Dynamical two-dimensional model of pre-explosion phase of microprotrusion heating by plasma contacting the wall

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A two-dimensional dynamical picture of surface heating by plasma contacting the wall with micro-relief was achieved. Non-uniformity on surface is given by microprotrusion (~1μm) geometry, which heats up faster than whole wall. Heating of surface by plasma was taken into account by power fluxes brought by ions and electrons, when surface cooling has been provided by thermo-field electron emission. Heating processes were investigated in wide range of plasma parameters: $\{10^{20}cm^{-3};1eV\}$ – $\{10^{14}cm^{-3};10keV\}$, with average time ~1-10ns. It was shown that explosive character of heating (namely increasing of growth rates of temperature and current: $\partial^2T/\partial t^2>0$, $\partial^2 j/\partial t^2>0$ in the final phase, when achieved: $T\sim10^4K$, $j\sim10^8 A/cm^2$) depends on threshold power flux ~200MW/cm^2. Temperature maximum shifting towards the protrusion bottom was observed. With power fluxes <100MW/cm^2 final dependencies T(t) and j(t) come to saturation.

1. Introduction

In plasma surface interaction micro-explosion processes play an important role. As follows from vacuum arc and spark investigations cathode spot functioning is provided by consequence of micro-explosions on the surface. Each explosion is accompanied by plasma jets and emitted electron portions named ectons [1]. The ecton character size is about ~1μm and time scale of its functioning is about 1-10ns. Initiations of these micro-explosions and ectons can occur e.g. under influence of a dielectric layer breakdowns or micro non-uniformities over-heating. Last mechanism looks a more common one as plasma surface interaction is accompanied by strong surface modification. So the sputtering can lead to cones or whiskers growth, as well as blistering lead to macroscopic destruction. In terms of the ecton model over-heating of a microprotrusion lead to electron emission, and followed additional Ohmic heating by current flowing through protrusion. This self-sustained mechanism results in the protrusion explosive destruction.

Unipolar arcing and droplets ejection from surface both are results of micro-explosions. Droplets ejected from surface as well as dust particles [2] both are disadvantage for any magnetic confinement system. By droplets impurities arrive into the hot plasma core, coming through divertor. Furthermore, the droplet-surface interaction itself can lead to the ectons initiation [1].

Despite of microprotrusion heating models with fixed boundary conditions – like total current [3] or potential drop [4], our aim was to obtain self-consistent picture of growing and sustaining of temperature and current.

In [5] the interaction of a dense plasma ball, formed due to previous explosion, with surface was considered. Here we try to describe the uniform plasma interaction with non-uniformity on the wall.

In [4] the explosive character of a microprotrusion heating by plasma was obtained. Explosion means that final temperature achieves a critical value (~8000K for copper cathode) and still grows. Plasma was assumed produced by previous explosion and not expanded yet, so in [4] the cold dense plasma was considered. And the new ecton formation occurs in neighborhood of a previous one. Therefore, achieving of heating evolution picture in wide range of plasma parameters is of interest.

2. Problem description

Microprotrusion geometry was specified by Gauss function $\Gamma(r,z)\equiv z_0+h\cdot Exp(-(r/r_0)^2)$ (fig.1). Wall material – tungsten, plasma ions – deuterium (D^+), ions are cold $T_i << T_e$ (Bohm criterion satisfied), electron velocities distribution is Maxwellian. So electrons and ions fluxes are:

$$\phi_e = n\sqrt{\frac{T_e}{2\pi m_e}}Exp\left(-\frac{u}{T_e}\right),\ \phi_i=\frac{1}{2}n\sqrt{\frac{T_e}{M_i}}. \quad (1)$$

Corresponding to them heat fluxes are: $q_e=(2T_e+e\varphi)\cdot\phi_e$, $q_i=(u+T_e/2+eI)\cdot\phi_i$. There are n and T_e denotes plasma density and electron temperature, u – sheath potential in [eV], $e\varphi$=4.5eV, eI=13.6eV – work function and ionizing potential accordingly.

