CZECH TECHNICAL UNIVERSITY IN PRAGUE

DOCTORAL THESIS STATEMENT

Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Telecommunication Engineering

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ANTENNA MODELLING FOR ION CYCLOTRON RESONANT HEATING OF TOKAMAK PLASMAS

Ph.D. Programme: Electrical Engineering and Information Technology

Branch of study: Telecommunication Engineering

Doctoral thesis statement for obtaining the academic title of "Doctor", abbreviated to "Ph.D."

Prague, April 2013

The doctoral thesis was produced in *combined* manner Ph.D. study at the department of Telecommunication Engineering of the Faculty of Electrical Engineering of the CTU in Prague

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The doctoral thesis statement was distributed on ……...

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ABSTRACT

The most successful current device for fusion research is the tokamak, a sort of big transformer where the secondary coil is hydrogen in plasma state enclosed in a toroidal chamber, in which the plasma is trapped by a static magnetic field and heated by strong current induced by the primary coil. The different machines operating so far have a plasma discharge time duration of order of 1 s – 10 s. An important mean to heat the plasma to thermonuclear fusion temperatures is using high power waves in the Ion Cyclotron Range of Frequencies (ICRF 30 – 80 MHz), as shown by experiment results performed for about two decades, from 1985 to 2005.

However, more recently, ASDEX Upgrade (AUG) tokamak, which is pioneering the use of a tungsten (W) first wall, as useful for ITER, found not tolerable high impurity sputtering rates during ICRF power coupling. A similar failure in tokamak operations was found in early ICRF experiments (from 1980 to 1984) that used metallic vessel. In this thesis it has been hypothesised that the improvement of the ICRF operations, later obtained, in the years from 1985 to 2005, would be not attributed to improvement of antenna design, as generally believed but, mainly, to the circumstance that these experiments used low-Z plasma faced components (PFCs), which reduce the impurity influx under high level of coupled ICRF power. Therefore, the failure of ICRF operation in ITER-relevant high-Z PFCs would be produced by phenomena of physics of the edge, like RF sheaths, which rectify the RF potential and accelerate plasma ions of the edge, thus enhancing the sputtering for impact on metallic obstacles. Consequently, it is necessary to assess the RF potential in realistic condition of experiment, in order to produce modelling useful for interpreting the observed phenomenology, and address the solution of the problematic failure in the ICRF operations, occurring in recent reactor-relevant tokamak experiments.

This thesis focuses on the analysis and comparison of performance of two ICRF antennas that are currently installed on the AUG tokamak with the TOPICA (TOrino Polytechnic Ion Cyclotron Antenna) program, for various operational scenarios. The work aims at estimating distribution of the quantities that are considered as the main drivers for the impurity production: $E_{//}$ and RF potentials in realistic conditions of antenna geometry and plasma loading. Further, rectified potentials are estimated based on the simple RF sheath models and also using more appropriate tool: asymptotic version of the numerical code SSWICH (Self-consistent Sheaths and Waves for IC Heating) that characterizes better the RF sheath mechanism. This analysis is necessary for assessing phenomena responsible of producing impurity influx, which prevents operations in reactor-graded condition of metallic vacuum chamber. The estimated values are compared with the sheath potential drops that correspond to the maximal measured values of tungsten sputtering yield at the antenna limiters for typical concentrations of light impurities that bombard W surface and that can be found in AUG.

The unsuccessful ICRF experiment on the National Spherical Torus Experiment (NSTX) has been also considered, which did not produce any effect of the coupled RF power to the plasma bulk, but only parasitic deposition at the very edge of the plasma column. In this regard, the non-linear wave-plasma coupling phenomenon occurring at the edge has been studied, as example of a not proper transfer of the RF power coupled by the antenna to useful ICRF waves.

1. CURRENT SITUATION OF THE STUDIED PROBLEM

Multi-megawatt ICRF power was successfully utilised in tokamaks with low atomic number (low-Z) plasma faced materials and obtained, for two decades, successful results of plasma ion heating. However, these operations became problematic in experiments on AUG and ALCATOR C-Mod tokamaks using a reactor relevant high-Z metallic vessel. A not sustainable ingress of impurities in the plasma was produced, indeed, at levels of RF power that were markedly lower than in previous operations with low-Z plasma facing material [1-5]. The phenomenon of the ingress of impurities has been interpreted in terms of sputtering by plasma ions accelerated by the RF electric field. This field is rectified in layers of plasma edge in which a line of the tokamak confinement magnetic field intercepts a metallic obstacle, in presence of a sufficiently intense RF electric field component aligned to the confinement magnetic field ($E_{//}$). These RF sheaths cause acceleration of ions impacting on the obstacle and, consequently, enhance sputtering and localised heat flux. The RF sheath rectification was described for the first time in [6] and later with respect to the ICRF antennas in [7, 8]. However it still needs to be corroborated from the experiments and better studied.

Ideally, the ICRF antenna is designed to launch a fast wave. In reality, the ICRF antenna can also launch a slow wave (either evanescent or propagating), that is linked with $E_{//}$ component, at the plasma edge when the magnetic field is not perfectly aligned with the antenna structure. Additionally, when the fast wave encounters a material structure, the Maxwell equation boundary conditions require that it couples to the slow wave. The slow wave interacts with a material boundary (wall, antenna limiters, divertor, any obstacle or PFCs) and drive RF-enhanced sheaths there.

According to [9], parallel image RF currents $j_{//}$ flowing on the antenna structure plays the dominant role in the formation of antenna parallel near-fields. Design of the ICRF antenna should be thus optimized in order to minimize this mechanism and improve ICRF heating compatibility with high-Z PFCs. Further, RF sheaths should occur also at large distances from the antenna, where a metallic obstacle (e.g., a limiters of the machine or limiters belonging to other antennas) is cut by a confinement magnetic line, and the $E_{//}$ component exceeds a certain threshold value.

For fusion community, it is important to improve rather poor understanding the underlying mechanisms driving the wave-plasma interactions and to develop a quantitative modelling capability for experimental design and interpretation, which does not yet exist. A big effort is put in self-consistent accurate quantitative modelling of ICRF antennas and sheath effects which is an difficult computational problem. In order to calculate the RF sheath effects, it is necessary to have an accurate description of the launched RF waves and the RF sheath potential distribution over the boundary surface.

Because of the impossibility of testing these antennas in experiments with plasmas, an accurate and efficient simulation tools are necessary in order to analyse and optimize the ICRF antenna performance. These needs have driven development of codes such as TOPICA [10], FELICE [11], ICANT [12], RANT3D[13] and others. These codes can include dielectric tensors of magnetized plasmas, but on the other hand they usually adopt only very simplified antenna geometries. Among these codes, TOPICA is the most advanced tool up to now because it can handle the realistic 3D geometry of ICRF antennas and it includes 1D inhomogeneous hot plasma model. Non of these codes include any sheath model, i.e., perfect electric conductors are assumed in direct contact with the plasma.

The other option is to use the commercial 3D full-wave electromagnetic simulators such as ANSYS HFSS and CST MICROWAVE STUDIO. These programs allows to simulate realistic antenna description and results can be detailed. The main disadvantage of such codes is that none of them can account for a fusion plasma which is replaced by water or an unaxial medium.

Related to the sheath modelling, simple RF sheath models [7], [8] and several more self-consistent models can be found in the literature [14-21]. These models were so far studied only in very simple geometries, and are not available for realistic antenna description. A more self-consistent approach requires including plasma in the region between the sheaths and modifying the boundary condition (BC) to take account of the sheath capacitance. The BC incorporates plasma dielectric effects and is required for self-consistency of computed RF fields and sheath potential.

Another example of self-consistent approach is the SSWITCH (self-consistent sheaths and waves for ion cyclotron heating) program. In this program a minimal two-field fluid approach is used to describe RF wave propagation in the bounded SOL plasma of magnetic fusion devices self-consistently with direct current (DC) biasing of this plasma (both ends of open magnetic field lines). The RF and DC parts of the model are coupled by non-linear RF and DC sheath boundary conditions at both ends of open magnetic field lines [22]. The physical model include slow wave and lateral walls normal to the straight confinement magnetic field. The system is excited by 2D RF field map imposed at the outer boundary of the simulation domain in order to simulate a complex antenna structure. Further, the physical model allows interaction between neighbouring flux tubes via the exchange of self-consistent RF and DC currents. The code is still under development.

