Direct approach to helicon physics and transport phenomena by plasma diagnostics at the Resonant Antenna Ion Device

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Abstract

The **R**esonant **A**ntenna **I**on **D**evice (RAID) [1] is a linear, steady-state plasma device operated at the Swiss Plasma Center. It is dedicated to research on basic helicon physics, tokamak-edge plasma phenomena, and validation of spectroscopic plasma techniques for fusion applications, including state-of-the-art laser spectroscopy measurements.

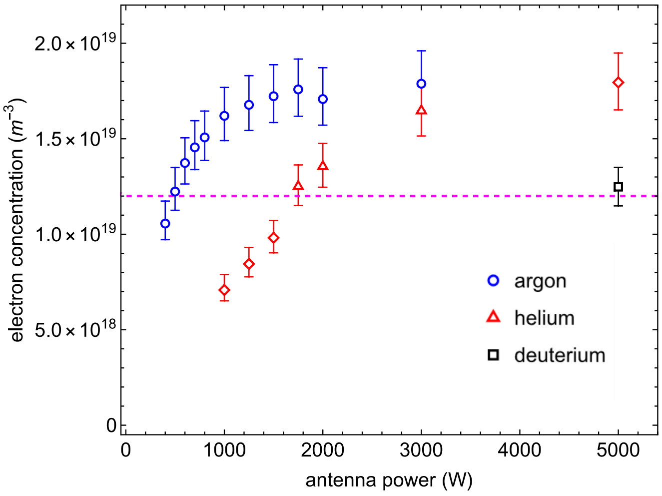

Figure 1. Values of axial peak electron concentrations reached for different types of gas. The magnetic field was set to 650 G and the gas pressure was 0.5 Pa.

Interpretation of experiments conducted on RAID require plasma diagnostics which provides reliable values of electron density ne (~ 10^{18} to few 10^{19} m^{-3}) and electron temperature Te (1 – 10 eV). For this, an incoherent **T**homson **s**cattering (TS) setup has been developed similarly to that of the Advanced WAKEfield Experiment (AWAKE) at CERN [2,3,4]. The TS system provides invaluable data to benchmark diagnostic probes, advance the understanding of helicon wave physics, and to verify collisional radiative models which are also relevant for astrophysical research.

In this work we are showing experimental mappings of the heating of the plasma by helicon waves and its comparison with the result of the reliable simulation. In the presented experiment have reached the same axial electron density (~1.4×10^{19}) for plasma generated in different gases (see **Figure 1**) and we have compared radial scans for those conditions. The goal of such an experiment was to:

- check how the type of gas (including the mass of the ion and the chemistry of the plasma) could imply the helicon wave physics,
- test the reliability of our plasma model involving finite-elements simulation method in the COMSOL® environment.

Introduction to helicon waves

Before considering a more complex physical example of a plasma source, let us examine a simple model for which an analytical solution can be obtained. The fundamental model of the helicon wave has been presented by Chen in 1991 [4]. To follow it, let us take a set of three, linearised equations

$$\nabla \times \vec{E}(\vec{x},t) = -\frac{\partial \vec{B}(\vec{x},t)}{\partial t}, \qquad \nabla \times \vec{B}(\vec{x},t) = \mu_0 \vec{j}\,(\vec{x},t), \qquad \vec{E}(\vec{x},t) = \frac{\vec{j}(\vec{x},t)\times\vec{B}_0}{e\,n_0}, \quad (1)$$

where $\vec{B}_0$ is the constant component of the magnetic field (external magnetic field) parallel to the z axis, and n_0 is the constant, equilibrium electron density. The above equations are, respectively, the Faraday's law, the Ampère – Maxwell law with the displacement current neglected, and the electron fluid equation of motion. The solution of those equations in cylindrical coordinates is

$$\begin{gathered} B_r(r,\theta,z) = \tilde{B}[(\alpha+k)J_{m-1}(Tr) + (\alpha-k)J_{m+1}(Tr)]\cos\Phi, \quad E_r(r,\theta,z) = \frac{\omega}{k}B_\theta \\ (r,\theta,z), B_\theta(r,\theta,z) = \tilde{B}[(\alpha+k)J_{m-1}(Tr) - (\alpha-k)J_{m+1}(Tr)]\sin\Phi, \quad E_\theta(r,\theta,z) = -\frac{\omega}{k}B_r \\ (r,\theta,z), B_z(r,\theta,z) = 2\tilde{B}TJ_m(Tr)\sin\Phi, \quad E_z(r,\theta,z) = 0, \end{gathered} \tag{2}$$

with the phase

$$\Phi = m\theta + kz - \omega t.$$

In the above equations m is some integer, and J_m is the m-th Bessel function of the first kind. The dispersion relation of the resultant wave is given by

$$\alpha = \frac{\omega}{k}\frac{\mu_0\, e\, n_0}{|\vec{B}_0|}, \tag{3}$$

and the transverse wave number T is given by

$$T^2 = \alpha^2 - k^2. \tag{4}$$

The common experimental configuration (insulating or conducting cylindrical tube as a plasma vessel) imposes the boundary condition

$$B_r(r = a, \theta, z) = 0, \tag{5}$$

where a is the radius of the vessel (or radius of the plasma column).

