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-Integrated Operational Scenario (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 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, 30-100MHz in present devices) 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 processes could hinder the machine lifetime if they cumulate their effects over long periods. A further challenge is to combine ICRH with other subsystems in Integrated Operational Scenarios (IOS). ICRF-induced SOL modifications might perturb the operation of the other actuators, *e.g.* Lower Hybrid (LH) 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 new 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.

ICRF waves are meant either to heat the main ion species of the plasma discharge at harmonics of their cyclotron frequency, or a minority species at its main cyclotron frequency. Minority ions are introduced on purpose in typical concentrations of a few percents. Energetic ions from Neutral Beam Injection (NBI) or intrinsic light impurities can also play this role. In future devices ICRF waves may also be used for current drive *via* a combination of electron Landau damping and Transit-Time Magnetic Pumping. In general the scenarios are devised so that the resonant wave/particle interactions occur near the plasma centre. Once accelerated, the renonant species re-destributes the power gained from the waves to the other plasma constituents *via* collisions. Unless explicitly mentioned, the reported results were obtained with the D[H] minority heating scheme. The main exceptions are the NSTX spherical tokamak and the LAPD linear device, both using high-harmonic fast wave heating of D^+ and He^{2+} plasmas respectively. Although these are the workhorse scenarios of present devices, they are not the main heating schemes intended for future DT machines. It is believed that by their nature, the SOL processes described below are qualitatively generic. However the ICRF-induced SOL modifications might vary in amplitude with the ICRF wave coupling properties or the single pass power absorption through the plasma core, that are scenario-dependant. The mass of the main ions, together with the presence light impurities, are also known to affect the sputtering of wall materials. The paper will discuss our present knowledge on these aspects and the uncertainties for extrapolating quantitatively to DT machines.

While the magnitude of adverse effects should be minimized, we also emphasize the 3D spatial distribution of the SOL modifications. Figure 1 sketches the typical structure of present ICRF wave launchers. They consist of phased arrays of current straps housed in individual metallic boxes electrically grounded to the machine vessel. The straps are generally oriented along the poloidal direction of the tokamak, but may be tilted perpendicular to the local confining magnetic field. The number of straps is variable. Each is fed by an independent coaxial transmission line. But the straps may be grouped to reduce the number of feeding lines and/or improve the load resilience. Antenna boxes are generally partially closed on their plasma side by a Faraday screen, a tight array of metallic rods ideally parallel to the confinement magnetic field. Antenna boxes are generally surrounded by private limiters. The active straps induce RF currents on all neighboring passive metallic structures. Understanding the RF-sheath complex 3D patterns, in relation with the plasma magnetic topology and the spatial distribution of all these RF currents, provides hints for judicious port allocation, antenna design and operation. It clarifies which plasma-facing components (PFCs) are more likely to be eroded, and which species are sputtered in mixed-materials walls like ITER. Reproducing the measured patterns also puts strong constraints on interpretative RF-sheath models. Reference [3] proposes a recent tutorial on RF sheath modelling in magnetic fusion plasmas. References [4], [5] and [6] reviewed some comparisons of experiments with modelling in realistic geometry.

The paper is organized as follows. Part 2 describes the physical nature of ICRF-induced SOL modifications, stressing its consistency with expectations for RF-sheath rectification. We also present briefly other physical processes that might affect the SOL, as well as specific techniques used to measure key SOL quantities averaged over thousands of RF periods. Part 3 outlines the complex 3D spatial structure of these SOL modifications. We separate regions connected ("near field") and not connected magnetically to the active ICRF wave launchers ("far field"). Part 4 and 5 discuss respectively the roles of antenna design and electrical setup, and then of the local plasma parameters on the "near field" SOL modifications. Part 6 attempts some extrapolation of the present results to future long pulse metallic DT machines, and outlines some remaining uncertainty in this prospect.

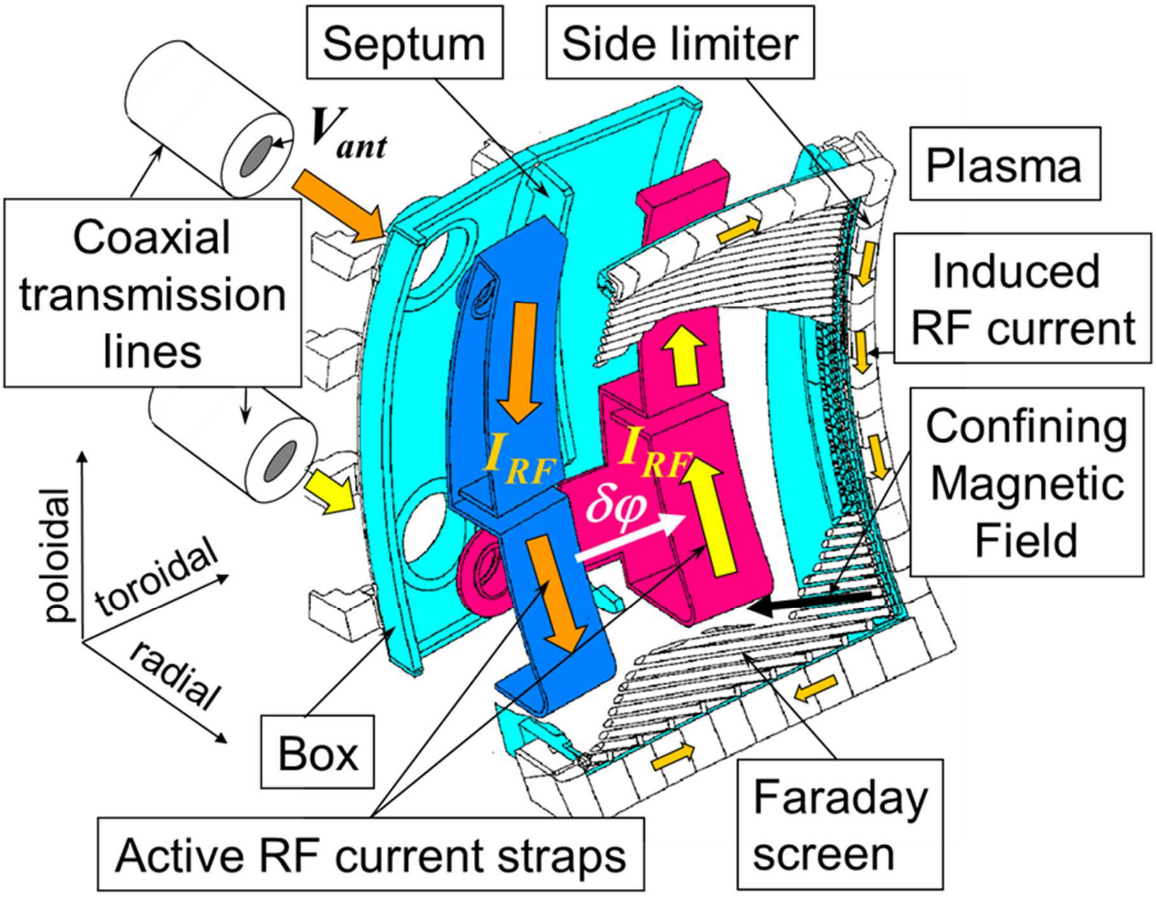

Figure 1: sketch of a typical present-day ICRF wave launcher, showing its main components. Schematic definition of antenna RF voltage V_{ant} and phasing $\delta\varphi$ between adjacent strap RF currents.

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

2.1. RF-sheath rectification basics

The Scrape-Off Layer (SOL) of magnetized plasma devices is a region where open magnetic field lines intercept material boundaries. The plasma is not confined along the field lines, whose extremities are therefore subject to large particle and heat fluxes. 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 bulk 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. The textbook *I-V* characteristic writes

$$I = I_{sat}\left[1 - \exp\left(-\frac{e(V - V_{f0})}{kT_e}\right)\right] \qquad (1)$$

where I_{sat} is the ion saturation current, T_e is the local electron temperature and V_{f0} is the floating potential in the absence of ICRF. On the right-hand side, the two terms correspond respectively to the collected ion and electron currents. While ordinary sheaths are static, intense RF electric fields in the vicinity of the wall may induce strong RF oscillations V_{RF} of the sheath voltage at the wave frequency. Since the sheath electrical properties (*e.g.* *I-V* characteristic (1)) are non-linear, V_{RF} tends to shift the time-averaged (Direct Current (DC)) I_{DC}-V_{DC}

characteristic of the sheath with respect to its thermal expression (1). The modified characteristic takes the general form

$$I_{DC} = I_{sat}\left[1 - \exp\left(-\frac{e\left(V_{DC} - V_b(V_{RF}) - V_{f0}\right)}{kT_e}\right)\right] \tag{2}$$

Rectification thus acts as if the local wall elements (generally grounded in tokamaks) were electrically biased to the DC potential V_b. Several expressions for V_b were proposed in the literature. For example one can obtain a quasi-static limit by inserting $V(t)=V_{DC}+V_{RF}\cos(\omega_0 t)$ into (1) and then averaging $I(t)$ over time [7]

$$\frac{eV_b(V_{RF})}{kT_e} = \ln\left[\mathrm{I}_0\left(\frac{e|V_{RF}|}{kT_e}\right)\right] \tag{3}$$

where $\mathrm{I}_0(z) \equiv \frac{1}{\pi}\int_0^{\pi} \exp[z\cos(\varphi)]d\varphi$ is the modified Bessel function of order 0. In all the proposed formulae, V_b scales as $|V_{RF}|$ when $e|V_{RF}|>>kT_e$. Most of the phenomenology described below is common with more familiar biaising experiments using electrodes, except that the DC bias is not controlled from outside but imposed by the RF waves. This "self-biasing" is described in textbooks for non-magnetized sheaths in RF discharges [8] [7] but is more complicated in the presence of a static magnetic field tilted with respect to the wall [3]. In LAPD, reference [9] diagnosed the electrical RF and DC properties of RF-driven sheaths on a grounded plate magnetically connected to an ICRF antenna. The sheath RF impedance at the plate, defined as V_{RF}/I_{RF} at the wave frequency, was measured as a function of the DC sheath voltage V_{DC} and compared to models.

