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COMMUNICATIONS

DESIGN OF THE NANOGUN–10B ECR ION SOURCE

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The design of 10 GHz ECR ion source NANOGUN-10B for the electrostatic accelerator EA-300 is described. The ion source is based on permanent magnets FeNdB. Remarkable features of the source are as follows: i) original ECR zone, ii) the basic hexapole and magnetic structure producing axial field are made by permanent magnets, iii) the microwave port is placed above the plasma chamber, iv) the microwave frequency will be variable from 8 to 18 GHz. The outer size of the hot plasma chamber is designed to be $\phi\,36\,\mathrm{mm} \times 80\,\mathrm{mm}$. Total weight of the magnetic structure is about 36 kg.

Keywords: ECR ion source, FeNdB permanent magnet, hexapol, axial magnetic field

1 INTRODUCTION

The ECR ion source (IS) NANOGUN-10B is an ion source designed for the production of monoenergetic ion beams dedicated not only for applications in nuclear physics but also to specific surface treatments and modification of materials. The basic structure of the ECRIS has been developed by R. Geller and his collaborators at Grenoble [1] and at Caen [2]. Based on their works, we have designed a very compact 10 GHz ECRIS in order to extend the beam energy of the 300 kV electrostatic accelerator EA-300 at Bratislava [3–4]. To install the ion source at the high-voltage terminal where the available space and electric power feeding are limited, the magnetic field is formed only by permanent magnets (FeNdB) and a UHF power up to 200 W is supplied by a tunable power supply. The permanent magnet measures are: 15.7 cm length, and 3.6 cm and 20 cm in inner and outer diameters, respectively. The maximum mirror field is 0.8 T and the mirror ratio $M = 2.7$ ($M = B_{\max}/B_{\min}$).

Ions will be accelerated by a 300 kV electrostatic accelerator EA-300 in order to generate around 1 MeV ion energy. Such energy is still attractive for improvement studies of a deep region of new materials. To improve these situations, we are developing this mini-ECR ion source, mainly for the production of heavy ions with charges from 2+ to 4+. The ion source will produce heavy ion beams in an energy range of 0.3–1.2 MeV from gases as N_2, O_2, Ne, Ar, Kr and Xe in the first phase. This type of the ion source will also be possible to use for on line ionization of radioactive atoms [2].

2 PRINCIPLE OF ECR ION SOURCES

The layout of an ECRIS is shown in Fig. 1. There are shown the main components of the ion source. Every ECRIS is equipped with radial and axial minimum magnetic field B. The radial magnetic multipole is usually a hexapolar one made of permanent magnets. The plasma of the ECRIS is kept together by the magnetic field inside a magnetic bottle. The field consists of a longitudinal one, made by coils or permanent magnets and a transversal one, made by the hexapole, which is usually compound from FeNdB permanent magnets. The magnetic bottle is the region surrounded by a closed surface of a constant magnetic field B. The magnetic field inside the plasma region is lower than that on the surface of the magnetic bottle. The stronger the magnetic field inside the magnetic bottle, the higher the frequency of the resonance electrons. Hence, we can obtain a higher plasma density, which results in larger ionization possibility.

The electrons in the ECRIS plasma are heated by interacting with waves at cyclotron resonance on one of the closed $|B|$ surfaces of such a magnetic configuration, where the equal $|B|_{ECR}$ surface is defined by $\omega_c = e|B|_{ECR}/m_e = \omega_f$, where B is the magnetic field in the region where plasma is kept, e the charge of the electron, m_e the mass of the electron and ω_f ($\omega_f = 2\pi f$) the microwave frequency matching the electron cyclotron frequency ω_c ($\omega_c = 2\pi f_c$). For $f_c = 10$ GHz we need $|B|_{ECR} = 0.36$ T and $|B|_{ECR} = 0.5$ T for $f_c = 14$ GHz. The extracted ion currents at one end of the device are actually the ion losses of the trapped plasma. Several comprehensive references about ECRIS have been published [5–7]. Theoretical and experimental studies of electrons in the ECRIS plasma can be found in [8].

