# ICRF-Edge and Surface Interactions

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# ICRF-Edge and Surface Interactions

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**Abstract**

This paper describes a number of deleterious interactions between radio-frequency (rf) waves and the boundary plasma in fusion experiments. These effects can lead to parasitic power dissipation, reduced heating efficiency, formation of hot spots at material boundaries, sputtering and self-sputtering, and arcing in the antenna structure. Minimizing these interactions is important to the success of rf heating, especially in future experiments with long-pulse or steady-state operation, higher power density, and high-Z divertor and walls. These interactions will be discussed with experimental examples. Finally, the present state of modeling and future plans will be summarized.

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## 1. Introduction

Plasma heating and current drive with ion cyclotron range of frequency (ICRF) antennas has been quite successful in past tokamak experiments and is foreseen to play an important role in ITER. However, in addition to the desired heating or current drive in the core plasma, unwanted interactions with the edge plasma and material surfaces also occur in some regimes of operation. Many of these interactions are caused by the formation of *rf-enhanced sheaths* on the boundary surfaces (see [1,2] for reviews of nonlinear ICRF interactions and an extensive list of references). The requirements for control of rf sheaths are much more stringent in long-pulse or steady-state experiments than in present devices. These issues impact the functioning and survivability of the antennas, walls and divertors; the choice of wall material and the lifetime of the boundary surfaces; the heating efficiency of the ICRF antennas; and the impurity concentration of edge and core plasmas. Thus, it is important to develop a *quantitative* modeling capability for experimental design and interpretation, which does not yet exist. The goal of this paper is to give researchers in edge and wall physics a concise overview of the physical mechanisms for rf-surface interactions and a brief report on the state of rf sheath modeling.

The goal of ICRF heating is to launch a fast wave (FW) which propagates into the core plasma and is completely absorbed there. In practice, the ideal is not always achieved: (i) the fast wave can propagate around the scrape-off-layer (SOL) and be partially absorbed by boundary structures [3] ; (ii) the single pass absorption in the core plasma can be low for some wave components, so that rf wave energy propagates through the plasma to the wall [4]; and (iii) the FW antenna can also launch a slow wave (SW) component (either evanescent or propagating) in the SOL when the magnetic field is not perfectly aligned with the antenna structure. Additionally, for mechanisms (i) and (ii) when the FW encounters a material structure, the Maxwell equation boundary conditions require that it couple to the SW at the wall.

Thus, in all of these situations, the problem stems from that fact that SWs come in contact with a material boundary (wall, antenna or divertor) and drive rf sheaths there. The existence of the sheath depends on both the wave polarization and the equilibrium magnetic field geometry. The component $E_{\|} = \mathbf{B} \cdot \mathbf{E}_{rf} / B$ of the SW rf electric field accelerates electrons out of the plasma, with the result that a large (up to several hundred V) rf sheath potential forms to confine the electrons and maintain ambipolarity. The sheath can be treated as a thin vacuum region of finite capacitance, which separates the plasma and the material surface; the sheath boundary oscillates in time at the rf frequency and can heat electrons by Fermi acceleration [5]. As shown in Fig. 1, the plasma acts to rectify the oscillating rf voltage, producing a dc ("rectified") potential of order $e\Phi_0 \sim eV_{rf} + 3T_e$, where $2V_{rf}$ is the difference between the highest and lowest values of the oscillating rf potential. Both $V_{rf}$ and the electrons heated by Fermi acceleration (resulting in higher $T_e$) increase the dc sheath potential.

The sheath interacts with the plasma in several ways. The rectified sheath potential accelerates ions out of the plasma. This provides a source of energetic ions for sputtering the boundary [6], and results in unwanted edge power dissipation [7]. The sheath power dissipation reduces the overall heating efficiency and can also cause hot spots [8] and physical damage on material structures, especially in long-pulse experiments. Finally, the spatial variation of the sheath potential drives radial $\mathbf{E}\times\mathbf{B}$ convection in front of the antenna [9, 10]. This rf-driven transport increases the radial flux of plasma to the wall and therefore the strength of interactions such as sputtering and power dissipation. In some cases, the sheath voltage or area is asymmetric at the two ends of the field lines, and parallel currents flow along the field lines [11,12]. For example, if the antenna is not sufficiently protected, it can act like a large rf probe and currents will flow from the antenna to the limiter [11]. In some cases, these currents can contribute to arcing. All of these effects have been shown at least qualitatively by comparison of models with experimental data from tokamaks (JET, TFTR, Tore Supra, C-MOD, ASDEX-U, etc.) and will be discussed in more detail in Sec. 2.

