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# IShTAR: a helicon plasma source to characterise the interactions between ICRF and plasma

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**Abstract**. IShTAR (Ion Sheath Test ARrangement) is dedicated to the investigation of the interactions between an ICRF antenna and a plasma in the conditions (plasma temperature and density, magnetic configuration) representative of the plasma edge of a magnetic confinement fusion machine. The test bed is composed of a helicon plasma source and a main vessel, in which a dedicated single strap ICRF antenna is installed. Firstly, the optimisation of the plasma source in order to get the highest density and most radially uniform plasma is presented (by changing of the position of the source and by scanning the operational parameters). In addition, the efficiency of the installed diagnostics (compensated/non-compensated Langmuir probes, B-dot probes, a wideband spectrometer) is discussed. The second part addresses the effect of the ICRF operation on the generated plasma; the wave profiles in vacuum and plasma are recorded. The impact of the eigenmodes due to the small size of the vessel on the wave field at the interface antenna/plasma is evaluated. The effect of the additional ionisation on the density profile is also measured with the spatial variation of the plasma potential near and inside the RF sheath in front of the antenna strap. Finally, the feasibility of a diagnostic to directly measure the electrical field in the sheath by using the change in emission from energy levels modified by Stark effect and mixing is discussed.

## 1. Introduction

The operation of the Ion Cyclotron Resonant Frequency (ICRF) antenna on tokamaks revealed spurious effect like sputtering, hot spots and loss of powers due to the interaction of the electromagnetic field with the plasma sheath and the creation of a rectified DC voltage. Several theoretical tools have been developed to analyse these effects (cf. contrib. on ICRF this conference). Their validation requires experimental data which can be difficult to measure given the complexity and multi-scale (in time and space) nature of the phenomena occurring in the antenna region: energy and particles transport in a magnetised inhomogeneous plasma, radiation and propagation of Radio-Frequency fields, sheath effects at the boundary conditions. The in-situ investigation in tokamaks cannot provide all necessary information because of the limited time, the lack of control on the plasma parameters near the antenna and the difficult access for the diagnostics. Therefore the Ion Sheath Test ARrangement (IShTAR) has been developed to experimentally investigate this region and measure the rectified electric field in the surrounding of the antenna including the sheath, which is suspected to be the main driver of the ICRF/plasma interactions [1, 2].

The test bed is presented in figure 1. It consists of a main vessel where the ICRF antenna is located and where conditions representative of a tokamak's edge are recreated: two main coils build a static magnetic field up to 0.2 T and an external RF plasma source creates a plasma with a density around $10^{18}$ m$^{-3}$ for argon $10^{17}$ m$^{-3}$ for helium and a temperature between 5 and

10 eV. This plasma source is designed to reach helicon discharge mode with a helical antenna and five small 0.1 T coils to get high densities and uniform radial profiles along the cross-section.

