THE GEOMETRY OF ICRF – INDUCED WAVE-SOL INTERACTION.
A multi-machine experimental review in view of ITER operation.

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Abstract

As part of ITPA-IOS activities, this contribution reviews recent experimental characterization of Radio-Frequency (RF)-induced Scrape-Off Layer (SOL) modifications on various tokamaks worldwide and on the LArge Plasma Device (LAPD) at UCLA. The observed phenomenology, as observed using a large variety of measurement techniques, is consistent with the expectations from RF-sheath rectification. Emphasis is then put on the complex 3-Dimensional (3D) spatial patterns of RF-SOL interaction, in relation to the magnetic topology and the spatial distribution of RF currents over the metallic

structures surrounding the RF wave-launchers. Dependence on the local plasma parameters in the antenna vicinity is also briefly addressed. The final part discusses implications for future devices.

1. INTRODUCTION

Of the three additional heating methods envisaged for ITER, waves in the Ion Cyclotron Range of Frequencies (ICRF) are attractive as the only one capable of direct ion heating and central power deposition at high density. Yet, since their first use in magnetic fusion devices, the non-linear interaction of ICRF waves with the Scrape-Off Layer (SOL) plasma has attracted attention. This interaction is now generally attributed to radio-frequency (RF) sheath rectification. In view of ITER, the topic has gained renewed interest. ICRF was applied in metallic machines where RF-enhanced wall sputtering might increase the core plasma contamination with high-*Z* impurities. Even when not critical on short pulses, such spurious process could hinder the machine lifetime when cumulated over long periods. A final challenge is to combine ICRH with other subsystems in Integrated Operational Scenarios (IOS). SOL modifications by the different subsystems might interfere, *e.g.* Lower Hybrid (LH) and ICRF wave coupling and hot spots in present devices. A recent multi-machine task in view of ITER was to ease ICRF coupling by localized gas injection, while disturbing as little as possible the plasma core [1].

Within ITPA-IOS, this contribution reviews experimental characterization of ICRF-induced SOL modifications over the past 20 years on various tokamaks worldwide and on the LArge Plasma Device (LAPD). Reference [2] reviewed earlier experiments. Most of the reported results were obtained with D[H] minority heating, but are not scenario-specific. We emphasize the 3D spatial structure of the SOL modifications. Present ICRF wave launchers consist of phased arrays of poloidal current straps in individual metallic boxes, partially closed on their plasma side by a Faraday screen and surrounded by private limiters. Understanding the RF-sheath complex 3D patterns, in relation with the magnetic topology and the spatial distribution of RF currents over the metallic antenna structures, provides hints for judicious port allocation, antenna design and operation. It clarifies which plasma-facing components are more likely eroded, and which species are sputtered in mixed-materials walls like ITER. Reproducing the measured patterns also puts strong constrains on interpretative RF-sheath models. Reference [3] proposes a recent tutorial on RF sheath modelling in magnetic fusion plasmas.

2. NATURE OF ICRF-INDUCED SOL MODIFICATIONS, SPECIFIC MEASUREMENT TECHNIQUES

At any plasma-material interface, sheaths spontaneously build-up as thin boundary layers, in order to equilibrate the ion and electron fluxes onto the wall, thus preserving the electro-neutrality of the plasma far from the wall. This equilibration is governed by a *I*-*V* electrical characteristic linking the current density *I* onto the wall to the voltage drop *V* across the sheath. While ordinary sheaths are static, intense RF electric fields in the vicinity of wall may induce strong RF oscillations V_{RF} of the sheath voltage at the wave frequency. Since the sheath electrical properties are non-linear, V_{RF} tends to shift the time-averaged (Direct Current (DC)) I_{DC}-V_{DC} characteristic of the sheath. Rectification thus acts as if the local wall elements (generally grounded in tokamaks) were electrically biased. This “self-biasing” is described in textbooks for non-magnetized sheaths in RF discharges [4] [5] but is more complicated in presence of a static magnetic field tilted with respect to the wall [3]. In LAPD, reference [6] diagnosed the electrical RF and DC properties of RF-driven sheaths on magnetic field lines connected to a grounded plate at one end and an ICRF antenna at the other end. The sheath RF impedance at the plate, defined as V_{RF}/I_{RF} at the wave frequency, was measured as a function of DC sheath voltage V_{DC}, controlled by varying the RF current applied to the antenna. The impedance was compared to models.