Thermal balance $T(r,z)$ of fragment of surface with microprotrusion was calculated in two-dimensional thermal conductivity equation:

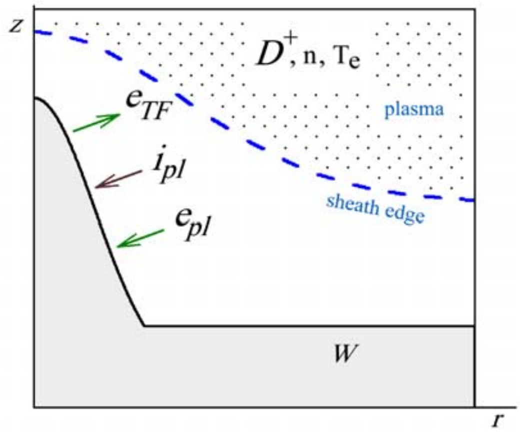

Fig.1. Problem geometry view

$$c\rho\frac{\partial T}{\partial t}=div(\lambda\cdot gradT)+\sigma(grad\varphi)^2. \qquad (2)$$

Material coefficients are considered as temperature functions $\lambda=\lambda(T)$, $\sigma=\sigma(T)$, $\lambda/c\rho\equiv a(T)$. The value $(\sigma\cdot grad\varphi)=j$ is density of current, flowing through microprotrusion.

Surface heating by plasma was taken into account by energy fluxes brought on the surface by ions and electrons. Surface cooling was taken into account by electron emission. The boundary condition is:

$$-\lambda(T)\cdot\left.\frac{\partial T}{\partial n}\right|_\Gamma=q_i+q_e-\delta\varepsilon\cdot j_{TF}/e.$$

Last term describes the emission power flux. Due to both high electric field and high temperature we have to use general thermo-field (*TF*) expression for emission [6]. Both thermo-field emission current density j_{TF} and emitted electron energy distribution (and average electron energy $\delta\varepsilon$) were obtained numerically in WKB approximation.

Both vaporization of surface material and radiation cooling are negligible in our case.

It should be noted, that the Ohmic heating (last term in (2)) play an important role through moving of maximum of temperature toward microprotrusion bottom [4]. Distribution of current flowing through microprotrusion was derived from potential $\varphi(r,z)$:

$$div(\sigma\cdot grad\varphi)=0.$$

Boundary condition was defined by current balance of coming from plasma ions and electrons and emitted electrons $j_i=e\phi_i$, $j_e=e\phi_e$:

$$-\sigma(T)\cdot\left.\frac{\partial\varphi}{\partial n}\right|_\Gamma=j_i-j_e+j_{TF}.$$

Sheath potential distribution $U_0(r,z)$ in vacuum was obtained from $div(gradU_0)=0$. Problem geometry was modeled by the planar diode with microprotrusion at the cathode. Electric field strength was calculated from weighting sum: $E_0|_\Gamma=(1-f)\cdot U_{fl}/L_d+f\cdot\{-\nabla U_0\}|_\Gamma$, where weight multiplier $f(h)=Exp\left(-3.6\cdot(2h/L_d-1)^2\right)$ – is a function of microprotrusion height h, U_{fl} – floating potential, L_d – Debay length. Value f – is the "two-dimensionality" parameter, which becomes negligible if ratio $2h/L_d$ is very small or very big.

Decreasing of electric field at the wall due to high electron emission was derived from Mackeowen-like equation:

$$\left.\frac{E^2}{8\pi}\right|_\Gamma=\chi^2 enT_e\left\{\sqrt{2u/T_e+1}-2+Exp(-u/T_e)\right\}- -j_{TF}\sqrt{2m_e}\left(\sqrt{u+|\delta\varepsilon|}-\sqrt{|\delta\varepsilon|}\right).$$

Function $\chi\equiv E_0|_\Gamma\cdot L_d/U_{fl}$ – is the form factor.