As further problem met in experiment using ICRF power, any effect of penetration of the coupled RF power was not found in the NSTX tokamak in Princeton (USA) during experiments aimed at heating and driving current in the plasma [23]. The unsuccessful ICRF experiments are characterised by the deposition of the coupled RF at the very edge of the plasma column. This undesired effect is documented by the absence of any effect of heating of the plasma bulk, and by the occurrence of a particular frequency spectrum of the signal collected by a small loop antenna faced in front to a port of the machine. Namely, besides the operating frequency line, it was observed also a few lines down shifted by multiples of the ion-cyclotron frequency near the edge. These side band waves represent signatures of a non-linear wave-plasma phenomenon, namely the parametric instability (PI), which is produced by the beating of the component of the RF electric field ($E_{//}$) parallel to the confinement magnetic field with a mode of the thermal background of plasma density fluctuations, whose frequency lies in the range from about 100 kHz to a few megahertz. The component of the coupled RF power excites quasi-electrostatic waves, named lower hybrid (LH) waves, whose electric field is indeed quasi-aligned to the wave vector.

2. AIMS OF THE DOCTORAL THESIS

It is impossible to reproduce completely the tokamak experimental conditions and thus to verify the antenna global performance by proper tests performed outside the tokamak. Given this, an accurate simulation of these conditions and prediction of the antenna performance is clearly crucial in the antenna design. A reliable simulation and prediction of at least some of the physical effects of a given ICRF antenna geometry is the key point for its successful optimization. The TOPICA (Torino Polytechnic Ion Cyclotron Antenna) software has been utilised here as the main tool for modelling. It has the unique features of handling the realistic conditions of geometry of the antennas and load that is represented by plasma modelled with sufficient accuracy.

One of the main focuses of the thesis consist in showing that early experiments that tested for the first time the coupling of ICRF power in large tokamaks, at the beginning of the years ’80 of the last century, discovered that a strong ingress of impurity occurred, detrimental for useful plasma operations. The ICRF experiments became successful, instead, since the middle of the years ’80 and they maintained successful for two decades. This result was attributed to have followed a more suitable antenna design in the utilised systems. However, recent experiments on AUG, have been characterised by the same failure that occurred in early experiments. It is highlighted here that to have used a metallic wall in early experiments and in AUG should be the more important cause of the observed strong impurity ingress induced by the coupled RF power, rather than different antenna configurations. Successful ICRF experiments occurred before AUG only by using walls coated by carbon or beryllium, i.e., low-Z materials.

To help the interpretation of the aforementioned phenomenology is essential for enabling the ICRF power to become a robust tool for the modern research on thermonuclear fusion energy based on the tokamak concept. Consequently, the thesis focuses also on producing modelling useful for helping the interpretation of phenomenology discussed above, and to address the debate on how it should be overcome. In regard to the problematic extrapolation of ICRF experiments to regimes using reactor relevant metallic vessel, I show results based on numerical solution of the electromagnetic problem of the antenna, in realistic condition of the metallic vessel geometry and plasma loading.

In order to address the understanding of the problems occurred in the recent ICRF power experiments on AUG, it is useful to analyse the performance of the two types of AUG ICRF antennas. The work aims at characterising the antennas in terms of conditions that they can produce in favouring impurity influx, which prevents operations in reactor-relevant condition of metallic vacuum chamber.

The main focuses of the work related in the thesis are:

a) Comparison of the impedance matrix computation performed with the ANSYS HFSS and TOPICA microwave software, considering the flat AUG ICRF antenna. The results can provide also an additional validation of the TOPICA software.

b) Computation and analysis of the following issues: i) scattering matrix, ii) coupled power, iii) induced currents on the antenna parts, iv) map of the RF field, in particular, the $E_{//}$ component useful for assessing the role of the RF sheath in producing impurity influx. This map should include layers located at large toroidal distance from the antenna. The work carried out here represents the basis for developing, in future, the assessment of the ICRF field structure at large distances form the antennas. The antenna coupling should be evaluated taking into account loads approximated by a dielectric, or using a more realistic plasma model. Moreover, the flat and the more realistic curved antenna geometries should be taken into account, together with different antenna phasing values of the RF power feeding the antennas. Further, a scan of the radial layer under test, used for evaluation of $E_{//}$ should be performed.

c) Evaluation of the RF rectified potentials assuming simple sheath model with independent flux tubes. A comparison of the poloidal distributions of the rectified potential with the measured sputtering yield of tungsten on the ICRF antenna should be performed. The sputtering yield is defined as the ratio of sputtered metallic flux over the incoming flux of deuterium. The rectified potential obtained by modelling should be compared to the potential drop in the RF sheath, which corresponds to the measured value of tungsten sputtering yield on the ICRF antenna.

d) Providing $E_{//}$ field map in front of the antenna mouth as input for the asymptotic version of the numerical code SSWICH (Self-consistent Sheaths and Waves for IC Heating) that better characterizes the RF sheath mechanism. Parameters of the antenna with smaller dimensions, originally used in AUG, have been considered. The DC plasma potential, V_{DC}, near the initial antenna side limiters, should be calculated in order to build hypothesis on how the sheath effects are poloidally distributed.

As further problem met in experiment using ICRF power, any effect of penetration of the coupled RF power was not found in the NSTX tokamak of Princeton (USA) during experiments aimed at heating and driving current in the plasma. Unexpectedly, only signatures of non-linear wave-particle interaction, namely parametric instability, were observed to occur. Further aim is analytical derivation of the parametric instability dispersion relation. To solve this equation has been useful for interpreting the signatures, found on NSTX, which document the occurrence of non-linear wave-particle interactions, which accompany the failure of penetration of the coupled RF power to the plasma core.

3. WORKING METHODS

3.1 Overview of ICRF heating experiments in metallic wall tokamaks

Relevant literature was studied to try to understand the problem why: a) early experiments that for the first time, in the years ’80 of the last century, tested the ICRF heating scenario in tokamaks that used metallic wall, obtained an impurity influx not tolerable for performing useful plasma operations, b) next experiments carried out for two decades (from about the years 1986 up to about 2005) obtained, instead, successful results of plasma heating accompanied by small impurity influx, c) finally, recent results on AUG (ASDEX Upgrade) tokamak found, instead, a much stronger impurity influx, which is similar to that occurring in early ICRF experiments. What is common with early ICRF experiments has been identified here in the circumstance that reactor-relevant metallic plasma faced material has been used in AUG. It has been shown, indeed, that ICRF experiments became successful not only, as generally believed, thanks to the utilised new antenna configuration but, more probably, by the use low-Z plasma faced materials, which have the intrinsic property of mitigating the ingress of impurity under RF power coupling to plasma.

3.2 AUG ICRF antennas simulations

3.2.1 Comparison of impedance matrix computation with ANSYS HFSS and TOPICA microwave software for flat AUG ICRF antenna

The ANSYS HFSS software was the only tool routinely used in the past for AUG ICRF antenna performance prediction and design optimization. A more accurate and efficient modelling would be necessary to optimize the ICRF antenna design for realistic operation parameters. The TOPICA software would satisfy this need. Performing comparison in terms of Z matrix and was the first step on the way of utilizing the TOPICA software for AUG ICRF antennas.

In order to compare both tools, it is necessary to set up the same input condition of the simulations. Simulations are performed for frequency 30 MHz which is typically used for the AUG ICRF heating experiments. Three different loads are considered for the comparison: vacuum ($\varepsilon_r = 1$), water ($\varepsilon_r = 81$) and lossy dielectric medium with real part of complex relative permittivity equal to relative permittivity of water and imaginary part ($\varepsilon'' = \sigma/\omega\varepsilon_0$) corresponding to effective conductivity $\sigma = 4$ S/m. This lossy dielectric medium was chosen because it had been routinely used for AUG ICRF antenna performance prediction and design optimization by the ICRF team of AUG tokamak. According to [9] such lossy dielectric mediums can preserve realistic coupling to the fast wave.

Similar results of both programs would exclude any error in the geometry and meshing and provide validation of TOPICA against ANSYS HFSS, that has not been done before. Further, the results could be considered more trustworthy as the programs are based on different approach. This would encourage the use of programs like TOPICA and ANSYS HFSS for reliable prediction of some aspects of the ICRF antenna performance.

3.2.2 TOPICA simulations

The presented modelling results are focused on the antenna performance in terms of RF sheath effects that lead to enhanced impurity production. Antenna performance, with regard to impurity production, can be expressed with the RF sheath-driving potentials $V_{//}$. Most of simulations presented in this section have been performed in presence of plasma, to keep the useful information about wave propagation which is lost when a dielectric load is assumed.

Two types of ICRF antennas that are currently installed on the AUG tokamak have been considered: a) the narrow antenna configuration, early installed on AUG, and b) the partly optimized new antenna that has wider dimensions. Each step of modelling is outlined and the main assumptions are discussed.