The SOL plasma is expected to react to the RF-sheath rectification in a similar way as to an electrostatically biased electrode, by raising its DC potential V_{DC} with respect to the (grounded) wall. References [7-11] measured V_{DC} directly using emissive probes, while reference [12] estimated it from a Retarding Field Analyzer (RFA). In [10] the emissive probe was incorporated into a compound diagnostic also measuring the local RF field amplitudes for different polarizations. Changes of V_{DC} were also deduced indirectly from the integration of DC radial electric fields in references [9,13-15]. V_{DC} in the range of several hundred Volts were reported near C-mod antennas energized at megawatt levels. V_{DC} was also inferred from variations of Langmuir probe floating potential, *e.g.* in references [16-22]. Interpreting floating potentials might however be ambiguous (see below).

DC SOL biasing is expected to increase the energy of the ions impinging the wall, thereby enhancing the Plasma-Wall Interaction (PWI). References [12] and [23] showed how ICRH modifies locally the ion parallel energy distribution onto a RFA. Mean ion energies exceeding 150eV were reported near ASDEX upgrade (AUG) 2-strap antennas phased [0π] delivering 500kW, while the ion temperature was 12.5eV in ohmic regime.

Heat loads onto the wall are locally increased during ICRH and were documented from surface temperature measurements using infrared (IR) cameras on JET [24], Tore Supra [25-28], NST-X [29] and WEST [22]. Reference [24] reported typical heat fluxes in the range of several 500kW/m^2 normal to JET A2 antenna septa, while reference [27] estimated up to 1MW/m^2 normal to Tore Supra Faraday screen bars. In actively-cooled machines, quantitative information on heat fluxes is available from calorimetry, which compares inlet and outlet coolant temperatures for a given measured water flow in the pipes. Reference [28] used concretely the calorimetry to compare the local sheath losses with two types of Faraday screens. A few per cent of the energy launched by a Tore Supra antenna was dissipated on the antenna structure itself.

Ions with higher energies are also more efficient for sputtering wall elements. RF-specific impurity production during ICRH has been mainly studied in metallic machines, using as a proxy the line emission in the visible range for tungsten (W, ref. [17], [22], [30-36]), molybdenum (Mo, ref. [7], [9]) and beryllium (Be, ref. [38], [39]). Visible spectroscopic signals are mainly representative of the local gross erosion, while prompt redeposition may be important, especially for high-Z impurities. Visible spectroscopy was generally used in conjunction with VUV spectroscopic line emission from the plasma core, to assess the central contamination for W (references [17], [22], [30-37]), Mo (references [7], [9], [22], [36], [37]), but also nickel on JET (reference [40]), titanium or iron on EAST (references [36], [37]). Reference [22] showed first experimental correlations between local heat loads and local WI line radiation at 400.8nm on WEST ICRF antenna limiters.

The RF-induced SOL biasing is generally highly inhomogeneous spatially. The DC electric field ∇V_{DC} is dominantly transverse to the confinement magnetic field and likely generates **E×B** flows. On LAPD this flow has been measured using Mach probes and correlated experimentally to ∇V_{DC} [11]. On C-mod, a Gas Puff Imaging (GPI) diagnostic mapped the convection of density fluctuations in 2D and attributed the flow to electric drifts to estimate V_{DC} profiles [9], [13-15]. Convection redistributes the local density in the antenna vicinity. Local density modifications were evidenced using Langmuir probes [11], [16], [23], [41], [42], edge reflectometry [42-45], or Lithium beam emission spectroscopy [20], [45]. This modified the wave coupling properties on LH waveguides magnetically connected to active ICRF antennas [16], [44], [46-49], as well as LH-related hot spots, evidenced *via* IR thermography [47], [50], [51].