In high-power ICRF heating experiments the typical sheath has $eV_0 >> 3T_e$, so that rf sheath formation can make a substantial (sometimes qualitative) change in the nature of the wall interactions. For example, it can increase the sputtering energy of high-Z impurities to the point that self-sputtering becomes an important process [6], making high-Z surfaces problematic near rf antennas.

## 2. Sheath-plasma interactions

In this section, we describe the physics of sheath-plasma interactions and some of the experimental results in more detail.

*RF-enhanced sputtering*. One of the original motivations for studying rf sheaths in the fusion program was to explain the phenomenon of rf-enhanced impurity generation. Detailed modeling of early JET experiments [6] showed that a combination of rf-sheath-enhanced sputtering and self-sputtering could account qualitatively for the dependence of the antenna impurity influx on phasing, magnetic field angle and screen coatings [6,13]. A large increase in the Ni influx at large sheath potentials was attributed to self-sputtering avalanche [6].

The influx of impurity neutrals of species j due to sputtering is given by

$$\Gamma_j A_\perp = \frac{Y(E,\theta)\ n_i \mathbf{v}_i \cdot \mathbf{A}}{1-f} \quad , \tag{1}$$

where Y is the sputtering yield per incident ion, $n_i v_i$ is the incident ion flux, A is the surface area and $f < 1$ is the fraction of species j that contributes to self-sputtering. The sputtering yield Y depends on the incident energy E and the angle of incidence $\theta$. The limit $f \rightarrow 1$ corresponds to impurity avalanche and only occurs for high-Z materials in the limit of large energy E and strong ionization. There is an implicit sum over all incident species in the numerator and an implicit sum over all charge states of the wall impurity j in the definition of f. Light impurity species can substantially increase the primary sputtering (numerator of Y) [6,14].

This simple formula couples a large number of physical processes, all of which must be taken into account in quantitative modeling. The rf sheath increases the ion energy E, and modifies the ion orbits and thus the angle $\theta$. The local density $n_i$ at the wall depends on rf convection, turbulent (blob) transport, local ionization and recycling. The self-sputtering factor f depends on ionization and may be strongly modified by blobs in the far SOL, which give large intermittent changes in the local density and temperature [15,16].

*Sheath power dissipation*. In the limit $eV_{rf} >> 3T_e$, the rate of sheath power dissipation due to ion acceleration is given by the product of the ion flux along B, the ion energy gain, and the projection of the area perpendicular to B, viz.

$$P_{sh} = C_{sh}(n_i c_s)(Ze\Phi_0)A_\perp \quad , \qquad (2)$$

where $C_{sh}$ is an order unity rectification coefficient [17]. This mechanism for sheath power dissipation is in reasonable agreement (to within experimental uncertainties) with the measured power losses during early experiments on JET that studied the dependence of sheath effects on antenna phasing and on magnetic field alignment with the antenna [7].

*Rf-driven convection.* In the 1D sheath model, the rf sheath drive varies on each field line, and the rectified potential $\Phi_0(\mathbf{x})$ is set independently on each field line. In front of the antenna, $\Phi_0(\mathbf{x})$ takes the form of an array of nested convective cells [9] , which enhance the flux of the plasma into the Faraday screen (FS). Integrating the current conservation equation $\nabla \cdot \mathbf{J} = 0$ between the two contact points of the magnetic field line with the boundary, we obtain the following vorticity equation for the potential:

$$\frac{c^2}{B^2} n m_i \frac{d}{dt} \nabla_\perp^2 \Phi = \left. \frac{J_\|}{L_\|} \right|_{-L_\|/2}^{+L_\|/2} \equiv \frac{J(\Phi - \Phi_0)}{L_\|} \quad , \qquad (3)$$

where the function $J(\Phi - \Phi_0)$ denotes the sheath current-voltage relation specifying the net current flowing out of the plasma. In the limit $\Phi = \Phi_0$, this reduces to the 1D sheath model, but when $\Phi >> \Phi_0$ the sheath potential is two-dimensional. The solution of this equation was given in [9].

The ion polarization drift physics has two important consequences. First, there is a strong $\mathbf{E} \times \mathbf{B}$ convection of plasma into the antenna, which increases the strength of sheath-plasma interactions such as sputtering and power dissipation. The resulting flattening of the radial density profile were directly measured on TFTR [18] with a reflectometer, and the poloidal damage pattern associated with the convective cells was observed on Tore Supra [10]. The second effect is to allow radial current flow, thereby connecting the circuit between the antenna and the wall even if a limiter or some other obstacle is in the way [12,19].