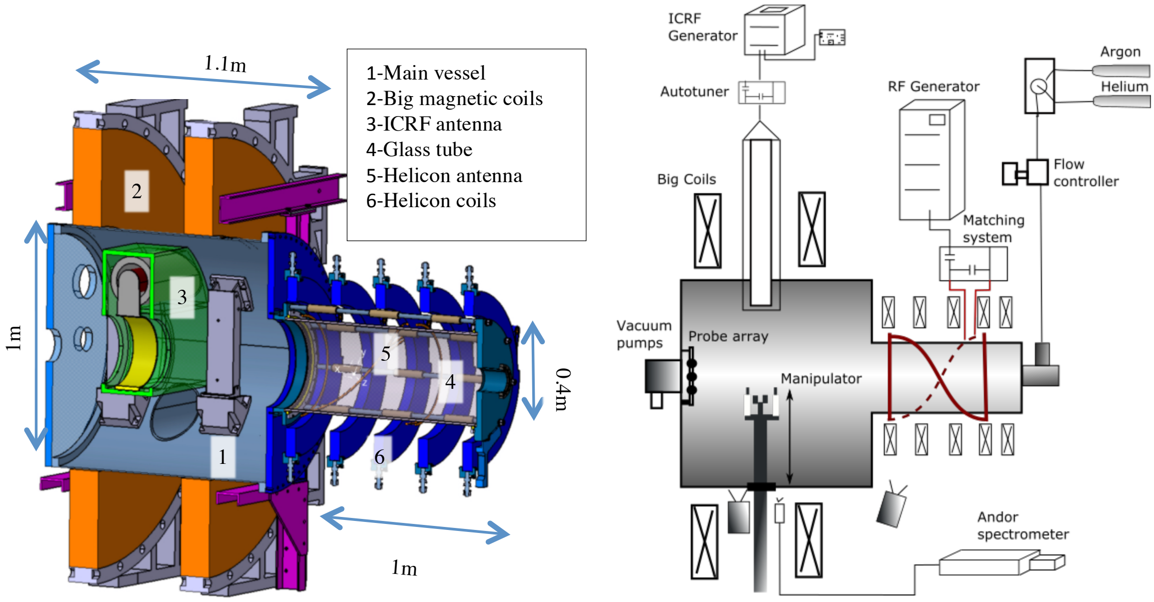


Figure 1: Experimental setup. (a) Cutaway view (b) upper cross-section

The test bed is equipped with an array of cylindrical Langmuir probes on the back flange, a movable manipulator with a set of B-dot probes and Langmuir probes to get the radial profiles, video cameras and optical fibres connected to a high-resolution spectrometer equipped with an iCCD camera able to follow fast events. A typical plasma discharge is presented in figure 2.


Figure 2: Plasma operation with helium in the RF source.
The effect of the magnetic field gradient is visible.

Three tasks have been carried out: first, the analysis and optimisation of the RF plasma source operation with the purpose to get a high density and uniform plasma in front of the ICRF antennas. It was also the occasion to test and improve the different diagnostics. Second a dedicated single-strap ICRF antenna was design and manufactured. We have studied the interaction of the wave delivered by this antenna with the specific environment of IShTAR before integrating it into the vessel. Third, we have started to develop the tools to measure the electric field produced by the ICRF wave inside the sheath on the antenna limiters and to test the method in real conditions. Each of these steps will be presented in the next sections.

## 2. Characterisation of the plasma

### Validation and improvement of diagnostics

The antenna region can be properly studied only in plasma conditions that make it possible to get RF waves with the same dispersion relations as in tokamaks. It was shown that an argon density around $10^{18}$ $m^{-3}$ for a magnetic field of 0.1 T and an ICRF frequency of 5 MHz is needed. To reach this objective, it is necessary to have reliable diagnostics to measure the plasma characteristics and to tune the operating parameters (injected RF power, magnetic field and neutral gas pressure) of the plasma source without ICRF operation. The measurements are presently done with Langmuir probes for the density and temperature, and B-dot probes for the RF field. The Langmuir probes are very sensitive to the RF background noise and ground loops [3, 4]. Notch filters and wavelet techniques have been developed to enhance the quality of the signal. The improvement is presented in figure 3. In addition, RF compensated probes have been tested that eliminate the RF component of the plasma source. No particular effect was detected for the maximum level of RF power (3 kW) and it was decided to use only non-compensated probes, which are easier to operate as long as this range of power is maintained.

