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ABSTRACT

The use of mixed (monopole-dipole) phasing of a set of ICRF antennas is potentially useful to optimize tokamak performance and to do interesting physics experiments. However, recent mixed-phasing experiments on JET, described here, showed undesirable antenna-plasma interactions under certain circumstances. We explore a possible physical mechanism: parallel currents flowing between adjacent antennas with different phasings can lead to arcing on the antenna with the largest sheath voltage. Means of controlling the interaction are discussed.

INTRODUCTION

The use of mixed-phasings for a set of ICRF antennas is potentially useful, both for optimizing tokamak performance and for doing interesting physics experiments. Dipole antennas are routinely employed to heat the core plasma without perturbing the edge, whereas monopole antennas can be used to modify edge and scrape-off-layer (SOL) properties by driving edge convection [1]. It has been suggested that the rf-driven convection can affect H-mode properties, such as the particle confinement time and ELM repetition rate, and reduce the divertor heat load by broadening the SOL [1, 2]. The convection may also be a useful tool in basic physics studies, e.g. by perturbing edge and SOL turbulence. To be successful, it must be possible to operate in mixed-phasings without deleterious interactions between adjacent antennas.

Mixed-phasing experiments on JET with the A2 antennas showed undesirable antenna-plasma interactions under certain circumstances. Phasing the four antennas alternately in monopole (0000) and dipole ($0\pi0\pi$) around the torus produced heavy interaction with a monopole antenna, and the strong interaction region was connected by the field lines to the adjacent dipole antenna. A similar interaction was not observed using either pure monopole or pure dipole phasing. A sheath analysis suggests that the interaction is due to arcing [3], induced by a large dc sheath potential difference and resulting current flow [4], between antennas with mixed phasings.

The present work extends previous sheath analyses, which dealt with local effects (sputtering, convection, power dissipation, etc.) that were insensitive to the relative phasing of adjacent antennas. By contrast, the parallel current (and hence arcing) is a global effect that depends on the asymmetry between the two sheath contact points.

EXPERIMENT

An experiment to study the effect of sheath potentials on the ICRF heating efficiency of plasmas was carried out during the 2000 EFDA-JET Workprogram (C3 Campaign, November 2000). The four 4-strap A2 ICRF antennas (called Modules A, B, C, D) were used to heat H minority ions in a D plasma with various combinations of monopole (0000) and dipole ($0\pi0\pi$) phasings at $\omega = \omega_{cH} = 42$MHz. The target was a standard flux expansion plasma with $I_p = 2.6$ MA, $B_T = 2.8$T, $n_e = 2 \times 10^{19}$ m^{-3} (before application of ICRF). The plasma-antenna distance was kept constant at 4cm.

In Pulse No: 52673 the phasing was chosen to have toroidally alternating monopole and dipole antennas with Mod. C (0000) viewed by the CCD camera to monitor possibly damaging interactions with the first wall structures (poloidal limiters, antenna septum, railings and Faraday screen). The rf power was ramped up to 2 MW in 2s on all four antennas (8MW total) at the same time, followed by 2s periods of alternated 0000 (Mod. A and C) and 0π0π (Mod. B and D) with 2MW per antenna; all modules (8MW) were on again for 2s and then ramped down to zero power.

Strong interactions with the antenna structure of Mod. C (0000), with release and acceleration of particulate matter into the plasma, were visually observed from the torus CCD camera at several times in the discharge when mixed phasings were present. When the first interaction started, one observed a sudden increase of edge density (measured at R = 3.75m with the high temporal resolution FIR interferometer) and D_α line intensity, which coincided with a very localized (spatially and temporally) increase in edge T_e (as seen by the heterodyne radiometer). The increase in edge T_e rapidly decreased with decreasing R and was not present for R < 3.80. (The separatrix position, from the T_e profile, is R_{sep} @ 3.83m.) Following the n_e, T_e spikes there was a release of oxygen, carbon and (to a lesser degree) nickel in the plasma. The analysis of this data suggests that intense localized heating released first wall material, giving rise to a local increase of density and high Z impurities, during the high-power ramp-up with mixed-phasings. No interactions were observed during the periods of exclusively monopole or dipole phasing. In the second period with mixed-phasings, an interaction was visually observed, but no spikes in either n_e, T_e of high Z material line intensities were observed, with the possible exception of a small increase in the CIV line. The reduced severity of the latter interaction was probably due to the unsteady power delivered by Mod. D during this time segment.