Basically an ECRIS has the property of confining hot electron plasma, and its main components are: i) a magnetic configuration, *ie* a plasma container, ii) a UHF power input, *ie* a source of energy that heats up and sustains the plasma electrons in a magnetic trap, iii) internal (ionization) and external sources of electrons, which al-

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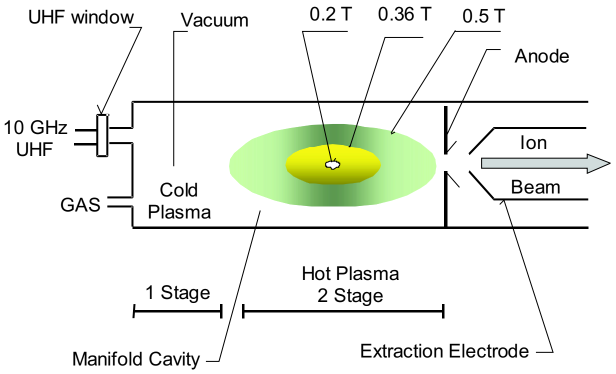

Fig. 1. Layout of an ECR ion source.

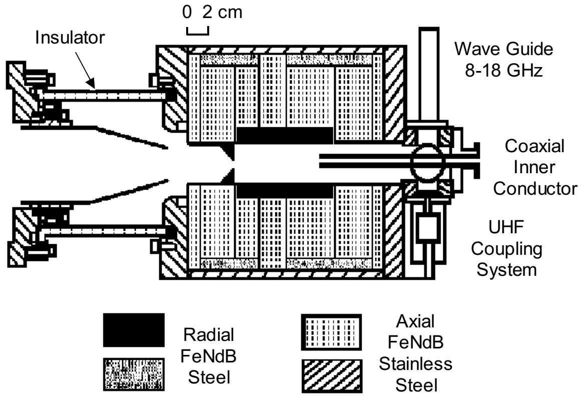

Fig. 2. Sections of the NANOGUN-10B.

low electron density to be built up, iv) injected gases or metals, *ie* the fuel injected in order to compensate the loss and to control the neutral pressure.

The maximum ion beam current extracted from an ECRIS is given by the following scaling law [9]: $(I_q)_{\max} \sim B^2 sL$, where $(I_q)_{\max}$ is the maximum current of the ions of charge state q, B the resonance magnetic field, s the extraction area and L the plasma length, which determines the main plasma volume. The scaling low indicates that the magnetic structure should be designed to form strong B with long L. According to this concept, the configuration of the NANOGUN-10B magnetic structure has been designed.

3 PHYSICAL AND TECHNICAL CHARACTERISTICS OF THE NANOGUN–10B

The NANOGUN-10B (see Fig. 2) is a small 10 GHz ion source equipped with radial and axial minimum B magnetic fields. The full magnetic structure is made of permanent magnets, which saves cooling and electric power consumption. The radial magnetic multipole is hexapolar and is made of permanent magnets FeNdB. Using the technology of permanent magnets the magnetic structure for the multiply-charged ion production was optimized at the room temperature. The body of the source is reduced to an outer diameter of 200 mm, the plasma chamber has diameter 36 mm and length 80 mm. A multipolar permanent magnet of ϕ 64 mm outer diameter forms the radial field around this plasma chamber. The UHF coupling is designed to connect a rectangular to co-axial wave-guide transition, where the inner conductor can be a ϕ 6–8 mm copper tube. This tube will be also used for gas injection. The introduction of the micro-oven on the axis of the source could also be possible [2].

