NEUTRON ACCELERATING TUBES WITH MICROWAVE DEUTERONS SOURCE USING ELECTRON-CYCLOTRON RESONANCE EFFECT

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Abstract

The physical principles of increased efficiency neutron accelerating tubes based on the microwave sources of heavy hydrogen nuclides, using the electron-cyclotron resonance effect (ECR) are considered. The authors' theoretical results consist of electromagnetic oscillations generation in the working volume of the ion source of the accelerating tube with the boundary excitation of a microwave discharge. Resonator and waveguide modes for ECR-plasma excitation are examined. Features of neutron generation in these accelerator neutron tubes based on microwave source of heavy hydrogen nuclides are analyzed. The algorithm is developed and numerical simulation of neutron pulse formation in neutron generators based on microwave source is done taking into account target shape and the possible deuterons resonant recharge. Frequency dependences of the energy flux density transmitted from an alternating electromagnetic field to the electron component of the plasma are obtained. They depend on the constant longitudinal magnetic field induction and pressure in the discharge chamber. The results of these studies could form the basis for the efficient domestic portable neutron generators development based on accelerating tubes with microwave hydrogen nuclides sources.

Modern development of several areas of science and technology requires a new generation of compact electro-physical neutron sources - neutron generators [1, 2]. The main units of neutron generator are accelerating tube, high-voltage source, as well as of its operation and energy supply systems. Accelerating tube consists of an ion source of heavy hydrogen, the target, accelerating and focusing electrode system. In an accelerating tube for receiving hydrogen ions Penning sources with heated, cold or hollow cathodes, duoplasmatron, sources with high-frequency and superhigh-frequency (microwave) discharges, vacuum-arc discharge or laser plasma could be used [2-4]. The results of studies related to the development and production of neutron generators with the microwave oven sources of nuclides of hydrogen, in which the effect of an electron-cyclotron resonance (ECR) is realized, were published at [5-6].

The presence of the ECR and the magnetic constriction of the discharge allow to the increase of energy input into the plasma to achieve and maintain a high degree of ionization k (70%) with electron temperature θ (up to 10 eV) and the ion concentration n (to ~ 10^{19} m^{-3}). Thus intense beams of nuclides hydrogen with output source current density 0.1 – 10 kA/m^2 are formed;

$$j=\left(\frac{e^3}{2\pi M}\right)^{1/2} n\left(\frac{\theta}{A}\right)^{1/2}. \qquad (1)$$

where e - elementary electric charge, M - the mass of a proton, A - the atomic mass of a nuclide of the hydrogen extracted from plasma.

Plasma generation in a microwave ion source is carried out in the course of cyclotron acceleration of electrons in the field of electrodynamics cavity or waveguide. Thus dynamics of an electron in considered local area of the resonator will be defined by the following differential equation:

$$m\frac{d^2\mathbf{r}}{dt^2}=-m\omega_e^2\mathbf{r}-e\mathbf{E}\cos 2\pi ft-e\left[\frac{d\mathbf{r}}{dt},\mathbf{B}\right]-m\nu\frac{d\mathbf{r}}{dt}, \qquad (2)$$

where m - electron mass, **r** - radius vector in the local coordinate system, **E**, **B** - vectors of the electric field and the magnetic field at a given point of the resonator, f - microwave generator frequency, ν - the average electron collision frequency. The influence of an alternating magnetic field in equation (2), as shown by computer simulations carried out, can be neglected, if the power of the microwave generator does not exceed 1 kW. Equation (2) can be solved by an equivalent system of differential equations. To the electrons of the plasma which are in the set unit of volume, energy of an electromagnetic field will be transferred in unit of time ($J\cdot m^{-3}\cdot s^{-1}$):

$$q(f,p,b,z)=en\mathbf{E}(z)\left\langle\frac{d\mathbf{r}}{dt}\cos 2\pi ft\right\rangle.$$

This function has a resonant character. On Fig.1,2 as an example, shows the calculated dependencies $q(f,p,1,0)$ and $q(f,0.25,b,0)$. The point z = 0 corresponds to the center of the discharge space. The calculation of these temperature dependencies of was chosen at $\theta \approx 10$ eV. Such temperature is typical for ECR plasma, obtained as a result of the probe measurements (see, for example [7]). On these curves can be clearly seen two peaks. Their presence is a consequence of the ECR. Calculations show that the presence of two such peaks occurs at commensurability of Larmor and Langmuir frequencies.

