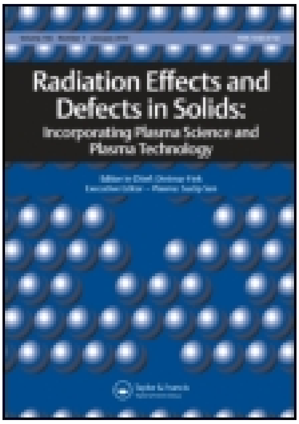

Radiation Effects and Defects in Solids: Incorporating Plasma Science and Plasma Technology

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/grad20

Effects of radio frequency waves on plasmas

J.J. Martinell[a], S. Sen[bc] & G. Vahala[c]

[a] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, A. Postal 70-543, México D.F., Mexico;

[b] National Institute of Aerospace, Hampton, VA 23666, USA;

[c] College of William and Mary, Williamsburg, VA 23187, USA

Published online: 08 Oct 2013.

To cite this article: J.J. Martinell, S. Sen & G. Vahala (2013) Effects of radio frequency waves on plasmas, Radiation Effects and Defects in Solids: Incorporating Plasma Science and Plasma Technology, 168:10, 866-872, DOI: 10.1080/10420150.2013.831859

To link to this article: http://dx.doi.org/10.1080/10420150.2013.831859

Radiation Effects & Defects in Solids, 2013
Vol. 168, No. 10, 866–872, http://dx.doi.org/10.1080/10420150.2013.831859

Taylor & Francis
Taylor & Francis Group

Effects of radio frequency waves on plasmas

J.J. Martinell[a]*, S. Sen[b,c] and G. Vahala[c]

[a]*Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, A. Postal 70-543, México D.F., Mexico;* [b]*National Institute of Aerospace, Hampton, VA 23666, USA;* [c]*College of William and Mary, Williamsburg, VA 23187, USA*

(*Received 24 July 2013; final version received 31 July 2013*)

A novel technique is proposed for creating transport barriers by the rf waves. This is that the transport barriers can be created by the rf induced ponderomotive force itself and *no* rf induced flow shear generation is necessary. It is demonstrated that the ponderomotive force of the rf waves can stabilize the ion temperature gradient mode, considered nowadays as the dominant source of anomalous energy losses in the low confinement (L) mode. The underlying physics of this stabilization mechanism is identified and is found to be rather general in the sense that all potential drift-like instabilities are expected to be affected in a similar way. It is also shown that this stabilization can be achieved for rather modest values of the rf power, and, hence should be easily obtained in actual fusion devices. Applications to other areas are also discussed.

Keywords: plasma; instabilities; transport

1. Introduction

In order for the tokamak to become a leading contender for a fusion reactor, a magnetic configuration should be developed that has good confinement and stability and a large fraction of bootstrap current. Progress towards this end has been made by the recent discoveries of various enhanced performance operational regimes like the high (H) modes, the very high (VH) modes and the enhanced reverse shear (ERS) modes. Foremost of these is the ERS mode, which is believed to provide the characteristics desirable for a fusion reactor. However, while a sheared poloidal (toroidal) flow is found to be responsible for the H- (VH-) modes, a non-monotonic q profile (hence normally a hollow current profile) is necessary for the ERS modes. Most tokamaks, however, operate with inductive current drive which, in general, produces a peaked current density profile at the magnetic axis because of the strong dependence of the plasma conductivity on the electron temperature. Only by noninductive current drive or transient techniques can a hollow current density profile be generated. The ERS modes therefore suffer from the inherent shortcoming of being transient in nature and, hence, may not be an obvious choice for a reactor-grade self-sustaining plasma.