The camera showed the interaction area on Mod. C to be roughly $^1/_2$ of the antenna, and this region is connected to Mod. D by the field line mapping. The reciprocating probe data indicated the presence of strong sheath rectification. At the time when the first interaction on Mod. C occurred, the rf power showed evidence of generator tripping and the trace of line-averaged Z_{eff} showed a sudden peak (30% increase), both of which are consistent with the presence of arcing.

MODEL

We propose that the JET mixed-phasing results can be explained by arcing [3] induced by sheath-driven currents [4]. Our model has the following elements:

(i) The RF sheath potential is larger for 0000 than for 0π0π phasing, giving an asymmetry at the two ends of the field lines connecting Modules C and D. The rf sheath distribution was analyzed for the flatbed mockup [5] of a 4-strap JET A2 antenna using the ARGUS antenna [6] and ANSAT sheath [7] codes. The latter code calculates the rf sheath driving voltage $V = ds\ E_{\|}$, where $E_{\|}$ is the rf electric field parallel to **B** and the integral is taken along the field lines between the two contact points. We computed the poloidal distribution V(θ) on field lines just in front of the screen and used the maximum of V(θ) as a rough measure of the strength of the sheaths, finding an asymmetry in V between monopole and dipole of roughly a factor of 2 – 3. The rectified sheath potential F in dipole is typically >1kV in dipole and > 2kV for 2MW rf power per antenna module.

(ii) The asymmetry in F can drive large parallel currents on field lines connecting the antennas, with the monopole antenna serving as the cathode on which the arc forms. Sheath-driven currents flowing between powered ICRF antennas and the belt limiter have been documented on TEXTOR [4].

The simplest model is to represent the two antennas as two capacitor plates with rf bias voltages V_{rfj} ($j = 1, 2$) connected by B-field lines in plasma. Assume that the plates have equal area A, and the time-averaged plate potential is at ground. A symmetric version of this model with $V_{rf2} = - V_{rf1}$ is described in the Appendix of Ref. [8]. In the asymmetric case, the instantaneous plasma potentials V_{pj} relative to the two plates and the time-averaged plasma potential V_0 (relative to ground) are related to the driving voltages by $V_{pj} = V_0 - V_{rfj} \cos(\omega t)$, where w is the rf frequency. The requirement that the time-averaged net current lost from the system must vanish (by quasineutrality) determines the dc plasma potential V_0. Then the time-averaged throughput current (the relevant quantity for arcing) is given by

$$\langle I_{thro} \rangle = I_{sat} \frac{I_0(\xi_1) - I_0(\xi_2)}{I_0(\xi_1) + I_0(\xi_2)} \quad , \tag{1}$$

where $I_{sat} = An_e ec_s$ is the ion saturation current, I_0 is a Bessel function, and $\xi_j = eV_{rfj} / T_e$. V_0 is relatively insensitive to the asymmetry between ξ_1 and ξ_2, but the net current I thro vanishes when $\xi_1 = -\xi_2$. *This is the fundamental reason why the mixed- phasing case differs from the case where all antennas have the same phasing*. Taking the most asymmetric case, $\xi_1 = \xi$, $\xi_2 = 0$, we find that $I \approx I_{sat}$ for $\xi > 5$, or $V > 100$ volts for typical parameters, which is easily met for high-power ICRF heating. Fixing V ($\xi = 10$) and modeling the asymmetry by $\xi_1 = (1-g)\,\xi$, $\xi_2 = -g\,\xi$, we find that only modest asymmetry ($g < 0.3$) is needed to reach the ion saturation current limit.