2.2. SOL DC biasing due to RF-sheath rectification

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 local DC potential V_{DC} with respect to the (grounded) wall. If we request the sheath in equation (2) to float, the rectified V_{DC} becomes

$$V_{DC}=V_{f0}+V_b(V_{RF}) \tag{4}$$

References [10] [11] [12], [13] and [14] measured V_{DC} directly using emissive probes, while reference [15] estimated it from a Retarding Field Analyzer (RFA), and reference [16] used triple Langmuir probes. Reference [13] also used ion sensitive probes suitable to measure V_{DC} at high SOL densities. The emissive and ion-sensitive probes were incorporated into a compound reciprocating diagnostic also measuring the local RF field amplitudes for different polarizations. References [17] [18] [12] [19] deduced changes of V_{DC} indirectly from the integration of DC radial electric fields. All techniques recorded V_{DC} in the range of several hundred Volts near Alcator C-mod antennas energized at megawatt levels. V_{DC} was also inferred from variations of Langmuir probe floating potential V_f, *e.g.* in [10] [20], [21], [22], [23], [24], [25], [26], [27]. Interpreting the floating potentials might however be ambiguous: although V_f is related to DC plasma biasing, it is rather indicative of DC currents collected by the grounded probe (see below).

2.3. Enhanced heat loads

DC SOL biasing is expected to increase the energy of the ions impinging the wall, thereby enhancing the Plasma-Wall Interaction (PWI). References [15] and [28] 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 the ohmic regime. Simulations in reference [15] suggest that, due to the sheath oscillations, the time-averaged energy distribution of the collected ions is not necessarily mono-energetic: it could exhibit two peaks if the wave frequency is lower than the local ion plasma frequency. Such distributions have been observed in capacitive plasma discharges [Cha11].

Heat loads onto the wall are locally increased during ICRH and were documented from surface temperature measurements using infrared (IR) cameras on JET [29] [30] [31] [32], Tore Supra [33], [34], [35], [36], NSTX [37] and WEST [27]. Reference [31] reported localized heat fluxes in the range of several MW/m^2 normal to JET A2 antenna septa, depending on the RF voltage on the transmission lines, local density and RF feeding scheme. Reference [35] 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. The principle is to compare inlet and outlet coolant temperatures for a given measured water flow in the pipes. Reference [36] 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. The amount of power dissipated in the SOL plasma is generally modest. One exception is NSTX, exploiting the high-harmonic fast wave heating scheme, where the core heating efficiency was reported to drop by up to 60% in adverse scenarios (lower $k_{//}$ in excited specrum, lower magnetic field) [38].

2.4. Enhanced wall erosion and core plasma contamination

More energetic ions 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) [21], [39], [40], [41], [42], [43], [5], [44], [45], [27], [46], molybdenum (Mo) [10][12] and beryllium (Be) [47] [48]. In the absence of systematic measurements of V_{DC}, ASDEX Upgrade and WEST publications used the ratio of W over D line brightness as a proxy of the effective W sputtering yield to assess the magnitude of rectified DC potentials. Reference [27] showed first experimental correlations between local heat loads and local WI line radiation at 400.8nm on WEST ICRF antenna limiters: they exhibit a similar characteristic poloidal shape along the limiters, that will be detailed in section 3.3. Visible spectroscopic signals are mainly representative of the local gross erosion, while prompt redeposition may be important, especially for high-Z impurities, as verified for thermal sheaths on the JET divertor [49].

Visible spectroscopy was generally used in conjunction with VUV spectroscopic line emission from the plasma core, to assess the central contamination for W [21], [39], [40], [41], [42], [51] [43], [Gon17], [5], [44], [45], [50], [27], [46], Mo [10][12] [45], [50], [27], but also nickel on JET [53] [54] [55], titanium or iron on EAST [45] [50], iron and copper on Tore Supra [56] and silver on WEST [27], [46]. [27]Contamination of the plasma core is studied extensively, as large radiation from the plasma centre can hinder the fusion performance or even the stability. Contamination is however the consequence of many combined physical processes: the gross impurity production at the wall, but also redeposition, transport to the core and MHD. When analysing the variations of core impurity concentrations, it is therefore difficult to disentangle these various processes. Transport is generally associated with modified spatial distribution of the impurities and of the plasma radiation, as assessed by bolometric and soft X-ray tomographies [51] [52]. Changes in the sources are generally correlated with changes in the visible spectroscopy signals, over specific experimental protocols discussed in section 3.5. ICRH acts on both the sources and the transport. JET discharges with mixed ICRH and NBI feature higher radiation than pure NBI-heated plasmas with the same additional power [40], [51] This is sensitive to the antenna electric setting, and attributed to larger impurity production. However, applying ICRF waves allows flattening the tungsten profiles, that can even become hollow for central power deposition, unlike pure NBI discharges. Reference [52] invoked modified impurity transport due to flatter density profiles and more peaked temperature profiles to interpret this change. High performance JET discharges used ICRH extensively to avoid tungsten accumulation in the plasma core [51]. We will however focus the rest of the paper on RF-induced impurity sources.

2.5. RF-induced local plasma convection

The RF-induced SOL biasing is generally highly inhomogeneous spatially. Due to the large parallel DC conductivity of the plasma, 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} [14]. 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 [17] [18] [12] [19]. GPI recorded poloidal velocities in the range of several km/s, strongly sheared radially, while turbulent radial velocities in the SOL are typically 10-100m/s with rather flat radial profiles. On top of other SOL transport processes (turbulence, parallel losses) the RF-induced **E×B** convection redistributes the local density in the antenna vicinity. Local density modifications were evidenced using Langmuir probes [57] [20] [28] [58] [14] [59], edge reflectometry [60] [61] [58] [62], or Lithium beam emission spectroscopy [25] [62]. Although density depletion was generally reported, over-density was sometimes observed on the same experiments, depending on the probed radial/poloidal location [63], [62]. This modified the wave coupling properties on LH waveguides magnetically connected to active ICRF antennas [64] [65] [20] [66] [61] [67], as well as LH-related hot spots, evidenced *via* IR thermography [65] [63] [30].

2.6. DC currents circulation and floating potential of Langmuir probes

The above-mentioned DC current equilibration by the sheaths should be understood on average over the device: DC electric currents I_{DC} are allowed locally in conductive media (plasma, wall, …) but should form closed circuits, thereby coupling the sheaths at different locations on the machine. As a paradigmatic example, open magnetic field lines have two extremities l and r, 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 all along the flux tube V_{DC} adapts to the electrode with larger $|V_{RF}|$ and I_{DC} flows from the high-$|V_{RF}|$ boundary to the low-$|V_{RF}|$ one. If I_{DC} flows only in the parallel direction one gets [4]

$$\frac{e\left(V_{DC}-V_{f0}\right)}{kT_e} = \ln\left[\frac{\exp\left(\frac{eV_{br}}{kT_e}\right)+\exp\left(\frac{eV_{bl}}{kT_e}\right)}{2}\right] \tag{5}$$

$$\frac{I_{DC}}{I_{sat}} = \tanh\left[\frac{e\left(V_{bl}-V_{br}\right)}{2kT_e}\right] \tag{6}$$

In the latter formula, I_{DC} is counted positively if it flows from l to r. DC current transport transverse to **B**, although weak compared to the parallel DC conductivity, further complicates the electrical paths in the SOL. References [21] and [68] studied DC currents collected on the side limiters of ASDEX Upgrade ICRF antennas. As expected from (6), limiter tiles of active antennas collect negative DC currents. On a passive antenna connected to an active one, the DC currents can be of either sign. Negative currents correspond to tiles with strong RF pickup, suggesting that the active antenna could induce rectification remotely. Reference [69] invoked DC currents to interpret arcs in mixed phasing JET experiments. DC currents also change the electron particle and heat fluxes onto the wall. Reference [70] invoked them to interpret left-right heat load asymmetry on Tore-Supra antennas with left-right power unbalance. Reference [14] measured the DC plasma potential together with its RF oscillations using an emissive probe magnetically connected to an active antenna 65cm away. Although V_{DC} increased significantly during ICRF, the RF oscillations were ~9times lower in magnitude, suggesting that the rectification occurred at the antenna side of the open field lines and not near the probe. The coupled field line extremities were used explicitly as an experimental technique in LAPD: reference [9] diagnosed the sheaths at a grounded plate magnetically connected to an active ICRF antenna. The DC sheath voltage at the plate was controlled by varying the RF current applied to the radiating strap.