Recently, there has been considerable interest in whether rf waves can be used to create the transport barrier to reduce the loss of particles and energy from the plasma (*1–3*). In most of these cases, the formation of transport barriers by the rf waves relies on the hypothesis of the

*Corresponding author. Email: martinel@nucleares.unam.mx

generation of rf driven flow shear and consequent suppression of turbulence. However, although rf can introduce toroidal flow, the momentum transferred to the electrons from the rf field is dissipated quickly by the background ions and in reality toroidal rotation induced by rf is rather small (*4*). This has also been confirmed in the recent experiments on the Joint European Torus (JET) (*5*). Similarly, poloidal flows from both the direct launch and mode-converted Ion Bernstein Waves (IBW) have been observed in the last run of experiments in the Tokamak Fusion Test Reactor (TFTR) (*6*), but not of the magnitude believed to be required to obtain a barrier (*7*). The underlying physics seems to be that a wave–particle interaction cannot impart that much momentum to the plasma as a particle–particle interaction does (*e.g.* momentum imparted by the Neutral Beam Injection (NBI)). Therefore, a transport barrier by rf waves has so far proved elusive in a fusion device.

In this work, we propose a novel technique for creating transport barriers by the rf waves. Namely, that the transport barriers can be created by the rf-induced ponderomotive force *itself* and *no* rf-induced flow shear generation is necessary.

2. Analysis

2.1. *Theoretical technique*

First, the linearized nonlocal stability analysis of the instabilities is carried out assuming, for simplicity, a Cartesian co-ordinate system and a two-fluid model for instabilities in the presence of radio waves. Initially, a low β collisionless plasma (hence neglecting any electromagnetic fluctuations) can be assumed. In the simplest case the ponderomotive force will be modeled by a profile $F_{\mathrm{RF}}(x) \equiv F_{\mathrm{RFoo}} + (x/L_{\mathrm{RF1}} + x^2/L_{\mathrm{RF2}}^2)F_{\mathrm{RFoo}}$, where, $\mathrm{d}F_{\mathrm{RFo}}/\mathrm{d}x = F_{\mathrm{RFoo}}/L_{\mathrm{RF1}}$, $\frac{1}{2}(\mathrm{d}^2F_{\mathrm{RFo}}/\mathrm{d}x^2) = F_{\mathrm{RFoo}}/L_{\mathrm{RF2}}^2$, which is a simple Taylor series expansion about the reference mode rational surface. However, other profiles like the 'tanh-profile' can be used to simulate the reversal as the case may rise. From the linearized equations of continuity, momentum transfer for ions and electrons appropriate for the instability considered and by applying the quasi-neutrality condition the radial eigen-value equation can be obtained.

Under certain simplifications, the equation can be solved analytically and then a closed form for the dispersion relation can be obtained from which the stability/instability properties of the mode are found. However, for some instabilities even the linearized case is not expected to be solved analytically and we need to solve it numerically. The results obtained in this way are then compared with the observations. These results, however, have only a limited validity as a non-linear stability analysis should be more appropriate to compare with the data obtained from various space missions. A non-linear evolution of the model is also necessary for the turbulence and transport study. The only way a non-linear case can be solved is by the numerical analysis.

Coming to the type of instabilities that can be of relevance, it is expected that they will be of low frequency in the ionosphere. The study could be extended to higher frequencies to cover other instabilities in both electrostatic and electromagnetic versions. The model considered for this analysis is based on the two-fluid theory (a one fluid magnetohydrodynamic [MHD] model could also be studied to get a simplified analysis). In the simplest version of the linear theory in a 1D geometry, it is possible to get a Weber-type equation which may be solvable analytically in some cases. This simple model is used to get a physical insight into the actual more complicated non-linear problem which is expected to be solved only numerically.

We now present an outline of this analysis. The starting point is a plasma in equilibrium in a sheared magnetic field with a slab geometry, $\mathbf{B}(x) = B_0\hat{z} + B_y(x)\hat{y}$, where the poloidal component is taken locally (around a rational surface) as $B_y(x) = B_0x/L_s$, with L_s the shearing scale length and x the radial co-ordinate. The equilibrium plasma variables are only functions of x. Then, perturbations of the form $\phi(\mathbf{r}, t) = \phi_1(x)\exp[\mathrm{i}(k_y y + k_z z - \omega t)]$ are applied assuming the regime of small gyroradius, $k_\perp \rho_i \ll 1$. The drive for the instability is the ion temperature gradient (ITG) which is responsible for the diamagnetic fluid drift $\mathbf{v}_D = (c/eBn_i)\hat{b} \times \nabla_\perp p_i$. Additionally, the presence of rf waves is included through the effect of the associated ponderomotive force $\mathbf{F}_{\mathrm{RF}}$, which in turn gives rise to a drift velocity

