26^{th} EPS Conf. on Contr. Fusion and Plasma Physics, Maastricht, 14 - 18 June 1999 ECA Vol.23J (1999) 1261 - 1264

$E \times B$ Type drifts in vapour layers evolving over vaporizing surfaces subjected to hot plasmas

P. Lalousis*, R. Schneider**, and L. L. Lengyel**
*Institute of Electronic Structure and Laser, Foundation for Research and Technology-HELLAS,Heraklion 71110,Greece,
**Max-Planck-Institut für Plasmaphysik,Euratom Association, D-85748 Garching, Germany

During off-normal operational regimes in large-scale tokamaks, e.g. hard disruptions and giant ELMs, an intense flux of high-energy plasma particles confined by a skewed magnetic field impacts the plasma-facing machine components. The initially bare surface is exposed to incident particles, electrons and ions of equal number fluxes (ambipolarity condition), without any gasdynamic shielding present. As time goes on, the surface temperature increases to values at which intense vaporization begins. The surface becomes covered by a dense vapour layer which rapidly expands due to the pressure gradients evolving. Owing to intense heating by the incident plasma particles, the eroded particles begin to ionize at some distance from the surface. Similar processes occur in ablating cryogenic or solid pellets in fusion machines. The energy carriers primarily responsible for solid surface erosion are charged particles originating from the plasma. The penetration and spatial deposition of different charged species with different masses and energies in the vapour layer generate a field-aligned electrostatic field component, whose strength can be calculated on the basis of the quasi-neutrality and ambipolarity conditions.
A two-dimensional model has been developed for calculating the time evolution of radiating vapour clouds formed over ablating solid surfaces subjected to magnetically confined energetic plasma particles. The electric field and current distributions are determined self-consistently on the basis of a properly posed boundary value problem. The representative computational results presented show the formation of rather intense electric fields and subsequently the production of $\mathbf{E} \times \mathbf{B}$ type lateral drifts which sweep the vapour layer aside, thus seriously impairing its shielding characteristics on the anti-drift side. This impairment on the vapour shielding characteristics has the effect of substantially increasing the erosion rate of the solid surface on the anti-drift side. Quantitative results are also provided on the effect of the inner (base plate) and outer (vapour-plasma interface) boundary conditions on the resulting erosion rates.

The physics model is defined in terms of the same set of resistive MHD equations that had been used in earlier 1-D and 1.5-D models[1]. The expansion dynamics of the vapor layer is described in the usual continuum MHD approximation by means of a single-fluid single-temperature model with allowance for seven different species corresponding to the different ionization states of carbon. In a two-dimensional model, only $\partial/\partial z = 0$ and current loops may form in the x, y plane, while the $\nabla \cdot \mathbf{j}_\Sigma = 0$ condition is still satisfied in the entire domain and at the boundaries. In this case, the $\mathbf{E}$ field is uniquely defined by the potential equation that can be derived from Maxwell's equation and Ohm's law, and the boundary conditions applied. For computational convenience (the implementation of the boundary conditions), preference was given in the analysis to computing the current distribution rather than the potential distribution. As will be seen, the $\mathbf{E}$ field distribution can be determined in this case from the current distribution by means of Ohm's law. Note that the current

distributions, conductive and/or total, depend upon the beam current distribution, i.e. on the collisional depletion of the energy carriers, and the set of boundary conditions prescribed.
The projections of the 'beam current' on the y and z axes are given by $\mathbf{\Gamma} \equiv e(\mathbf{\Gamma}_e - \mathbf{\Gamma}_i) = \hat{\mathbf{b}}\Gamma$, where $b_y = \sin\alpha$,and $b_z = \cos\alpha$. The magnetic field $\mathbf{B}$ is kept constant in this analysis. The total current represented by the sum of the conduction current and the beam current can be written as $\mathbf{j}_\Sigma = \mathbf{j} + \mathbf{\Gamma}$. It has three components $(j_x,\ j_y + b_y\Gamma, j_z + b_z\Gamma)$ and is divergence-free: $\nabla\cdot\mathbf{j}_\Sigma = 0\cdot$
Using this definition of the total current density, Ohm's law can be rewritten as:

$$\mathbf{j}_\Sigma + \beta_e(\mathbf{j}_\Sigma \times \hat{\mathbf{b}}) = \sigma\left(\mathbf{E} + \mathbf{v}\times\mathbf{B} + \frac{1}{en_e}\nabla p_e\right) + \hat{\mathbf{b}}\Gamma\ . \tag{1}$$