Open magnetic field lines have two extremities, connected by a plasma channel with very large parallel DC conductivity. If the sheaths at the two extremities are subject to different levels of rectification, basic double Langmuir probe theory shows that V_{DC} adapts to the electrode with larger $|V_{RF}|$ and a DC current I_{DC} flows from the high-$|V_{RF}|$ boundary to the low-$|V_{RF}|$ one. Transverse DC currents further complicates the electrical circuits in the SOL. Reference [17] evidenced DC currents collected on the side limiters of active ICRF antennas. Reference [52] invoked DC currents to interpret arcs in mixed phasing JET experiments. Reference [53] explained how I_{DC}, on top of voltage rectification, modifies the floating potential of Langmuir probes, in particular changes its sign. This led to re-interpretating Langmuir probe data on NST-X [53] and EAST divertor [54].

All of the above phenomenology looks consistent with the expectations from RF-sheath rectification. One cannot exclude however that other RF-induced edge processes might co-exist locally: development of resonant wave modes [55], absorption at peripheral Lower Hybrid resonance [56], ponderomotive forces [57], especially in the vicinity of ICRF antennas. These additional processes will not be further discussed below.

3. 3D SPATIAL STRUCTURE OF RF-INDUCED SOL MODIFICATIONS

RF-induced SOL modifications have been widely observed on the active ICRF wave launchers themselves and on magnetically connected objects: nearby limiters, LH waveguides, divertor… Field-aligned bright filaments passing in front of an active antenna and reaching the divertor were visualized on NSTX [29]. On JET, the footprint of an active 4-strap (A2) antenna on a nearby outboard limiter moved vertically over a scan of the edge safety factor (q_{95}) on the images of a Be I filtered camera [38]. Probe, reflectometry, Li beam diagnostics mentioned above measure the SOL properties several meters away toroidally from the active antennas. Parallel propagation was extensively exploited to produce 2D (radial-poloidal) mappings from these diagnostics by combining radially-resolved measurements over steps of q_{95} [16], [20], [23], [42], [45], [50]. Reference [11] combined 2D probe movements over repetitive LAPD discharges. Implicitly assumed is that the measurements along the diagnostic lines of sight are representative of the SOL on the antennas. Although the SOL is modified at long toroidal distances, little is known of its parallel variation. ICRF likely affects the EAST divertor probes even if an obstacle is interposed between the antenna and the diagnostic [54]. Besides, most diagnostics probe magnetic field lines connected to the *lateral sides* of the antennas. More intense effects may arise in the *private SOL* created by the 2 antenna side limiters, as antenna reflectometry suggests on AUG [42].

2D mappings, IR images on WEST and GPI data on C-mod, feature strong spatial inhomogeneity transverse to **B**. ICRF-induced LH wave coupling modifications were sometimes opposite on different LHCD waveguides depending on their magnetic connections to the active ICRF antennas [50]. In the radial direction, local maxima are observed near the leading edge of the antenna limiters, with a typical extension of a few centimetres on both sides, including field lines not connected to the antenna. On WEST, the peak of floating potential shifted radially consistently with the radial movements of a mobile antenna [22]. The bright filaments on NSTX extend radially up to the separatrix [29]. Reference [15] investigated the parametric dependence of the peak radial extension. This extension might reveal a transverse transport mechanism possibly enabling the DC bias to go round an obstacle, also coupling the *private SOL* between antenna limiters to the *free SOL* around. A limited radial extension explains why on JET the ICRF coupling resistance is fairly independent of RF-induced density depletion [58]. It might also explain why, on JET [59] and C-mod [60], [61], nitrogen (N_2) injected near the RF-induced convective cells penetrates the core plasma in a similar way as N_2 puffed far away toroidally from the active antennas.

In the poloidal direction, the strongest RF-induced interaction does not necessarily occur at the antenna mid-plane, even if it is closer radially to the separatrix. Instead, local maxima of the heat loads or the effective sputtering yield often develop near antenna box corners. This multi-hump poloidal structure was observed on many devices using many techniques, over a large variety of antenna types [11], [13], [17], [22], [23], [27], [37], [38], [42], [50]. RF-induced density convection further complicates this poloidal structure: references [25], [27] and [28] invoked the convection to interpret up-down heat load asymmetries on Tore Supra antenna boxes, that reversed upon **B**-field reversal.