When a grounded wall element collects DC current, the floating potential V_f of a Langmuir probe at this location is modified. Reference [71] explained how I_{DC} acts on top of voltage rectification and can reverse the sign of V_f. Within the double probe analogy developed above, the floating potentials at the l and r extremities of a biased open field line are opposite

$$V_{fr} = -V_{fl} = V_{bl} - V_{br} = \frac{2kT_e}{e}\,\text{atanh}\left(\frac{I_{DC}}{I_{sat}}\right) \tag{7}$$

This led to re-interpreting Langmuir probe data on NSTX [71] and EAST divertor [59] during ICRF. On fixed divertor probes connected magnetically to ICRF antennas, V_f varied in opposite ways on the two devices during ICRF application. V_f polarity on NSTX was consistent with divertor sheaths being rectified. On EAST it is consistent with voltage rectification on the antenna sheaths and I_{DC} flowing from antennas to divertor. In addition V_f polarity changed its sign on divertor probes connecting *in front* of the EAST antennas when they were energized (see also [50]).

2.7. Other RF-induced edge processes

Figure 2 summarizes the phenomenology observed above and sketches its consistency with the expectations from RF-sheath rectification. These physical mechanisms are qualitatively independent of the awave absorption mechanisms at the plasma centre. They are therefore expected for all ICRF heating scenarios. LAPD measured all the phenomena, except DC currents, on similar plasmas [14]. On top of this phenomenology other RF-induced edge processes might co-exist locally. References [34] and [72] evidenced heat loads onto Tore Supra ICRF antenna limiters due to fast ion losses from the plasma core. Resonant wave modes [73], wave-filament bound states [74], RF power absorption at the peripheral Lower Hybrid (LH) resonance [75] or ponderomotive forces [76] have been proposed in the literature, the latter especially in the vicinity of ICRF antennas. These additional processes likely exist but have not been clearly evidenced in experiments. Consequently they will not be further discussed below.

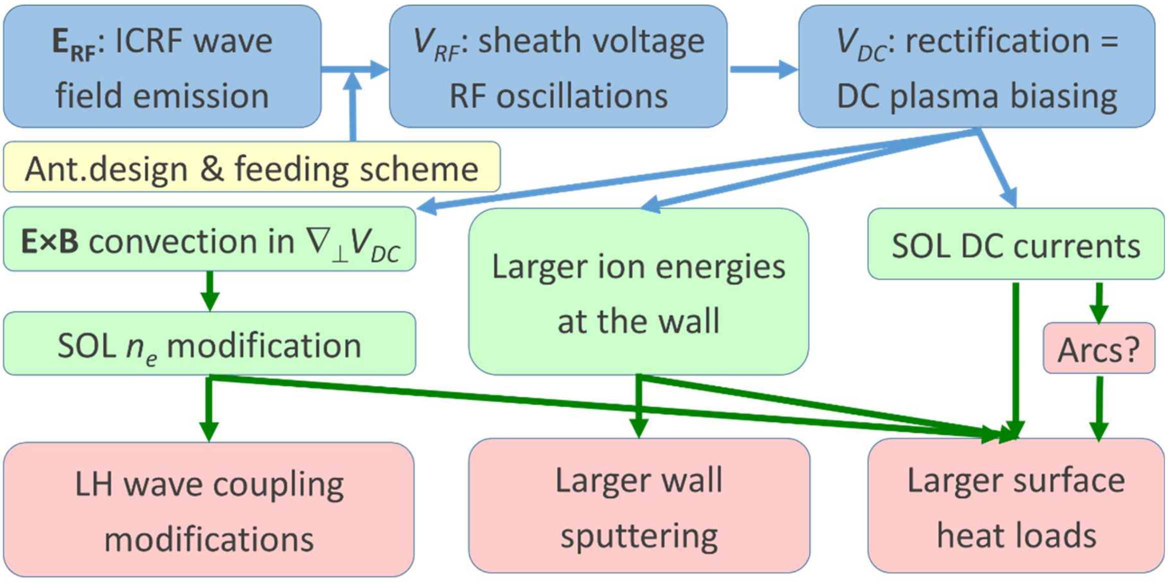

Figure 2: sketch of ICRF-induced SOL modifications due to sheath rectification and its consequences. Blue boxes: main steps of plasma self-biasing. Green boxes: main effects of localized DC bias on SOL plasma (not specific of RF rectification). Red boxes: main operational consequences of SOL modifications, including plasma-wall interaction. The link between $\mathbf{E}_{RF}$ *patterns and spatial structure of* V_{RF}*, via antenna design and feeding scheme (yellow box), is addressed in part 5 of this contribution.*

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

3.1. Parallel structure of "near-field" effects

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… Figure 3 visualizes in the visible range field-aligned bright filaments passing in front of an active NSTX antenna and reaching the upper and lower divertors [37]. On ASDEX Upgrade energizing an ICRF antenna influenced the W production as well as RF and DC currents on the limiters of a magnetically connected passive antenna [21] [68]. 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 [47]. Although a direct excitation of sheath RF oscillations by RF waves propagating to the remote objects cannot be fully excluded, this long parallel extension is more likely related to the large parallel DC conductivity of the plasma, in comparison with more modest transverse transport of DC current. In any case the launched ICRF waves are not supposed to propagate strictly parallel to **B**. Probe, reflectometry and Li beam spectroscopy diagnostics mentioned above measured 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} [20] [63] [28] [25] [58] [62]. Reference [14] 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 [59], a situation described as "blocked open field lines" in reference [13]. 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 [58].

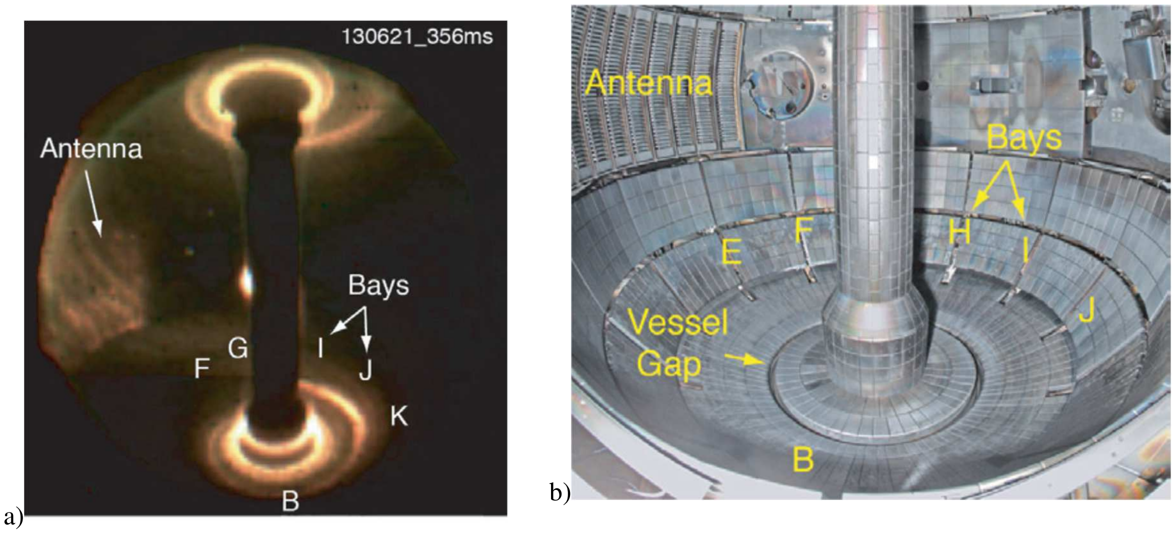

Figure 3: a) visible light image of NSTX main chamber during ICRF application in shot 130621. The plasma conditions are toroidal field 0.55T, NBI power 2MW. 12-strap antenna operated at 30MHz, delivering 1.8MW with toroidal phasing -90° between adjacent straps (main k_ϕ in radiated spectrum $8m^{-1}$). b) Image of NSTX vessel during maintenance, showing position of the antenna, tiles, vessel gap and toroidal bay locations. View rotated 30° toroidally relative to a). Reprinted from reference [37], with kind permission of the authors.

