# NONRELATIVISTIC ELECTRONICS

# POWER ABSORPTION INSIDE HELICON PLASMA OF HELIUM RF ION SOURCE IN NONAXIAL MAGNETIC FIELD

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The paper studies integral and one-dimensional distribution of RF electromagnetic field absorption in a helicon plasma with external magnetic field directed at an angle to a plasma plane. A simplified model of a helicon plasma plane layer is used here. Calculation results are used to explain power absorption in a compact helicon ion source with nonuniform external magnetic field. An ion source is a part of a nuclear scanning microprobe (NSMP) injector at the Institute of Applied Physics NAS of Ukraine. Calculations for ion source parameters of the NSMP injector show a resonant behaviour of integral RF power absorption as a function of a magnetic field inclination angle. A model (planar) geometry is verified here for solution of this problem.

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## INTRODUCTION

Among various inductively coupled low pressure sources RF plasma sources are widely used because they meet economic requirements and have sufficiently long service life. They can operate in different modes; RF sources operating in a helicon mode generate plasma more effectively [1 - 4].

In helicon ion sources, input power may be concentrated at a periphery under an antenna, may be uniformly absorbed by volume or be concentrated in a paraxial region of a discharge chamber. The latter case is more suitable for the NSMP ion source, since a precision ion beam is formed out the paraxial plasma region where the plasma density is supposed to be maximal. Increase of plasma density in an ion source is important question as it is one of ways to obtain high brightness ion beams [5].

In articles [6, 7] power absorption resonances are shown to be not equivalent as to their power distribution by volume of the discharge chamber in the case of uniform external magnetic field, generator frequencies of 27.12 MHz, definite geometry of the discharge chambers and with neutral gas pressure and electron temperature considered. Ranges of magnetic field where input power is paraxially absorbed are also recommended. Numerical estimates were compared to experimental data and were found in a good agreement.

In the article [8] increase of plasma was experimentally found for the first time in a helicon source with a nonuniform magnetic field. Later various hypotheses were suggested for explanation of the plasma density increase in a nonuniform magnetic field like reduction of helicon wave phase velocity, formation of a neutral gas barrier, reflection of helicons from a surface behind the antenna [9 - 12].

The above mentioned hypotheses were refuted by the experiments described in works [13, 14]. Hot electrons layer was experimentally found. The electron layer expands into plasma along magnetic field lines. The experiments have shown the absence of standing electromagnetic modes in plasma. A small scale wave structure was identified inside the hot electrons layer. To explain the experiments with the cylinder discharge chambers over 7 cm in radius, and over 20 cm in length, a theoretical model was used: semi-infinite plasma in plain geometry in a uniform magnetic field directed at the $\theta$ angle. Input power of some kW into plasma is meant here. For numerical evaluations to be verified, penetration of 80% power flux into plasma was suggested to be defined with a model of semi-infinite plasma. If the penetration was less than a plasma radius, the numerical evaluations were considered proper.

## 1. PHYSICAL MODEL

A problem of power absorbed in the cylinder discharge chamber with external nonuniform magnetic field from an assembly of annular permanent magnets is a very complicated since it requires satisfaction with boundary conditions at the edges of the discharge chamber for the electromagnetic field components in plasma. If unbounded in *z*-direction plasma cylinder in nonaxial magnetic field as a physical model is considered, that analytical solutions for electromagnetic field components inside plasma can not be obtained.

This article the following model is considered: a plasma layer is restricted along a vertical *x*-axis and unbounded along the *y* and *z* axes. Uniform magnetic flux density $B_0$ is directed at an angle $\theta$ to the plasma plane (Fig. 1). This model was chosen to be used for consideration absorption of electromagnetic waves in compact helicon ion sources (length of a discharge chamber is up to 12 cm, radius is up to 2 cm) with nonuniform distribution of external magnetic field from the annular permanent magnets assemblies (Fig. 2).

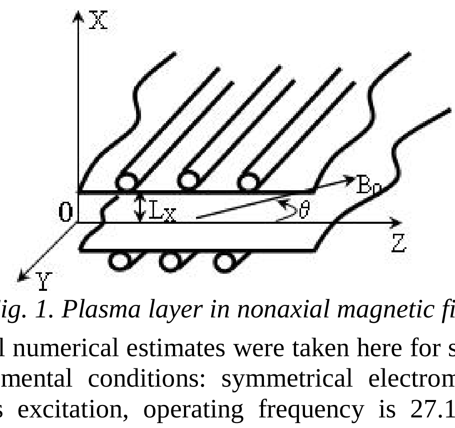


*Fig. 1. Plasma layer in nonaxial magnetic field*

All numerical estimates were taken here for standard experimental conditions: symmetrical electromagnetic modes excitation, operating frequency is 27.12 MHz, electron temperature of 5 eV, ion temperature of 0.1 eV.