Far less documented than the above "near-field" effects are RF-induced SOL modifications in regions never connected magnetically to the active antennas. On C-mod, DC SOL biasing was observed in the shadow of an outboard limiter and is ascribed to "far-field" sheaths [10]. Impurity production associated with "far-field" effects is also suspected on EAST [37]. Mo is found mainly on one inner wall sector facing the EAST 4-strap I-port antenna. Core Mo contamination is observed mainly when this specific antenna is energized. The Mo^{31+} brightness increases as the emitted power spectrum moves to low-$k_{//}$. This is ascribed to lower single-pass absorption (SPA). The detailed geometry of "far-field" effects is largely unknown. On top of antenna properties, it is likely sensitive to the plasma scenario, governing the propagation and core damping of the ICRF waves.

Also scarcely addressed is the contribution of each object to the central impurity contamination. Parametric dependencies on JET [31] and EAST [37] indicate that the W production near the divertor strike points is *not* dominated by RF effects, despite disturbed floating potentials on the EAST divertor Langmuir probes. On AUG, replacing the W-coated limiters with B-coated ones on the 2-strap antennas led to ~70% reduction in the incremental W content during ICRH [30]. Significant contribution from W tiles on new LH limiters is also reported on EAST, even in ohmic regime, from USN/LSN comparisons of the VUV spectroscopic measurement [37]. On C-mod, localized boronizations helped identifying small-size sources of Mo near the divertor entrance on magnetic field lines connected to the antennas and contributing to the core contamination [62].

4. LINK WITH THE GEOMETRY OF RF CURRENTS FLOWING ON THE ANTENNA STRUCTURE

For a given plasma and antenna setting, LAPD checked the linearity of V_{DC} with the feeding RF current, with some offset due to the thermal sheath [63]. Antenna RF voltages also influence scaling laws for the RF-induced heat loads in ref. [24], [26], [27]. For a given power, the link between the topology of "near-field" V_{RF} and the RF current flows on the antenna structure or the pattern of emitted RF electric fields in realistic geometry is a topic of active research. The challenge is to find an electric scheme efficient for launching the Fast Wave while minimizing SOL disturbances. Once the antenna electric design is frozen, the remaining degrees of freedom are the ways to energize the strap array, *i.e.* the power sharing and phasing between the feeding transmission lines.

For 2-strap arrays the wave-SOL interaction is minimized with balanced strap power and [0π] phasing. Over a phase scan, the local minimum is not pronounced: on WEST the WI line brightness was reduced by ~1.8 on the antenna limiters over the phase range [80°,180°] [64]. Besides the plasma radiation could be reduced to a level comparable to LH-heated discharges at similar power. On Tore Supra 2-strap arrays phased [0π], when the power was unbalanced the heat loads increased on the antenna limiter near the strap with larger voltage, and decreased on the opposite limiter [28]. Similar observation was made for the RF current on the limiters of the AUG 2-strap antenna [65]. The toroidal width of the antenna limiters [30] and the type of Faraday screen [27] [28] also influence the magnitude of RF-sheath effects. The poloidal location of "near-field" effects around the JET ITER-like antenna depends on whether its lower or upper part is energized [39].

On JET 4-strap A2 antennas with power balanced between straps, the core plasma performance was degraded with [00ππ] phasing, compared with [0π0π] or [0ππ0] phasing, despite lower antenna voltages [66]. ASDEX upgrade emulated a balanced 4-strap array by pairing two nearby 2-strap antennas phased [0π] at the same frequency [30], [67]. The phasing between antennas was real-time controlled. It somehow affected WI line brightness at the antenna limiters, the core W content and plasma performance, suggesting that the whole array behaves as a single antenna below a minimal toroidal distance. This is so far less true when pairing 2-strap and 3-strap AUG antennas [68].

While strap arrays are ordinarily purely poloidal, one option to further reduce the impurity production was to align the whole antenna structure with the oblique confinement magnetic field for a standard value of q_{95}. On C-mod the power radiated by the plasma was 20%–30% lower for a 4-strap field-aligned-antenna (FA) heated discharge than a discharge heated with the toroidally-aligned-antennas (TA) [9]. However, GPI and emissive probes observed nearly identical V_{DC} near an antenna box corner for FA and TA antennas when operated in dipole phasing. Moreover, the highest V_{DC} were observed using monopole phasing with the FA antenna. Thus, while impurity contamination and sources are indeed reduced with the FA antenna configuration, the reasons of this improvement remain to be understood.