3.2. "Near field" effects: radial structure

2D mappings using probes, 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 how they connected magnetically to the active ICRF antennas [63]. In the radial direction, local maxima of V_{DC} were 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 [10], [17], [19]. Figure 4 shows the floating potential V_f recorded by a popup Langmuir probe embedded on a WEST outboard limiter over its radial stroke [27]. The probe is magnetically connected to ICRF antenna Q2. When antenna Q2 is passive, V_f is slightly negative and exhibits a smooth monotonic radial profile. When Q2 is active a peak of positive V_f appears in the profile. Its radial shape is reproducible on the inward and outward movements of the probe. Antenna Q2 is mobile radially, and its radial position was changed from pulse to pulse. The radial location of the peak shifted radially consistently with this position. The bright filaments on NSTX extend radially up to the separatrix [37]. Reference [19] investigated the parametric dependence of the peak radial extent. This width 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 extent explains why on JET the ICRF coupling resistance remains constant as the RF power increases, despite larger RF-induced density depletion [25]. It might also explain why, on JET [77] and C-mod [78] [79], 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.

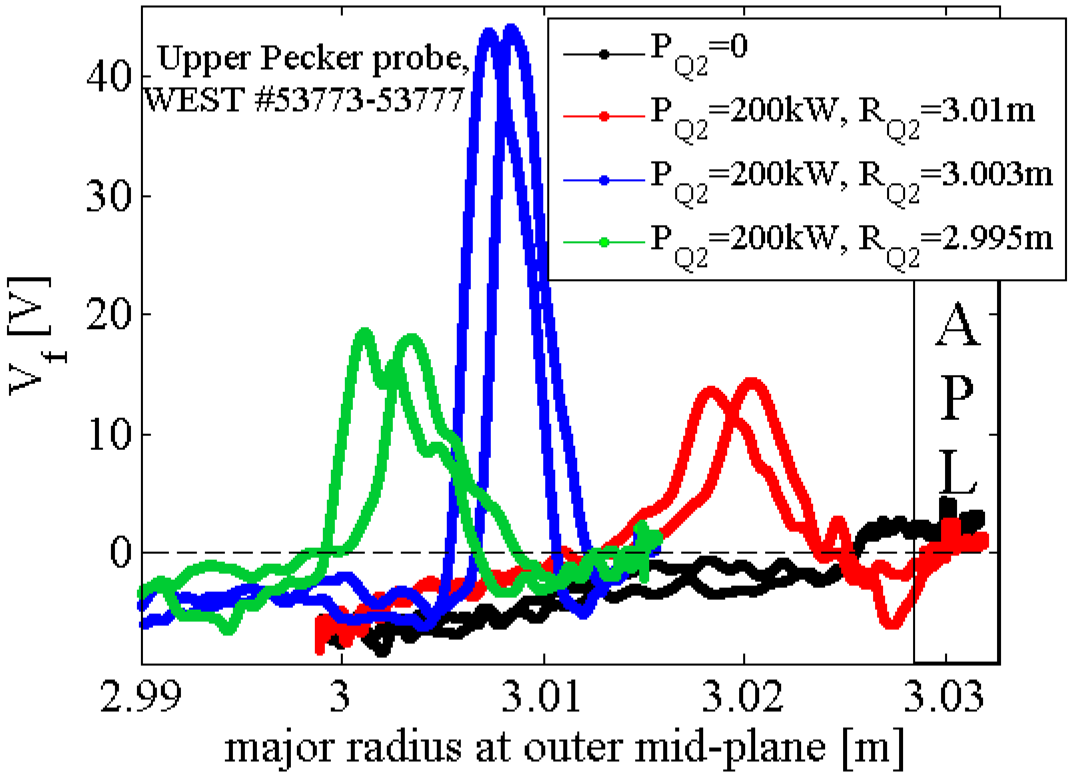

Figure 4: Floating potential of a popup Langmuir probe embedded in the WEST outboard Antenna Protection Limiter (APL) versus radial probe location mapped to the outer mid-plane. Four probe reciprocations are represented, for several radial positions of the moveable ICRF antenna Q2. The radial location for the leading edge of the antenna limiters is indicated in the box. The inward and outward probe movements are left separate. Adapted from reference [27], with kind permission of the authors.

3.3. "Near-field" effects: poloidal structure

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 (Langmuir probes, emissive probes, RFA, GPI), over a large variety of antenna types [16] [63], [21], [17], [35], [47], [28], [58], [14], [50], [27]. Figure 5 maps in 2D transverse to **B** the DC potential V_{DC} recorded by a mobile emissive probe on LAPD [14]. In the absence of ICRF, V_{DC} remains below 10V. During ICRF application the picture shows two peaks located near the top and bottom of the antenna box, with V_{DC} maxima exceeding 90V. The JET ITER-like antenna (ILA) is organized as two strap arrays stacked on top of each other, that can be operated independently. References [48] and [62] showed that the poloidal distribution of "near-field" effects around the ILA depends on whether its lower or upper part is energized, suggesting a strong link with RF currents flowing on the antenna structure.

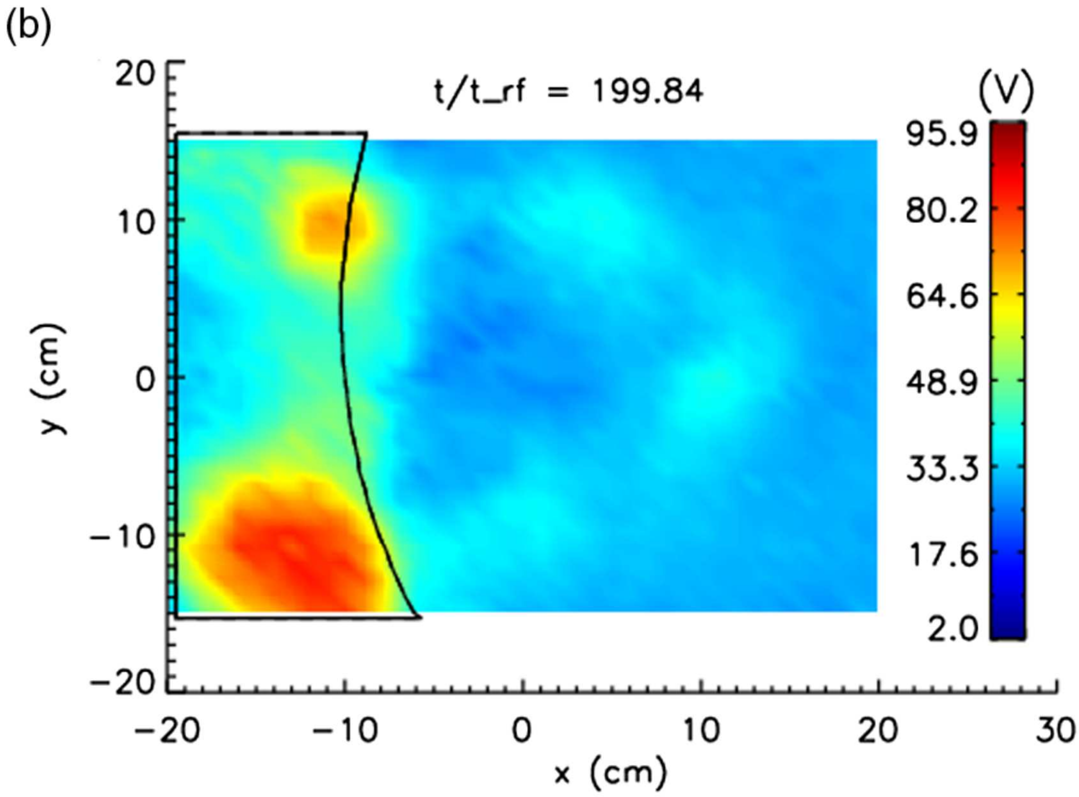

Figure 5: 2D (radial, azimuthal) map of V_{DC} recorded by a mobile emissive probe during ICRF on LAPD. The main plasma is to the right of the figure, while the antenna is on the left. The probe was located at longitudinal position z=65cm, while the active ICRF antenna was at z=0. The probe moved in 2D between repetitive plasma pulses. He plasma, B_t=0.1T, $n_e=10^{17}$-$10^{18}m^{-3}$, T_e=2-7eV, T_i~1eV, single strap antenna in metallic box operated at 2.38MHz, 150kW. The black curves show the limits of the antenna box. Reprinted from reference [14], with kind permission of the authors.