Accuracy of the numerical estimates was verified as in works [13, 14] based on definition of 80% power flux penetration into plasma.

To excite symmetrical electromagnetic waves in plasma a system of straight current-carrying conductors was used as an antenna. Such current system is an analogue of a turns ($m$=0) antenna in a cylindrical geometry. There are three current-carrying conductors on an upper and bottom layer boundary that corresponds to a three-turn ($m$=0) antenna for a cylindrical geometry. The plane plasma layer is $2L_x$=2.6 cm in width along the $x$-axis and is unbounded along the $y$ and the $z$-axis.

It is assumed that a partially ionized electron-ion plasma with a uniform distribution of electron and ion density $n_{0e}=n_{0i}=n_0$ have already been created in the plasma layer. Neutral atoms density of the considered gas is given by the gas pressure.

We study the case when operating frequency $\omega$ is higher than lower hybrid frequency $\omega_{LH}$ in plasma. Here plasma ions may be considered immovable.

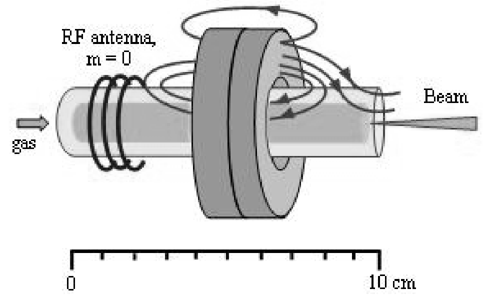

*Fig. 2. Helicon ion source layout*

The solution is sought for a set of longitudinal wave numbers $k_z=(\pi/12;\ \pi/10;\ \pi/7)$ cm$^{-1}$ only. This corresponds to longitudinal wave numbers that are excited in the cylinder discharge chamber of $L_z$=(12; 10; 7) cm in length. The solution is sought as traveling waves. For annular permanent magnets assemblies are very important to know local power absorption which they create. For this reason integral power absorption is calculated through a part of the layer of $l$=0.1 cm in width along the $z$-axis and sides $2L_x$, $2L_y$ along the $x$ and the $y$ axes, correspondingly, where $L_x$=1.3 cm, $L_y=L_x$. Value $S=2L_x\times2L_y$ is about a cross section of the discharge chamber of 1.5 cm in radius.

## 2. DIELECTRIC PERMEABILITY TENSOR, ANTENNA CURRENT AND BOUNDARY CONDITIONS

For a nonaxial magnetic field, a tensor of dielectric permeability of cold magnetoactive plasma has a form [14]:

$$\varepsilon_{ik}(\omega)=\begin{pmatrix}\varepsilon_\perp+\varepsilon_0'\sin^2\theta & ig\cos\theta & \varepsilon_0'\sin\theta\cos\theta\\ -ig\cos\theta & \varepsilon_\perp & ig\sin\theta\\ \varepsilon_0'\sin\theta\cos\theta & -ig\sin\theta & \varepsilon_{||}-\varepsilon_0'\sin^2\theta\end{pmatrix}, \quad (1)$$

where $\theta$ is a inclination angle of a magnetic field to the $z$-axis and $\varepsilon_0'=\varepsilon_{||}-\varepsilon_\perp$.

For solution of this problem, electromagnetic fields in plasma and vacuum are found as traveling waves:

$$\vec{E}=\left[\vec{e}_xE_x(x)+\vec{e}_yE_y(x)+\vec{e}_zE_z(x)\right]\ \exp\left[i\left(k_zz-\omega t\right)\right],$$
$$\vec{H}=\left[\vec{e}_xH_x(x)+\vec{e}_yH_y(x)+\vec{e}_zH_z(x)\right]\ \exp\left[i\left(k_zz-\omega t\right)\right]. \quad (2)$$

Current density of the antenna is as follows:

$$\vec{j}_a=\vec{e}_y\,j_y(x)\exp\left[i\left(k_zz-\omega t\right)\right]. \quad (3)$$

Amplitude of the antenna current density is:

$$j_y(x)=\left(I_a\ /\ L_z\right)\cdot\delta\left(x-x_a\right), \quad (4)$$

where $I_a$ is amplitude of current equal to 2 A that is typical for experimental conditions; $x_a$ is a coordinate position of a current – carrying conductor along the $x$-axis, it is assumed as $L_x$.