In this work we didn't calculate two-dimensional dynamics of sheath potential distribution. Nevertheless, we can estimate changes in the sheath potential near emitting protrusion as follows. Problem geometry can be schematically drawn on figure 2. If we specify the current δJ flowing through protrusion bottom into the wall it is possible to consider various cases by choosing δJ value. From $\delta J=Sj_{TF}$, which corresponds to perfect protrusion conductivity (then floating potential of protrusion not changes), to $\delta J=0$, which describes insulated from surface protrusion (then floating

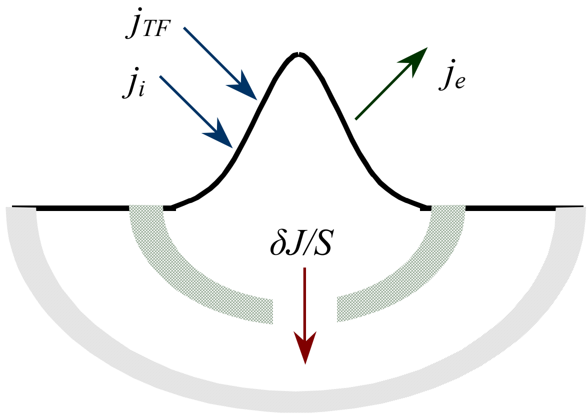

Fig.2. For evaluation emitting protrusion sheath potential

potential of protrusion maximally decrease due to emission). Proceeding from current balance (see fig. 2): $\delta J/S=j_i-j_e+j_{TF}$ one can obtain the sheath potential between plasma and emitting protrusion:

$$u=U_{fl}-T_eLn\left(1+\frac{j_{TF}-\delta J/S}{j_{Bohm}}\right), \qquad (3)$$

where $j_{Bohm} = j_i$ – Bohm current density, $\delta J/S$ – current density flowing into the wall. This expression describes decreasing of the sheath potential fall at the high enough emission current.

As known [7], in stationary case sheath potential (3) cannot be zero. Here we presume, that, due to short times and virtual cathode formation, floating potential of emitting body (3) decrease to zero, i.e. slowing down the plasma electrons field disappears.

3. Results

In wide range of plasma densities and electron temperatures $\{10^{20}\text{cm}^{-3}; 1\text{eV}\}$, $\{10^{14}\text{cm}^{-3}; 10\text{keV}\}$ (Fig. 3) the plasma parameters were obtained, when in final heating phase the growth rates of temperature and current increase in time, i.e. second derivatives are positive $\partial^2 T/\partial t^2 > 0$, $\partial^2 j/\partial t^2 > 0$ (Fig. 4). Here we state, that such growth of T and j in time together with extremely high values of temperature and current (10^4K, 10^8A/cm^2) will lead to consequent "explosion" of a protrusion. It was shown, that this "explosive" growth of T and j is defined by power flux q on the surface. Obtained threshold value is about $q_{thr} \sim 200\text{MW/cm}^2$. The total heat power flux from plasma is given by:

$$q_{tot}(u) = q_i + q_e = \frac{1}{2} n \sqrt{\frac{T_e}{M_i}} \left\{ u + \frac{T_e}{2} + eI + (2T_e + e\varphi)\sqrt{\frac{2M_i}{\pi m_e}} Exp(-u/T_e) \right\}. \quad (4)$$

Without taking into account sheath potential shifting (3) the threshold needs to be achieved by $q_1 \equiv q_{tot}(U_{fl}) = (U_{fl} + 2.5T_e + eI + e\varphi)\cdot \phi_i$, which is mostly ions power flux $q_1 \sim q_i$ (as also noted in [4]). In the case of potential shifting due to high emission according to (3) it is necessary only that power flux $q_2 \equiv q_{tot}(0)$ exceeds the threshold 200MW/cm^2. This value is mostly electrons power:

$$q_2 \equiv \left\{ \frac{T_e}{2} + eI + (2T_e + e\varphi)\sqrt{\frac{2M_i}{\pi m_e}} \right\} \cdot \phi_i \approx q_0^e,$$

where $q_0^e \equiv (2T_e + e\varphi) n \sqrt{T_e / 2\pi m_e}$ – is the power flux, that brought from plasma by electrons without slowing down in potential fall (u=0).