3.4. Evidence of "far-field" sheath effects

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, on unconnected field lines. The plasma potential enhancement there was correlated with the magnitude of local RF electric fields with Fast Wave (FW) polarization [13]. Besides, both FW fields and measured V_{DC} were modulated by sawteeth, suggesting a link with modulated Single-Pass Absorption (SPA). V_{DC} was therefore ascribed to "far-field" sheath excitation. Impurity production associated with "far-field" effects is also suspected on EAST [50]. 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. Figure 6 shows that, unlike other spectral lines, the Mo^{31+} line brightness from the plasma core increases as the phasing $\delta\varphi$ between adjacent straps (see figure 1) decreases and the power spectrum emitted by the I-port antenna moves to low-$k_{//}$,. This is ascribed to lower SPA. Fe on Tore Supra and Ni on JET are elements of the metallic alloys used for the main chamber wall radially far from the plasma. References [56], [53] [54] and [55] documented ICRF-specific plasma contamination by these elements: for given plasma conditions their concentration in the plasma edge is larger when using ICRH than other heating methods. The Ni concentration in JET is fairly independent of the divertor strike point position, further suggesting a production in the main chamber. When ICRH is present, Fe and Ni densities are sensitive to the minority concentration, both in standard minority and in 3-ion heating schemes. In this latter case, Ni contamination is minimized in conditions of good wave absorption. The Ni densities also depend on the antenna phasings: they increase as the main $k_{//}$ in the launched spectra decreases, correlatively with lower SPA. The underlying physical mechanism is not fully identified. Candidates are fast ion losses and "far-field" RF sheaths. 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.

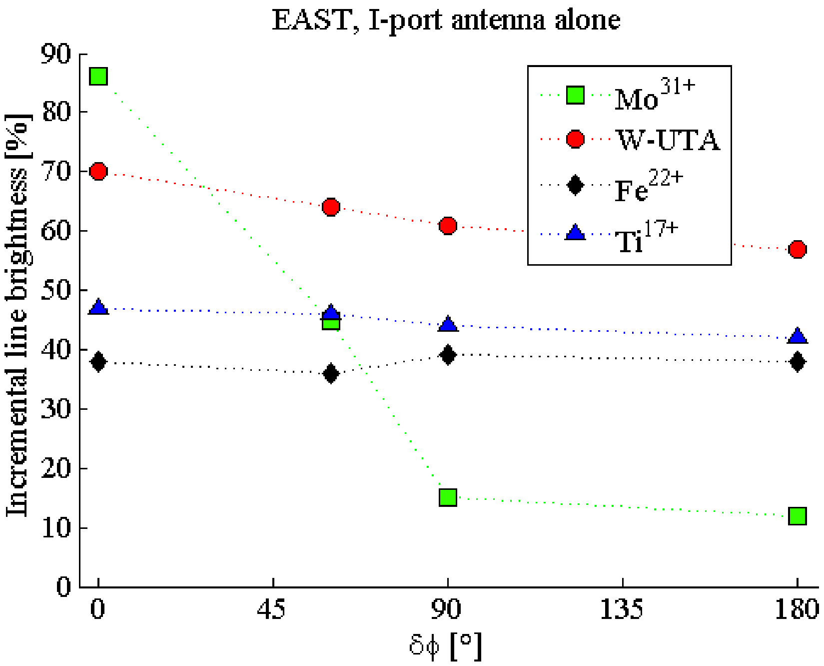

Figure 6: Increment during ICRH of normalized line brightnesses for several metallic ions in the VUV range recorded on EAST tokamak. Mo^{31+}*(127.868Å); W-UTA(40-70Å);* Fe^{22+} *(132.91Å);* Ti^{17+}*(144.759Å). The line brightness was normalized to the integrated density along the central line of sight of interferometry. The increments are the difference during ICRH pulse minus before ICRH . The increments were subsequently normalized to the maximum increase over the list of pulses analysed, and expressed in %. Measurements are plotted versus the phase difference between the RF currents in adjacent straps of the I-port 4-strap ICRF antenna on EAST, in pulses where this antenna was energized alone. Adapted from [50] with kind permission of the authors.*

3.5. Contributions to the core impurity contamination

Also scarcely addressed is the contribution of each object to the central impurity contamination. Section 2.4 explained that this is a difficult task requiring specific experimental protocols. On JET no RF-specific W-source could so far be localized directly [40]. Candidate locations could at best be "guessed" indirectly from the SOL field lines subject to RF-induced density modifications [62]. The exercise is easier on EAST than on other devices: each region on this tokamak is characterized by a specific material that can be monitored by a specific VUV spectroscopic line [50]. In the discharges studied in figure 6, Mo is mainly found on the inner wall of the machine, W on the upper divertor, Fe on the Faraday screens, while a test Ti plate was bolted on purpose on a limiter connected magnetically to the B-port antenna. Figure 6 shows that the contamination by the different species can exhibit very different parametric behaviours, so that reference [50] evidenced physical processes specific to each region in the machine. Parametric dependencies on EAST [50] and JET [40] 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 far from the strike points. Although a useful means to evidence RF-induced PWI, the Ni content in JET contributes only a small percentage of the radiated power [54]. On WEST silver (Ag) is mainly found as a coating material for the antenna elements. Ag radiation in the VUV range is detected specifically during ICRH. It is attributed to a sputtering of the Faraday screens exposed to the plasma, but is not considered as the main radiator on WEST plasmas. On AUG, the W-coated antenna limiters were identified as major contributors to the core contamination, with or without ICRH [80]. Replacing W with B on the limiters of 2-strap antennas reduced the measured core W density [39] [41]. The estimated reduction in the incremental W content during ICRH could reach 70% [39]. Significant contribution from W tiles on LH antenna limiters is also reported on EAST, even in ohmic regimes, from USN/LSN comparisons of the VUV spectroscopic measurement [50]. Reference [10]characterized Mo sources Γ_{Mo}, the core Mo content N_{Mo} and their dependences on the Alcator C-Mod operational regimes. The penetration of Mo into the core plasma under different conditions was analysed using the concept of penetration factor, PF = N_{Mo}/Γ_{Mo} (s). This concept however mixes source and transport effects. The probed locations included the divertor, the inner wall and the ICRF antenna limiters. In general, the inner wall Mo source was large, but was found to be relatively uncorrelated with the core Mo content in diverted plasmas. The outer divertor source likely dominates the core Mo content during diverted ohmic discharges. With the addition of ICRF heating the antenna protection tile sources, even though generally smaller than that of the outer divertor, likely become an important contributor. Localized boronizations allowed identifying small-size sources of Mo near the divertor entrance on magnetic field lines connected to the antennas and contributing to the core contamination [81].

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

Linking the spatial distribution of V_{RF} and the pattern of RF current flows on the antenna structure or that of emitted RF electric fields in realistic geometry is a topic of active research. The exercise only makes sense for "near-field" effects, that depend on a limited number of antenna and plasma parameters. The challenge is to find an antenna electric setup efficient for launching the Fast Wave while minimizing the SOL disturbance. In the antenna design phase, the main task is optimising the shapes of main antenna components (straps, boxes, Faraday screens, septa, see figure 1). The optimisation followed several guidelines, with variable success. Once the antenna electric design is frozen, the remaining operational degrees of freedom are the ways to energize the strap array, *i.e.* the power sharing between the feeding transmission lines and phase difference between feeding voltages. Below we will write between squatre braquets […] the phases of the successive straps in the array in radians.

4.1. Scaling of "near-field" effects with RF voltages on feeding transmission lines

For a given plasma and antenna electrical setting, LAPD checked the linearity of V_{DC} on connected field lines with the amplitude of the RF current feeding the strap, with some offset due to the thermal sheath [82]. Consistent with this check, at fixed feeding scheme and fixed background plasma, V_{DC} on connected field lines in C-mod generally scales as $P_{local}^{1/2}$, where P_{local} is the ICRF power delivered by the connected antenna [11], [17], [12], [19]. The amplitude V_{ant} of RF voltages in the transmission lines (see figure 1) also influence the RF-induced heat loads. Empirical scaling laws were proposed in [34] [29] [35] [31]: at fixed antenna phasing heat fluxes scale as V_{ant} (proportional to V_{DC}) or faster. This latter parametric dependence is attributed to RF-induced local density increase at the hot spot locations, while scaling laws rely on unperturbed SOL densities measured far from the antenna. The RF-induced density change is expected to depend on ∇V_{DC}, whose magnitude increases with larger V_{ant} (see e.g. [25] [14]) Linear RF power coupling to the core plasma scales as V_{ant}^2, while RF sheath power dissipation scales differently and is expected to dominate the antenna loading at low V_{ant}. This led reference [83] to propose low-power RF measurements as a way to diagnose "near-field" RF-sheath losses.

4.2. 2-strap antennas: effect of strap phasing and power sharing between transmission lines.

For 2-strap arrays the wave-SOL interaction is minimized with balanced strap power and [0π] phasing. On WEST the phasing $\delta\varphi$ between left and right RF voltages on the matching capacitors (see figure 1) is controlled in real time [84]. Figure 7 plots the WI line brightness on two antenna side limiters and on a nearby passive limiter over a dynamic $\delta\varphi$ scan. Although dipole phasing is a local minimum, the WI line brightness is significantly larger than in ohmic regime, and at similar power on a passive antenna. As $\delta\varphi$ decreases from 180° to 80° the brightness on the right limiter increased by a factor 1.5, although the coupled power P_{ICRF} decreased by a factor of 2. If we apply a factor $\sqrt{P_{ICRF}}$ to compensate for lower RF power the normalized brightness increases by ~1.8. Over the same phase scan, $\Delta P_{rad}/P_{ICRF}$ evolves from 45% (comparable to LH-heated discharges) to 80%. On JET discharges at similar antenna voltage and density at the antenna, the heat loads were 2.5 higher with -90° phasing than with 180° phasing [31]. An overshoot of the heat loads was recorded at the beginning of the ICRF pulses, when the RF votages were not properly balanced between straps. On Tore Supra 2-strap arrays phased [0π], when the power was unbalanced on purpose, the heat loads increased on the antenna limiter near the strap with larger voltage, and decreased on the opposite limiter [36]. A similar observation was made for the RF current on the limiters of the AUG 2-strap antenna [85]. The toroidal width of the antenna limiters [39] and the type of Faraday screen [35] [36] also influence the magnitude of RF-sheath effects.