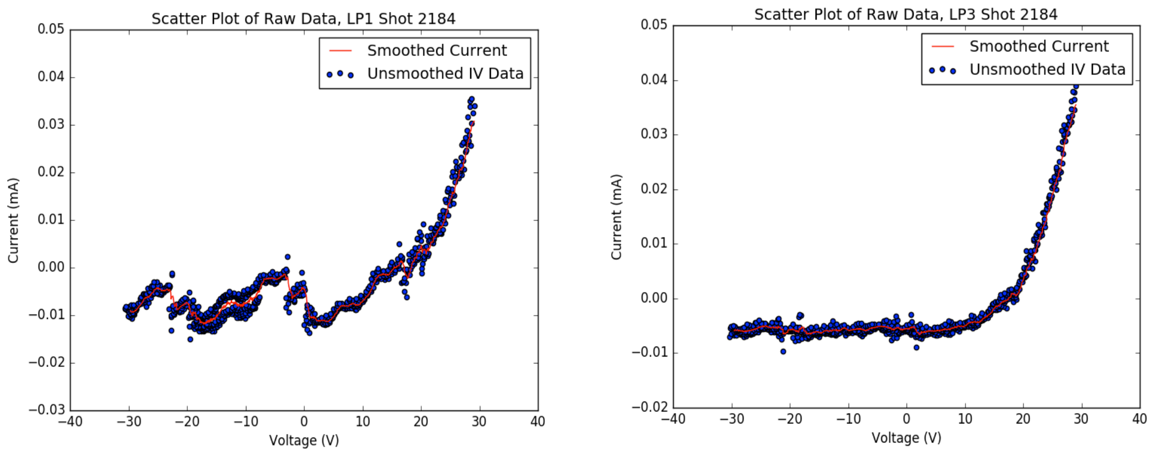


Figure 3: Effect of Langmuir probe data processing. a) raw data b) noise filtering

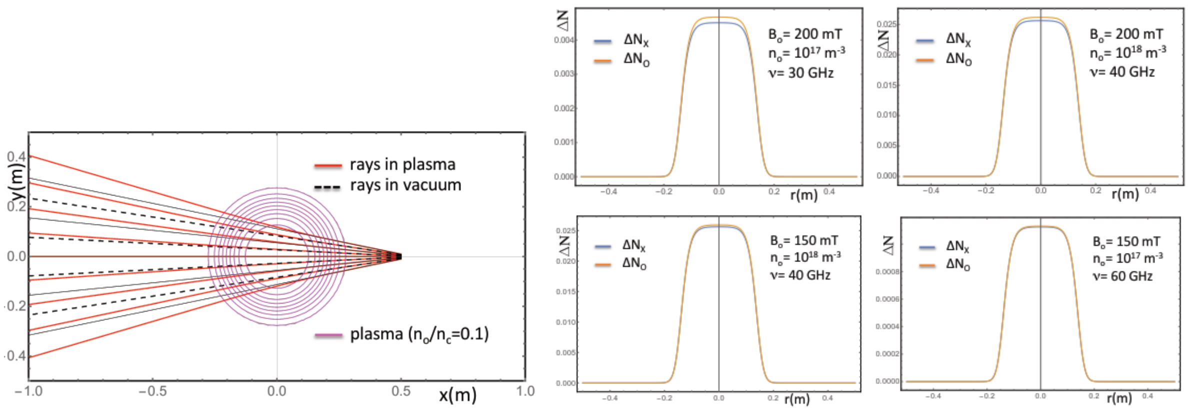


Figure 4: Interferometry feasibility study: (a) Trajectory of the rays in the case of an IShTAR plasma with $n_e$ = 1.5 $10^{18}$ $m^{-3}$ launched in O-mode at 35 GHz in Gaussian-like plasma density profile (assuming a plasma radius of 20 cm and the emitter horn on the vacuum window). (b) Spatial evolution of the $N_O$ and $N_X$ index variations compared to vacuum in 4 different cases, where both $n_e$ and the probing frequency are changed.

The feasibility of an interferometer has been studied with a frequency bandwidth from 30 Ghz to 60 GHz to be able to benchmark without the RF effects the values given by the Langmuir probes. The deviation of the trajectories due to plasmas with a typical Gaussian-shaped plasma as found in IShTAR and the spatial variation of the index are presented in Figure 4. The X-modes and O-modes give basically the same results especially at low magnetic field. Sweeping the probing frequency and the use of a heterodyne system to measure the phase variation should help to have a density measurement accurate enough for IShTAR needs.