The simple RF sheath model, assuming independent flux tubes, has been taken into account in this section. Within this simple model [6], each open flux tube of the confinement magnetic field is treated as double Langmuir probe. Between extremities of the open flux tube, powered ICRF antenna drives RF potential

$$V_{//} = \int E_{//}\, dz \qquad 3.1$$

where integration is performed over the open field lines that are extended toroidally far away on both sides of the antenna structure and connect (magnetically) the antenna vicinity with other PFC. As a response of the double probe to the sinusoidal RF drive $V_{//}$ and due to the non-linear I-V electrical characteristic of the sheath, the flux tube gets biased to a DC rectified potential V_{DC} with respect to the material boundary as discussed in Chapter 3.

According to [24], assuming $e|V_{//}| \gg kT_e$ and $\omega_0 \ll \omega_{pi}$, $V_{DC}/|V_{//}|$ ranges from $1/\pi$ to 0.5, depending on the parametric domains. In this section of the thesis, formula coming from the simple RF sheath models [7]

$$V_{CD} = 0.4\,|V_{//}| \qquad 4.2$$

is used. Evaluation of $V_{//}$ according to Equation 4.1 is not self-consistent, as the sheath potentials are estimated from $E_{//}$ component without considering proper sheath boundary conditions. Moreover it was proved that whenever nearby flux tubes are coupled, also the 2D (radial/poloidal) topology of rectified DC potentials transversally to the flux tubed can change. Nevertheless producing the maps of $E_{//}$ component and $|V_{//}|$ gives a first important insight into the distribution of V_{DC}. Regions with high $E_{//}$ have also high rectified DC potentials.

3.2.2.1 RF field mapping and plasma parameters

The first step of the simulation process includes preparation and meshing of an antenna model in a drawing and preprocessing tool. For the purposes of this thesis, the GiD preprocessor and post-processor [25] has been used.

a) b)

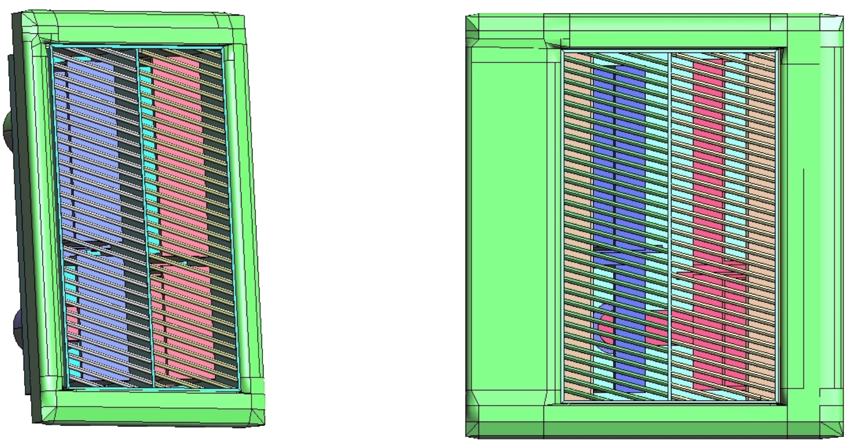

Figure 3.1: Flat models Curved models of (a) initial narrow ICRF antenna model and (b) partly optimized wide antenna configuration with thinner straps and asymmetric wider limiters.

The flat and curved models of the initial (narrow) and partly optimized (wide) AUG ICRF antennas have been assumed (see Figures 3.1 and 3.2). Flat models were drawn directly in GiD software. Curved models were imported from the technical drawings and, therefore, all the geometrical details of the antennas are included. All antenna models are meshed in boundary elements of triangular shape.

a) b)

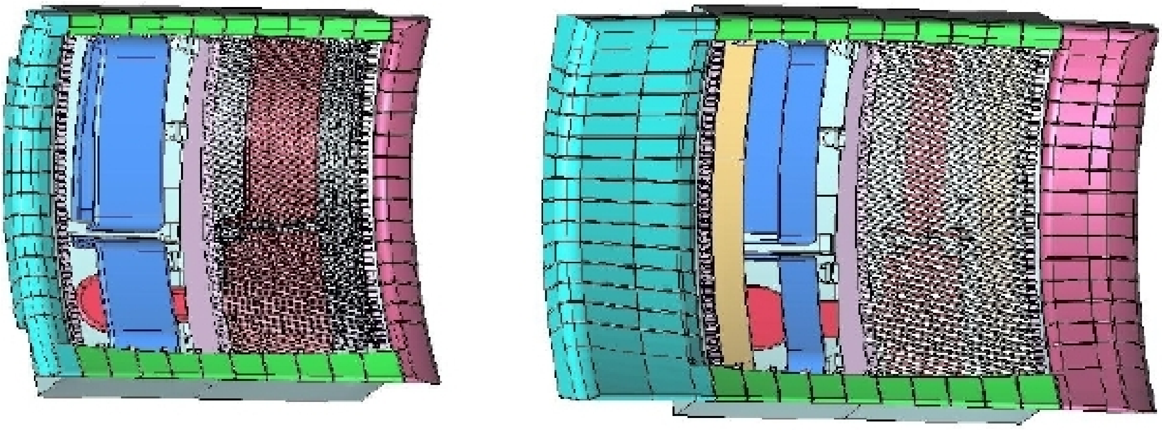

Figure 3.2: Curved models of (a) initial narrow ICRF antenna model and (b) partly optimized wide antenna configuration with thinner straps and asymmetric wider limiters. (To see better the radiating strap part of the Faraday screen was removed).

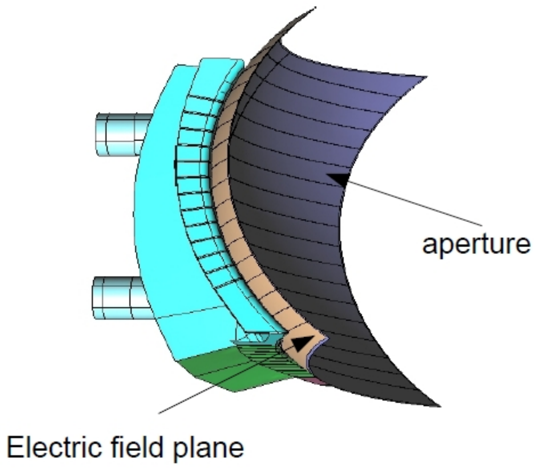

Figure 3.3: Shape and location of plasma boundary (aperture) and surface where $E_{//}$ values are calculated provided curved antenna model.

In order to perform simulation in TOPICA software, an antenna model is placed into a recess and limited by aperture that follows curvature of the antenna limiters and represents load (plasma) boundary. The chosen shape of the plasma boundary corresponds to the plasma shape with low triangularity, which is defined for example in [26]. The plasma boundary is located 8 mm in front of the antenna limiters. In this position, the plasma density is already very low and therefore it is reasonable when the plasma is approximated by vacuum in the region between the plasma boundary and the antenna. In this vacuum region a surface for $E_{//}$ component calculation is defined. This surface follows the shape of the load (plasma) boundary (Figure 3.3). In addition, for a consistent comparison of both antennas the same mesh density and shape of load boundary and surface for $E_{//}$ field calculations are assumed to reduce any source of additional differences.

Computation of the integral of $E_{//}$ component along the magnetic field lines is performed in MATLAB (Matrix Laboratory) numerical computing environment with adoption of an algorithm based on the Inverse Distance Weight. Further, a simple interpolating algorithm 'smooth' is applied. This algorithm is available in

MATLAB using a moving average filter.

The average spatial resolution used for all simulations is 3.8 cm and 1.1 cm for the plasma boundary surface and the surface for $E_{//}$ component calculations, respectively. The maximal spatial resolution is dictated by the available computer resources. Only recently, a more powerful computer system HPC-FF (High Performance Computing for Fusion) with computing power of 101 teraflop/s became available for European fusion community in Jülich in Germany. This circumstance allowed simulating detailed curved antenna models with reasonable resolution.

In all plasma simulations, the typical radial profile of AUG tokamak magnetic equilibrium has been assumed (see Figure 3.4). The confinement magnetic field value at the antenna mouth is 1.49 T, and its direction is tilted of 11° with respect to the toroidal direction. Moreover, all plasma simulations are performed for the L-mode phase of confinement, with plasma consisting of 3% of hydrogen minority in deuterium, and for the typical operating frequency of 30 MHz used for the minority heating experiments on AUG. All simulations have been performed without considering any tuning and matching system, and the coupled power has been calculated assuming V_{max} = 30kV, in infinite coaxial lines.

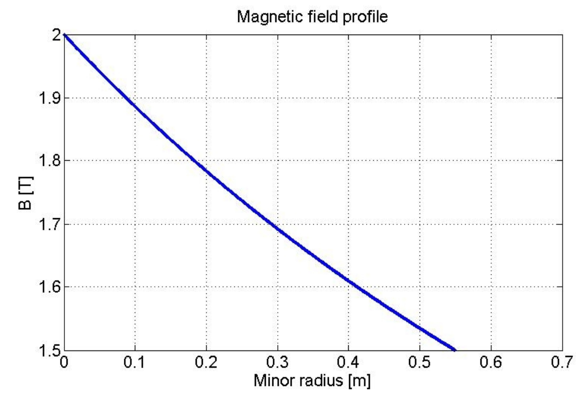

Figure 3.4: The confinement magnetic field profile used for the TOPICA simulations.

