ELECTROMAGNETIC SURFACE WAVE EXCITATION AND ENERGY TRANSPORT ALONG A PLANE PLASMA BOUNDARY

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A simple construction for excitation of Surface Wave (SW) in plasmas is proposed. The metal plate is used both as an antenna with surface current and as a wall of the waveguide structure. Second wall of the waveguide structure is a plasma boundary. Electromagnetic wave which is incident on plasma surface initiates the plasma oscillations which form an electromagnetic field of surface type in plasma if the characteristics of the incident field (wave frequency and wave vector direction) are chosen properly. It is shown that SWs can exist in high and low frequency ranges. The SW from high frequency range can have large penetration depth into plasma and large power flux along plasma surface inside plasma. The SW from low frequency range can have large tangential electric field on plasma surface. The paper answers the questions which geometry and surface current have to be chosen to see the SW in the structure with the preferable characteristics.

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INTRODUCTION

Surface electromagnetic waves in plasmas (unlike the volume waves) propagate along a surface which bounds plasma or separates two different plasmas [1]. The amplitude of the waves decays exponentially from the surface into plasmas. In such a way the electromagnetic oscillations occur in plasma in some region near the surface and the electromagnetic power is transmitted along the surface (but not away from the surface into the plasmas). That is why the SWs are widely used in processes of etching, polishing and cleaning [2, 3]. But these technologies are based mostly on the experimental observations and their analytical and numerical descriptions are still required to optimize the processes.

There are two general problems which have to be solved on the way to a practical application of the SW in the technologies. First one is a possibility to excite effectively the SW in a waveguide structure. Since the SWs are eigen waves of the structure they can but are not obligated to propagate in the waveguide structure. Second problem is the transient processes of the SW formation during the excitation. The SW dispersion and the electromagnetic field structure are known from the theory in large time limit only when all the transient processes have already finished. But transient processes can take essential time. Moreover the power fluxes during the transient processes differ essentially from ones known in large time limit. Knowledge of transient fluxes can be important for a construction and safely work of an experimental set up which is based on the SW propagation.

The paper presents the recommendations on the experimental excitation of the SWs in a simple waveguide structure. The parameters of the waveguide structure are defined for which the excitation is possible. Moreover the parameters for most effective excitation are predicted. The transient processes are still out of the consideration since they require a direct numerical simulation. The numerical modeling of the transient processes supposes to be carried out using Finite Difference Time Domain (FDTD) code.

1. SEMIBOUNDED PLASMA- SEMIBOUNDED DIELECTRIC

A simplest geometry of the bounded plasma where the SWs can exist is semibounded plasma-semibounded dielectric. The dispersion relation of the structure is well known (see, for example, [1, 4]):

$$\frac{k_d}{\varepsilon_0} + \frac{k_{pl}}{\varepsilon} = 0\,, \tag{1}$$

where ε_0 is dielectric permittivity, $\varepsilon \equiv 1 - \omega_{pl}^2 / \omega^2$ is plasma permittivity, ω_{pl} is plasma frequency, ω is wave frequency, $k \equiv \omega / c$ is wave vector in vacuum, c is speed of light, k_y is a component of the wave vector along the plasma surface (it is of the same value both in plasma and dielectric and has to be found from the dispersion relation (1)), $k_d \equiv \sqrt{\varepsilon_0 k^2 - k_y^2}$ is normal component of the wave vector in dielectric, $k_{pl} \equiv \sqrt{\varepsilon k^2 - k_y^2}$ is normal component of the wave vector in plasma. If $\varepsilon k^2 < k_y^2$ the wave is of the surface type in plasma and $k_1 = \sqrt{k_y^2 - \varepsilon k^2}$ is a penetration coefficient of the SW in plasma (inverse value defines a penetration depth of the SW in plasma). If $\varepsilon_0 k^2 < k_y^2$ the wave is of the surface type in dielectric.

