results from the last version of CAPRICE[4] and GANIL ECR4[5] remind us to test two different axial magnetic field configuration. The both field configurations have a higher magnetic field peak (1.2 $T$) near the first stage and a relatively intense gradient in the region between the first stage and the second stage, which might be beneficial to raising the beam current. We also pay a special attention to increasing deliberately the axial field gradient at the resonance position. The two field configurations share with almost the same distribution in the injection region. The only difference is in the extraction region. The designed structure makes it easy to vary the field configuration from one to another.

In the first configuration with an asymmetry distribution, the special shaped ring in the extraction region allows us to optimize the field distribution and define the position of the second peak. The mirror is inside of the chamber. A stainless puller will be used in such configuration.

In the second configuration with a symmetry distribution, a special iron puller is adopted to raise the second peak and define its position. Meanwhile the use of the iron puller makes it possible to inject amount of backward energetic electrons into the source through the extraction hole. These electrons entering the source as a beam of high energy might substantially contribute to the formation of the multicharged ions, and this effect is enhanced by the high magnetic field on the injection side[6]. Such symmetrical magnetic structure might make the source to generate two closed ECR layers. All of these are supposed to be good for the production of high charge state ions. The magnetic peak on the extraction side in such field configuration is around the extraction hole.

## 2.4 Calculation of Cooling Water Pressure for the Coils and the Plasma Chamber

### 2.4.1 Cooling Water Pressure for Coils

The power dissipated in the coils may be expressed as the integral on all the coils :

$$P = \int r d\theta ds \frac{j^2}{\sigma f} \qquad (3)$$

where $ds = drdz$ is the coil section element. $j$ is the wire current density averaged on the copper conductor, the cooling water hole and the insulator. $\sigma$ is the wire conductivity and $f$ is packing factor.

In practice,we often use a uniform current distribution. Then the formula (3) may be simplified as:

$$P = \frac{\pi(r_{in} + r_{ex})N}{\sigma s} I^2 \qquad (4)$$

where $r_{in}$ and $r_{ex}$ is internal and external radius of the coils respectively. $N$ is the total turns. $s$ is the area of the wire section conductor, and $I$ is the electric current.

We assume that the cooling water can absorb all of heat produced by those coils. Then the flow rate of cooling water is given by:

$$V_f = \frac{14.4P}{\Delta T} \qquad (5)$$

where $V_f$ is the flow rate of cooling water ($l/min$). $P$ is electric power ($kw$). $\Delta T$ is the water temperature difference cooled from minimum to maximum (*centigrade*).

The water pressure can be calculated from the Darcy-Weisbach equation[7]:

$$\Delta P = \frac{\rho f L V^2}{2Dg} \tag{6}$$

where $\Delta P$ = water pressure
$L$ =length of the wire pipe
$D$ =internal diameter of the wire pipe
$V$ =flow velocity, $V = \frac{4V_f}{\pi D^2}$
$g$ =gravitational constant
$f$ =friction factor, for turbulent flow, f is calculated from Colebrook equation:

$$\frac{1}{\sqrt{f}} = -2log_{10}(\frac{\varepsilon}{3.7D} + \frac{2.51}{R\sqrt{f}}) \tag{7}$$

where $R$ = Reynolds number $\frac{VD}{\nu}$
$\nu$=Kinematic Viscosity
$\varepsilon$=absolute roughness, here the unit of $\varepsilon$, and $D$ is feet.

After optimization of the coils, we decided to use two solenoids. Each solenoid consists of 4 double pancakes with 11 layers of 5.0 $mm$ hollow-core copper wire. With such coils and our field configuration, the maximum power consumption is about 40 $Kw$ for the axial magnetic field peak 1.2 $T$. The water flow rate is 11 $l/min$ (30°$C$ cooling water difference). The cooling water pressure is less than 4 $atm$.

### 2.4.2 Cooling Water Pressure for the Plasma Chamber

In our new source, the cooling for the hexapole is realized by a double wall of plasma chamber in order to avoid corrosion

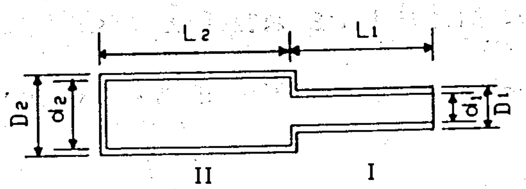

Figure 4: The model of the double wall chamber.

problems. So the cooling water is running around the double wall chamber and the water is never in contact with the hexapole. In such case, the evaluation of the cooling water pressure for the double wall chamber is essential.

We can assume a simple model of the double wall chamber for the calculation convenience, shown in Fig.4. We suppose it could be divided into two part, one half for the cooling water flowing in, and the other half for the water flowing out. If we neglect the losses due to sudden expansions from part $I$ to part $II$ and sudden contractions from part $II$ to part $I$, the water pressure for the double wall chamber can be calculated as following:

$$\Delta P_{wall} = \frac{4\rho f V_f^2}{\pi g}(\frac{L_1}{D_{eq_1}^3} + \frac{L_2}{D_{eq_2}^3}) \tag{8}$$

where $\rho, f, V_f, g$ have the same meaning as those in eq.(6). $L_1$ and $L_2$ are the length of the double wall chamber in the first stage $I$ and the second stage $II$ respectively. $D_{eq_1}$ and $D_{eq_2}$ are the equivalent diameter corresponding to $I$ and $II$ . The equivalent diameter is equal to four times the hydraulic radius[7].

$$D_{eq_1} = \frac{\pi(D_1^2-d_1^2)}{\pi(D_1+d_1)+2(D_1-d_1)} \qquad D_{eq_2} = \frac{\pi(D_2^2-d_2^2)}{\pi(D_2+d_2)+2(D_2-d_2)}$$

If we assume the main quantity of heat in the chamber comes from the rf power (maximum 800 $W$), according to our calculation, the cooling water pressure for our double wall chamber is less than 1.0 $atm$. So the double wall chamber can share with the same cooling system as those magnetic coils.