Components of dielectric permeability tensor (1) are in form [3]. Since a condition $\omega>\omega_{LH}$ is true, then only electron plasma component in dielectric permeability tensor is retained. In dielectric permeability tensor components $\varepsilon_{||}$, $\varepsilon_\perp$, $g$ the items describing Landau damping of waves are kept. Landau damping is not observed for considered $k_z$ and plasma parameters at $f$=27.12 MHz [6, 7], but it is very crucial for $f$=13.56 MHz [2].

Anti-Hermitian part of dielectric permeability tensor that defines the electromagnetic waves absorption by an electron subsystem due to a mechanism of binary collisions is characterized by effective electron collision frequency with neutral atoms and gas ions formed:

$$\nu_{eff}=\nu_{en}+\nu_{ei}\,. \quad (5)$$

For helium plasma at electron temperature of 5 eV and neutral gas pressure of 1 mTorr, $\nu_{en}$=2.7 MHz. Coulomb electron-ion collisions were considered with averaging over Maxwellian function of electron velocity distribution.

Electric and magnetic field strength (2) in plasma satisfy the Maxwell's equations with dielectric permeability tensor (1). Substitution (2) to the Maxwell's equations gives differential equations system with constant coefficients for Fourier amplitudes of the field components.

$$\begin{cases}\dfrac{dE_z(x)}{dx}=iA_1H_y(x)+A_2E_y(x)-iA_3E_z(x),\\ \dfrac{dE_y(x)}{dx}=iA_4H_z(x),\\ \dfrac{dH_z(x)}{dx}=A_2H_y(x)+iA_5E_y(x)-A_6E_z(x),\\ \dfrac{dH_y(x)}{dx}=-iA_3H_y(x)-A_6E_y(x)+iA_7E_z(x).\end{cases} \quad (6)$$

Explicit analytical form of electromagnetic field components for equations (6) is cumbersome, expressed in terms of $A_1\ldots A_7$, therefore only $A_1\ldots A_7$ gives here:

$$\begin{aligned}&A_1=\omega\mu_0\left(\frac{k_z^2}{k^2\alpha_1}-1\right), A_2=\frac{gk_z\cos\theta}{\alpha_1}, A_3=\frac{k_z\alpha_3}{\alpha_1},\\ &A_4=\omega\mu_0, A_5=\omega\varepsilon_0\left(\varepsilon_\perp-\frac{k_z^2}{k^2}-\frac{g^2\cos^2\theta}{\alpha_1}\right),\\ &A_6=g\omega\varepsilon_0\left(\frac{\alpha_3\cos\theta}{\alpha_1}+\sin\theta\right),\\ &A_7=\omega\varepsilon_0\left(\frac{\alpha_3^2}{\alpha_1}+\left(\varepsilon_{||}-\varepsilon_\perp\right)\sin^2\theta-\varepsilon_{||}\right),\end{aligned} \quad (7)$$

where $\alpha_1=\varepsilon_\perp+\varepsilon_0'\sin^2\theta, \alpha_3=\varepsilon_0'\sin\theta\cos\theta.$

For areas outside the plasma layer electromagnetic field components represent as a superposition TE and TM waves.

Integral absorption of RF power is calculated as:

$$P_{abs}(x) = \frac{\omega\varepsilon_0}{2}\iiint_V P(x)dV \,. \qquad (8)$$

The expression under integral (8) defines spatial distribution of the absorbed RF power. For nonaxial magnetic field, taking into account the tensor (1), obtain:

$$\begin{aligned} P(x) = \frac{\omega\varepsilon_0}{2}\Big[ & \operatorname{Im}\left(\varepsilon_\perp + \varepsilon_0' s_1^2\right)\cdot\left|E_x(x)\right|^2 + \operatorname{Im}\varepsilon_\perp \left|E_y(x)\right|^2 + \\ & + \operatorname{Im}\left(\varepsilon_\parallel - \varepsilon_0' s_1^2\right)\cdot\left|E_z(x)\right|^2 + \operatorname{Im} g\left(\operatorname{Im}E_x(x)\operatorname{Re}E_y(x) - \right. \\ & \left. - \operatorname{Im}E_y(x)\operatorname{Re}E_x(x)\right)\cdot c_1 + \operatorname{Im} g\left(\operatorname{Im}E_y(x)\operatorname{Re}E_z(x) - \right. \\ & \left. - \operatorname{Im}E_z(x)\operatorname{Re}E_y(x)\right)\cdot s_1 + 2\left(\operatorname{Re}E_x(x)\operatorname{Re}E_z(x) + \right. \\ & \left. + \operatorname{Im}E_x(x)\operatorname{Im}E_z(x)\right)\cdot s_1 c_1\Big], \end{aligned} \qquad (9)$$