The plasma electrode is placed at the maximum of the magnetic mirror field and can be made of an 8 mm extraction hole. The extraction electrode will be a conic one with the Pierce angle of 22.5°. The extraction gap will be adjusted. The extraction geometry is designed according to T.S. Green [10]. In our case, the ratio $S = a/d = 4/52$ and the saturated ion current density J_s, which can be extracted from a plasma boundary is:

$$J_s = n_i e \sqrt{\frac{kT_e}{M}} \,. \tag{1}$$

The corresponding perveance P is:

$$P = \frac{I}{U^{3/2}} \sqrt{\frac{M}{q}} = P_0 \big(1 - 1.6 \frac{d}{r_c}\big) \tag{2}$$

$$P_0 = 1.72 \times 10^{-7} \Big(\frac{a}{d}\Big)^2 \,, \tag{3}$$

where n_i is the density of ions, e the electron charge, k the Boltzmann constant, T_e the temperature of electrons, P_0 the perveance for plane parallel electrodes, M and q are the ion mass and charge, d the extraction gap, r_c the radius of plasma curvature, a the radius of aperture in the anode, U the extraction voltage and I the extracted current: $I = \pi a^2 J_s$.

In a more general case the equation

$$P_0 = \pi \frac{4\epsilon_0}{9} \sqrt{\frac{2qe}{M}} \Big(\frac{a}{d}\Big)^2 \tag{4}$$

is used for the parallel plate extraction or for protons $(q = 1)$

$$P_0^p = 1.71 \times 10^{-7} \Big(\frac{a}{d}\Big)^2 \,, \tag{5}$$

where ϵ_0 is the dielectric constant of vacuum.

We have considered the current flow from a small circular area of a spherical surface for a curved plasma boundary. This gives a perveance of

$$P = P_0 \left[1 - 1.6 \frac{\Theta}{S}\right] = P_0 [1 - 20.8\Theta] \,, \tag{6}$$

here Θ is the convergence angle toward the extraction electrode. It is also possible to show that the convergence

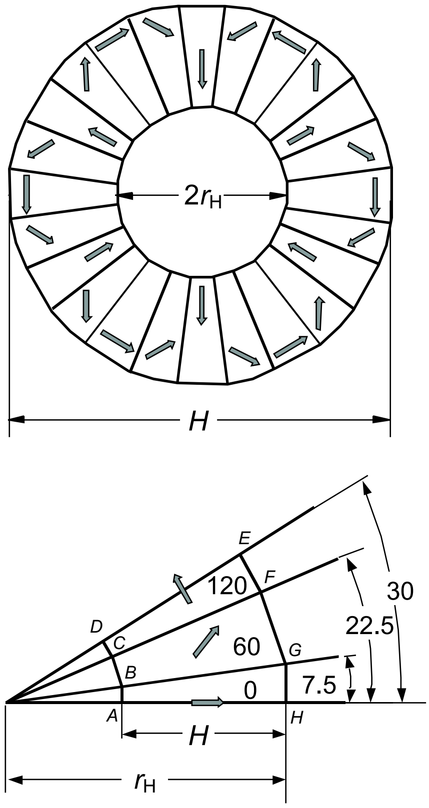

Fig. 3. Cross section of the hexapolar structure of the NANOGUN-10B ion source. Here, r_H is the radius, H the thickness, $2r_H = d_H$ the inner diameter, D_H the external diameter of the hexapole and ABCDEFGH is a characteristic segment of the hexapole.

or divergence of the extracted beam (Θ) for the circular curvature is

$$\Theta \simeq 0.625 S \Big(1 - \frac{P}{P_0}\Big) \ \text{rad}\,. \tag{7}$$

Taking into account the lens effect of the extractor, the resulting beam divergence ω is given by [11]

$$\omega = 0.29 S \Big(1 - 2.14 \frac{P}{P_0}\Big) \ \text{rad}\,. \tag{8}$$

By using equations (7–8) one can further obtain that $\omega = 0$ for $P = 0.47 P_0$, and $\Theta \simeq 0.33\,\text{rad}$ for $S \simeq 1$, $\omega = 0$, what is the optimum value for beam transmission. In practice, however, the divergence can never drop down to zero. In our conditions, where the extraction gap is $d = 52$ mm and the hole inside the extraction electrode is 25 mm, the resulting angle $\Theta = 1.5°$ can be obtained. Then the beam would have converge.