**Characterisation and optimisation of the plasma**

The operating parameters (injected RF power, neutral gas pressure and magnetic field) were scanned to observe the effect on the plasma density and temperature measured in the centre of the main vessel. The purpose is to select the set of parameters that optimises the density. The results of the parametric studies are presented in figure 5. At a constant magnetic field, the density increases almost linearly with the power. A small drop around 1.8 kW is observed, which may be due to an internal resonance. However no step in the scan is seen, which would correspond to a change of regime from inductive to helicon mode. This is probably due to a too low level of power with respect to the volume to ionise. The electron temperature does not feature any evolution inside a band between 4 and 7 eV, except for a peak at the same assumed resonance at 1.8 kW. This would confirm that the increased injected power is used to generate denser plasmas and not to heat. At constant injected power, two different trends are observed when the magnetic field is ramped up. At low pressure, the density reaches a plateau at 0.06 T and saturates before starting to drop at 0.14 T. At higher pressure, the density increases almost linearly with the magnetic field. The temperature presents a slight trend towards an increase, but there is not much difference between the high- and low-pressure cases. The cause for the saturation of the density is not yet clear and will require comparison with theoretical models, which are presently not yet available. The radial profiles of the plasma density and of the RF fields were measured with the manipulator over several discharges and are presented in figure 6 for two different magnetic fields at constant injected power of 2.5 kW and a neutral pressure of $10^{-4}$ mbar. The density profile has a Gaussian shape with a mean width of 10 cm, half the length of the plasma source geometrical radius. The profile does not change with the magnetic field, which corresponds to the "saturation" effect described above. However, the profiles of the perpendicular and parallel components (with respect to the static B-field) of the RF fields are changing with the evolution of the static field.

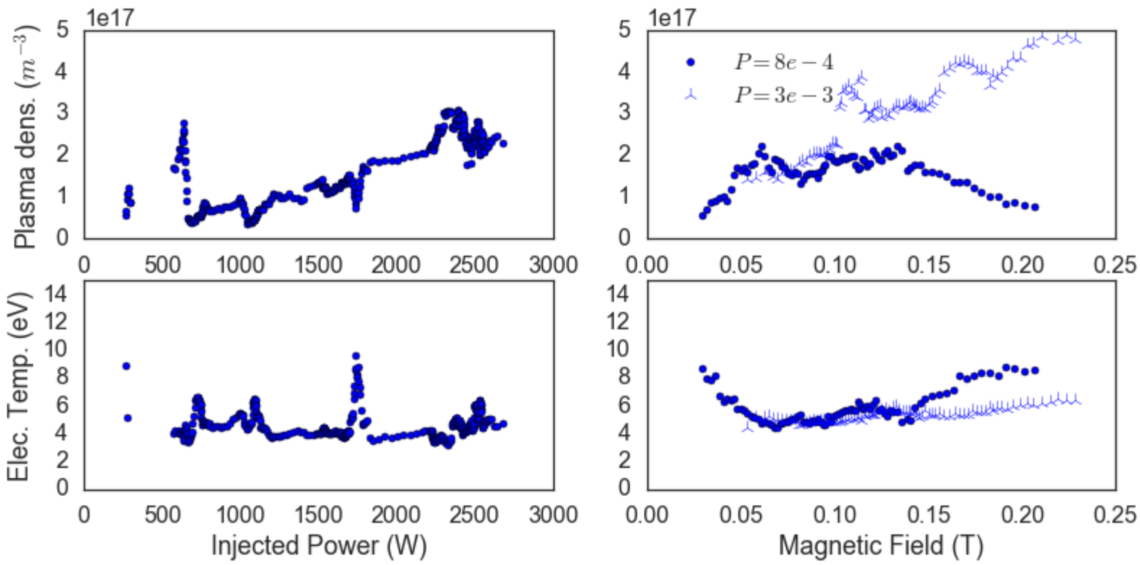


Figure 5: Scan of argon plasma parameters (a) as a function of the injected power at constant magnetic field (0.1 T) and neutral gas pressure P ($10^{-4}$ mbar) (b) as a function of the magnetic field and neutral gas pressure P at constant injected power (2.5 kW).