The standard analysis shows that the roots of the equation (1) exist only if $\varepsilon < 0$ and $k_y > \sqrt{\varepsilon_0} k$. Therefore the SWs can exist in the structure of the semibounded plasma-semibounded dielectric but they can not be excited by the vacuum waves.

In the paper [4], the same geometry was discussed and the excitation of SWs in plasma by the plasma waves was studied. We would like to separate the processes of the plasma wave formation (which are not trivial [5]) and the SW excitation. Therefore the structure is preferable where the SW formation (excitation) in plasma does not require volume wave propagation in plasma.

2. SEMIBOUNDED PLASMA AND METAL PLATE

Let's consider another simple waveguide structure. The geometry of the structure is shown in Fig 1. A metal plate is at a distance d from the semibounded plasma. Space between plasma and metal plate is filled by dielectric with permittivity ε_0.

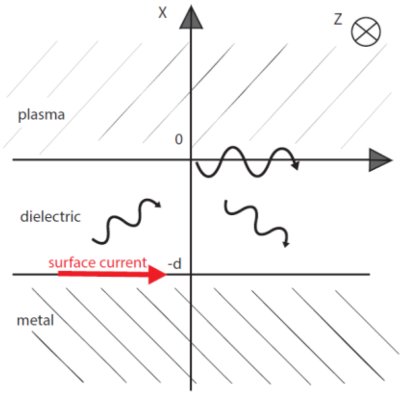

Fig. 1. Geometry of the problem

We are interested in the waves which propagate along plasma surface. The axis y is chosen in this direction. The direction of axis x is normal both to the plasma boundary and the metal plate. The plasma boundary coordinate is $x = 0$. The metal plate coordinate is $x = -d$. An expectation from such structure is clear: the metal plate can be used simultaneously as an antenna with surface current and as a waveguide wall. But when and how the SW can be excited in such structure?

The dispersion relation of the waveguide structure is

$$i\frac{k_d}{\varepsilon_0}tg(k_d d) - \frac{k_{pl}}{\varepsilon} = 0. \qquad (2)$$

Equation (2) has solutions of two types: a) surface type wave both in plasma and dielectric ($k_{pl} \in iR, k_d \in iR$); b) surface type wave in plasma but volume type wave in dielectric ($k_{pl} \in iR, k_d \in R$). Second case is preferable to excite the SW's in plasma since surface type wave in dielectric supposes the restricted possibilities to transfer power from metal wall to plasma surface. In contradiction to this case the volume type field in dielectric provides quick power transfer from antenna to the plasma surface. Therefore just the second case is tested below for the SW excitation. In this case the dispersion relation (2) becomes:

$$\frac{k_d}{\varepsilon_0}tg(k_d d) - \frac{k_1}{\varepsilon} = 0. \qquad (3)$$

Dispersion relation (3) has two sets of solutions: first for $\varepsilon > 0$ (it is called here as High Frequency (HF) solutions) and second for $\varepsilon < 0$ (Low Frequency (LF) solutions). Let's consider them separately; below, we deal with vacuum ($\varepsilon_0 = 1$) as the dielectric for simplicity.

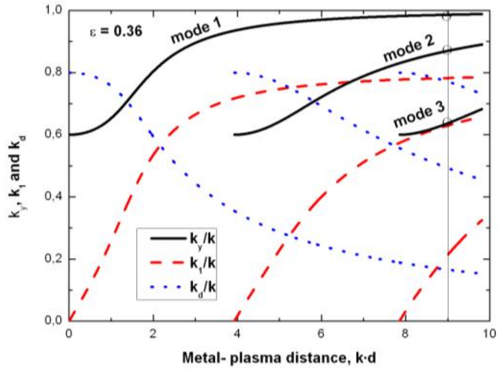

Fig. 2. Dispersion curves (solid lines) of HF waves. The normal component of wave vector in vacuum, k_d (dotted lines) and wave penetration coefficient in plasma, k_1 (dashed lines) are shown for the related dispersions. All values are normalized by the vacuum wave vector k