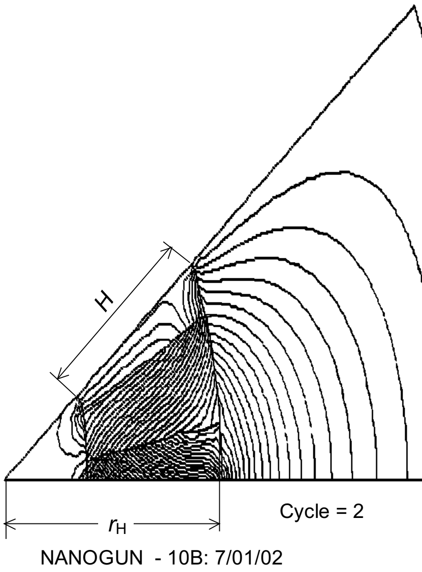

Fig. 4. Calculated magnetic flux lines inside the hexapole. The radius r_H, the length l_H and the thickness H of the hexapole are: $r_H = 1.8$ cm, $l_H = 7.5$ cm and $H = 1.4$ cm, respectively.

Figure 3 shows the cross section of hexapolar structure of the NANOGUN-10B. We have chosen the thickness of the hexapole $H = 1.4$ cm (see also Fig. 2). In order to find the maximum of the magnetic field $B_{\max}$, the region of $r_H \in \langle 1.3, 6\rangle$ cm has been investigated. It was shown that suitable radius of the hexapole can be from the region $r_H \in \langle 1.7, 3.2\rangle$ cm. It was also shown that the magnetic field at the plasma surface of the NANOGUN-10B is 0.45 T ($r_H = 1.8$ cm). It is assumed that the plasma chamber will be constructed using a non-magnetic stainless steel tube 1.77 mm thick [12].

The FeNdB with a remanence field of 1.1 T and a coercivity of 800 kA/m has been used in our calculations. The calculated hexapole consists of 24 trapezoidal segments, where the angle of magnetization varies by 60° from one segment to the next one.

The magnetic field inside the hexapole is shown in Fig. 4. The PANDIRA two-dimensional magnetic field code has been used to calculate the magnetic flux lines inside the hexapole. A detailed description of the hexapole geometry can be found in [13].

The magnetic structure of the NANOGUN-10B is formed by the superposition of the hexapolar field and the mirror field. The higher is the hexapolar field, the stronger is the confinement of the plasma in the radial direction.

A well-known rule of plasma physics says that the higher is the mirror ratio $M (M = B_{\max}/B_{\min})$ of a magnetic structure, the smaller is the number of particles lost from the confined plasma. In the NANOGUN-10B, the values are (see Fig. 5): $M = 2.7$, $B_{\max}/B_{ECR} = 2.2$, $B_{\max} = 0.8$ T, $B_{\min} = 0.29$ T and $B_{ECR} = 0.36$ T.

The axial magnetic mirror field is also designed with FeNdB permanent magnets instead of solenoidal coils. The shape of the axial magnetic structure is shown in

Fig. 6. The PANDIRA two-dimensional code has also been used to calculate the axial magnetic field. Every result of the calculation is shown in the file OUTPAN. It contains constant values (CON) in the solutions, a table giving the magnetic properties of used materials, the history of the iteration, and an edit of the solution in the defined regions as well as radial and total magnetic fields in the determined points. The calculated values are used at making of the picture of the magnetic field. Other output from the axial magnetic field calculation can also have the shape, which is shown in Fig. 7.

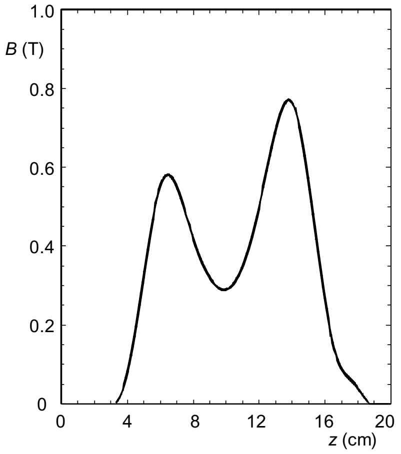

Fig. 5. Axial magnetic field.