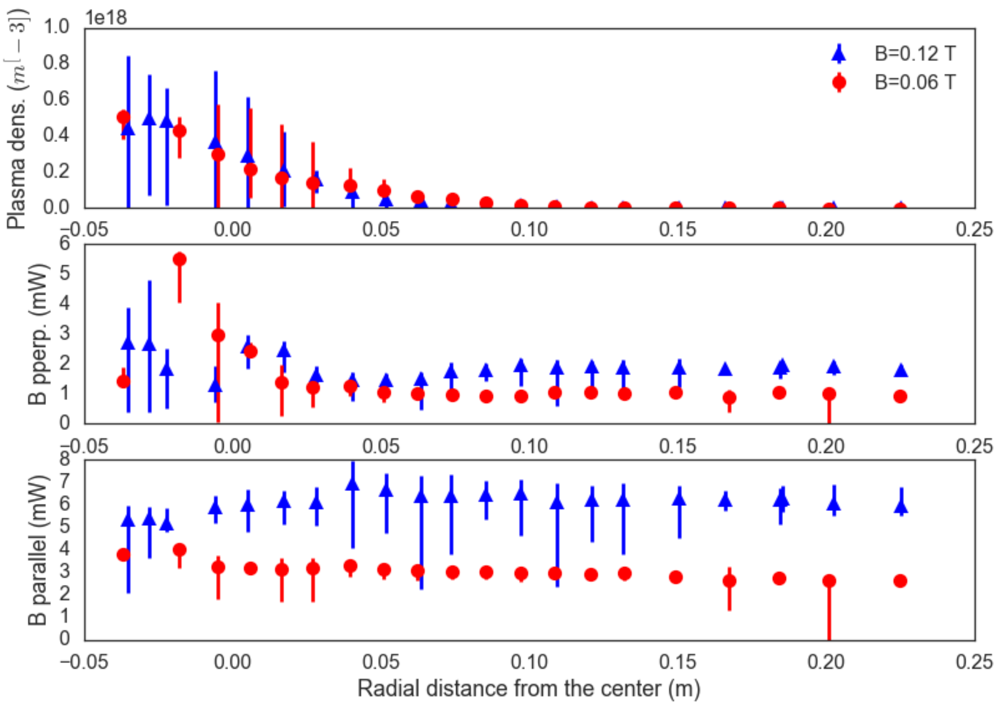


Figure 6: Radial profile measurements of the plasma density and of the perpendicular and parallel components of the RF magnetic fields with respect to the static B-field.

## 3. ICRF operations

The ICRF system is made of a FPGA signal generator working at 5MHz, a 1kW Bonn amplifier, a pre-tuner and an automatic matching system. The system was tested and validated with a simple strap shown in figure 7a (left antenna). The principal difficulty was to get a proper matching and limit the reflected matching with evolving plasma conditions. As shown in figure 7b, the auto-tuner was able to handle these varying boundary conditions.

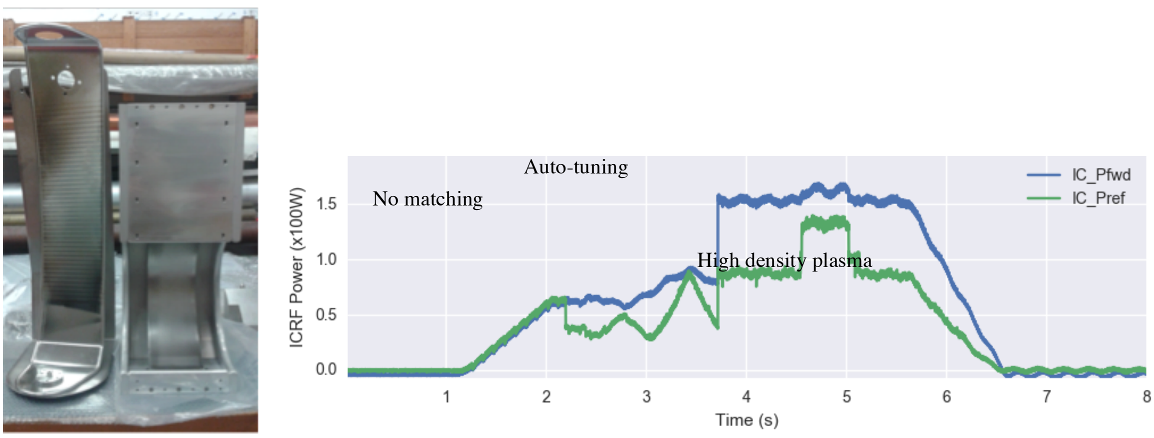


Figure 7: (a) ICRF antennas (b) evolution of forward and reflected power during a plasma discharge to show the effect of auto-tuning and plasma density evolution

An improved antenna box was designed and constructed with a geometry optimised for the IShTAR plasma (figure 7a right antenna with small length and high curvature) [5].