A 3-strap array phased [0π0] [32], [33] and 4-strap arrays phased [0ππ0] [69] or [0π0π] [69], [70] achieved strong RF-sheath reduction on the antenna side limiters by requesting more power on the inner straps. JET A2 antennas with [0π0π] phasing also achieved a locally minimal Be production, but with excessively unbalanced strap powers [69]. Minimization comes with less flexible $k_{//}$ spectrum (*e.g.* less easy current drive) and lower maximal power in the case of JET A2 antennas. All local minima, including on 2-strap arrays, correspond to lower RF currents induced on *both toroidal sides* of the antenna box, as evaluated by linear antenna codes without sheaths, and measured on AUG antenna side limiters [34]. For the AUG 3-strap antenna with optimal feeding, the image currents were nearly cancelled. LAPD operated a single strap inside a box with bulk ceramic side walls [63]. The measured V_{DC} outside the box nearly vanished, confirming a key role of the box in the RF-sheath generation. Antenna box currents might explain the universality of the multi-hump poloidal structure observed for "near-field" effects over a large variety of strap electric schemes. For JET A2 antennas, the RF currents on the central septum also need to be reduced [34]. One can hardly cancel them simultaneously with those on antenna box sides.

5. EFFECT OF LOCAL PLASMA ON THE NEAR-FIELD RF-INDUCED SOL MODIFICATIONS

Sheath rectification is a plasma process likely affected by the plasma parameters. This section restricts the discussion to the role of local plasma parameters on "near-field" effects. "Far field" sheaths likely depend on more global profiles governing the wave propagation, scattering and damping in the plasma core.

The sputtering yield of Mo and W by tokamak SOL plasmas is mainly governed by light impurities present in quantities of a few per cent in a background of D^+. Reference [17] provides sputtering yield estimates for W in presence of C, O and B impurities with several ionization states, while [8] shows similar curves for Mo with B^{3+} and Mo^{3+} ions. Although scarcely documented the metallic production might strongly change from one experimental day to another, likely due to varying light impurity content. Reference [71] reported enhanced W production on AUG antenna limiters in N_2 seeding experiments aimed at enhancing the divertor radiation. On the contrary, the peak values of V_{DC} estimated by GPI on C-mod decreased by about 30% with seeding with low-Z gases (helium, nitrogen and neon) [15]. It is speculated that higher neutral contents during seeding may substantially increase the collisionality/resistivity and affect V_{DC}.

The local plasma density and temperature determine the flux of particles hitting the wall and the charge state of light impurities. This, together with the ion energies and the DC currents, determine the heat loads and gross erosion rate of the PFCs. At given antenna voltage, the scaling laws for heat loads on the wave-launching structures depend on the local density at the antenna [24], [27]. At given antenna voltage, the gross W production on WEST antenna limiters was larger when ICRF waves were applied in LH-heated discharges than in ICRH-only pulses [35]. This was ascribed to enhanced particle fluxes onto the antenna limiters in presence of large LH power, as indicated by larger DI_δ line brightness recorded by visible spectroscopy and larger ion saturation current collected by Langmuir probes embedded on the LH antennas.

Local gas injection was applied successfully to restore good LH wave coupling in ICRF-disturbed convective cells [47] and to enhance ICRF wave coupling without disturbing the plasma core in H mode [1]. This also lowered the W production at the AUG antenna limiters [30], [71].

6. OUTLOOK FOR FUTURE LONG PULSE METALLIC DT MACHINES

This contribution reviewed recent experimental characterizations of RF-induced SOL modifications in various tokamaks and LAPD linear device. Mainly “near-field” effects were documented. “Far field” RF-sheaths are suspected in some devices but remain largely unknown. The only efficient method to reduce them is to ensure high single pass absorption for the launched Fast Wave. This is the case for most heating scenarios envisaged for ITER [72] [73]. Avoiding the excitation of low-$k_{//}$ power spectra also improves the wave absorption in the core. Besides it reduces the excitation of coaxial modes or wave damping at the peripheral LH resonance [56].