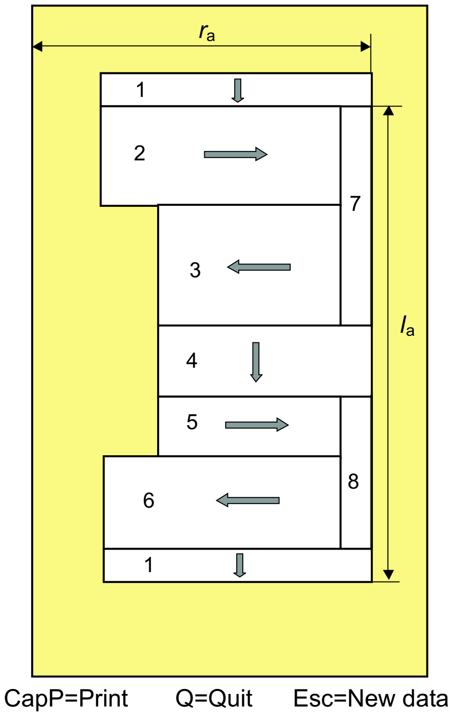

Fig. 6. Axial magnetic structure of the NANOGUN-10B. The radius r_a and the length l_a of the magnetic structure are: $r_a = 10$ cm and $l_a = 15.7$ cm, respectively.

A tunable Hewlett-Packard microwave frequency emitter from 8 to 18 GHz with a maximum power of 200 W will be available in order to tune the ion source.

The source has two working stages. The first one is at about 10^{-1} Pa pressure and a cold plasma is ignited by the ECR, which then diffuses towards the second stage at low gas pressure with the hot electrons and minimum B confinement. The extraction system will be pumped by rotary and turbomolecular pumps to reach vacuum about 10^{-5} Pa.

A double wall water cooled chamber will keep the permanent magnets at temperature below 50 °C.

4 CONCLUSIONS

The compact ECRIS NANOGUN-10B will be installed at the high voltage terminal of the electrostatic accelerator EA-300. We expect that the source will produce tens of μAe of Ar^{4+} by optimizing the operation parameters, the extraction system, and the gas pressure in the plasma chamber. The permanent magnet technology is utilized at the design of the NANOGUN-10B with the reduced dimensions of the source.

It was shown by P. Sortais [2] that it is possible to build ECRIS with performances relatively similar to the classical one but for a total cost 5 to 10 times smaller. This aspect is also used in our design. Because of the optimized magnetic structure of the NANOGUN-10B we can await that the generated yields of ions will be higher as in the Pantechnik NANOGAN ion source [14].

The NANOGUN-10B does not have any hot filament, it can be started or stopped at any time without negative influence on beam quality. The project is feasible in our conditions as it is not too expensive. In spite of the complexity of the realization problems, we are confident to obtain a relevant multiply-charged ions facility with a reasonable investment in few years.

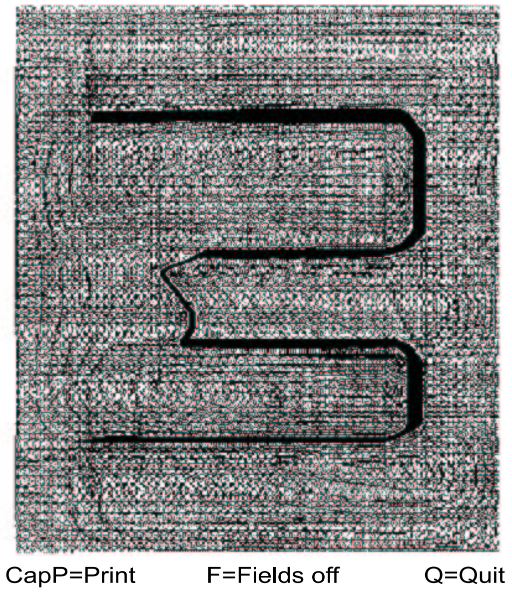

Fig. 7. Calculated magnetic flux lines inside the axial magnetic structure.

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