$$s_1 = \sin\theta, c_1 = \cos\theta .$$

Boundary conditions are written for Fourier amplitudes of the field components and for Fourier amplitudes of the antenna current density.

$$E_z^{pl} = E_z^{vac}; E_y^{pl} = E_y^{vac};$$
$$H_z^{pl} - H_z^{vac} = j_y \,.$$

After determining the unknown constants in a plasma layer and vacuum areas, the expressions for Fourier amplitudes of the electromagnetic field components in a plasma layer may be obtained.

## 3. WAVE DISPERSION

Eigenvalues that satisfy the system of equations (6) are, in fact, transverse wave numbers of electromagnetic waves excited in a plasma layer.

A problem on eigenvalues gives the equation of the fourth degree:

$$a\kappa^4 + b\kappa^3 + c\kappa^2 + d\kappa + e = 0 \,. \qquad (10)$$

The coefficients *a, b, c, d, e* are cumbersome, and they are not mentioned here.

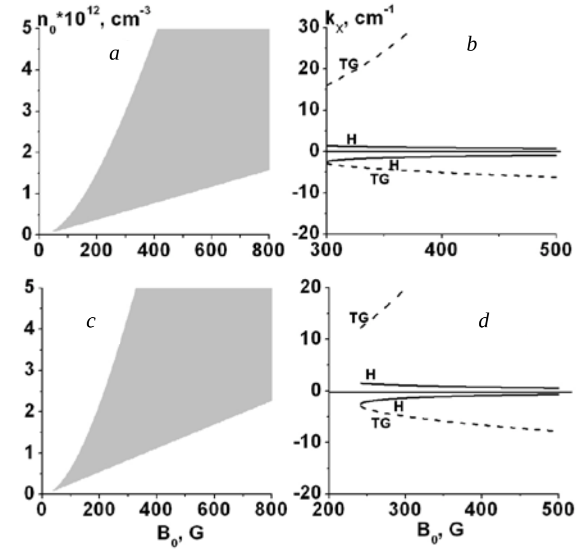


*Fig. 3. Transparency region and dispersive characteristics of waves in a plasma layer at magnetic field inclination angle $\theta$ =1°, $n_0$ = 3·10$^{12}$ cm$^{-3}$: $k_z$=π/12 cm$^{-1}$ (a, b); $k_z$=π/10 cm$^{-1}$ (c, d)*

Numerical analysis of the equation (10) in a collisionless limit provides the results for electromagnetic wave dispersion as follows.

Figs. 3, 4 shows two essentially different cases of electromagnetic wave dispersion. A TG wave (Figs. 3,b,d) and a helicon wave (area $k_x>0$), and local oscillations of an electromagnetic field (area $k_x<0$) may exist in plasma. These oscillations are originated inside a hot electrons layer and are transferred into depth of plasma along the field lines [13, 14].

A helicon wave (area $k_x > 0$) may exist in plasma (Fig. 4,b,d), other three solutions correspond to the above mentioned oscillations.

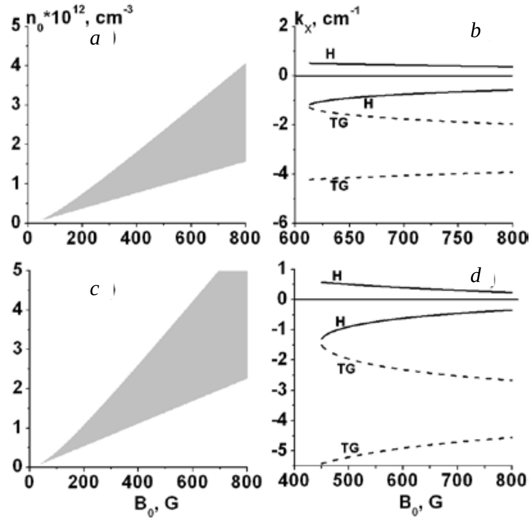


*Fig. 4. Transparency region and dispersive characteristics of waves in a plasma layer at magnetic field inclination angle $\theta$ =5°, $n_0$=3·10$^{12}$ cm$^{-3}$: $k_z$=π/12 cm$^{-1}$ (a, b); $k_z$=π/10 cm$^{-1}$ (c, d)*

As $k_z$ increases, the oscillations become more small-scale at the same external magnetic field inclination angle.