Thus, asymmetrically-driven rf sheaths induce a time-averaged current to the plate with the lowest instantaneous plasma potential V_{pj}, i.e. at the plate with the largest $|V_{rfj}|$. The maximum magnitude of the net current is I_{sat}, achieved for modest rf voltages, $V_{rf} > 5T_e/e$, and a small amount of asymmetry.

(iii) The actual picture is more complicated because the antennas are separated by poloidal limiters which protrude $\Delta x = 1.1$cm into the SOL, and the current must flow around the limiters to complete the circuit. The radial current is supplied by rf sheath-driven convection [1] (which explains why the effect requires that both antennas be powered). In the convective cell (CC), the divergence of the parallel current is balanced by $\nabla \cdot J_\perp$ due to the ion polarization drift. The ratio $J_\perp/J_{||}$ scales [1] as $J_\perp/J_{||} \approx (L_{||}/\rho s)(\pi\rho_\phi/L_{\,y})^4$ and the radial CC width scales as $L_x \approx \rho_\phi\,(\pi L_{||}/Ly)^{1/3}\,(e\Phi/T_e)^{1/6}$, where L_y is the poloidal scale length (e.g. screen periodicity length), $\rho_s = c_s/\Omega_i$, $\rho_\phi = c_\phi/\Omega_i$, $c_s = (T_e/m_i)^{1/2}$, and $c_\phi = (e\Phi/m_i)^{1/2}$. For example, taking $L_y = 2$cm, $L_{\,||} = 200$cm, $T_e = 50$eV, $\Phi = 1000$ eV, and $B = 3$T, we find that $J_\perp/J_{||} = 19$ and $L_x/\Delta_x = 1.6$. When $J_\perp/J_{||} >>1$, the current path forms a tight helix, circulating rapidly in cross-field eddies while flowing parallel to B. In the limits $J_\perp/J_{||} >>1$ and $L_x/\Delta_x > 1$, the convection provides an effective radial current path around the limiters and restores the current flow between adjacent antennas.

(iv) If the parallel current to the monopole antenna exceeds a threshold condition, $I_{sat} > 1-10$ Amps [3], an arc can be triggered on the antenna surface, causing extensive damage. For $n_e = 10^{11}$ cm^{-3}, $T_e = 50$eV, and $A_\perp \approx (100\text{cm})^2 \sin 3° \approx 500$ cm^2, we estimate $Is_{at} = n_e ec_s A_\perp \approx 40$ A, which is easily sufficient to sustain an arc.

SUMMARY AND DISCUSSION

The present model agrees qualitatively with the experiment as follows:

(a) the antenna interaction requires an asymmetry in the sheath potentials (and hence in the antenna phasings);

(b) the interaction is observed on the antenna with the largest sheath potential (the monopole antenna); (c) there is a minimum rf power requirement on both antennas to trigger the effect (viz. the radial convection current must be sufficiently large);

(d) there is a lag time between the turn on of rf power and the observed interaction (the arc trigger involves surface heating, which takes a finite time);

(e) the model is consistent with the observations of SOL currents (driven by sheaths), generator tripping and release of high-Z material (due to arc currents). Points (a) and (c) imply that no interaction is expected if either the monopole or dipole antennas are turned off, which is consistent with the recent experimental observations.

The model suggests some ways to minimize the antenna interactions during mixed-phasing operation:

(1) increase the electric field threshold for arcing (and hence the rf power threshold) by cleaning the antenna surfaces;

(2) eliminate the radial current path around the limiters (achieve $J_\perp/J_\| << 1$ or $L_x/\Delta_x << 1$) by extending the limiters (larger Δ_x) or reducing $L_x \propto \rho_\phi$; or

(3) reduce the ion saturation current below the minimum current to sustain arcing ($I_{sat} < 1A$) by reducing the density in the vicinity of the antenna. Point (2) could be achieved by limiting the antenna power or increasing the magnetic field; point (3) by increasing the antenna-plasma separation and/or by increasing the radial extent of the antenna limiters.

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