“Near field” RF-sheath effects appear on open magnetic flux tubes connecting near active ICRF antennas. High-Z materials should be used with care there. Other objects might be affected along these field lines. Apart from the wave launchers themselves, small-size regions far away toroidally from the antennas can also be sputtered and contribute to the core plasma contamination. On JET no RF-induced W-source could so far be localized directly [31]. Candidate locations could at best be “guessed” indirectly from the SOL field lines subject to RF-induced density modifications [45]. Although the RF-induced SOL disturbances can reach the divertor, there is no sign in present devices that sheath rectification dominates the sputtering there and enhances the core contamination. In present devices, the disturbed zones extend radially a few centimetres in front of the antenna limiters. This suggests that SOL modifications could be kept far away from the separatrix by increasing the radial gap to the antennas (nominal value ~12cm in ITER), at the expense of lower ICRF coupling resistances.

Recent experiments clarified the link between “near-field” RF sheaths and the RF currents over the antenna metallic surfaces. On ALCATOR C-mod a field-aligned antenna successfully reduced the impurity production and contamination [9]. Yet the reason for this improvement remains unclear. Such antennas hardly fit in a mid-plane port. Together with tilting the antenna, image current suppression on antenna box sides is a promising technique successfully tested on various antennas already. Using insulators for antenna boxes looks difficult in reactor environments, due to the aging of ceramics under neutron fluxes. Active cancellation with metallic antenna boxes requires arrays of 3 straps at least, with constrained $k_{//}$ spectra and possibly power limitations. Calculations however show that antenna box currents could be cancelled on the ITER antenna box, using [$0\pi\pi0$] phasing and with reasonable power balance between straps ($P_{central}/P_{tot}$ close to 0.5) [34]. Electromagnetic calculations also stress the need to avoid protruding elements on the antenna front face. Other antenna concepts have been proposed for fusion reactors, *e.g.* Travelling Wave Arrays (TWAs) [74]. Although attractive, due *e.g.* to Fast Wave excitation far away from the separatrix, TWAs remain to be tested in metallic environment.

The magnitude of RF sheaths depends on the local plasma parameters. Light impurities contribute to the sputtering. This stresses the need to maintain good machine conditioning over long high-power discharges. Wall erosion also changes with the majority species. While most present experiments were conducted in D^+ plasmas, fusion reactors will operate with a DT fuel mix, with a small amount of He ash. Both T^+ and He^{2+} exhibit higher sputtering yields than D^+. Besides the Fast Wave propagation and damping properties (*e.g*. cut-off density) depend on the mass and charge of the majority species. JET presently investigates isotopic effects on RF-SOL interaction. Local gas puffing was proposed from dedicated gas valves close to the ITER antenna, to simultaneously improve the ICRF coupling and reduce the local impurity production [75]. This technique can be more easily used when the SOL is not opaque to neutrals. These can then penetrate relatively far away from the gas valve before getting ionized. This needs to be assessed in the more opaque ITER SOL. With a poor fuelling efficiency, gas puffing in the ITER SOL should be easily decoupled from core plasma fuelling. Active control of the local plasma requires measuring the SOL density as close as possible to the antenna, ideally with embedded diagnostics.

Due to the low melting temperature of beryllium (1250°C), heat fluxes onto the PFCs surrounding the ITER ICRF antennas raise concern. IR thermography is more difficult in metallic environments than in past carbon machines, due to low (and evolving) surface emissivity, together with spurious light reflections. Quantifying fluxes from IR surface temperatures also requires knowing antenna thermal properties. Cooling down time constants, however, suggest that these properties can slowly evolve over experimental campaigns or antennas. On Tore Supra and JET [24], inspection at shutdown revealed localized carbon deposits on the surface of CFC tiles or localized flaking of the B_4C coatings. To help the IR film interpretation, it is, therefore, useful to develop monitoring pulses and repeat them regularly over the experimental campaigns, especially after incidents.

On Tore Supra, using specific diagnostics, one physical mechanism was identified as causing hot spots for each region of interest on the antenna front face, together with one relevant actuator able to modify hot spots in real-time: total power, or local power from one specific IC or LH launcher. In inertial machines, only a soft stop can be triggered in case of excessive heat loads. On actively cooled machines more clever control schemes can be developed, *e.g.* continuing the pulse at reduced power compatible with launcher integrity. On Tore Supra five such schemes were implemented simultaneously for the record-long pulses with ICRH and LHCD [76].

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