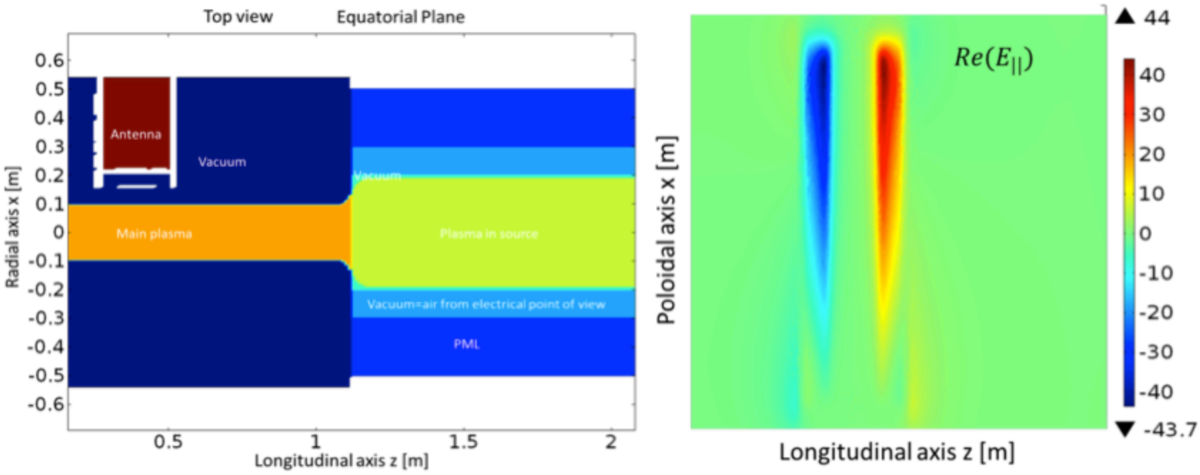


Figure 8: (a) Cut view of the equatorial plane of the electromagnetic model in COMSOL. (b) RF $E_{//}$ field map of the radiating pattern of the antenna (1V excitation) along a curved plasma at 1 cm in front of the antenna.

This antenna is being mounted in the vessel. Numerical simulations were carried out first with COMSOL and Microwave Studio with dielectric loading [4]. Similar results are obtained with both models. Then a cold magnetised plasma (argon or helium) description was implemented into the COMSOL model characterised with the Gaussian like radial density profile to evaluate the ICRF electric field in presence of the external cylindrical plasma. A cut view from the equatorial plane of the COMSOL model is shown in figure 8a. The antenna is facing an externally created plasma (in the plasma source) that is squeezed that the gradient in magnetic field downstream at the interface between the source and the main chamber. The squeeze follows a hyperbolic tangent function instead of the magnetic field lines for simplicity while keeping radial integrated density constant. Since the glass tube is transparent to RF waves, perfectly matched layers (PMLs) are implemented to absorb outgoing waves without reflection. Figure 8b shows the real part of the RF electric field on a curved surface placed 1 cm in front of the antenna. The electric field map is similar qualitatively to results obtained with dielectric media. It also appears that when changing the size of the plasma in the main vessel to obtain direct contact between the strap and the plasma that the strap is short-circuited along the curved part of the strap and not at its normal short-circuits position down the box. The electrical pattern is therefore significantly modified.

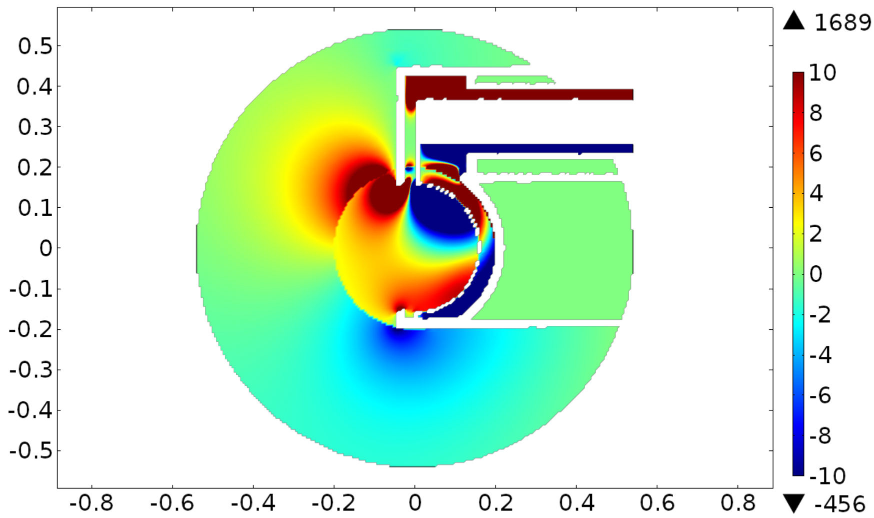


Figure 9: Field map of the radial electric field generated by the ICRF antenna in present of plasma.