$$\mathbf{v}_{\mathrm{RF}} = (c/B)\mathbf{F}_{\mathrm{RF}} \times \hat{b}.$$

The perturbed equations of continuity, parallel momentum and adiabatic pressure evolution for ions, in the linear approximation, can be reduced to the following equation for the electrostatic potential (*8*):

$$\frac{\mathrm{d}^2\tilde{\phi}}{\mathrm{d}x} + (T + Qx + Mx^2)\tilde{\phi} = 0, \tag{1}$$

where

$$T = -k_y^2 + \frac{1 - \Omega + (F_{\mathrm{RF0}}/k_y v_D)(1/L_{\mathrm{RF}} + v_D)}{\Omega + K},$$
$$Q = \frac{(F_{\mathrm{RF0}}/k_y v_D L_{\mathrm{RF}})(1/L_{\mathrm{RF}} + v_D)}{\Omega + K} \quad \text{and}$$
$$M = \frac{s^2}{\Omega^2(1 - \Gamma s^2 x^2/\tau\Omega^2)} + \frac{F_{\mathrm{RF0}}}{2k_y(\Omega + K)L_{\mathrm{RF}}^2}.$$

Here, x is the distance from the mode rational surface and all quantities are made dimensionless according to $\tilde{\phi} = e\phi/T_e$, $\tilde{v} = v/c_s$ and distances to a characteristic length L of the order of the density scale length L_n. The following parameters are defined:

$$\tau = \frac{T_e}{T_i}, \quad s = \frac{L_n}{L_s}, \quad K = \frac{1 + \eta_i}{\tau}, \quad \Omega = \frac{\omega}{k_y v_D}$$

and Γ is the ratio of specific heats. K measures the relative size of the density to temperature gradients since $\eta_i = \mathrm{d}\ln T_i/\mathrm{d}\ln n$. To model the ponderomotive force, an expansion in terms of a Taylor series was assumed $F_{\mathrm{RF}}(x) = F_{\mathrm{RF0}}(1 + x/L_{\mathrm{RF1}} + (x/L_{\mathrm{RF2}})^2$ so that the wave intensity has a maximum at the mode rational surface and L_{RF} is the width of the deposition profile (for simplicity, we assume $L_{\mathrm{RF1}} \sim L_{\mathrm{RF2}} \sim L_{\mathrm{RF}}$).

When $\Gamma = 0$ the eigen-value equation reduces to a simple Weber equation whose properties and solutions are well known. The solvability condition gives the dispersion relation

$$\frac{Q^2}{4M} = T - \mathrm{i}\sqrt{M}, \tag{2}$$

which can be solved for the real and imaginary parts of $\omega = \omega_r + \mathrm{i}\gamma$. In Ref. (*8*), it has been shown that the growth rate γ decreases as F_{RF0} is increased and when L_{RF} is reduced, for a given value of $k_y\rho_i$. The real frequency is also reduced in absolute value under the same conditions. As a function of k_y, γ presents a maximum for a certain value $k_{y,M}$ which would give the effective growth rate for the overall mode, and the value of $k_{y,M}$ increases with F_{RF0}. For $F_{\mathrm{RF0}} \geq 0.1$ and $L_{\mathrm{RF}} \leq 0.1$ the mode is almost completely stable and has $\omega_r \approx 0$. For finite Γ the dispersion relation cannot be found analytically but the results obtained numerically are qualitatively the same.