Since $\nabla\cdot\mathbf{j}_\Sigma = 0$ and $\partial/\partial z = 0$, a two-dimensional current density stream function γ can be introduced for the total current density distribution in the x, y plane: $j_{x\Sigma} = \frac{\partial\gamma}{\partial y}$, $\quad j_{y\Sigma} = -\frac{\partial\gamma}{\partial x}$.
The basic equation defining the current stream function γ is given by the z-component of the vector equation that can be obtained, after some algebraic manipulation, by taking the curl of Eq.(1). The resulting equation is a second-order, reaction-diffusion type, partial differential equation of the form[3]

$$a\left(\frac{\partial^2\gamma}{\partial x^2}\right) + b\left(\frac{\partial^2\gamma}{\partial y^2}\right) + c\left(\frac{\partial\gamma}{\partial x}\right) + d\left(\frac{\partial\gamma}{\partial y}\right) = S\ . \tag{2}$$

where a, b, c, d and S are coefficients involving the various parameters of the plasma and the magnetic field.
The electric field distribution is related to the current distribution by Ohm's law (see eq. (1)) and can be calculated on the basis of a matrix equation[1]. If the relation $\sigma_\perp \neq \sigma_\parallel$ is taken into account, the resistivity tensor becomes notably more complicated[1].
The boundary conditions supplementing Eq (2) are as follows:

(**a**) Insulator plate (insulator sections) at $y = 0$:

$j_y = j_{y\Sigma} = -\partial\gamma/\partial x = 0$, i.e. γ= constant along an insulator plate, the plate surface representing a current 'streamline'.

(**b**) Conductor plate (conductor sections) at $y = 0$:

The condition $E_x = -v_y B_z + v_z B_y + (j_x + b_z\beta_e j_{y\Sigma}) = 0$ yields the relation

$$\frac{\partial\gamma}{\partial y} = [\sigma(v_y B_z - v_z B_y) + +\beta_e(b_z\frac{\partial\gamma}{\partial x} + b_y\sigma v_x B_y)](1 + b_y^2\beta_e^2).$$

Since at an impermeable solid wall $v_y = 0$ and $\beta_e = \omega_e\tau_e \to 0$, this boundary condition reduces to $\partial\gamma/\partial y = -\sigma v_z B_y$.

(**c**) At cloud - vacuum interfaces (outside the beam domain) the normal current component vanishes, $j_n = j_{n\Sigma} = 0$, and γ remains constant along the interface. Hence the interface contour (vacuum boundary) is a current streamline.

(**d**) Cloud - 'beam plasma' interface:

Since $\nabla\cdot\mathbf{j}_\Sigma = 0$ and thus the surface integral $\int\mathbf{j}_\Sigma\cdot d\mathbf{a} = 0$ vanishes (d$\mathbf{a}$ being a surface differential), the integral of $d\gamma$ taken along the interface contour line vanishes as well.

The energy transfer from the disruptive plasma to the vapour cloud and the solid plate is calculated by mean of a stopping length algorithm. The incident charged particle fluxes are

funneled along the magnetic field lines and are depleted by collisional interactions with the cloud particles. Maxwellian energy distributions are assumed for the energy carriers.
Finite difference(finite volume) techniques have been implemented to solve the system of equations, described above, in the x, y plane. The system of equations: particles conservations equations, the momentum equation (three velocities), the energy equation, the radiant energy equation, and the equation for the stream function of the current density, are first and second order partial differential equations in Eulerian description. The finite difference methods are based on a Godunov scheme with second order correction[4], and on a iterative method for large sparse matrices arising from the implicit discretization of second order partial derivatives.