HF solutions:

$$\begin{aligned} &\sqrt{\varepsilon}k < k_y < k, \\ &0 < k_1 < \sqrt{1-\varepsilon}k, \\ &\sqrt{1-\varepsilon}k > k_d > 0. \end{aligned} \qquad (4)$$

There is $k_d^{\max,HF} \equiv \sqrt{1-\varepsilon}k$ which defines a number of the roots of the equation (3) for given distance from metal to plasma. Each root defines new mode which can propagate in the structure. If one defines $\lambda^{HF} \equiv 2\pi / k_d^{\max,HF}$ then for $0 < d < \lambda^{HF}/2$ there is only one mode, for $\lambda^{HF}/2 < d < \lambda^{HF}$ these are two modes, etc. In other words: increasing the vacuum layer width by a half of λ^{HF} produces new wave mode.

LF solutions:

$$\begin{aligned} &0 < k_y < k, \\ &\sqrt{-\varepsilon}k < k_1 < \sqrt{1-\varepsilon}k, \\ &k > k_d > 0. \end{aligned} \qquad (5)$$

In this case $k_d^{\max,LF}$ is equal to vacuum wave vector k. Therefore equation (3) has not roots for $0 < d < \lambda/4$, where λ is wave length in vacuum. For the range $\lambda/4 < d < 3\lambda/4$ only one root can exist. In the range $3\lambda/4 < d < 5\lambda/4$ second root has to appear, etc. In other words: each new mode appears with increasing d by $\lambda/2$ starting from $d = \lambda/4$.

The solutions of equation (3) for HF and LF modes are presented in Figs. 2 and 3 respectively. The plasmas with $\varepsilon = 0.36$ and $\varepsilon = -0.36$ have been chosen as the examples. The dispersion is presented by the curves with

k_y dependence, and the dependences of k_1 and k_d are presented as well in the same figures to understand corresponding field structure in plasma and vacuum.

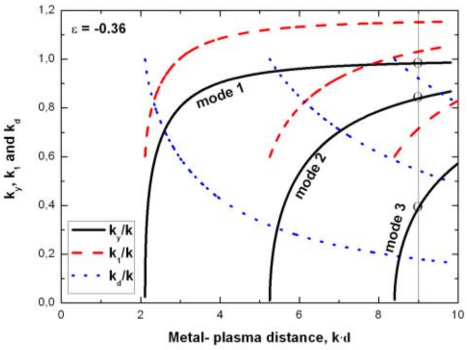

Fig. 3. Dispersion curves (solid lines) of LF waves. All inscriptions correspond to the caption of Fig. 2

3. WAVE FIELD STRUCTURE

The wave field structure is written with unity normalization of the magnetic field on the metal plate. It is convenient since the magnetic field on the metal plate can be fixed (or controlled) by the surface current. Also it is convenient to introduce the constant A to simplify the field expressions:

$$A \equiv \frac{1}{\cos(k_d d)(1+tg^2(k_d d))}.$$

Wave fields in plasma:

$$H_z = Ae^{-k_1 x}e^{i(k_y y-\omega t)},$$
$$E_y = \frac{k_1}{k\varepsilon}Ae^{-k_1 x}e^{i(k_y y-\omega t+\frac{\pi}{2})}, \quad (6)$$
$$E_x = -\frac{k_y}{k\varepsilon}Ae^{-k_1 x}e^{i(k_y y-\omega t)}.$$

The field decays in x direction with the penetration coefficient k_1.