Figures 4 and 5 corresponds to the evolution of heating of protrusion 0.5μm in height by plasma with n=10^{16}cm^{-3}, T_e=387eV. Dates on fig. 5 correspond to the top of the protrusion.

The explosive T and j growth is accompanied by the shifting of temperature maximum from top toward the protrusion bottom (fig.6). As the conductivity decrease with temperature Ohmic-heating intensifies at temperature maximum, so heating in volume is bigger than heating at surface.

If the total heat flux on surface not exceeds

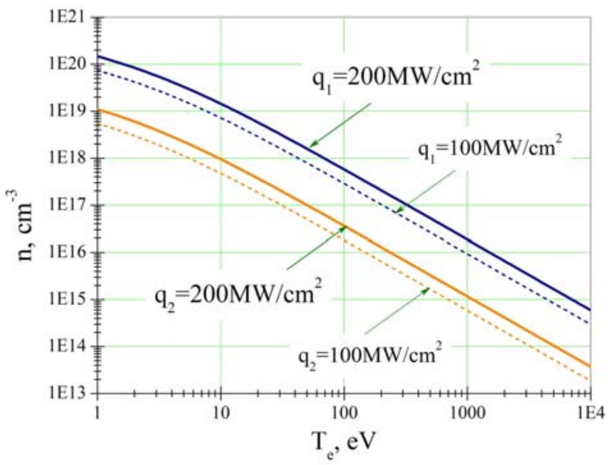

Fig. 3. Plasma power fluxes on the n – T_e plot

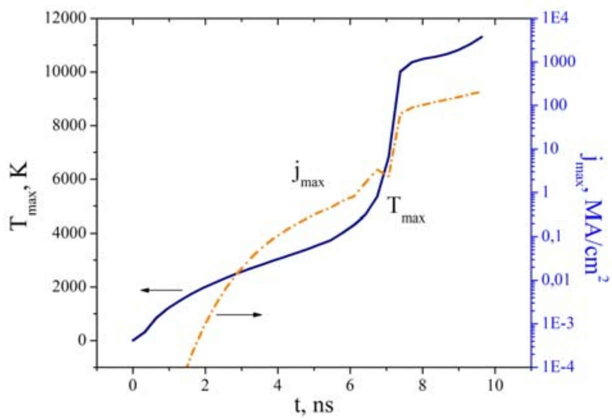

Fig. 4. Maximal values T and j evolutions

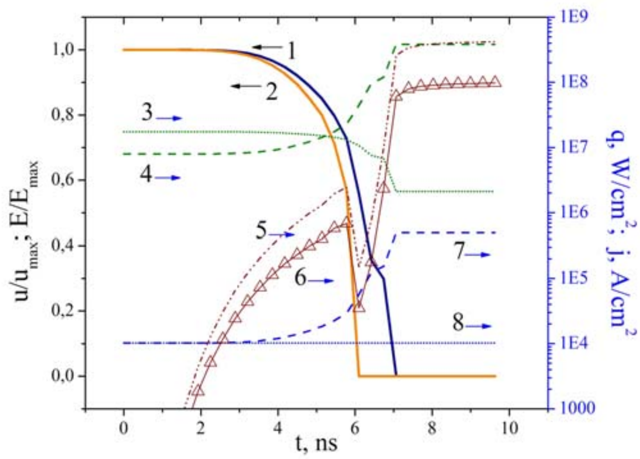

Fig. 5. 1,2 – sheath potential and electric field divided on their maximal values; 3,4,5 – power fluxes of plasma ions, plasma electrons and emitted electrons accordingly, 6 – emitted current density, 7,8 – current densities of plasma electrons and ions (= Bohm current) accordingly

100MW/cm^2 the final dependencies of temperature and current come to saturations (slowing down of growth rates $\partial^2 T/\partial t^2 < 0$ and $\partial^2 j/\partial t^2 < 0$).

With power flux ~10MW/cm^2 only the shifting of temperature maximum towards the protrusion base is observed in ~10ns. With decreasing of the incident power temperature gradients becomes smoother.