Plasma density and temperature radial profiles used for the simulations were either measured (Figure 3.5) or analytically derived from the measured data (Figure 3.6). The measured profiles were obtained from the Integrated Data Analysis [27]. This method allows to combine the measured data from heterogeneous and complementary diagnostics to consider all dependencies within and between diagnostics for obtaining validated and more reliable results in transparent and standardized way. Data from the following diagnostics are taken into account: lithium beam impact excitation spectroscopy, interferometers, electron cyclotron emission measurements, Thomson scattering and reflectometers. The final plasma density and temperature profiles used for simulations with TOPICA software are derived by averaging the experiment profiles obtained during plasma discharges 25634, 25654, 25655, in which ICRF heating was used, and considering three time windows 2.65-2.8 s, 2.65-2.8 s; 3.0-3.2 s in each plasma discharge (Figure 3.5).

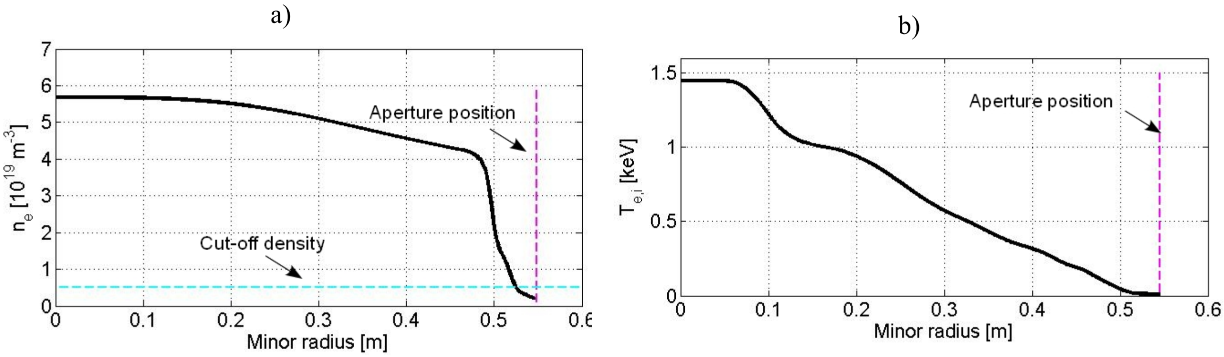

Figure 3.5: Measure density (a) and temperature (b) profiles used for simulations. Cyan line represents the antenna cut-off density, magenta lines represent position of the plasma edge.

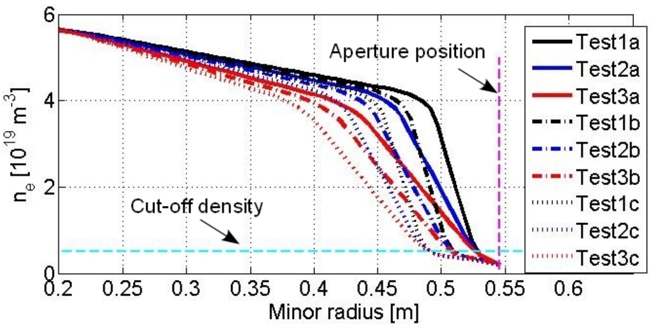

Figure 3.6: (a) Density profiles used for the sensitivity study. Magenta lines represent position of the plasma edge.

3.2.3 Preliminary results of SSWITCH simulations

The main aim of the SSWITCH simulations is to check qualitatively how the sheath effect is distributed poloidally. Only the narrow AUG ICRF antenna configuration has been assumed for simulation. This is due to the limitation of the SSWITCH program that does not allow including the width of the antenna limiters. The physical model implemented in the program already includes slow wave and lateral walls normal to the straight confinement magnetic field and, for this reason, the antenna model does not include any limiters.

As first step of simulation, near RF field maps are produced in the vicinity of the antenna using the TOPICA software. In order to remove any additional vacuum layer, the plasma edge is located 3 mm in front of the Faraday screen bars, following softly the poloidal curvature of the antenna with narrow configuration, and the $E_{//}$ field component is calculated directly at the plasma edge surface. The average spatial resolution used for the simulation is 3.8 cm boundary surface and also for $E_{//}$ calculations. Simulations were performed assuming an input forward voltage of 12kV applied at the antenna feeders which corresponds to 1M W of coupled power to plasma.

3.3 Interpretation of NSTX experiment results

The unsuccessful ICRF experiment on the National Spherical Torus Experiment (NSTX) has been also considered, which did not produce any effect of the coupled RF power to the plasma bulk, but only parasitic deposition at the very edge of the plasma column. In this regard, the non-linear wave-plasma coupling phenomenon occurring at the edge has been studied, as example of a not proper transfer of the RF power coupled by the antenna to useful ICRF waves.

The ICRF experiment on NSTX was characterised by the deposition of the coupled RF at the very edge of the plasma column. This undesired effect is documented by the absence of any effect of heating of the plasma bulk, and by the occurrence of a particular frequency spectrum of the signal collected by a small loop antenna faced in front to a port of the machine. Namely, besides the operating frequency line, it was observed also a few lines down shifted by multiples of the ion-cyclotron frequency near the edge. These side band waves represent signatures of a non-linear wave-plasma phenomenon, namely the parametric instability (PI), which is produced by the beating of the component of the RF electric field ($E_{//}$) parallel to the confinement magnetic field with a mode of the thermal background of plasma density fluctuations, whose frequency lies in the range from about 100 kHz to a few megahertz. The component of the coupled RF power excites quasi-electrostatic waves, named lower hybrid (LH) waves, whose electric field is indeed quasi-aligned to the wave vector.

We have analytically derived the parametric dispersion relation (PDR), i.e., the equation whose solutions determine the conditions for the onset of a PI, when a certain value of the coupled RF power density is exceeded, being fixed the local values of the plasma kinetic profiles and other parameters. Namely these parameters are: the toroidal magnetic field, refractive index of the launched (pump) wave and low frequency mode, operating RF frequency and antenna geometry. The PDR solutions give frequencies and growth rates of the non-linearly coupled modes of PI.

4. MAIN RESULTS

4.1 Comparison of impedance matrix computation with ANSYS HFSS and TOPICA microwave software for flat AUG ICRF antenna

It can be concluded that the programs are on average in a good agreement for vacuum, water and chosen dielectric in terms of Z matrix, assuming the flat narrow AUG ICRF antenna. The maximum difference for real part of self-terms is 6.5% and for imaginary part 3.1%. In case of mutual terms, the maximal difference is 6.1% and 6.8% for real and imaginary part respectively. These differences can be due to the different approaches between the programs, mainly in meshing, slightly different input conditions and little geometrical discrepancies. This result provides an additional validation of TOPICA software.

4.2 TOPICA simulation results

Figures 4.1 and 4.2 present $E_{//}$ field map for the plasma the load, assuming the curved initial narrow and wide antenna configurations. An input forward voltage of 1V is applied at the antenna feeders which exhibit a characteristic impedance 25Ω (which corresponds to 0.02 W of incident power). The plane for $E_{//}$ solution calculation is situated 2 mm radially away from antenna limiters. Fields are in all cases predominantly real due to the chosen antenna phasing. It can be seen that special structures develop in the region of the antenna corners, and therefore locally high potentials are expected there. The presented $E_{//}$ field maps, which show that strong $E_{//}$ values can exist on all the structures surrounding the antenna, and in particular on the antenna limiters, that carry image currents of the antenna straps. The radially protruding limiters are the locations where $E_{//}$ component mostly appear due to intersection of the limiter with magnetic field lines. The electric fields are forced to be perpendicular to the protruding surfaces and get a large parallel component. Depending on the alignment of the limiter curvature with respect to the magnetic field lines, either positive or negative $E_{//}$ values appear on the limiter sides. It can be seen that, the $E_{//}$ values are less intense for the wide antenna configuration. This result is in agreement with assumptions that $E_{//}$ component can be reduced by putting the locations of the intersection of the protruding parts with magnetic field lines further away from the antenna. In this condition, the effect of the image currents and electric fields of the antenna is lower.