*Parallel currents and arcing.* When the sheaths at the two ends of the field lines are asymmetric (e.g. cover different areas or have different voltages), this asymmetry will drive parallel currents. The throughput current can be estimated as [12]

$$\langle I_{thro} \rangle = I_s \frac{I_0(\xi_1) - I_0(\xi_2)}{I_0(\xi_1) + I_0(\xi_2)} \tag{4}$$

where $I_0$ is a Bessel function, the subscripts 1 and 2 label the two ends, $I_s = Aen_i c_s$ is the ion saturation current and $\xi = eV_{rf}/T_e$. If an arc should arise locally at some point where the local fluctuation in electric field or potential is large, this sheath-induced parallel current can sustain arcing if $I_{thro} \sim I_s > I_{min}$ . The minimum current $I_{min}$ to sustain an arc is in the range $I_{min}$ ~1-10 A. Factors influencing the threshold for initiating the arc include the presence of hot electrons and properties of the surface (such as secondary electron emission, surface roughness and thermal conductivity). Under strong sheath conditions (monopole phasing, reversed magnetic field), arcing across the FS was observed at high rf power on JET [7]. This model was also invoked to explain the later JET mixed-phasing experiments [12], in which two antennas linked by field lines were phased differently, so that the sheath potential was much greater at one antenna than at the other. The observed melting and impurity release at the antenna serving as the cathode was consistent with arcing.

**3. RF Modeling**

In order to calculate the effects described in Sec. 2, it is necessary to have an accurate description of the launched rf waves and the rf sheath potential distribution over the boundary surface. Until recently, rf sheaths were mainly studied in the vicinity of the antenna, and they were estimated using the “vacuum field” approximation to the sheath voltage (e.g. see [6]), viz.

$$V_{sh} = \oint ds\ E_{\|}^{(vac)} \tag{5}$$

where the rf $E_{\|}$ is calculated from an antenna code that solves for the rf fields in a vacuum, i.e. without plasma dielectric effects in the antenna region itself, and the integral is taken between the two contact points of the magnetic field with the conducting boundary. This approach has proved useful for antenna design studies. [14,20,21].

A more self-consistent approach [22,23] requires including plasma in the region between the sheaths and modifying the boundary condition (BC) to take account of the sheath capacitance. This “sheath BC” is given by

$$\mathbf{E}_t = \nabla_t(\Delta \mathbf{D}_n), \tag{6}$$

where the subscripts n and t denote "normal" and "tangential" to the sheath surface, and for self-consistency the sheath width $\Delta$ and sheath voltage $V_{rf}$ have to satisfy the nonlinear Child-Langmuir constraint, $\Delta = \lambda_D (e\Phi_0 / T_e)^{3/4}$, where $\lambda_D$ is the Debye length and $\Phi_0$ is the rectified sheath potential ($\Phi_0 \propto V_{rf}$). This BC incorporates plasma dielectric effects and is required for self-consistency of computed rf fields and their associated sheath potential. It is also useful for analytic calculations of both near- and far-field sheaths. We have carried out a number of these calculations for different sheath geometries; see the Introduction of [24] for a summary of this work, which illustrates the effect of sheath capacitance on the rf fields and sheath formation.

**4. Discussion**

Deleterious rf sheath interactions need to be minimized in future long-pulse, high-power experiments. This will require accurate quantitative modeling of sheath effects in both antenna coupling and ICRF wave propagation codes. This is a difficult computational problem because (a) sheath formation is sensitive to the detailed geometry of antenna and PFCs (plasma facing components) in the SOL, and (b) it requires treatment of both the ion and electron Debye length space scales, either explicitly or by the sheath boundary condition, which imposes a nonlinear constraint.

Work has begun on developing numerical techniques to meet this challenge. As part of the rf SciDAC project, MIT and Lodestar are collaborating on the development of a new finite-element code [25]. The goal of this project is to calculate rf wave propagation in the SOL, and sheath formation on the boundary using the sheath BC. The code will be applied first in simple 2D geometry but eventually in axisymmetric tokamak geometry and with a realistic wall shape.

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## Figure Captions

Fig. 1 Basic sheath physics. The sheath forms to equalize electron and ion loss rates. The resulting potential enhances electron confinement by forming a potential barrier for electrons, i.e. the sheath of width $\Delta$. The sheath potential accelerates ions into the plates, providing an important mechanism for sheath dissipation of the power. For the rf-sheath, the driving voltages $\pm V_{rf}$ at each end oscillate in time and the central potential must remain ($\sim 3T_e$) above the maximum voltage at either end. (Figure reproduced from Ref. [1])

**Fig. 1**