Numerical calculations were performed for the following scenario: a carbon plate occupying the lower half-space $y \leq 0$ is subjected to the action of plasma particles stemming from a disrupting plasma and confined to an infinite strip $z \leq \pm\infty$ of given width in the lateral direction: $1.5 \leq x(cm) \leq 2.5$. Within this strip, the plate is assumed to be an electrical conductor (due to the high temperatures evolving) and an insulator outside the strip. The disrupting plasma particles are of Maxwellian energy distribution, $T_{e0} = T_{i0} = 5keV$, $n_{e0} = n_{i0} = 10^{20}m^{-3}$, $B_0 = 6tesla$, and the angle of incidence of the magnetic field lines $\alpha = 5degr$. The Hall parameter β_e was assumed to be zero in this series of calculations.
Figure 1 shows the current streamline pattern monitored at 10 μs after plasma-wall contact. The two dotted lines represent the heat deposition channel of the disrupting plasma. The streamlines are separated by equal increments of the total current: $\Delta\gamma$=50kA/m (current per unit length in the z-direction), an exception is the last (outer) streamline. The maximum γ values monitored in Fig. 1 is 300 kA/m at 10 μs. This value corresponds to δB_z = 0.35 $tesla$, i.e. to a normalized perturbation field amplitude of 6 per cent. In Figure 2, the the erosion depth is shown as a function of the lateral coordinate (x) at a time instant 10μs following the start of the plasma-wall interaction. The asymmetry of the erosion depth is clearly visible: it is, at the given time instant, almost twice as large at the right edge than at the left edge. The cause of this asymmetry is the fact that the cloud formed over the eroding surface is swept from the right to the left by the $\mathbf{E} \times \mathbf{B}$ drift, thus impairing the shielding characteristics of the cloud on the right side. Hence the disrupting beam heats more effectively the solid at the right edge. The origin of this $\mathbf{E} \times \mathbf{B}$-type drift was discussed in detail in the framework of one-dimensional analysises[1,2].
Vector plots of the velocity and electrostatic field distributions in the poloidal (x,y) plane are shown in Figs. 3 and 4 for the cloud domain in the vicinity of the base plane.
The asymmetry of the velocity distribution, i.e. the drift from the right to the left sides, is clearly visible. The expansion velocity in the direction normal to the plate is of the order of $10^4 m/s$, in agreement with 1-D and 1.5-D calculations[1]. As can be seen, the magnitude of the drift velocity is of the order of 10^3 to $10^4 m/s$, and is again in agreement with results stemming from 1-D and 1.5-D approximations[1,2]. As a result of this drift, the density and temperature distributions within the vapor cloud covering the plate become notably asymmetric.

Based on the results presented the following conclusions can be made:
1. Intense electric fields and strong eddy currents can be expected to form in vapor layers evolving over vaporizing surfaces subjected to energetic plasma particles, such as divertor plates.
2. An $\mathbf{E} \times \mathbf{B}$ - type lateral drift sweeps the vapor layer aside, thus seriously impairing its

shielding characteristics on the anti-drift side, as is clearly shown.

3. Excessive ohmic heating (melting/sublimation) and arc formation may take place at the edges of conducting wall segments, leading to local erosion rates higher than those anticipated until now.