As inclination angle increases, the oscillations become more large-scale at the same $k_z$.

The dispersion curves show that a magnetic flux density range is related to a specified value of plasma density, inclination angle of a magnetic field, and $k_z$ value. Tables 1, 2 refer to plasma with density $n_0$=3·10$^{12}$ cm$^{-3}$.

***Table 1***

| Angle, grad | Magnet field, G |
|---|---|
| 1 | 300…823 |
| 2 | 368…823 |
| 3 | 444…823 |
| 4 | 526…823 |
| 5 | 613…823 |

***Table 2***

| Angle, grad | Magnet field, G |
|---|---|
| 1 | 241…823 |
| 2 | 286…823 |
| 3 | 337…823 |
| 4 | 392…823 |
| 5 | 449…823 |

Table 1 is related to a case of $k_z$=π/12 cm$^{-1}$; Table 2 classifies a case of $k_z$=π/10 cm$^{-1}$. From Figs. 3, 4 it follows that transparency region narrows as an inclination angle grows.

## 4. RESULTS

Numerical results were obtained with Fourier amplitudes of the electromagnetic field components in a plasma layer and the expression (9). These numerical estimates are needed for local power absorption analysis inside a plasma layer as function of a magnetic field inclination angle, neutral gas pressure, operating frequency.

For above volume element of the plasma layer Figs. 5, 6 shows for plasma of density $n_0 = 3\cdot10^{12}$ cm$^{-3}$, and $k_z=\pi/12$ cm$^{-1}$; $\pi/10$ cm$^{-1}$, correspondingly, an integral power absorption and absorption distribution in the *x*-direction, as function of an angle between the magnetic field and plasma and the magnetic field value. As pressure grows, maxima of integral power absorption are seen to be slightly shifted to magnetic field increase. For pressure $p$=6 mTorr, maxima of integral power absorption in Fig. 5,a,c are related to the magnetic flux density of 626 G, 742 G; for pressure of 10 mTorr they are related to 628 G, 748 G; for pressure of 15 mTorr they are related to 632 G, 757 G.

Fig. 6,a,c show that for pressure $p$=6 mTorr, maxima of integral power absorption are related to the magnetic flux density of 503, 578 G; for pressure of 10 mTorr, they are related to 507, 585 G; for pressure of 15 mTorr, they are related to 512, 590 G.

Graphs of absorption distribution along the *x*-axis (Figs. 5,b,d; 6,b,d) are plotted for the above mentioned values of the magnet field. Here magnetic field is seen to be 100 G less than that of case where $k_z = \pi/12$ cm$^{-1}$.

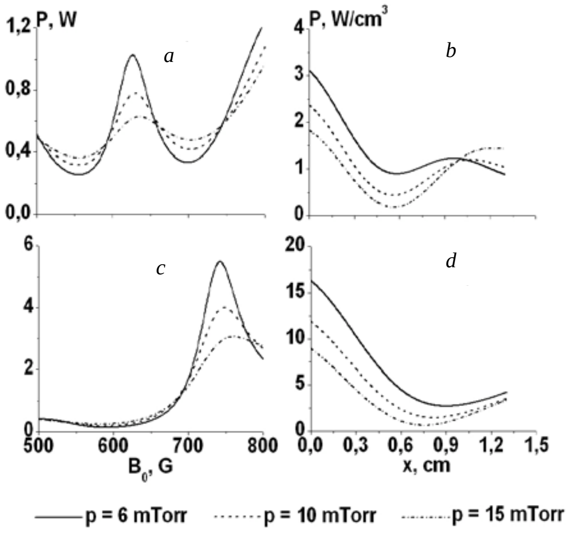


*Fig. 5. Integral power absorption and absorption along the x-axis for $k_z = \pi/12$ cm$^{-1}$: a), b) $\theta$ = 3°; c), d) $\theta$ = 3.5°*

Numerical estimates show that further increase of $k_z$ would not allow paraxial power absorption for plasma density $n_0>3\cdot10^{12}$ cm$^{-3}$. The above mentioned simulation logics considered, for plasma of density $n_0=4\cdot10^{12}$ cm$^{-3}$ and $k_z=\pi/12$ cm$^{-1}$, $k_z=\pi/10$ cm$^{-1}$, the following results were obtained (Fig. 7). Fig. 7,a,c,e show that for pressure $p$=6 mTorr maxima of integral absorption are related to magnetic flux density of 771, 619, 713 G; for pressure of 10 mTorr, they are related to values of 774, 624, 718 G, and to 780, 632, 728 G for pressure of 15 mTorr.