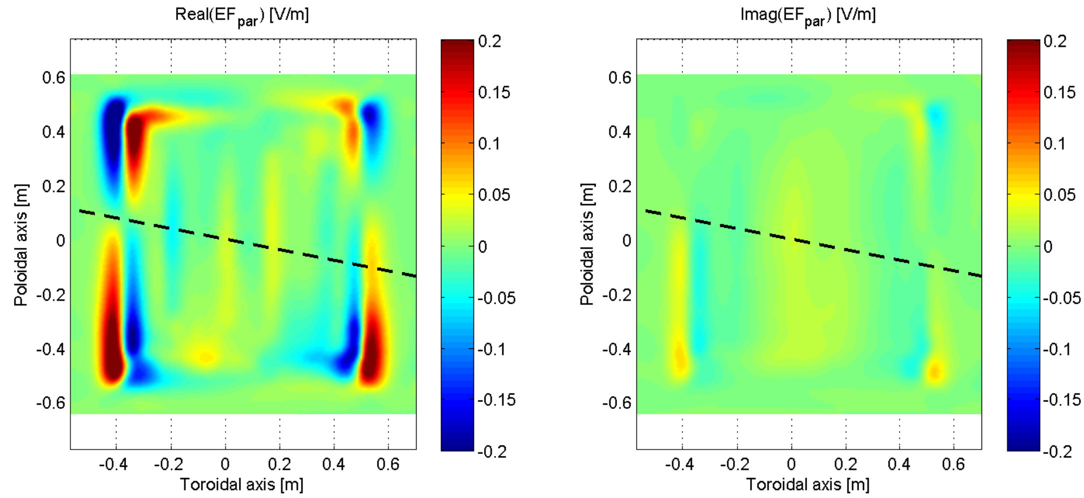

Figure 4.1: Distribution of real and imaginary part of $E_{//}$ for plasma load assuming the narrow antenna configuration.

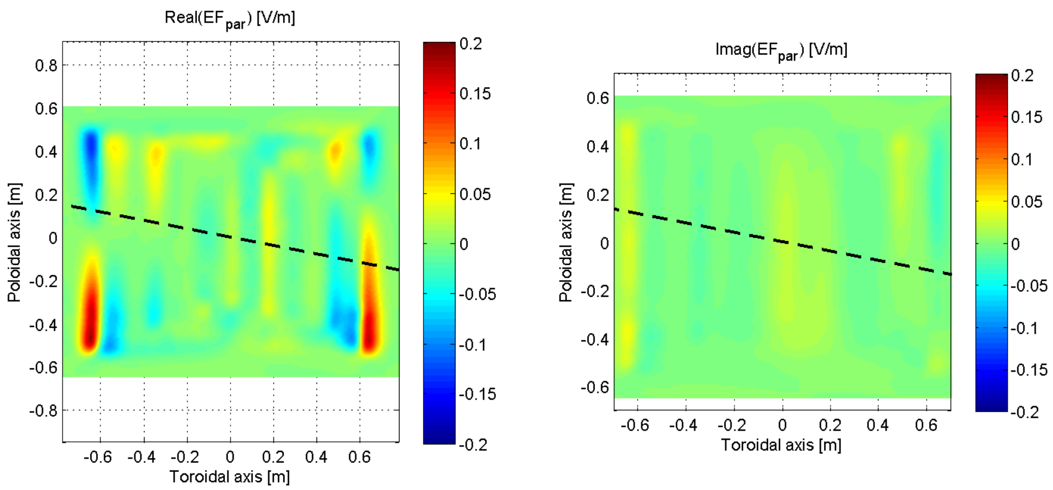

Figure 4.2: Distribution of real and imaginary part of $E_{//}$ for plasma load assuming the wide antenna configuration.

Figure 4.3 presents RF potentials $|V_{//}|$ for input forward voltage of 1V at the antenna feeders with characteristic impedance 25Ω (which corresponds to 0.02 W of incident power) and for 1MW of coupled power to the load. (0, π) phasing is assumed. The calculated values for vary along the vertical (poloidal) direction; the peak values are situated in the lower and upper parts of both antennas. The $|V_{//}|$ RF components are reduced approximately by a factor of 1.8 for the partly optimized wide antenna.

The detailed analysis indicates that there are remarkable differences in RF potentials both in terms of peak amplitude and location. It can be concluded that a flat model can be a reasonably good approximation of a real curved launcher when the power coupled to plasma has to be computed. In order to study more localised phenomena, such as RF potentials, a realistic antenna geometry is necessary, which should take into account even relatively small details that can however have influence on the the result of parameters under study.

a)

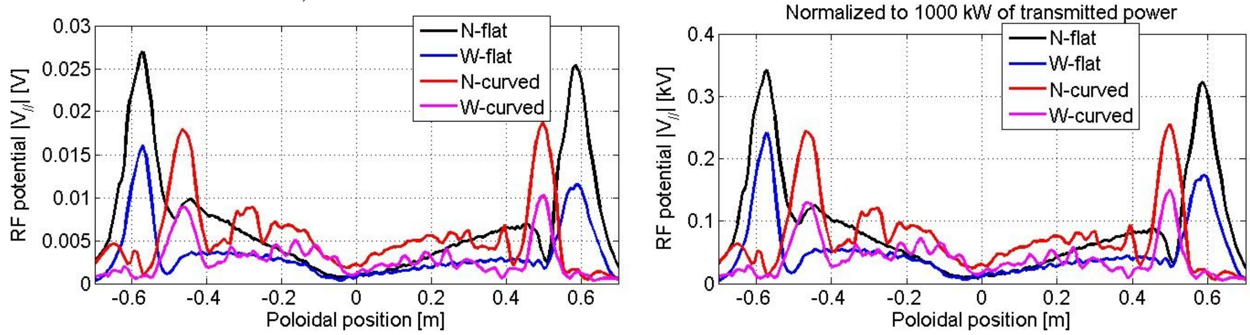

Figure 4.3: $|V_{//}|$ calculated for flat and curved antenna models for the input voltage of 1V at the antenna feeders (a) and for 1MW of coupled power to the plasma load (b).

Further, In order to estimate how $E_{//}$ and $V_{//}$ change with increasing radial distance from the antenna, the surface was moved to 4 and 6 mm in front of the antennas. Figure 4.4 documents RF potentials $|V_{//}|$ for different radial distances assuming an input forward voltage of 1V for both antennas. We can conclude that the more intense $E_{//}$ values are localized in the antenna vicinity.

a) b)

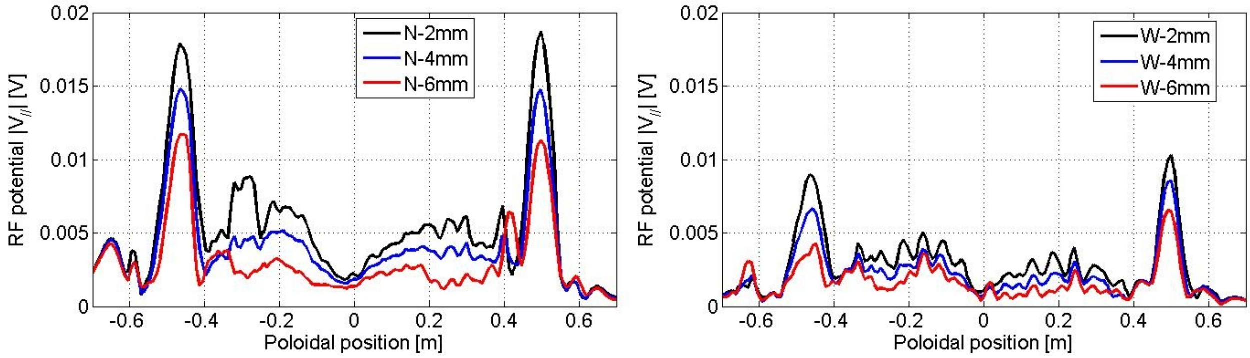

Figure 4.4: $|V_{//}|$ calculated for different radial distances for the narrow antenna (a) and for the wide antenna (b) configuration, assuming the forward voltage of 1V at the antenna feeders.

Further, considering the curved geometry, the impact of the antenna phasing on the RF potentials has been assessed. For the narrow antenna, The highest impurity production can be expected for (0,0) phasing. The peak values for (0, π) and (0, π/2) seem to be comparable. Nevertheless for (0, π/2) phasing, the area with higher values is larger, and slightly worse performance is expected to occur. The best performance is expected to occur instead using (0, π) phasing. These results are in good agreement with experimental observations for the same operating conditions. For the wide antenna, the same bad performance of the wide antenna can be expected for (0, 0) phasing. This situation is improved using the (0, π/2) phasing, and the best performance is reached for (0, π) phasing.

I have also analysed the sensitivity of density profile on coupling performance, considering the case of the curved antenna geometry. The coupled power increases with decrease of the density gradient and with decrease of the antenna cut-off distance. For smaller antenna cut-off distance the evanescent region, through which the fast magnetosonic wave has to travel, is shorter and more power is transferred to plasma. Further, the coupled power is lower for the partly optimized wide antenna, likely due to thinner radiating straps. Differences between antennas appear to be higher for lower density gradient and smaller antenna cut-off distance.