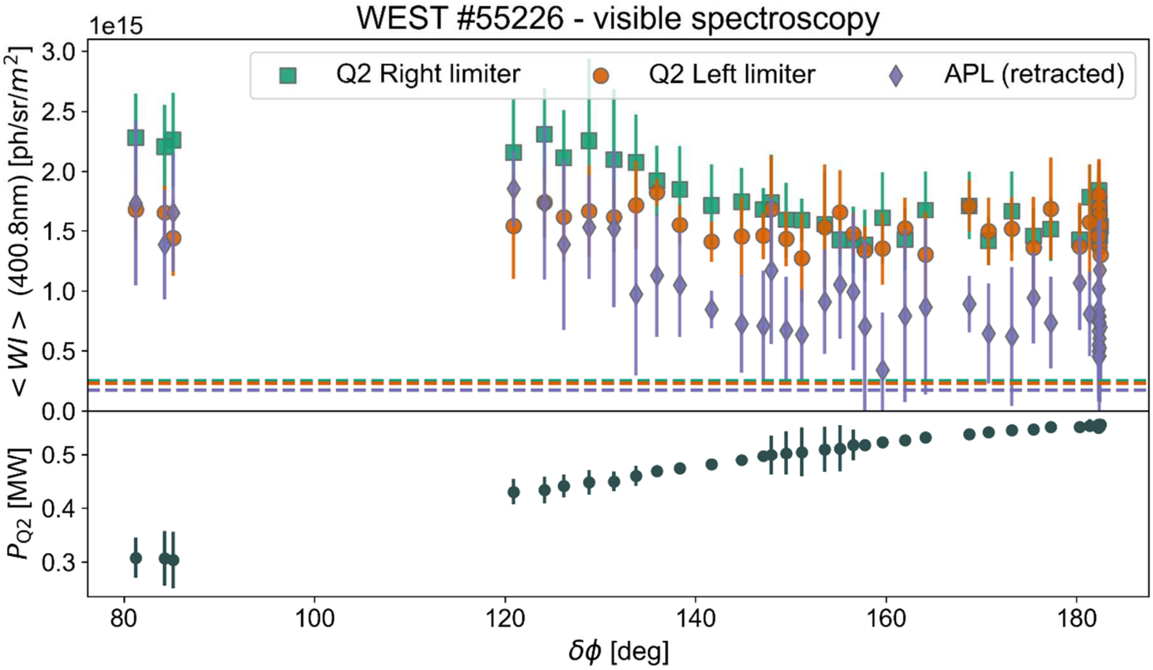

Figure 7: Upper panel: WI line brightness (wavelength 400.8nm) averaged over all lines of sights on left and right side limiters of active WEST ICRF antenna Q2 (as seen from plasma side), as well as outboard limiter (APL) connected to Q2 antenna and retracted 2cm behind it. Points plot the line brightness versus strap toroidal phasing during ICRF, vertical lines represent the rms fluctuation level over 50ms-wide sliding time windows. Dashed lines: value before ICRF. Lower panel: coupled ICRF power verus phase. Reprinted from [84]

4.3. 4-strap antennas with balanced powers: effect of strap phasing.

On JET 4-strap (A2) antennas with power balanced between straps, the core plasma performance was degraded with [00ππ] phasing, as compared with [0π0π] or [0ππ0] phasing at similar coupled ICRF power, despite lower RF voltages on the feeding transmission lines [86]. Switching from [0π0π] to current drive strap phasing enhanced the heat loads on JET A2 antennas [29], [31], the core W contamination [40] and the RF-induced SOL density modifications [25]. ASDEX Upgrade emulated a balanced 4-strap array by pairing two nearby 2-strap antennas phased [0π] at the same frequency [87], [88], [39]. The phasing between antennas was real-time controlled. It affected the local WI line brightness at the antenna limiters, suggesting that the whole array behaves as a single wave launcher below a minimal inter-antenna toroidal distance. However the brightness variations with phase were location-dependant, and sometimes opposite on the two antennas, so that the net effect the core W content and plasma performance is less pronounced than the local variations. Reference [89] reported first attempts at pairing 2-strap and 3-strap AUG antennas.

4.4. RF-sheaths at antenna box corners

SOL modifications often exhibit local maxima on tilted magnetic field lines connecting near antenna box corners, *i.e.* that do not pass in front of all the radiating straps in the array. To act on the RF-sheaths at these specific locations, the Faraday screen of one AUG 2-strap antenna was partially closed there by metallic corner covers. References [87] and [21] compared W sputtering yields with and without cover with balanced power and [0π] phasing: the local maxima were still present at the same location, suggesting that the excitation of sheath oscillations cannot be reduced to a matter of line-integrated RF electric field.

4.5. Field-aligned antennas

While current straps are ordinarily purely poloidal, reducing the radiated parallel RF electric field integrated along tilted magnetic field lines, especially for 4 straps phased [0000], motivated aligning the whole antenna structure with the oblique confinement magnetic field for a standard value of q_{95}. On C-mod, figure 8 shows that the power radiated by the plasma was 20%–30% lower for a 4-strap field-aligned-antenna (FA) heated discharge than a similar plasma heated with the toroidally-aligned-antenna (TA) phased [0π0π] [12]. Correlatively the MoI line brightness decreased on lines of sight both near the FA antenna and far from it, and the MoXXXI line radiation was reduced in the core. However, GPI and emissive probes observed nearly identical V_{DC} near an antenna box corner for FA and TA antennas when operated in [0ππ0] phasing. Moreover, the highest V_{DC} were observed using [0000] phasing with the FA antenna. Thus, while impurity sources and contamination are indeed reduced with the FA antenna configuration, the reasons for this improvement remain to be understood.

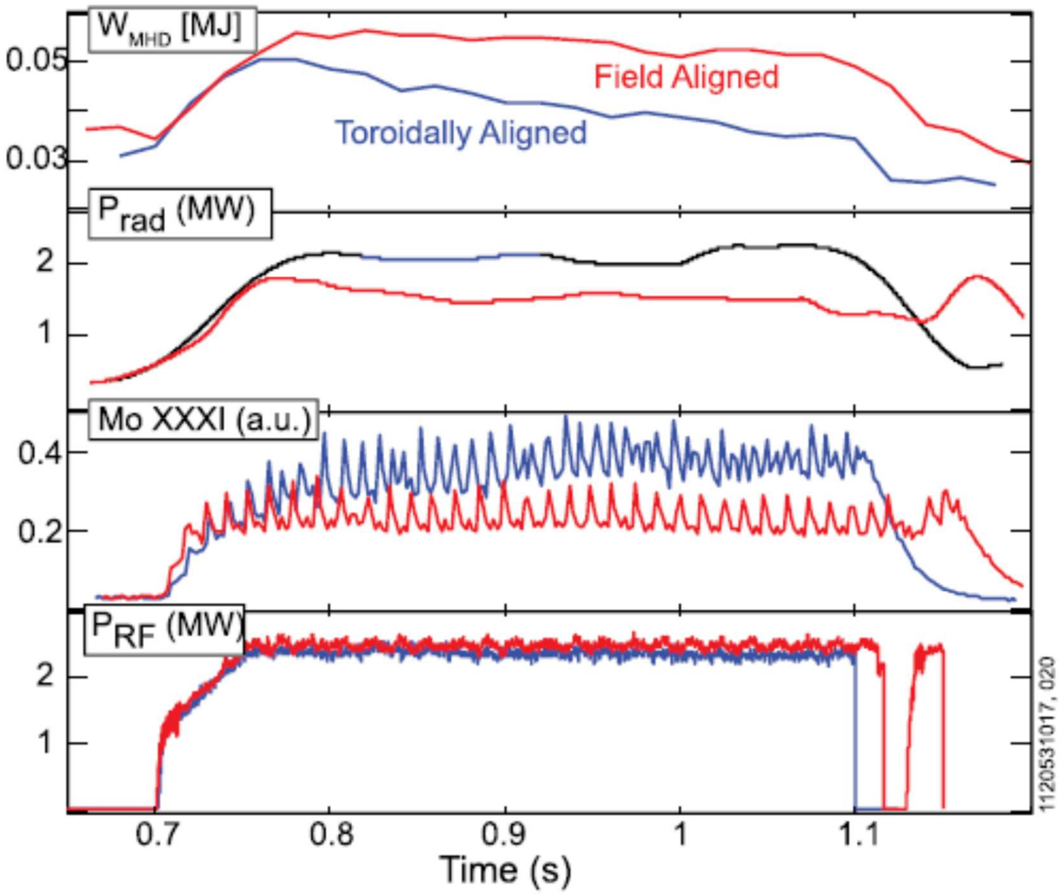

Figure 8: time traces of plasma energy content, power radiated by the plasma, MoXXXI line brightness, and ICRF power coupled by TA antenna (blue) and FA (red) antenna phased [0π0π] on C-mod. Reprinted from [12] with kind permission of the authors.