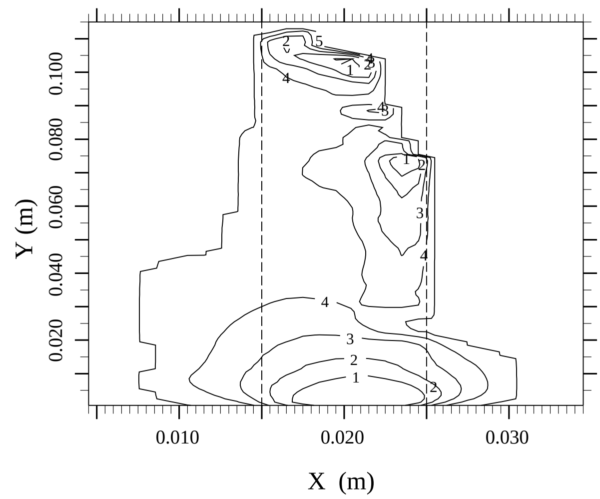

Figure 1: Contours of the current density stream function γ at $10\mu s$

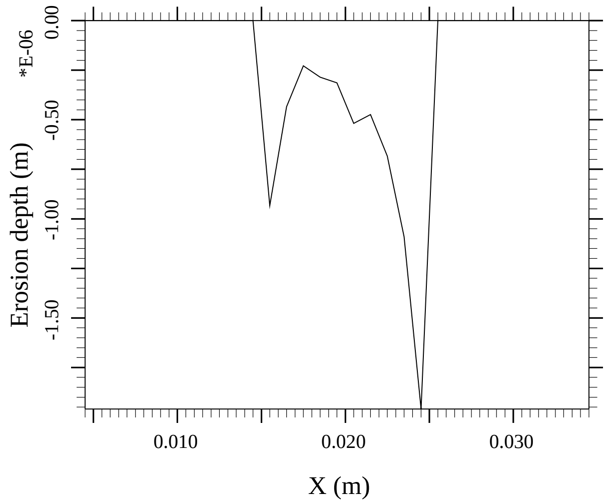

Figure 2: Erosion depth at 10 μs.

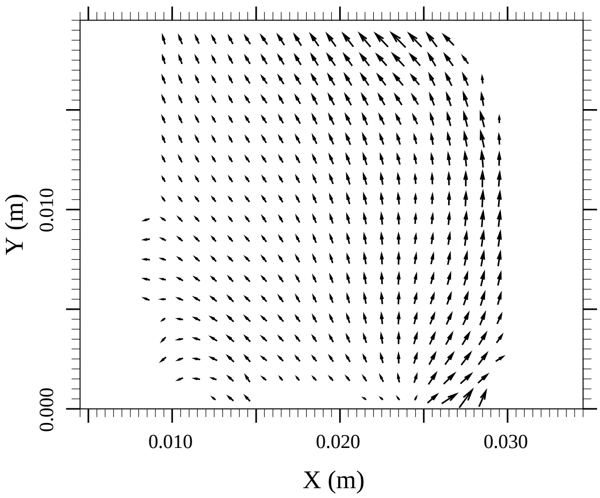

Figure 3: Vector plots of v_x and v_y, at $10\mu s$ (max. vect. ampl. = $2.0x10^4 ms^{-1}$)

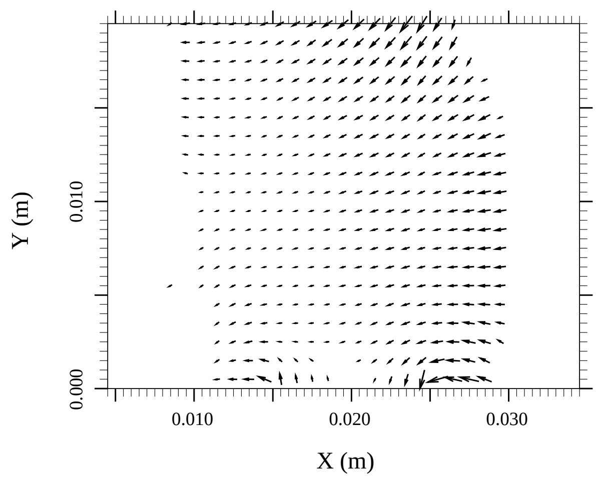

Figure 4: Vector plots of E_x and E_y (max. vect.ampl. = $4.0x10^4 Vm^{-1}$)

REFERENCES

[1] L.L. Lengyel, K. Lackner, P.J. Lalousis, and P.N. Spathis, et al., 'Divertor Plate Erosion and Radiating Vapour Shield Formation During Hard Disruptions, Theory and Numerical Modelling', Nucl. Fusion **38** 1998, 1435-1459.

[2] L.L. Lengyel, V.A. Rozhansky, I.Yu. Veselova, and P.J. Lalousis, Nucl. Fusion **37**, 1245 (1997).

[3] L.L. Lengyel, Phys. Letters **29A**, 60 (1969), see also AIAA Journal **9**, 1957 (1971), and Energy Conversion **9**, 13 (1969).

[4] R. J. LeVeque, *Numerical Methods for Conservation Laws* , Birkhauser-Verlag, Basel, 1990.