Graphs of absorption distribution along the *x*-axis (Fig. 7,b,d,f) are plotted for the above mentioned values of magnet field.

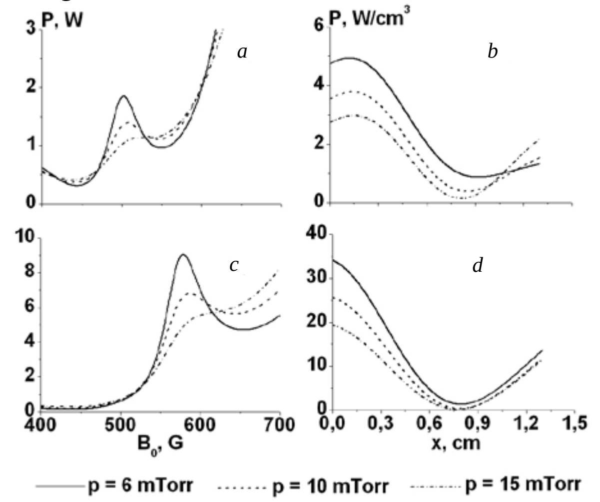


*Fig. 6. Integral power absorption and absorption along the x-axis for $k_z = \pi/10$ cm$^{-1}$: $\theta$ =3.5° (a, b); $\theta$ = 4° (c, d)*

Numerical results for penetration of 80% power flux into plasma are provided. A value $dQ_x = \left(\vec{E}\times\vec{H}\right)_x dz$ was preliminary calculated the condition (11) was verified.

$$Q_x\left(x=\delta x\right)=0,2Q_x\left(x=0\right). \qquad (11)$$

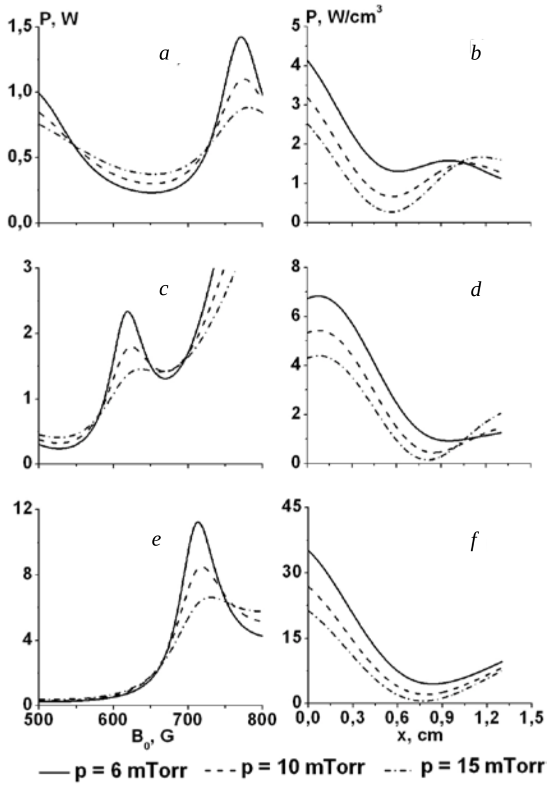


*Fig. 7. Integral power absorption and absorption along the x-axis for: $k_z = \pi/12$ cm$^{-1}$, $\theta$ = 3° (a, b); $k_z = \pi/10$ cm$^{-1}$, $\theta$ = 3,5° (c, d); $k_z = \pi/10$ cm$^{-1}$, $\theta$ = 4° (e, f)*

At Fig. 5,a pressure $p$=6 mTorr corresponds to $\delta x$=0.95 cm, $p$=10 mTorr corresponds to $\delta x$=0.96 cm, $p$=15 mTorr corresponds to $\delta x$=1 cm.

At Fig. 6,a pressure $p$=6 mTorr corresponds to $\delta x$=0.9 cm; $p$=10 mTorr corresponds to $\delta x$=0.91 cm, $p$=15 mTorr corresponds to $\delta x$=1.05 cm.