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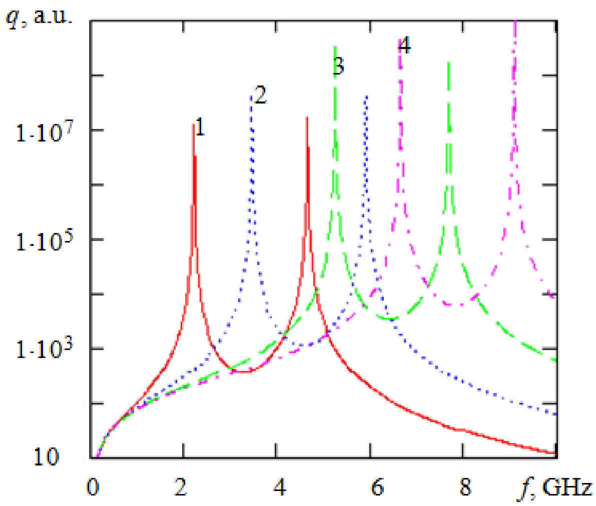

Figure 1: Dependencies of the energy flux density, in arbitrary units, obtained for $b = 1$ and p =: 1- 0.25; 2 - 0.5; 3 - 1.0; 4 - 1.5 Pa.

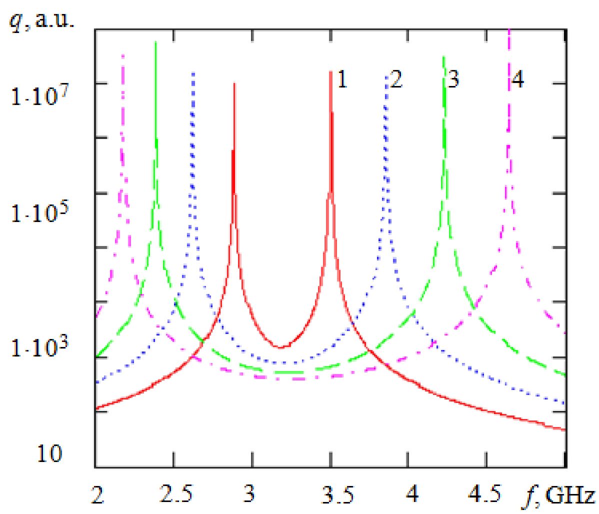

Figure 2: Dependencies of the energy flux density, in arbitrary units, obtained for p = 0.25 Pa and b =: 1- 0.25; 2 - 0.5; 3 - 0.75; 4 - 1.0.

There are two possible options of ECR discharge excitation. In the first case [5-6] of the microwave power from the generator (magnetron) by a rectangular waveguide through ceramic plate, which is the waveguide window, was supplied into a cylindrical cavity, where the electric discharge with the ECR effect is occurred. For this purpose in the cavity by means of system of ring magnets create a longitudinal magnetic field. It is necessary to notice that in other case plasma can be obtained in a mode of a running wave. In this source the waveguide segment has to be used instead of the cavity. Extraction of deuterons is carried out through an exhaust outlet in a resonator edge.

Another option of realization of a source of hydrogen nuclides using the ECR effect provides the location of the discharge area between the two electrodes [7]. One of them is the central conductor of the coaxial line connected with the microwave generator, and the second - the central conductor of a coaxial loop with the short-circuited plunger which length is. In this loop input impedance selected so as to compensate for the reactive component of the complex impedance of the plasma. The magnetic field in this case is formed by two coaxial coils with the magnetic shield.

The average power transmitted from the microwave field to the electrons per unit of volume of plasma formation, in both these cases can be estimated as follows:

$$\langle q(f,p)\rangle \approx \frac{1}{L}\int_0^L dzq[f,p,b(z),z],$$

where L - the longitudinal dimension of the plasma formation. The dependence $b(z)$ can be calculated using the algorithm described in [8], and for obtaining dependence of $E(z)$ it is possible to use modeling of electromagnetic fields in the cavity of deuterons source. Considered ion sources operate at authorized power frequency of 2.45 GHz. ECR condition providing requires a longitudinal constant magnetic field with induction in the center of working area of a source 87.5 mT.