One major difference between the plasma facing model and the dielectric facing plasma is the electric field pattern in the cross-section of the cavity as shown in figure 9. The structure of the eigenmodes in the mostly closed cavity is presently not yet understood. The highest values are found on the top of the antenna box, near the transmission line output. The radial symmetry is lost due to the off-axis current injection; this also means that the radial profiles given by the manipulator B-dot probes will not give a complete overview of the field. Local measurements will be necessary

## 4. Methods to measure the electric field

With proper conditions in the plasma and an ICRF antenna ready to work, it was possible to start the development of a diagnostic to measure the DC electric field in the sheath of the antenna region. The difficulties are the complex geometry, the small size of the sheath volume and the superposition of multiple fields, either RF (from helicon source and from the ICRF antenna) or DC (from the rectified sheath and the static B-field) (Figure 10).

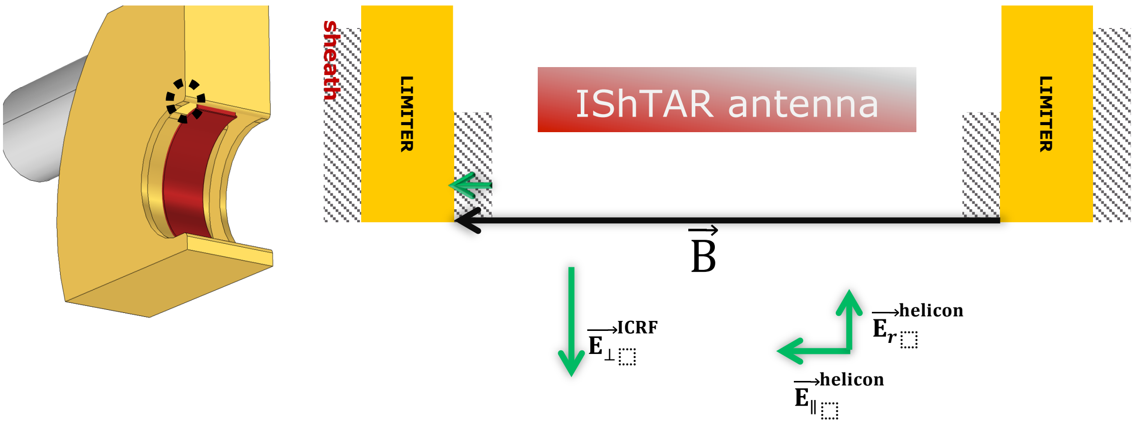


Figure 10: Schematic drawing of the antenna region where the electric field is measured. (a) The position with maximum electric field and (b) the geometry of the investigated region and configuration of RF and DC fields.

Several methods have been theoretically benchmarked, most of them based on the Stark effect, which splits and shifts selected wavelengths in the optical spectrum of the plasma (cf. simulation in figure 11): the EFILE [6] uses an external neutral helium beam prepared in a metastable state that is destabilised by being Stark mixed with an unstable state in presence of an external electric field and generates a strong ray at the transition frequency. It can measure small electric fields and is independent of the background plasma but is more sensitive to high frequencies (near the Lamb frequency) and requires an important external hardware. Another possibility is to directly measure the Stark effect on the existing plasma. The difficulty is here to get a good signal to noise ratio to observe the effective shift disturbed by the static magnetic field. But before investing in one of this method, it is necessary to evaluate the noise with a direct measurement. (Zeeman effect) and Doppler effects due to the thermal temperature. Different methods exist to decrease this noise: phase-resolved measurement, Laser Induced Fluorescence, Doppler-free Stark spectroscopy). An electrode has been installed in the plasma source at 5 mm from the metallic back flange and connected to a 20kV max voltage supply. A collimated optical fibres targets outside the source at the gap between the electrodes and connected to a high-resolution spectrometer. The purpose is to validate the stark measurement method and evaluate the factors that can affect the signal to noise ratio: the low pressure ($10^{-3}$ mbar), the disturbance from the plasma source RF field, the static magnetic field, the DC field too strongly shielded by the plasma. The task is to determine which factor dominates and to get rid of it, eventually by using a laser [8, 9, 10].