# 3 Characteristics and Prospects

We conclude the characteristics of this new 10 GHz ECRIS as following:

- Equipped with a new hexapole with continuous easy axis orientation. Thickness is only 25 *mm*, and the price is lower.
- A simple, flexible and compact structure .
- Lower electric power consumption.
- Lower cooling water pressure .
- Higher axial magnetic field peak.
- Operated with two different magnetic field configurations.
- Small and simple insulator, maybe available in commercial shop.
- Small and cheap rf generator.
- The price of the whole source maybe lower several times than the usual one.

Table 2

Parameter Comparison with CAPRICE and GANIL ECR4

| | $f_{ecr}$ GHz | $\phi_{int}$ cm | $L_{mir}$ cm | $B_{rwall}$ T | $B_{zmax}$ T | $P_{elec}$ Kw | W× H[a] cm × cm |
|---|---|---|---|---|---|---|---|
| CAPRICE[8] | 10 | 6.6 | 16(19)[b] | 0.8 | 1.1 | 70 | 38×65 |
| ECR4[8] | 14.5 | 6.6 | 16 | 0.9 | 1.1 | 50 | 40×40 |
| DECRIS-10[c] | 10 | 6.5 | 15.5(18)[b] | 0.8 | 1.2 | 40 | 34×43 |

*a*: *W* and *H* is width and height of ECRIS respectively
*b* : The symmetry field configuration with iron puller
*c* : The designed new ECRIS

The parameter comparison with CAPRICE and GANIL ECR4 is shown in Table 2. In view of those characteristics, it is promising and exciting to make such source into a commercial one. We are confident that it will have a good performance in the ion production of high intensity and high charge state.

In addition, the production of radioactive beams presents a world-wide interests for nuclear physics, and it is also very interesting to FLNR and other accelerator facilities. The ion source for the production of such radioactive beams should fulfill the following requirements: high ionization efficiency; short delay time; stable operation and long life time. Generally, radioactive elements are produced in very small amounts, so in order to transform them into ions the gas efficiency of the source is the most important parameter. It has turned out that ECR source is the only one[8] to produce good efficiency ions from *N* to noble gases. It is also clear that the trend of using ECR source to produce radioactive ions with heavy ion primary beams has been increasing. Up to now so many ECR sources have been put into operation for the production of radioactive beams, such as Louvain-la-Neuve ECRIS in Belgium[9], TISOL ECRIS at TRIUMF[10], NANOGAN ECRIS at GANIL[8], and so on. We have also observed that it is possible to use ECR source for the production of radioactive beams with high charge state corresponding to a suitable $Q/M$ value for post acceleration in cyclotrons

Due to the simple and flexible structure of our new ECR source, it is easy to change it into a source for the production of radioactive beams. So we think our new ECRIS will not only be used for the ion production of high intensity and high charge state, but also possible used for the production of radioactive beams after a little modification.

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**Разработка ионного источника ЭЦР-10 ГГц
с гексаполем новой конструкции**

Разработан новый ЭЦР-источник интенсивных пучков многозарядных ионов с частотой накачки 10 ГГц. Основной задачей при создании проекта явилась разработка простого дешевого источника с гибкой магнитной структурой. В источнике используется новая конструкция гексаполя с непрерывным изменением оси легкого намагничивания, что позволяет создать компактную магнитную систему с относительно низким потреблением энергии (менее 40 кВт) и давлением охлаждающей жидкости. Кроме того, для СВЧ-накачки источника предполагается использовать компактный дешевый генератор с выходной мощностью до 800 Вт. В результате проведенной оптимизации удалось получить необходимое аксиальное распределение магнитного поля с величиной в максимуме до 1,2 Т при двух различных конструкциях в районе экстракции. Приводится сравнение параметров источника с аналогичными — для источников CAPRICE и GANIL ECR4. Приводится методика расчета системы охлаждения катушек и ионизационной камеры, а также рассмотрены возможные области применения данного источника.

Работа выполнена в Лаборатории ядерных реакций ОИЯИ.

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Efremov A., Kutner V., Zhao Hongwei E9-93-441

**Design of a New 10 GHz ECRIS with a Hexapole
of Continuous Easy Axis Orientation**

A new 10 GHz ECR ion source for the ion production of high intensity and high charge state is planning to build at FLNR. The main point about the design of this source is that we try to get a very simple and cheap ECR source with a flexible structure which could be variable during operation according to different purposes. This source will be equipped with a new hexapole with continuous easy axis orientation. Because of such new hexapole, this source is very compact with a simple structure, lower electric power consumption (less than 40 kw), lower cooling pressure, and relatively low price. In addition, a very compact and cheap UHF generator with an output power 800 W will be used in this source. An intense axial magnetic field up to 1.2 T and a needed field distribution are got by a fine optimization. Two different field configurations with and without iron puller will be tested. The designed structure makes it easy to change field configuration from one to another. The comparison with CAPRICE and GANIL ECR4 are described. The detailed calculations of cooling water pressure for the solenoids and the double wall chamber are presented, and at last the features and prospects for the application of this source are reviewed.

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

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