Keeping constant the antenna cut-off distance for both antennas, gradient sensitivity analysis shows that similar values of $|V_{//}|$ occur, except obtaining a larger peak in the bottom part of the narrow antenna, for the steepest density profile. The $|V_{//}|$ values result to be more sensitive to the antenna cut-off distance. Keeping constant the plasma density gradient, $|V_{//}|$ tends decreasing by increasing the antenna cut-off distance. This tendency is in agreement with experimental observations.

4.2 Indirect comparison with experimentally measured values for the narrow antenna configuration

Calculated spatial distributions of RF potentials $|V_{//}|$ are in good agreement with poloidal variation of the floating potentials that were measured around ICRF antennas of Tore Supra tokamak, using reciprocating Langmuir probes [24] (Figure 5.33). Nevertheless, floating potential is not directly a measure of the plasma potential. It rather indicates that the two flux tubes, emerging from the two probe electrodes, draw DC current from their neighbours.

There is also agreement with poloidal distribution of the W sputtering yield that was spectroscopically monitored on the initial ICRF antenna limiter, during ICRF heating in AUG tokamak [5]. In this experiment, the array of spectroscopic measurements at one of the unpowered antennas with narrow configuration, was used to characterize the companion antenna. The latter was powered and connected to the unpowered antenna via lines of the static magnetic field of the tokamak..

The maximal values of W effective sputtering yield, around $1.8 \cdot 10^{-4}$, were measured on the magnetic field lines passing the upper corner of the powered antenna. The measurements were done for 1 MW of coupled ICRF power. The maximal measured values of W sputtering yield, for typical concentrations and charge states of light impurities, correspond to the sheath accelerating voltage. These values are slightly below 100V.

The estimated values of DC rectified potentials according to Equation 4.2 for selected plasma density profiles (presented in Figure 3.6) assuming both antennas are shown in Figure 4.5. The maximal values in the bottom and upper part of the antenna with narrow configuration lye in the range from 65 V to 110 V, which is far above the sputtering thresholds for W. The estimated values seem to provide correct order of magnitude with respect to values of accelerated voltage corresponding to the measured W sputtering yield. For the wide antenna configuration, the estimated values of rectified potentials are roughly a factor of two lower than for the narrow antenna configuration. The exact values depend on the actual plasma content and, for this reason, it is difficult to quantify the value precisely.

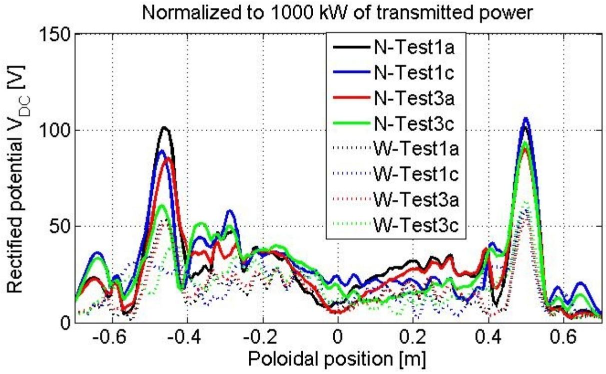

Figure 4.5: Calculated values rectified potential V_{DC} for selected density profiles for both antenna configurations.

4.3 Preliminary results of SSWITCH simulations

Figure 4.6 presents 2D radial/poloidal plots of the DC plasma potential obtained with SSWITCH program. It can be seen that, in the private SOL between the vertical limiters, the DC potentials are highest approximately 2 mm above the antenna Faraday screen, and reach even the level of 300 V. At the radial position of antenna limiter (6 mm above the FS) , the values of the DC plasma potential reach levels in the range from 70-130V.

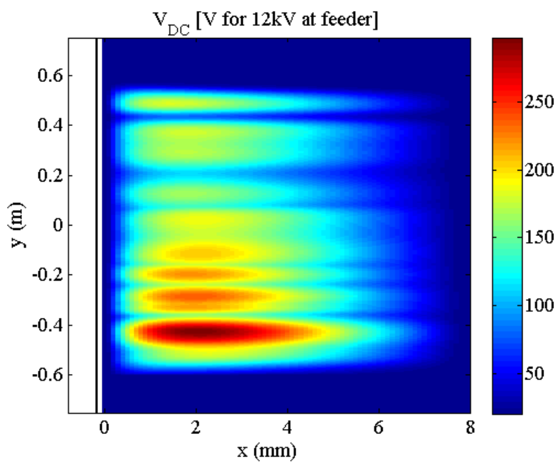

Figure 4. 6: 2D radial/poloidal plots of the DC plasma potential from RF sheath rectification.

In agreement with TOPICA results, high V_{DC} are present in the bottom part of the antenna. In contrast to the TOPICA results, no high peak is present in the upper part of the antenna. Further, poloidal variations that do not correspond to any physical object are present. This circumstance could be due to the used mesh resolution, but it needs to be better investigated in future work.

4.4 Interpretation of NSTX experiment results

Unstable solutions have been found with significantly high growth rate ($\gamma \geq \omega$) at frequencies in the range from about 100 kHz to a few megahertz. High growth rates have been also found at around harmonics of the ion-cyclotron frequency of the edge. These results are consistent with the results of the spectrum of the signal collected by the Langmuir probe located at the edge. We can thus conclude that the phenomenon that accompanies the failure of the penetration of the coupled RF power in the NSTX experiments is the parametric instability. This mechanism can be thus retained responsible of the undesired parasitic absorption of the launched RF power at the edge. Further analysis should be required in order to assess the amount of the power carried by the daughter waves, and determine the consequent effect of parasitic damping on plasma particles at the edge. This result indicates however that, in the NSTX experiment, a large fraction of the coupled RF power would excite waves with a too high $E_{//}$ component of RF field. This component is able to excite quasi-electrostatic plasma waves rather than fully electromagnetic ICRF waves, which are necessary for proper ICRF operations aimed at heating plasma ions and driving current. Consequently, a more suitable antenna design, which would reduce the spurious LH wave coupling, should be recommended for making successful experiments.

5. CONCLUSION

To couple multi-megawatt Ion Cyclotron Range of Frequencies (ICRF) power to tokamak plasmas is in principle an important tool for research of thermonuclear fusion energy. For the assessment of this tool, it is necessary to understand why the ICRF power was successfully utilised for decades, in tokamaks with low-Z plasma faced materials, whilst the extrapolation of these experiments to conditions of reactor relevant metallic vessel, performed more recently on ASDEX Upgrade AUG tokamak, resulted unexpectedly very problematic due to a not sustainable ingress of impurities in the plasma occurring also at relatively low ICRF coupled power.

In this thesis, I have considered the circumstance, indicated by experiments and calculations, that the phenomenon of RF sheath, which rectifies the RF potential and accelerates ions in regions of the plasma edge, would be cause of the undesired impurity injection. Consequently, this work has been mainly focussed on individuating and using the more appropriate modelling methods available so far, useful for assessing the RF potential, in realistic conditions of experiments, including plasma edge. This way, there are more chances of interpreting the unexpected results obtained by AUG, compared with previous successful experiments with low-Z plasma faced materials.

For the flat AUG ICRF antenna, I have compared the impedance matrix of antenna as computed by two different modelling tools, namely the ANSYS HFSS and TOPICA microwave software. Consequently, it can be concluded that the codes are on average in a good agreement for vacuum, water and dielectric in terms of Z matrix, which have provided an additional validation of the TOPICA software.

Further, I have used TOPICA for simulation of two types of ICRF antennas that are currently installed on the AUG tokamak have been considered: a) the narrow antenna, early installed on AUG, and b) the partly optimized new antenna that has wider dimensions.

Consequently, strong $E_{//}$ fields exist on all structures surrounding the antenna and, in particular, on the antenna limiters, which carry image currents of the antenna straps. The radially protruding limiters represent the locations where the $E_{//}$ component appear more pronounced, as the limiter intercepts there the confinement magnetic field lines. It can be seen that special structures develop in region of the antenna corners and, therefore, locally high potentials are expected there. In all simulated cases, RF potentials vary along the vertical (poloidal) direction; the peak values are situated in the lower and upper parts of both antennas. The $E_{//}$ and $|V_{//}|$ RF components are reduced approximately by a factor of 1.8 for the partly optimized wide antenna. The obtained spatial distributions of the RF potentials $|V_{//}|$ result in a good agreement with poloidal variation of the floating potentials measured around ICRF antennas of Tore Supra tokamak, using reciprocating Langmuir probes. There is also agreement with the poloidal distribution of the tungsten sputtering yield that was spectroscopically monitored on the initial ICRF antenna limiter, during ICRF heating in AUG tokamak.