At Fig. 7,a pressure $p$=6 mTorr corresponds to $\delta x$=0.97 cm, $p$=10 mTorr corresponds to $\delta x$=0.99 cm, $p$=15 mTorr corresponds to $\delta x$=1.03 cm.

At Fig. 7,c pressure $p$=6 mTorr corresponds to $\delta x$=0,9 cm, $p$=10 mTorr corresponds to $\delta x$=0.91 cm, $p$=15 mTorr corresponds to $\delta x$=1.07 cm.

All the above mentioned values of $\delta x$ are less than $L_x$ thus this simplified physical model may be applied for numerical estimates of power absorption inside cylinder discharge chambers compact ion sources.

## 5. DISCUSSION

Articles [6, 7] show for a uniform magnetic field and discharge chambers with length $L_z$=12 cm ($k_z=\pi/12$ cm$^{-1}$) and $L_z$=7 cm ($k_z=\pi/7$ cm$^{-1}$) that power input into a paraxial region of discharge chamber is possible at $p$=6 mTorr up to density $n_0=1.8\cdot10^{12}$ cm$^{-3}$, at $p$=10 mTorr to density $n_0=1.2\cdot10^{12}$ cm$^{-3}$. Figs. 5-7 for power distributions over the $x$-direction show that the distributions are paraxial even at pressure increase up to 15 mTorr, that is impossible for uniform magnetic field [6, 7].

Figs. 3, 4 for the transparency regions show that increase of plasma density is accompanied by increase of magnetic field values for given plasma density. Increase of a magnetic field value is known to degrade emittance characteristics of the extracted beam. Increased plasma density also modifies plasma boundary in an extraction system and necessitates higher voltage applied onto plasma electrodes of the extraction system. In these circumstances possibility of paraxial power absorption is considered for plasma density $n_0=3\cdot10^{12}$ cm$^{-3}$; $4\cdot10^{12}$ cm$^{-3}$. Numerical estimates were performed for $k_z=\pi/12$; $\pi/10$; $\pi/7$ cm$^{-1}$, that allows us to consider the creation of the same plasma density at various ranges of the magnetic field values.

For considered $k_z$ values, paraxial power absorption is possible only in a small range of magnetic field inclination angle (up to $\theta=4°$). Other angles provide peripheral power absorption.

As integral estimation is done for local power absorption not every calculation result may be suggested for a real experiment. In Fig. 5 only mode 5,a may be recommended, since power of about 10 W would be absorbed due to binary collisions on a 1 cm interval and taking into account applied power [15] of about 160 W.

In Fig. 6 only mode 6a may be recommended, since power of about 25 W would be absorbed as a result of binary collisions on a 1 cm interval and taking into account applied power of about 170 W. In Fig. 7 the modes 7,a and 7,c may be used.

It is also important that the magnetic field inclination angles for which volume power distribution was found be very close to extraction region of charged particles in an ion source.

A model (planar) geometry is verified here to solve this problem.


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## REFERENCES


1. K.P. Shamrai, V.B. Taranov. Resonance wave discharge and collisional energy absorption in helicon plasma source // *Plasma Phys. Control. Fusion (36)*. 1994, p. 1719-1735.
2. A.F. Aleksandrov, N.F. Vorobev, E.A. Kralkina, V.A. Obuxov, A.A. Ruxadze. Teoriya kvazistaticheskix plazmennyx istochnikov // *ZhTF*. 1994, p. 53-58 (in Russian)..
3. A.F. Aleksandrov. G.E. Bugrov, K.V. Vavilin, I.F. Kerimova, S.G. Kondranin, E.A. Kralkina, V.B. Pavlov, V.Yu. Plaksin, A.A. Ruxadze. samo-soglasovannaya model vch-induktivnogo istochni-ka plazmy, pomeshhennogo vo vneshnee magnitnoe pole // *Fizika Plazmy*. 2004, p. 398-412 (in Russian).
4. K.P. Shamrai, V.B. Taranov. Volume and surface rf power absorption in a helicon plasma source // *Plasma Sources Sci. Technol (5)*. 1996, p. 474-491.
5. V.I. Miroshnichenko, S.N. Mordik, V.V. Olshansky, K.N. Stepanov, V.E. Storizhko, B. Sulkio-Cleff, V.I. Voznyy. Possibility to increase RF ion source brightness for nuclear microprobe applications // *Nuclear Instruments and Methods in Physics Research B (201)*. 2003, p. 630-636 (in Russian).
6. O.V. Aleksenko, V.I. Miroshnichenko, S.N. Mordik. Prostranstvennoe raspredelenie poter vch-elektromagnitnogo polya v plazmen-nom istochnike gelikonnogo tipa // *Fizika Plazmy*. 2014, p. 764-770 (in Russian).
7. O.V. Alexenko, V.I. Miroshnichenko, S.N. Mordik. Resonant RF electromagnetic field input in the helicon plasma ion source // *Problems of Atomic Science and Technology*. 2014, № 5, p. 153-160.
8. G. Chevalier, F.F. Chen. Experimental modeling of inductive discharges // *J. Vac. Sci. Technol. A (11)*. 1993, p. 1165-1171.
9. O.V. Braginskij, A.N. Vasileva, A.S. Kovalev. Gelikonnaya plazma v neodnorodnom magnitnom pole // *Fizika Plazmy*. 2001, p. 741-749 (in Russian).
10. X.M. Guo, J. Scharer, Y. Mouzouris, L. Louis. Helicon experiments and simulations in nonuniform magnetic field configurations // *Phys. Plasmas (6)*. 1999, p. 3400-3407.
11. J. Gilland, R. Breun, N. Hershkowitz. Neutral pumping in a helicon discharge // *Plasma Sources Sci. Technol (7)*. 1998, p. 416-422.