4.6. Insulating materials.

Reference [90] explains how insulating materials could help tolocally mitigate the RF sheath rectification: as its RF impedance is put in series with the sheath RF impedance, a thin dielectric layer can take up part of the oscillating voltage induced by RF waves at the walls. As dielectrics behave capacively, this leads to V_{RF} reduction at the sheath, provided that the sheath is capacitive too. This arises mainly at low density such that the ion plasma frequency is smaller than the RF wave frequency [7] [3]. As the dielectric layer gets thicker, all RF currents can be suppressed locally. Insulating materials also block locally the DC currents. Yet this does not necessarily mean that the plasma DC potential is reduced: insulating wall elements are floating and no more grounded, V_{DC} is determined by more global I_{DC} balance over the device. On the Phaedrus-T tokamak, triple probe measurements in the edge region evidenced enhanced plasma potentials near the bottom of a 2-strap antenna equipped with a slotted-side Faraday screen, without antenna limiters [16] [91] [92]. Boron-Nitride (BN) insulating plates were subsequently installed at the sides of the FS. They suppressed the potentials and reduced the metallic impurity content of the core plasma. Following these promising results, bulk BN tiles were installed on Alcator C-mod antenna limiters [93], [81], [11]. The outcome was not fully satisfactory. In the first experiments, electric arcs occurred at BN-metal connections exposed to the plasma. Moving the interfaces farther from the plasma suppressed the arcs. Despite impurity source removal on the antenna limiters, large DC potentials were still recorded on connected field lines. RF-specific Mo sources were detected at other locations in the main chamber magnetically connected to active ICRF launchers. In addition, eference [94] suggests that bulk BN could act as hydrogen reservoir and complicate the control of the H minority fraction. Later LAPD operated a single strap inside a box with bulk ceramic side walls [82]. The measured V_{DC} outside the box nearly vanished, suggesting a key role of the box currents in the RF-sheath generation.

4.7. Active reduction/suppression of induced RF currents

A related mitigation route is active reduction/suppression of RF currents induced at key locations. A 3-strap array phased [0π0] [42] [43] [5] and 4-strap arrays phased [0ππ0] [95] or [0π0π] [96] [95] achieved strong RF-sheath reduction on the antenna side limiters by requesting more power on the inner straps. Figures 9c) and d) show the increment of local effective sputtering yield on the 3-strap AUG antenna, as well as the incremental tungsten density in the plasma edge, *versus* the phasing and power sharing between central and peripheral straps. They show a local minimum in local impurity production and contamination for P_{cen}/P_{tot}=0.7. JET A2 antennas with [0π0π] phasing also achieved a locally minimal Be production, but with excessively unbalanced strap powers [95]. 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 in RF-sheath effects, 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 [5]. For the AUG 3-strap antenna with optimal feeding, figures 9a) and b) show that the RF currents collected on the limiter tile were nearly cancelled, and the DC current circulation there was also largely reduced. 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 [5]. One can hardly cancel them simultaneously with those on antenna box sides.

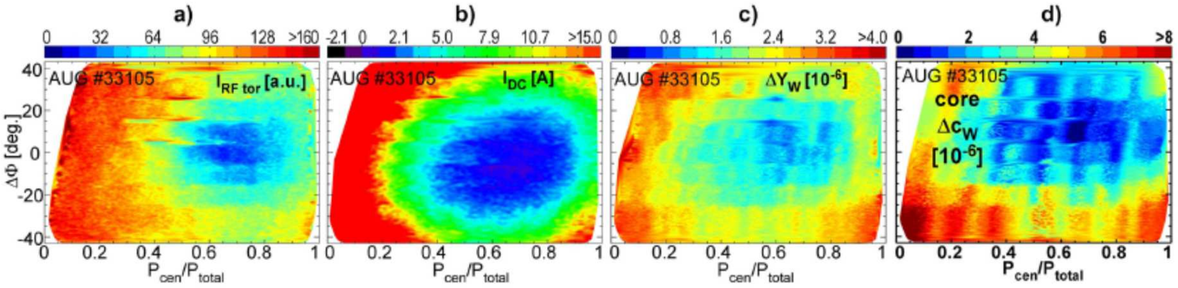

Figure 9: 2D diagrams of four quantities versus inter-strap power balance P_{cen}/P_{total} and phase deviation from dipole $\Delta\Phi$ on AUG 3-strap antenna. (a), (b), (c) – local measurements at a single antenna limiter tile (vertical position $z \approx 0.2$m, left limiter as seen from the plasma) of collected RF current amplitude $I_{rf\,tor}$ (a), DC current circulation I_{DC} (b) and increment of the W effective sputtering yield ΔY_W (c); d) increment of W content in plasma at $T_e \approx 1.5$ keV from quasi-continuum VUV emission. Plasma parameters in discharge #33105: ELM mitigated H-mode plasma at high density, with P_{ICRF}=1MW (P_{total}=500kW coupled from the observed antenna) and P_{NBI}=5MW, D[H] minority heating at f_0=30MHz and B_t=2.0T. Reference for increments in panels (c) and (d): NBI-only phase before ICRH. Reprinted from [5]

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" sheath effects. "Far field" effects likely depend on more global profiles governing the wave propagation, refraction and damping in the plasma core.

5.1. Role of local plasma parameters on particle fluxes

The local plasma density and temperature determine the flux of particles hitting the wall and the charge state of light impurities. The magnitude of DC currents collected by AUG antenna limiters also increases with the plasma density [68]. This, together with the ion energies, determines 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 radial location [29], [35], [31]. 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 [44]. This was ascribed to enhanced particle fluxes onto the antenna limiters in presence of large LH power, as indicated by larger DI$_\delta$ line brightness recorded by visible spectroscopy and larger ion saturation current collected by Langmuir probes embedded on the LH antennas. As stressed in reference [32], the local density and temperature may vary along the ICRF antenna limiters if their poloidal shape is not conformal to magnetic surfaces. Along WEST antenna limiters, this manifests by poloidal profiles of DI$_\delta$ line intensity [45], [46]. RF-induced density convection further complicates this poloidal structure: references [33] [35] [36] invoked the convection to interpret up-down heat load asymmetries on Tore Supra antenna boxes, that reversed upon **B**-field reversal. For all these reasons the geometry of heat fluxes or impurity sources may be even more complex than that of rectified DC potentials. Reference [68] reported that the poloidal variation of WI line emission depends not only on the 2-strap antenna electrical setup, but also on the plasma configuration.

5.2. Role of local density on DC potentials

The local plasma density may also act on the rectified plasma potentials. Upon a 20% increase of plasma density reference [22] reported a two-fold reduction of the floating potential on a Langmuir probe connected to a active antenna, while the antenna coupling resistance decreased by 20% only. Reference [13] observed opposite parametric variations of V_{DC}. When probing field lines connected to an active antenna, and for plasmas tenuous enough that the slow wave is propagative, V_{DC} increase was seen to appear above a critical local density, and then increase with density. This trend is qualitatively consistent with sheath rectification involving a slow wave propagating from the antenna. When probing field lines unmapped to an antenna, an opposite trend was found: V_{DC} decreased with local density over the explored (low) density range.

5.3. Control of local density with localized gas injection

On top of its "natural" evolution, the local density in the antenna vicinity may be controlled more actively. Local gas injection was applied successfully to restore good LH wave coupling in ICRF-disturbed convective cells [65] and to enhance ICRF wave coupling without disturbing the plasma core in H mode [1]. Local D_2 injection also lowered the W production at the AUG antenna limiters [97] [5]. Reference [5] showed that the reduction is all the more pronounced as the gas is injected close to the antennas toroidally. On JET, references [53] and [98] showed that the core plasma radiation, the W concentration estimated at r/a~0.3 as well as the Ni concentration in the plasma edge decreased as the amount of gas puffed increased. For a given amount, the total radiation was about 15–20% lower when the gas was fuelled from the main chamber as opposed to divertor fuelling, correlated with the lower core densities of W and Ni observed in these cases. The exact reasons for reduced impurity contamination with local gas puff are not fully understood. Larger ICRF coupling resistance reduces the local RF near field magnitudes for a given coupled power, thereby reducing "near field" RF-sheath oscillations and associated enhanced sputtering. Other possible causes include: local SOL plasma cooling, reduction of low-Z ion charge, local impurity dilution, reduced penetration of eroded material or modified prompt redeposition. More work is needed to sort out which mechanism prevails.