I have carried out the analysis of the impact of antenna load on RF potentials evaluation for flat antenna geometries. Consequently, the coupled power is approximately 35% for the dielectric load, and the $E_{//}$, $|V_{//}|$ components are less intense assuming the real plasma condition than with a dielectric load used for test.

The antennas with both flat and curved geometry have been also modelled, considering the realistic condition of plasma load. Consequently, for curved geometry results to couple 7% more power than the flat one. The $|V_{//}|$ component is approximately 35% lower for the curved than for the flat geometry. Detailed analysis indicates that marked differences in RF potentials occur, both in terms of peak amplitude and location. From the obtained data of power coupled to plasma, the flat model results to represent a reasonably good approximation of a launcher with realistic curved geometry. The realistic antenna geometry is particularly necessary for the considered main goal of the present thesis, consisting in assessing the role of the localized phenomena at the plasma edge, driven by the RF potentials, where even apparently small details can influence the final result.

I have made comparison of the narrow antenna, early installed on AUG, and the partly optimized new antenna that has wider dimensions. The coupling performance results higher for the narrow antenna: compared to the wider antenna, for the considered kinetic plasma profiles, the antenna coupling is 12% higher, considering the dielectric load, and 14% higher with the plasma load. Considering the curved geometry, the impact of the antenna phasing on the RF potentials has been assessed. For the narrow antenna, The highest impurity production can be expected for (0,0) phasing. The peak values for (0, π) and (0, π/2) seem to be comparable. Nevertheless for (0, π/2) phasing, the area with higher values is larger, and slightly worse performance is expected to occur. The best performance is expected to occur instead using (0, π) phasing. These results are in good agreement with experimental observations for the same operating conditions. For the wide antenna, the same bad performance of the wide antenna can be expected for (0, 0) phasing. This situation is improved using the (0, π/2) phasing, and the best performance is reached for (0, π) phasing.

I have analysed the sensitivity of density profile on coupling performance, considering the case of the curved antenna geometry. The coupled power increases by decreasing both the assumed density gradient and the radial distance of the antenna from the cut-off layer. Keeping constant the antenna cut-off distance for both antennas, gradient sensitivity analysis shows that similar values of $|V_{//}|$ occur, except obtaining a larger peak in the bottom part of the narrow antenna, for the steepest density profile. The $|V_{//}|$ values result to be more sensitive to the antenna cut-off distance. Keeping constant the plasma density gradient, $|V_{//}|$ tends decreasing by increasing the antenna cut-off distance. This tendency is in agreement with experimental observations.

After radial scan of $E_{//}$ and $V_{//}$, the values of $E_{//}$ at the antenna corners are reduced by increasing the radial distance, for both antenna geometries. It can concluded that the more intense $E_{//}$ values are localized in the antenna vicinity.

Preliminary results of SSWITCH (Self-consistent Sheaths and Waves for IC Heating) simulations show that, in agreement with TOPICA results, high V_{DC} are present in the bottom part of the antenna. In contrast to TOPICA results, significantly high peaks are not present in the upper part of the antenna. The occurring poloidal modulation of the potential appears quite problematic, and this issue should be investigated in future.

Finally, the problem of failure of penetration of the coupled RF power to the plasma core have been considered, which occurred on NSTX (National Spherical tokamak Experiment) during experiments aimed at heating and driving current in the plasma, operating at high harmonic of the ion-cyclotron frequency of Deuterium plasma. Only signatures of non-linear wave-particle interaction were observed to occur, which can be interpreted as effect of parametric instability produced by the $E_{//}$ component of the coupled RF power. This mechanism is described by the parametric dispersion equation, whose analytical derivation and solutions has been summarised here. Consequently, the instability is favoured by the relatively cold region of plasma periphery, an it is expected depleting significantly the RF power spectrum launched by the antenna, by side band waves that would produce the undesired deposition on particles of plasma edge.

Further work is necessary to be carried out in future, for fully assessing the phenomena that are responsible of the unexpected strong impurity influx in ICRF heating experiments in machines with reactor-relevant metallic walls, and the failure of RF power penetration to the plasma core in current drive experiments operating at high harmonic of the ion-cyclotron frequency of Deuterium plasma. The work presented in the thesis indicates how the map of the RF field should be extended, for realistic conditions of experiment, to regions of plasma edge located far from the antenna. This information is necessary to take into account the impurity production observed to occur also in regions that are toroidally located far from the antenna. Moreover, a complete assessment of the RF field pattern should be performed, considering experiments operating at high harmonic of ICRF power. The analysis has been indicated, which takes properly into account non-linear plasma-wave interaction phenomena. This work can address a more appropriate antenna design, which is necessary for reducing the contribution of the RF coupled $E_{//}$ component.

6. SUMMARY

The problem of the unsuccessful use of ICRF (ion cyclotron radio-frequency) power coupled to tokamak plasma in experiments aimed at heating or driving current has been considered here. Overcoming this issue is necessary for the progress of main thermonuclear fusion energy research.

Original information have been provided showing that early experiments that tested for the first time, in the years ’80 of the last century, the ICRF heating scenario in tokamaks by using metallic wall, obtained the same not tolerable impurity influx that occurred, more recently, on AUG (ASDEX Upgrade) tokamak. In the latter experiment, conditions of reactor-relevant Tungsten plasma faced material have been used, indeed, similar to those utilised in early ICRF experiments. It has been indicated that the more probable interpretation of the circumstance that, after the first attempts, the ICRF experiments became successful for two decades, since the middle of the years ’80, is not only due, as it was believed, to the use of a new

antenna configuration but, rather, to the utilised low-Z plasma faced materials. These materials are, however, not relevant for a fusion reactor. For this reason it is absolutely timely the content of this thesis, which is mainly focussed on the interpretation of the early and recent ICRF experiments, using reactor-relevant metallic plasma faced materials.

In order to address the interpretation of the important problem of how enable the ICRF power to be a tool useful for a thermonuclear fusion reactor, I have considered the role of some phenomena of wave-plasma interaction at the plasma edge. Namely, I have taken into account the phenomena of RF sheaths, producing impurity influx, and parametric instability, producing parasitic damping at the edge of the RF power coupled by the antenna. These phenomena should be mitigated in order to enable reactor-relevant operations in tokamaks, which require ICRF power for plasma heating and current drive.

I have produced new modelling work useful for assessing the RF field structure inside the main chamber of tokamak. As necessary for performing useful analyses of wave-plasma interaction phenomena at the plasma edge, this work has been carried out considering the complex conditions of both realistic geometry and antenna-plasma loading. These requirements are, indeed, necessary for assessing important details of the RF electric field pattern, useful for development of dedicated modelling and for comparing the expected antenna parameters with features measured during the experiments.

The content of the thesis provides the basic elements necessary for producing, in future, further and more complex modelling and experimental works. They are necessary for solving the important problems individuated so far for enabling the ICRF power to become a robust tool for a future thermonuclear fusion reactor. To assess the RF electric field behaviour, in realistic conditions of antenna geometry and plasma loading, provides essential information for solving the problems produced by parasitic plasma-wave interaction phenomena. In order to efficiently attack these problems, it is necessary, indeed, to interpret available data of experiments, address improvements in designing new antennas, and perform further experiments that are necessary for testing formulated hypotheses, as useful in scientific method. These issues require, as essential condition, the methods for RF electric field assessment, in complex antenna geometries, shown in the thesis.

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8. List of candidate's works relating to the doctoral thesis

8.1 Publications in impacted journals

<u>**Accepted for publications**</u>

1. **Estimation of radio-frequency potentials in front of ASDEX Upgrade ICRF antennas with the TOP-ICA code**

A. Krivska [1,2] (95%), S. Cessuzzi [2], D. Milanesio [3], V. Bobkov [4], A. Tuccillo [2], J.-M Noterdaeme [4]

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Accepted to Radioengineering journal

Published

2. **Assessment of ion cyclotron antenna performance in ASDEX Upgrade using TOPICA**

S. Cessuzzi [1], R. Cesario [1], A. Krivska [1] (15%), F. Mirizzi [1], G. Ravera [1], A. Tuccillo [1] , D. Milanesio [2], R. Maggiora [2], V. Bobkov [3], F. Braun [3], J.-M. Noterdaeme [4,5], I. Zammuto [3]

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International Journal of Applied Electromagnetics and Mechanics, Volume 39, Number 1-4 / 2012, Pages 59-64.

3. **ICRF Antennas optimized for operation with a high-Z metallic wall in ASDEX Upgrade**

I. Zammuto[1], A. Krivska [2,3](35%), V. Bobkov [1], F. Braun[1], R. Bilato[1], J.-M. Noterdaeme[1,4],

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[3] *Czech Technical University of Prague, Telecommunication Engineering Department,*

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Fusion Fusion Engineering and Design, Volume 84, Issues 7-11, June 2009, Pages 2031-2036.