Wave fields in vacuum:

$$H_z = A(\cos(k_d x)-\sin(k_d x)tg(k_d d))e^{i(k_y y-\omega t)},$$
$$E_y = \frac{k_d}{k}A(\sin(k_d x)+\cos(k_d x)tg(k_d d))e^{i(k_y y-\omega t+\frac{\pi}{2})}, \quad (7)$$
$$E_x = -\frac{k_y}{k}A(\cos(k_d x)-\sin(k_d x)tg(k_d d))e^{i(k_y y-\omega t)}.$$

The field structure in x direction is a standing wave.

The field structure (like the dispersion relation) is calculated for the stationary processes in large time limit and does not take into consideration the transient processes. In this limit there is no power transport in normal direction. Therefore a calculation of Poynting flux along y direction has only sense:

$$P_y = -\frac{c}{4\pi}E_x H_z. \quad (8)$$

Profile of its amplitude along x direction allows to see the x dependence of power transport and to compare the fractions of power transport through plasma and vacuum.

4. ANALYSIS AND DISCUSSIONS

Looking for optimal experimental conditions of SW propagation in plasma anybody has to consider three aspects: a) the penetration depth of the field in plasma; b) the amplitude of the Poynting flux at the plasma boundary; c) the amplitude of the tangential electric field on the boundary (E_y in our case).

Scenarios when k_y is close to k are not convenient for the SW excitation. In this case the power from antenna is transmitted mainly along waveguide structure. For effective excitation of SW the power flux should pass to plasma but not along the boundary.

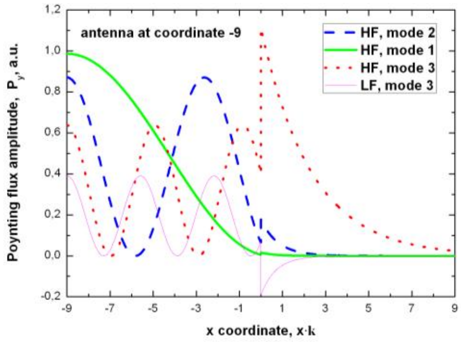

Fig. 4. Spatial distribution of Poynting flux amplitude (flux along the plasma surface) for HF modes. Each mode corresponds to the dispersion marked by circles in Fig. 2. LF mode is given for qualitative comparison

When $k_1 >> k_d$ the penetration depth of the wave in plasma is small and the wave power is concentrated mainly in vacuum. Therefore the relation $k_1 \le k_d$ is preferable for the SW observation.

When the value of k_y is close to 0 the amplitude of the Poynting flux is small at the plasma boundary (and exponentially decays inside the plasma). Therefore the cases with small k_y are not convenient for the experimental observation.

Taking into consideration all these discussions the following two scenarios are of interest for experimental studies. The HF modes can have large penetration depth in plasma and large fraction of electromagnetic power in plasma when k_y is close to $\sqrt{\varepsilon}k$. But the tangential electric field on the plasma boundary is small in this case. In technology the large tangential electric field can be requested. For this goal the LF modes are preferable with $k_y \approx \sqrt{(1+\varepsilon)/2}k$, but not too small.

Fig. 4 demonstrates the coordinate dependence of Poynting flux amplitude for HF modes. The dispersion points taken for the calculations are shown in Fig. 2. As it was reported above the large amplitude and large penetration depth of the SW are obtained when k_y is close to $\sqrt{\varepsilon}k$ (mode 3).

Fig. 5 demonstrates the coordinate dependence of the amplitude of the tangential electric field for LF modes. The dispersion points taken for the calculations are shown in Fig. 3.

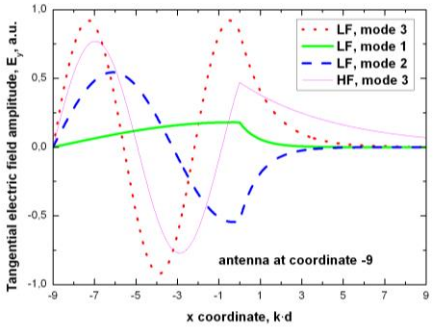

Fig. 5. Spatial distribution of tangential electric field amplitude for LF modes. Each mode corresponds to the dispersion marked by circles in Fig. 3. HF mode is given for qualitative comparison

Usually antenna launches a wide spectrum of vacuum waves. But there are distances when only one surface mode (mode 1) can be excited. But even for larger distances the lowest possible surface mode dominates over the other surface modes. The electromagnetic power fraction in vacuum also increases with increase in the number of surface modes (which decreases the power efficiency of SW excitation).