2.2. *Numerical transport analysis*

We describe here an outline of the transport simulations to be performed in a closed plasma system, aimed at estimating the effect of the transport barrier on plasma confinement. In order to obtain the diffusion coefficient, we use a mixing length estimate based on the growth rate γ for the unstable mode and its radial scale length, Δ. Then, the coefficient would be given by

$$D_a = \gamma \Delta^2.$$

As described earlier, the ITG mode growth rate is found by numerically solving the dispersion relation (2) and it is presented as a function of the normalized poloidal wavenumber, $k_y\rho_i$. The values of γ are in a range of the order of 0–0.3ω_{*e}, where ω_{*e} is the electron drift frequency. Since $\gamma(k_y)$ has a maximum, we take this value $\gamma(k_{r,M})$ for the evaluations and use the corresponding value of the real part for the same wavenumber $\omega_r(k_{r,M})$ where this is needed. For the mode width, we have estimated it from the structure of the eigenfunctions that describe it. They are determined by the differential Equation (1) that has the form of a Weber. Upon examination, the solutions are localized in a region of width $\Delta = (2\sqrt{M})^{-1/2}$, with M defined after Equation (1). Therefore, the diffusion coefficient, in terms of the normalized growth rate $\hat{\gamma} = \gamma/\omega_{*e}$, is

$$D_a = \left[\frac{\hat{\gamma}}{2\sqrt{M}}\right]\omega_{*e}. \tag{3}$$

This expression is used for the particle diffusion as well as the heat conductivities for both ions and electrons, but each one is multiplied by a constant to be determined by fitting to experimental values.

Transport analysis in performed using the Astra code (*9*) in the predictive mode. The Astra code solves the fluid equations for ions and electrons together with an equation for the neutral particles which acts as the source of plasma particles. The fluid equations are the continuity equation for density n (which is the same for ions and electrons since quasi-neutrality is assumed), the energy equations for electron temperature T_e and ion temperature T_i, and the longitudinal (to the B field) equation for the poloidal magnetic flux ψ

$$\frac{1}{V'}\left(\frac{\partial}{\partial t} - \frac{\dot{B}_0}{2B_0}\frac{\partial}{\partial\rho}\rho\right)(V'n) + \frac{1}{V'}\frac{\partial}{\partial\rho}\Gamma_e = S_e, \tag{4}$$

$$\frac{3}{2}\frac{1}{V'^{5/3}}\left(\frac{\partial}{\partial t} - \frac{\dot{B}_0}{2B_0}\frac{\partial}{\partial\rho}\rho\right)(V'^{5/3}nT_e) + \frac{1}{V'}\frac{\partial}{\partial\rho}\left(q_e + \frac{5}{2}T_e\Gamma_e\right) = P_e, \tag{5}$$

$$\frac{3}{2}\frac{1}{V'^{5/3}}\left(\frac{\partial}{\partial t} - \frac{\dot{B}_0}{2B_0}\frac{\partial}{\partial\rho}\rho\right)(V'^{5/3}nT_i) + \frac{1}{V'}\frac{\partial}{\partial\rho}\left(q_i + \frac{5}{2}T_i\Gamma_i\right) = P_i, \tag{6}$$

$$\sigma_\parallel\left(\frac{\partial\psi}{\partial t} - \frac{\rho\dot{B}_0}{2B_0}\frac{\partial\psi}{\partial\rho}\right) = \frac{J^2R_0}{\mu_0\rho}\frac{\partial}{\partial\rho}\left(\frac{G_2}{J}\frac{\partial\psi}{\partial\rho}\right) - \frac{V'}{2\pi\rho}(j_{\mathrm{BS}} + j_{\mathrm{CD}}), \tag{7}$$

with V the volume variable, ρ the radial co-ordinate, $V' \equiv \partial V/\partial\rho$, $G_2 \equiv (V'/4\pi^2)\langle(\nabla\rho/r)^2\rangle$, r the radial variable from the symmetry axis, B_0 and R_0 are the axial magnetic field and major radius at the magnetic axis, $J = I/R_0B_0$, I the poloidal current inside a magnetic surface, $\sigma_\parallel$ the parallel electrical conductivity and $\dot{B}_0 = \mathrm{d}B_0/\mathrm{d}t$. The particle and energy sources are S_e and P_e, P_i, while j_{CD} and j_{BS} are electrical currents due to current drive and bootstrap, respectively. The electron flux Γ_e, the electron heat flux q_e and the ion heat flux q_i are considered as total fluxes through a flux surface $\rho = $ const. In order to close the system of equations, these fluxes are expressed in terms of thermodynamic forces taken as derivatives with respect to ρ, according to the general transport matrix