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Ceccuzzi, S., Braun, F., Bobkov, V. el al. Assessment of ion cyclotron antenna performance in ASDEX Upgrade using TOPICA. International Journal of Applied Electromagnetics and Mechanics, Volume 39, Number 1-4 / 2012, Pages 59-64.

Noterdaeme, J.-M. Ion cyclotron frequency range (ICRF) power on the way to DEMO. Proceedings of ITC18, 2008.

4. **Assessment of compatibility of ICRF antenna operation with full W-wall in ASDEX Upgrade**

V. Bobkov[1], F. Braun[1], R. Dux[1], R. A. Herrmann [1], L Giannone [1], A. Kallenbach [1], A. Krivska [2] (5%), H.W. Muller [1], R. Neu, J.-M. Noterdaeme[1,3], T. Putterich [1], V. Rohde [1], J Schweinzer [1], A. Sips [1], I. Zammuto[1] and the ASDEX Upgrade Team[1]

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Nucleat Fusion 50 No 3 (March 2010) 035004 (11pp)

8.2 Web of Science excerpted publications

5. Density profile sensitivity study of ASDEX Upgrade ICRF Antennas with the TOPICA code

A. Krivska [1,2] (95%), S. Cessuzzi [2], D. Milanesio [3], V. Bobkov [4], F. Braun [4], J.-M. Noterdaeme [4,5], A. Tuccillo [2]

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RADIO FREQUENCY POWER IN PLASMAS: Proceedings of the 19th Topical Conference. AIP Conference Proceedings, Volume 1406, ISBN 978-0-7354-0978-1, pp. 93-96 (2011).

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Maggiora, R. and Milanesio, D. Mitigation of Parallel RF Potentials by an Appropriate Antenna Design Using TOPICA. AIP Conf. Proc. 1406, pp. 73-80; doi:http://dx.doi.org/10.1063/1.3664932.

Ceccuzzi, S., Braun, F., Bobkov, V. el al. Assessment of ion cyclotron antenna performance in ASDEX Upgrade using TOPICA. International Journal of Applied Electromagnetics and Mechanics, Volume 39, Number 1-4 / 2012, Pages 59-64.

6. Electromagnetic simulations of the ASDEX Upgrade ICRF Antenna with the TOPICA code

A. Krivska [1,2] (95%), D. Milanesio [3], V. Bobkov [4], F. Braun [4], J.-M. Noterdaeme [4,5] and the ASDEX Upgrade Team [1]

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RADIO FREQUENCY POWER IN PLASMAS: Proceedings of the 18th Topical Conference. AIP Conference Proceedings, Volume 1187, ISBN 978-0-7354-0753-3, pp. 137-140 (2009).

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Colas, L., Jacquot, J., Heuraux, S. et al. Self consistent radio-frequency wave propagation and peripheral direct current plasma biasing: Simplified three dimensional non-linear treatment in the “wide sheath” asymptotic regime. *Phys. Plasmas* 19, 092505 (2012).

Bobkov, V., Bilato, R., Braun, F. et al. Interaction of ICRF Fields with the Plasma Boundary in AUG and JET and Guidelines for Antenna Optimization (2009) *AIP Conference Proceedings*. In *AIP Conference Proceedings* 1187. p.125-132.

7. Interaction of ICRF Fields with the Plasma Boundary in AUG and JET and Guidelines for Antenna Optimization

V. Bobkov[1], R. Bilato [1], F. Braun[1], L. Colas [2], R. Dux[1], D. Van Eester [5], L. Giannone [1], M. Goniche [2], R. A. Herrmann [1], P. Jacquet [6], A. Kallenbach [1], A. Krivska [3,4](5%), E. Lerche [5], M.-L. Mayoral [6], D. Milanesio [7], I. Monakhov [6], H.W. Muller [1], R. Neu, J.-M. Noterdaeme[1,2], T. Putterich [1], V. Rohde [1] and the ASDEX Upgrade Team[1] and JET-EFDA Contributors

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RADIO FREQUENCY POWER IN PLASMAS: Proceedings of the 18th Topical Conference. AIP Conference Proceedings, Volume 1187, ISBN 978-0-7354-0753-3, pp. 125-132 (2009).

8.3 Other publications

8. **Application of microwave engineering in thermonuclear fusion**

A. Krivska [1,2] (100%)

[1] *Institute of Plasma Physics ASCR, Euratom Association, Prague, Czech Republic*

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A man in his earthly and cosmic environment, Bulletin of the papers from the conference, Úpice: Observatory in Úpice, 2010, p. 132-136, ISBN 978-80-86303-23-9.

9. ICRF Antenna Operation with Full W-wall in ASDEX Upgrade

V. Bobkov[1], F. Braun[1], R. Dux[1], R. A. Herrmann [1], A. Kallenbach [1], H.W. Muller [1], R. Neu, J.-M. Noterdaeme[1,2], T. Putterich [1], V. Rohde [1], A. Sips [1], A. Krivska [3,4] (7%), I. Zammuto[1] and the ASDEX Upgrade Team[1]

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Proceedings of the 22nd IAEA Fusion Energy Conference. Vienna: International Atomic Energy Agency, 2008.

9. List of candidate's other publications

9.1 Publications in impacted journals

1. Plasma edge density and lower hybrid current drive in JET (Joint European Torus)

R. Cesario[1], L. Amicucci[2], C. Castaldo[1], M. Kempenaars[3], S. Jachmich[4], J. Mailloux[3], O. Tudisco[1], A. Galli[2], A. Krivska[1] (10%) and JET-EFDA contributors

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Plasma Physics and Controlled Fusion, Vol. 53(8):085011, August 2011.

2. Power supply system for the COMPASS tokamak re-installed in IPP Prague

J. Zajac[1], R. Panek[1], F. Zacek[1], J. Vlcek[1], M. Hron[1], A. Krivska[1] (10%), R. Hauptmann[2], M. Danek[2], J. Simek[3], J. Prosek[4]

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[4] *ČKD Finergis a.s., Brno, Czech Republic*

Fusion Engineering and Design, Volume 84, Issues 7-11, June 2009, Pages 2020-2024.

9.2 Web of Science excerpted publications

3. EBE/ECE Radiometry on COMPASS tokamak – Desig nand First Measurements

J. Zajac [1], J. Preinhaelter [1], J. Urban [1], D. Sestak [1], A. Krivska [1,2] (10%), S. Nanobasvili [3]

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RADIO FREQUENCY POWER IN PLASMAS: Proceedings of the 18th Topical Conference. AIP Conference Proceedings, Volume 1187, ISBN 978-0-7354-0753-3, pp. 137-140 (2009).

10. ANOTACE

Nejúspěšnějším zařízením pro výzkum termojaderné fúze je tokamak. Pracuje na principu transformátoru, kde sekundární vinutí tvoří vodík ve stavu plazmatu uzavřený v prstencové komoře, ve které je plazma drženo statickým magnetickým polem a zahříváno silným proudem indukovaným primárním vinutím. Jedním ze způsobu dosažení termojaderných teplot je neinduktivní ohřev plazmatu vlnami s frekvencemi v oblasti iontové cyklotronní rezonance 30–80 MHz, jak vyplývá z výsledků experimentů provedených v letech 1985-2005.

Mezi problémy spojené s užitím této metody při vyzařování velkých výkonů (v řádu jednotek MW), je nárůst nečistot v plazmatu, pocházejících ze stěn komory tokamaku. Zřejmě díky přítomnosti lokálních a velmi intenzivních vysokofrekvenčních (VF) polí v blízkosti antény dochází k interakci plazmatu s materiálem stěn. Pokud jsou stěny komory tokamaku obloženy prvkem s nízkým atomovým číslem, jako je například berylium nebo uhlík, nepředstavují nečistoty do určité míry závažný problém. Obsahují-li ale prvky s vyšším atomovým číslem (např. wolfram), pak tyto těžké atomy putují do centra plazmatu, kde silně vyzařují a způsobují tím ochlazení a ztrátu energie plazmatu.

Tato práce je zaměřena na simulace chování a porovnání dvou antén pro iontově cyklotronní ohřev, které se nacházejí na tokamaku ASDEX Upgrade, který má vnitřní stěny z wolframu. Simulace jsou provedeny převážně v programu Topica (Torino Polytechnic Ion Cyclotron antenna) pro různé provozní scénáře a kinetické profily. Práce se zabývá odhadem a distribucí velikostí veličin, které jsou považovány za hlavní příčinu tvorby nečistot: $E_{//}$ a VF potenciálů.

Neúspěšný experiment NSTX byl rovněž vzat v úvahu. Užití vln na iontové cyklotronní frekvenci nevedlo k ohřevu plazmatu, ale pouze k parazitní interakci na okraji plazmatu.