12. F.F. Chen. The low – field density peak in helicon discharge // *Phys. Plasmas (10).* 2003, p. 2586-2592.
13. K.P. Shamraj, V.F. Virko, Yu.V. Virko, G.S. Kirichenko. Povyshenie effektivnosti gelikonnogo razryada v sxodyashhemsya magnitnom pole // *Problems of Atomic Science and Technology*. 2003, № 4, p. 241-246 (in Russian).
14. K.P. Shamrai, V.F. Virko, Yu.V. Virko, G.S. Kirichenko. Wave phenomena, hot electrons, and enhanced plasma production in a helicon discharge in a converging magnetic field // *Physics of Plasmas (11)*. 2004, p. 3888-3897.
15. M.A. Lieberman, A.J. Lichtenberg. *Principles of Plasma Discharge and Material Processing*. N.Y.: John Wiley & Sons, 2005, p. 330-335.

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## ПОГЛОЩЕНИЕ МОЩНОСТИ В ГЕЛИКОННОЙ ПЛАЗМЕ ВЧ-ИСТОЧНИКА ИОНОВ ГЕЛИЯ В НЕАКСИАЛЬНОМ МАГНИТНОМ ПОЛЕ

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Исследуются интегральное и одномерное распределения поглощения ВЧ-электромагнитного поля в геликонной плазме с внешним магнитным полем, которое направлено под углом к поверхности плазмы. Используется упрощенная модель плоского слоя геликонной плазмы. Результаты расчетов применяются для объяснения поглощения мощности в компактном геликонном источнике ионов с неоднородным внешним магнитным полем. Источник ионов входит в состав инжектора ядерного сканирующего микрозонда (ЯСМЗ) Иститута прикладной физики НАН Украины. Расчеты для параметров источника ионов инжектора ЯСМЗ показывают резонансный характер интегрального поглощения ВЧ-мощности в зависимости от угла наклона магнитного поля. Выполнена проверка правомерности применения модельной (плоской) геометрии для решения задачи.

## ПОГЛИНАННЯ ПОТУЖНОСТІ В ГЕЛІКОННІЙ ПЛАЗМІ ВЧ-ДЖЕРЕЛА ІОНІВ ГЕЛІЮ В НЕАКСІАЛЬНОМУ МАГНІТНОМУ ПОЛІ

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Досліджуються інтегральний та одномірний розподіли поглинання ВЧ-електромагнітного поля в геліконній плазмі із зовнішнім магнітним полем, яке має напрямок під кутом до поверхні плазми. Використано спрощену модель плоского шару геліконної плазми. Результати розрахунків застосовуються для пояснення поглинання потужності в компактному геліконному джерелі іонів з неоднорідним зовнішнім магнітним полем. Джерело іонів входить до складу інжектора ядерного скануючого мікрозонда (ЯСМЗ) Інституту прикладної фізики НАН України. Розрахунки для параметрів джерела іонів інжектора ЯСМЗ демонструють резонансний характер інтегрального поглинання ВЧ-потужності в залежності від кута нахилу магнітного поля. Виконано перевірку правомірності застосування модельної (плоскої) геометрії для вирішення задачі.