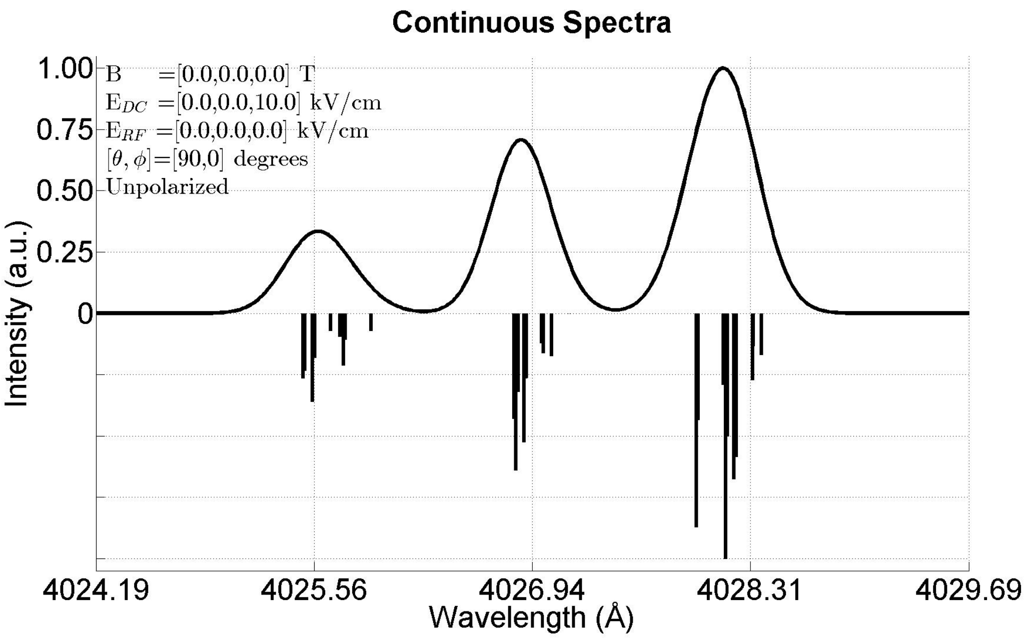


Figure 11: Modification of the spectrum in presence of a DC electric field: (a) numerical model based on ORNL code.

## 5. Conclusion and future plans

IShTAR is operating with plasma conditions representative of the plasma edge and has an operating ICRF system. The main work presently focuses on the objective of measuring the electric field in the sheath with the development of a diagnostic based on the Stark effect. In the meantime also improvements the plasma source are on-going to get more flexibility in the range of densities by using higher power, and to operate with hydrogen plasmas. Modulation capabilities to the RF power will be added in order to carry out measurement during the RF-free phases and remove part of the disturbances. In the next years, the test bed should provide numerical codes the data needed to validate the physical models and numerical codes in the antenna region, and thus help to predict the operations on ITER.

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**References**

[1] R. D'Inca et al, AIP Conf. Proc. 1689, 050010 (2015)
[2] K. Crombe et al, AIP Conf. Proc. 1689, 030006 (2015)
[3] F. F. Chen, Physics of Plasmas (1994-present) 3, 1783–1793 (1996)
[4] E. Faudot et al, Rev. Sci. Instrum. **86**, 063502 (2015)
[5] F. Louche et al, AIP Conf. Proc. 1689, 070016 (2015)
[6] L. Chérigier-Kovacic et al, Review of Scientific Instruments, 86, 063504 (2015)
[7] E. Martin et al, AIP Conf. Proc. 1689, 030011 (2015)
[8] M. Adamov et al, Phys. Rev. A 75, 013409 (2007)
[9] U. Czarnetzk et al, Phys. Rev. Lett. 81, 4592 (1998)
[10] E. R. Tracy, A. J. Brizard, A. S. Richardson, and A. N. Kaufman. "Ray Tracing and Beyond" ed Cambridge University Press 2014