$$\begin{pmatrix} \dfrac{\Gamma_e}{n} \\ \dfrac{q_e}{nT_e} \\ \dfrac{q_i}{nT_i} \\ V'G_1\dfrac{\mu_0 j_{\mathrm{BS}}}{B_p} \end{pmatrix} = -V'G_1 \begin{pmatrix} D_n & D_e & D_i & D_E \\ \chi_n^e & \chi_e & \chi_i^e & \chi_E^e \\ \chi_n^i & \chi_e^i & \chi_i & \chi_E^i \\ C_n & C_e & C_i & 0 \end{pmatrix} \begin{pmatrix} \dfrac{\partial n}{n\partial\rho} \\ \dfrac{\partial T_e}{T_e\partial\rho} \\ \dfrac{\partial T_i}{T_i\partial\rho} \\ \dfrac{E_\parallel}{B_p} \end{pmatrix}, \tag{8}$$

where the average poloidal magnetic field is $B_p = (1/2\pi R_0)\partial\psi/\partial\rho$. The most important terms in the matrix are those in the diagonal with the others representing special transport effects. Here, only diagonal terms are used for particle diffusion D_n, electron thermal conductivity χ_e and ion thermal conductivity χ_i.

Equations (4)–(7) are solved starting from a given initial state and for prescribed boundary values for the relevant variables at $\rho = a$ the minor radius. Usually, since the initial state is not known to be a valid equilibrium state, the code evolves until a steady-state is reached which is now self-consistent. All the coefficients in the matrix in Equation (8) must be specified beforehand, which is where the information about the plasma model properties is provided. In our case of interest, the source S_e comes from neutral particles that are puffed from the boundaries and this is managed by a routine that incorporates the atomic processes like charge-exchange and ionization. The transport coefficients have in general two parts, a neoclassical component and an anomalous contribution due to the microinstabilities.

The Astra code is run using the following transport coefficients for the anomalous component, based on the value of Equation (3), for particle diffusion D_n, electron thermal diffusivity χ_e and ion thermal diffusivity χ_i

$$D_n = k_n D_a, \quad \chi_e = k_e D_a, \quad \chi_i = k_i D_a. \tag{9}$$

Initially, we set $F_{\mathrm{RF0}} = 0$, to get the plasma radial profiles with no rf wave injection. The constants k_j $(j = n, e, i)$ are varied in order to fit the experimental profiles. The corresponding form of diffusion can be written as

$$D_a = D_{a0}\Gamma_a \left(1 + \frac{F_{\mathrm{RF0}}(K_a/s)^2(\hat{\omega}/\hat{k})^2}{2\hat{k}(K_a\hat{\omega}/\hat{k} + k)L_{\mathrm{RF}}^2}\right)^{-1/2},$$

where the no-rf-power diffusivity is

$$D_{a0} = 5.5\left(\frac{T_i}{0.4}\right)^{3/2}\hat{\omega}\hat{k}\ m^2/s, \tag{10}$$

$\Gamma_a = (\hat{\gamma}/0.31)(\hat{\omega}/0.3)(\hat{k}/0.5)$, $\hat{\omega} = \omega/\omega_{*e}$, $\hat{\gamma} = \gamma/\omega_{*e}$, $\hat{k} = k_y\rho_i$ and $K_a = \omega_{*e}\rho_i/v_D$. In writing Equation (10), the normalization length scale is taken as $L = \rho_i$ which together with the normalization for ω, which is ω_{*e}, gives the dependence $\sim T_i^{3/2}$. It can also be considered a case where D_{a0} is independent of T_i as a comparison point. The starting profiles are taken with a parabolic shape for the three quantities, $n_e(r)$, $T_e(r)$ and $T_i(r)$, and the code is advanced in time up to the point when a steady-state is reached, where we can say that a self-consistent equilibrium has been established. The results show that when rf is turned on, the stabilization of the instability, indeed, forms a transport barrier and consequently the temperatures increase in the confined system (*10*). The larger increase in the ion temperature can only be expected for the instability considered.