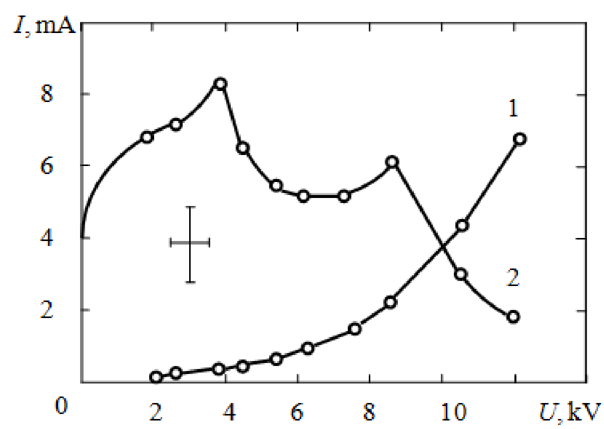

Figure 3: .Dependences of the deuterons current taken in the accelerating gap of the neutron generator (a curve 1) and the current getting on the extracting electrode (a curve 2) from voltage on the extraction electrode.

For higher current densities of hydrogen nuclides at the exit of a source and their transport to the neutron generator target in addition to the high emission parameters of plasma effective ion-optical systems of extraction of ions are required. Volt-ampere characteristics (VAC) of ion streams formation systems between the working volume - extracting electrode were carried out in MEPhI. Thus selection of ions was done from plasma boundary situated in the plane of the emission aperture, and the geometry of the ejection

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electrode corresponded to Pierce optics. Fig. 3 shows the corresponding VAC characteristics.

Computer simulations of working chambers of neutron generators was carried out, the modern package of applied programs which is based on differential methods of the numerical solution of the Masksvell equations with given boundary conditions are certainly was used. Parameters of electric and magnetic fields intensity, Q-factor, resonant and frequency dependences for considered neutron generators were calculated.

Cylindrical resonator working chamber has the following geometric dimensions - diameter 90 mm, length 100 mm, the aperture to the output beam of deuterium ions 60×6 mm^2. The resonator is made of stainless steel. The simulation shows that the structure of the electric and magnetic fields in the working chamber of the ion source corresponds to TE_{111} - mode, at a frequency of 2.45467 GHz. That's roughly the same as the default value for the frequency of magnetrons for power ECR discharge ion sources. The electric field in this kind of oscillation transverse axis of the resonator, on a sinusoid is maximum in the center and falls down at the ends. Calculation of parameters of intensity, Q-factors and electric fields is executed at frequency 2.45 GHz. Microwave power is supplied from rectangular waveguide WR-340. At the inlet into the chamber a thin membrane of alumina ceramics is established. It provides to support low pressure of deuterium in the chamber. Maximum electric field strength in the center of the cavity at a microwave power supply 400 W corresponds to $E = 4.5{\cdot}10^5$ V/m. This field strength is sufficient for ignition and microwave discharge burning in a deuterium plasma at pressures of less than 1 Pa. Calculated value of the induction of the microwave magnetic field was more than an order less than the induction of a constant magnetic field, which allows us to neglect the variable component of the magnetic field in equation (2).

Calculation of electrodynamics characteristics of the waveguide working chamber showed that a strong cross electric field arises in the chamber at the end wall bordering the alumina ceramics used as vacuum microwave window. Geometric dimensions of the chamber: diameter 40 mm, length 50 mm. Deuterium ions outlet aperture of diameter 2 mm is made axially at the end wall of the working chamber. Working chamber material is stainless steel. Value of the electric field amplitude on the axis of the chamber at a distance of 1 mm from the ceramic wall in the microwave power supply ≈ 300 W is $E = 2.9{\cdot}10^5$ V/m, also suggests the possibility of ignition and sustained discharge in deuterium at low pressure. Discharge has to ignite near the ceramic inlet. Deuterons diffuse toward the outlet, which has about few millimeters in diameter and locates in the center of the end of the working chamber.

Based on this analysis the choice of geometry of the working chamber of deuterons microwave source in the form of the rectangular cavity made on the basis of standard waveguides of section (for example the WR-340, WR-430 and WR-284 type) with the main wave of TE_{101} - mode was made. In this type of oscillations the electric field structure coincides with that in the cylindrical cavity TE_{111}-mode.

Numerical calculation for a cavity with dimensions of 72 mm × 34 mm × 114.83 mm showed that the maximum value of electric field amplitude in the cavity made of stainless steel at the power of magnetron of ≈ 400 W at frequency of 2.45 GHz and Q-factor - 2400 is $E = 4.56{\cdot}10^5$ V/m. For cavity with sizes of 86.36 mm × 43.18 mm × 86.17 mm – $E = 4.25{\cdot}10^5$ V/m, and for the cavity with sizes of 90 mm × 45 mm × 82.96 mm – $E = 4.15{\cdot}10^5$ V/m. For effective power supply system of microwave chambers of ion sources it is supposed to use magnetrons of continuous action with power up to 1 kW, which can be regulated by anode current of the magnetron.

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