With power fluxes <1MW/cm^2 it needs a "preliminary" heating up to 3000-4000K for sufficient increasing the emission current. This heating lasts longer time (>1µs) that we consider here for ecton formation (taking into account vaporization and radiation cooling is necessary).

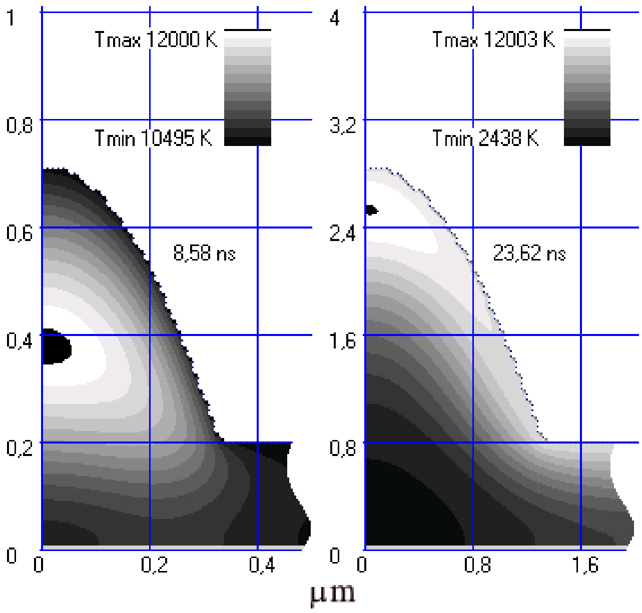

Fig. 6. Final T(r,z) – "before" explosion, for plasma with n=10^{14}cm^{-3}, T_e=8keV, for two protrusion heights: 0.5µm (left) and 2µm (right)

Exact view of protrusion geometry mostly defines the rate of heating. In particular, narrow protrusions heat faster; geometry also defines speed of temperature maximum moving towards the microprotrusion bottom due to the Ohmic heating.

The size of a protrusion weakly influences the explosion itself. Bigger one heats up longer (fig.7) and Ohmic heat release occurs close to the top (fig.6), so bottom of a big protrusion plays a negligible role.

4. Conclusions

The investigation of the pre-explosion phase of the ecton initiated by plasma-overheated microprotrusion on the surface was performed.

It can be pointed out, what achieved results defines following explosion of the microprotrusion on the surface due to the high temperature and current in final phase. The final temperature – T_{final}

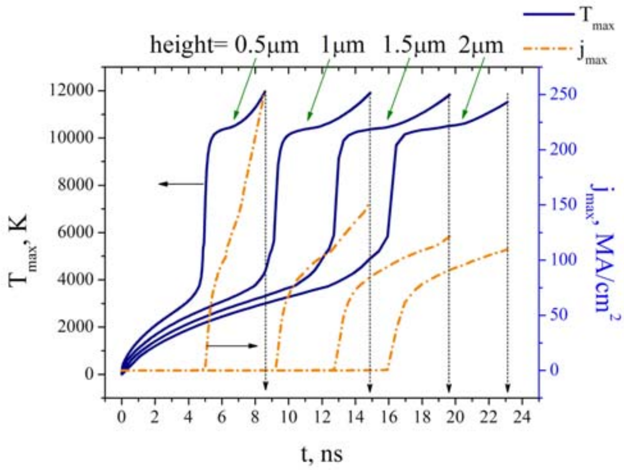

Fig. 7. Maximal T(t), j(t) for plasma n=10^{14}cm^{-3}, T_e=8keV, for various protrusion heights: 0.5; 1; 1.5; 2µm

exceeds critical temperature (~11880K for tungsten) even in case when T and j have saturation and T_{final} continues growth in case of explosive heating.

The microprotrusion size and geometry mostly defines the time of heating and the size of metal droplet ejected from surface. Although, we didn't consider here explosion process itself (as in [3]).

Occurring of the ring "rims", surrounding the explosion centers of unipolar arc [5], not follows from our work. Apparently, these ring "rims" forms after explosion due to the interaction of dense ecton plasma with surface (according to the [5]).

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5. References

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