Coming to the question of what type of rf waves would be most suitable for this stabilization, we note that the theory assumes that the rf wave is producing an oscillating (ion) fluid velocity, so this points towards a low frequency wave. One possibility is to use Alfvén resonance, which produces highly localized intensity maximum which coincides closely with the resonant flux surface.

Let us now estimate the actual rf power requirement in JET-like machine. If the oscillation velocity v_{RF} is $\sim 0.1C_s$ (this ratio typically corresponds to normalized $F_{\mathrm{RF}} \sim 0.1$), then this will typically be about $10^5\,\mathrm{ms}^{-1}$. This is related to the electric field by $E + V \times B_o \approx 0$. Therefore, taking $B_o \approx 3.2T$ from the JET we get $E \approx 3.2 \times 10^5$ V/m. This gives, in turn, an electric field energy density of about $0.226\,\mathrm{J/m^3}$. The energy in the magnetic field fluctuation is larger, from $\nabla \times E = -\partial B/\partial t$ we can estimate $C_A B \approx E$. The average magnetic energy density is then $B^2/4\mu_o \approx \epsilon_o E^2 C^2/4C_A^2$, which if we take $C_A \approx 0.1C$, gives about $22.6\,\mathrm{J/m^3}$. Following the JET, if we take a minor radius of 1 m, major radius 3 m and thickness of the resonance layer 1 cm, then we get a volume $\sim 4\pi^2 \times 1 \times 3 \times 0.01 \approx 1.2\,\mathrm{m}^3$ and a total energy, predominantly in the magnetic field fluctuations, of about 24.47 J. The Alfven frequency is typically of the order of a few megahertz. If the damping rate is a few percent of this, then we would get a damping rate of around 10^5 Hz and a power absorbed in the resonance of about 2.5 MW. These considerations indicate that the power requirement could be feasible with a well-localized, lightly damped Alfven resonance in a JET-like machine. One possibility might be to excite a toroidal Alfven eigenmode in the plasma.

3. Conclusion

In this section, we suggest a novel technique for the formation of transport barriers in a tokamak. We demonstrate that the ponderomotive force induced by the Alfven waves can create a transport barrier in a tokamak. It is shown if the radial profile of the rf field energy is properly chosen the ITG driven perturbation, considered nowadays as the dominant source of anomalous energy losses in the L-mode, is stabilized. This stabilization is achieved through the ponderomotive force arising due to the radial gradients in the rf field energy and is different from the stabilization mechanism due to the rf induced shear flow. This mechanism is general and as such all potential plasma instabilities are expected to be affected in a similar way. The estimate in a JET-like machine shows that the stabilization can be achieved for rather modest values of the rf power and should be easily obtained in actual experiments. As there is no time limit for how long rf power can be launched, a stationary, non-transient improved mode can be envisioned in the plasma core by this technique. This mode is expected to have all the advantageous features of the ERS plasma and at the same time will be, unlike the ERS mode, non-transient in nature and should in principle be sustainable for an unlimited period of time.

This work also has application in *space plasma*. It is likely that the proposed model might, on the one hand, predict the excitation of new instabilities and disturbances in the space; whereas, on the other hand, it might predict the *stabilization* of other known instabilities and disturbances *which, according to the prevalent notion, are excited by the rf waves!* Therefore, the expected outcome from the application of the analysis developed here might raise serious questions against the credibility of the longstanding prevalent hypothesis which proposes the high frequency radio waves as the origin of various ionospheric fluctuations and disturbances. We will follow these lines in order to give a new dimension to the space research and in particular to the ionospheric research.