CONCLUSIONS

Experimental conditions are defined for effective excitation of the SWs. The metal plate is used as the antenna with surface current and as the wall of the waveguide structure. The SW can exist in two frequency ranges. The SWs in HF range can provide large penetration depth, large normal electric field at the boundary and power flux in plasma. The SWs in LF range can provide large tangential electric field at the boundary but not the penetration depth.

HF waves can propagate in the structures with any distance between antenna and plasma but number of the modes increases with increasing the distance. Best characteristics of HF waves are reached when k_y is close to $\sqrt{\varepsilon}k$. LF waves can't propagate in the structure if the metal-plasma distance is less than $\lambda/4$. Best characteristics of LF waves are reached when k_y is close to $\sqrt{(1+\varepsilon)/2}k$ but it is not close to 0.

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ВОЗБУЖДЕНИЕ ПОВЕРХНОСТНОЙ ЭЛЕКТРОМАГНИТНОЙ ВОЛНЫ И ПЕРЕНОС ЭНЕРГИИ ВДОЛЬ ПЛОСКОЙ ГРАНИЦЫ ПЛАЗМЫ

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Предложена простая конструкция для возбуждения поверхностной волны (ПВ) в плазме. Металлическая пластина использована одновременно как антенна с поверхностным током и как стенка волноводной структуры. Второй стенкой волноводной структуры является поверхность плазмы. Электромагнитная волна, которая падает на поверхность плазмы, инициирует плазменные колебания, которые формируют в плазме электромагнитное поле поверхностного типа, если характеристики падающего поля (частота и направление волнового вектора) подобраны нужным образом. Показано, что ПВ могут существовать в высокочастотном и низкочастотном диапазонах. ПВ из высокочастотного диапазона могут иметь большую глубину проникновения в плазму и большой поток энергии вдоль поверхности внутри плазмы. ПВ из низкочастотного диапазона могут иметь большое тангенциальное электрическое поле на поверхности плазмы. Работа отвечает на вопросы оптимального выбора геометрии задачи и поверхностного тока для наблюдения в структуре ПВ с предпочтительными характеристиками.

ЗБУДЖЕННЯ ПОВЕРХНЕВОЇ ЕЛЕКТРОМАГНІТНОЇ ХВИЛІ ТА ПЕРЕНЕСЕННЯ ЕНЕРГІЇ ВЗДОВЖ ПЛАСКОЇ ПОВЕРХНІ ПЛАЗМИ

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Запропоновано просту конструкцію для збудження поверхневої хвилі (ПХ) у плазмі. Металеву пластину використано одночасно як антену з поверхневим струмом та як стінку хвилеводної структури. Другою стінкою хвилеводної структури є поверхня плазми. Електромагнітна хвиля, яка падає на поверхню плазми, ініціює плазмові коливання, які формують у плазмі електромагнітне поле поверхневого типу, якщо характеристики поля, що падає на плазму (частота та напрямок хвильового вектора), підібрані належним чином. Показано, що ПХ можуть існувати у високочастотному та низькочастотному діапазонах. ПХ з високочастотного діапазону можуть мати велику глибину проникнення до плазми та великий потік енергії уздовж поверхні в самій плазмі. ПХ з низькочастотного діапазону можуть мати велике тангенційне електричне поле на поверхні плазми. Робота відповідає на питання оптимального вибору геометрії задачі та поверхневого струму для спостерігання в структурі ПХ з бажаними характеристиками.