5.4. Role of intrinsic light impurities

The sputtering yield of high-*Z* materials by tokamak SOL plasmas is mainly governed by light impurities present in quantities of a few per cent in a background of D^+. Reference [21] provides effective sputtering yield estimates for W in presence of C, O and B impurities with several ionization states, while [11] shows similar curves for Mo with B^{3+} and Mo^{3+} ions. Although scarcely documented the metallic impurity production might strongly change from one experimental day to another, likely due to varying light impurity content. References [21] and [94] showed the benefits of boronizations both to reduce the amount of light impurities, and to cover the plasma-facing high-*Z* surfaces with low-*Z* coatings. Both papers however stress that these benefits last only for short periods, or equivalently for small cumulative injected energy. On C-mod, with ICRF, the erosion rate of low-Z films is estimated to be 15–20 nm/s indicating the eroding species energy is much higher than that normally found in the SOL [11]. Reference [94] also warned that thick boron layers might trap hydrogen. H might be released afterwards and raise the H minority content to such levels that the ICRF heating efficiency is degraded.

5.5. Antenna limiter erosion in light impurity seeding experiments.

References [97] and [41] reported larger W erosion on AUG antenna limiters in N_2-seeded discharges aimed at enhancing the divertor radiation, as compared to similar pure D_2–fuelled plasmas. Depending on the fraction of extrinsic impurities injected, the enhancement of effective sputtering yield could reach one order of magnitude on the limiters of a passive antenna [41]]. When the antenna was active the sputtering yield on its limiters increased by less than 50% in seeded discharges compared to plasmas with pure D_2 [97]. The impact of the seeding on the core contamination results therefore from a trade-off between enhanced divertor radiation and larger sputtering yield. Reference [41] showed that, while puffing more gas is beneficial to reduce the core W content, larger gas amounts are necessary to reach a given purity in seeded AUG discharges than in pure D_2 plasmas. On the other hand, 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) [19]. It is speculated that higher neutral contents during seeding may substantially increase the collisionality/resistivity and affect V_{DC}.

6. OUTLOOK FOR FUTURE LONG PULSE METALLIC DT MACHINES

This contribution reviewed recent experimental characterizations of RF-induced SOL modifications in various tokamaks and the LAPD linear device. Although not every aspect is fully clarified, significant progress has been achieved since the early review paper [2] in the comprehension and attenuation of undesirable wave-SOL interaction. This experience is extremely valuable. Indeed most of the dedicated diagnostics used in present-day machines (reciprocating probes, RFA, GPI, current sensors embedded in limiter tiles, …) can hardly be implemented in reactor-grade machines. Some diagnostics (*e.g.* IR thermography) will be harder to operate in a metallic environment, while other measurements (*e.g.* calorimetry of actively-cooled PFCs) can only be interpreted after the pulses. Experimental time dedicated to ICRF might be limited. Fututre devices will therefore need to rely more on numerical simulation, backed by scarce measurements, to operate their heating systems. The modelling tools have been so far scarcely validated against experiments in realistic geometry. One can therefore attempt some extrapolation of the present results to future long pulse metallic DT machines, but also outline some remaining uncertainty in this prospect. It is of course desirable to reduce this uncertainty via experiments or modelling.

The SOL phenomenology observed in present devices is consistent with RF-sheath rectification, although other processes might co-exist loacally and likely compete with rectification: resonant wave modes [73], wave-filament bound states [74], RF power absorption at the peripheral Lower Hybrid (LH) resonance [75] or ponderomotive forces [76], etc. RF-sheath rectification is qualitatively independent of the way ICRF waves are damped in the plasma core. The present results are qualitatively similar in the D[H] minority and in the high harmonic heating schemes, corroborating this relative independance. Therefore qualitatively similar phenomenology is expected in future DT devices, that will exploit other ICRF heating scenarios. However the magnitude of the ICRF-induced SOL modifications likely depends on the details of the heating scheme. This is a source of quantitative uncertainty, but general guidelines can be followed to mitigate the RF-sheath effects.

Mainly "near-field" effects were documented so far. "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. A large machine size and a hot plasma core increase this wave absorption. ITER plans to use ICRH at full nominal toroidal magnetic field (5.3T on magnetic axis), half field (2.65T) and third field (1.8T) to heat successively hydrogen, helium, deuterium and finally DT plasmas [99] [100]. For each field value and majority species, at least one ICRH scenario featuring good single pass absorption is available. The only exception is H plasmas at half magnetic field. For this specific application, operating ITER at 3T or 3.3T is presently explored. Avoiding the excitation of low-$k_{//}$ power spectra also improves the wave absorption in the core. It reduces as well the excitation of coaxial modes or wave damping at the peripheral LH resonance [75].

"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. 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 ~15cm in ITER), at the expense of lower ICRF coupling resistances.

Recent experiments clarified the link between the geometry "near-field" RF sheaths and the RF current patterns over the antenna metallic surfaces. On Alcator C-mod a field-aligned antenna successfully reduced the impurity production and contamination [12]. 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 image current cancellation on the sides of 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 [0ππ0] phasing and with reasonable power balance between straps ($P_{central}/P_{tot}$ close to 0.5) [5]. Electromagnetic calculations also stress the need to avoid protruding elements on the antenna front face. Field-alignment can be combined with image-current reduction to limit the ICRF-induced impurity production, as reference [96] proposed for the SPARC project. Other antenna concepts have been proposed for fusion reactors, *e.g.* Travelling Wave Arrays (TWAs) [101]. In TWAs, only the first and last strap of the array are connected to transmission lines, so that one cannot control from outside the ratio of (complex) RF currents between adjacent straps. However since the wave excitation is split between a large number of elements, the RF current magnitudes are reduced, which is attractive. TWAs remain however to be tested at high power in a metallic environment.

The magnitude of "near-field" RF sheath effects depends on the local plasma parameters. A large uncertainty remains both about the density value at the ITER wall, and how this local density acts on the RF-sheaths. For this reason, quantitative predictions of RF sheath effects remain delicate for future devices, although relative comparisons are certainly more reliable. ICRF coupling studies, *e.g.* in [75], mainly used low-density profiles in the SOL to estimate lower bounds of the power that can be launched by the ITER antenna. On the contrary, pessimistic estimates of the heat loads onto the wall elements surrounding the ITER antenna rather used high-density profiles, due to larger particle fluxes [102].

Light impurities contribute to the sputtering. This stresses the need to maintain good machine conditioning over long high-power discharges. Extrinsic light species might be injected on purpose for reducing the divertor heat loads. This should not however hamper other aspects of the scenario, and the global impact of impurity seeding on plasma performance should be assessed. 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^+. The propagation (*e.g.* cut-off density) and damping properties of the Fast Wave also depend on the mass and charge of the majority species. JET presently investigates isotopic effects on RF-SOL interaction, and will also experiment ICRF heating schemes planned for the DT phase at full-field in ITER. 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 [103]. 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 diagnostics embedded on the antenna.

Using ICRH in short-pulse D^+ plasmas, JET has achieved high-performance discharges with the mix of materials used for the ITER wall. The ITER ICRF antenna will be surrounded by Be PFCs in the main chamber. Although Be sputtering should not hamper the core plasma contamination, it could be a concern for the long-term integrity of the wall. Reference [104] simulated the Be erosion of a JET outer limiter connected to an active ICRF antenna, in order to match a 2-3-fold increase in the absolutely calibrated Be I and Be II line emissions during ICRH. According to the calculations, the erosion would range between 0.15 and 0.25 nm/s, depending on the assumptions. Under the same operational scenario and for an ITER-like 400s-long pulse, an erosion of 60–100 nm/pulse would be expected. Similar quantification should be repeated with SOL and antenna conditions as expected for ITER.

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 [72] and JET [29], inspection at shutdown revealed localized carbon deposits on the surface of CFC tiles or localized flaking of the boron carbide coatings. To help the IR data interpretation, it is therefore useful to develop monitoring pulses and repeat them regularly over the experimental campaigns, especially after incidents [72].

On Tore Supra, for each region of interest on the antenna front face, specific diagnostics identified one physical mechanism causing local hot spots, together with one relevant actuator able to reduce the hot spots in real-time: total power, or local power from one specific IC or LH launcher. A similar exercise was performed with a selection of metallic lines in the plasma core monitored in real-time by a dedicated VUV spectrometer [105]. In inertial machines, only a soft stop can be triggered in case of excessive heat loads or impurity contamination. 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 [65] [106].

The mix of materials used for ITER might not be compatible with a Fusion reactor. Several present devices have experimented full converage of their vacuum chamber with high-*Z* materials. High-performance operation on these devices was found difficult without boronization. This was not specific of ICRF-heated plasmas but the regions magnetically connected to active ICRF antennas experience enhanced plasma-wall interaction. There is a consensus that boronizations between pulses last less than one single nominal discharge envisaged for ITER. This calls for more active R&D on alternative conditioning techniques, alternative materials or alternative ICRF antenna concepts.

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