The result might also be applicable to the *plasma processing technology.* Plasma enhanced chemical vapor deposition (PECVD) is a process used to deposit thin films from a gas state (vapor) to a solid state on a substrate. Recent study from the X-ray diffraction spectra of SnO_2

films deposited as a function of rf power apparently indicates that rf power is playing a stabilizing role and hence is the better deposition. The results show that the rf power results in smoother morphology, improved crystallinity and lower sheet resistance value in the PECVD process. The PECVD processing allows deposition at lower temperatures, which is often critical in the manufacture of semiconductors. Following our present analysis, it is proposed to address two aspects of the problem, first to develop a model to study the mechanism of how the PECVD is affected by the rf power, and second to actually investigate the effect of rf power on PECVD in the Istituto di Fisica del Plasma (IFP) linear machine at Milan. As the PECVD is a very important component of the plasma processing technology with many applications in the semiconductor technology and surface physics, the research proposed here has the prospect to revolutionize the plasma processing technology through the stabilizing role of the rf power.

Acknowledgements

SS acknowledges European Commission's funding by Lancaster University and funding from Department of Science and Technology.

References

(1) Craddock, G.G.; Diamond, P.H. *Phys. Rev. Lett.* **1991,** *67,* 1535.
(2) Ono, M.; Bell, R.; Bernabei, S.; Gettelfinger, G.; Hatcher, R.; Kaita, R.; Kaye, S.M.; Kugel, H.; LeBlanc, B.; Manickam, J.; Okabayashi, M.; Paul. S.F.; Roney, P.; Sauthoff, N.; Sesnic, S.; Takahashi, H.; Tighe, W.; Timberlake, J.R.; Von Goeler, S. 15th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Vol. 1, Seville, Spain; International Atomic Energy Agency: Vienna, 1995; p 469.
(3) Tsypin, V.S.; Galvao, R.M.O.; Nascimento, I.C.; Elfimov, A.G.; Tendler, M.; de Azevedo, C.A.; de Assis, A.S. *Phys. Rev. Lett.* **1998,** *81,* 3403.
(4) Goloborod'ko, V.Ya.; Kolesnichenko, Ya.I.; Yavorskij, V.A. 10th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Vol. 2, London; International Atomic Energy Agency: Vienna, 1984; p 179.
(5) Ericksson, L.-G.; Johnson, T.; Hellsten, T.; Giroud, C.; Kiptily, V.G.; Kirov, K.; Brzozovski, J.; deBaar, M.; deGrassie, J.; Mantsinen, M.; Meigs, A.; Noterdaeme, J.-M.; Staebler, A.; Testa, D.; Tuccillo, A.; Zastrow, K.-D. *Phys. Rev. Lett.* **2004,** *92,* 235001.
(6) Wilson, J.R.; Bell, R.E.; Bernabei, S.; Hill, K.; Hosea, J.C.; LeBlanc, B.; Majeski, R.; Nazikian, R.; Ono, M.; Phillips, C.K.; Schilling, G.; von Goeler, S.; Bush, C.E.; Hanson, G.R. *Phys. Plasmas* **1998,** *5,* 1721.
(7) LeBlanc, B.P.; Bell, R.E.; Bernabei, S.; Hosea, J.C.; Majeski, R.; Ono, N.; Phillips, C.K.; Rogers, J.H.; Schilling, G.; Skinner, C.H.; Wilson, J.R. *Phys. Rev. Lett.* **1999,** *82,* 331.
(8) Sen, S. Invited Talk, International Ionospheric Reference Workshop, Kagoshima, Japan, 2009.
(9) Pereverzev, G.V.; Yushmanov, P.N. *ASTRA: Automated System for Transport Analysis*; IPP Report 5/98; Max-Planck-Institut fur Plasmaphysik: Garching, 2002.
(10) Martinell, J.J.; Sen, S.; Fukuyama, A. *Phys. Rev. Lett.*, to be submitted; also 37th EPS Conference on Plasma Physics 2010, ECA Vol. 34A, P1-1059.