In order to find the full structure of the space of solutions of (1) with the boundary conditionn (5) one needs to solve the system (3,4,5) for given m. That gives an infinite number of solutions $\{T_{m,n}, k_{m,n}, \alpha_{m,n}\}$, where $n = 1,2,3,\ldots$ tells us which zero of the Bessel function has been chosen to satisfy the condition (5). Finally, the chosen solution is enumerated by the azimuthal mode number m and by the radial mode numbner n. The **Figure 2** illustrates the mode structure of the full solution of (1) in terms of the electric field distribution.

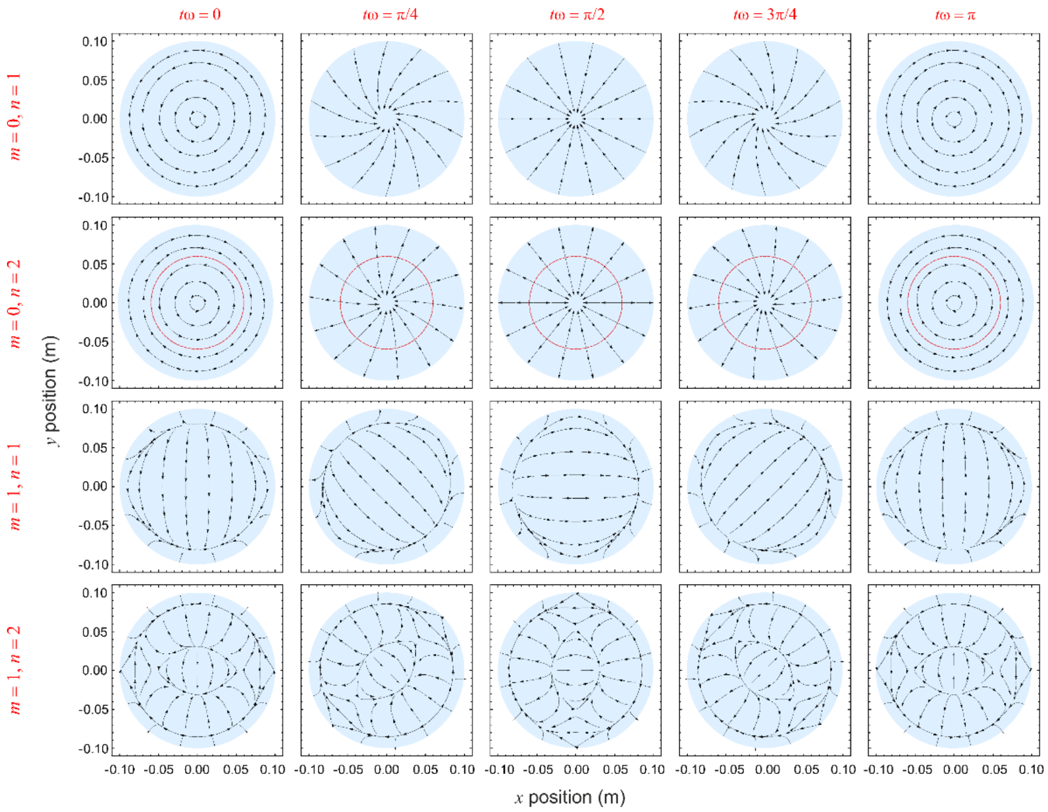

Figure 2. Mode structure of helicon waves.

There are two mechanisms of helicon waves dumping:

- colisional damping,
- Landau damping.

Full description of the wave structure with the description of the damping mechanism should give the answer for the question where the wave energy is deposited in the plasma source. In general, such a description for realistic experimental conditions (non-uniform n_0, non-trivial shape of the antenna, finite length of the vessel, etc.) is very complex, and has to be solved numerically.

The experiment

In order to measure the effect of helicon wave physics we involved the incoherent Thomson scattering method. It gave us radial distributions of electron density and its temperature within the plasma column. To do this we used pulsed, nanosecond Nd:YAG laser with the second harmonic generator. The laser beam has been focused on the axis of the plasma column using long focal length lens. The scattered light has been collected using an imaging lens system and analized using the prism spectrometer equipped with the ICCD camera. The example of the registered spectrum is shown in the **Figure 3**.

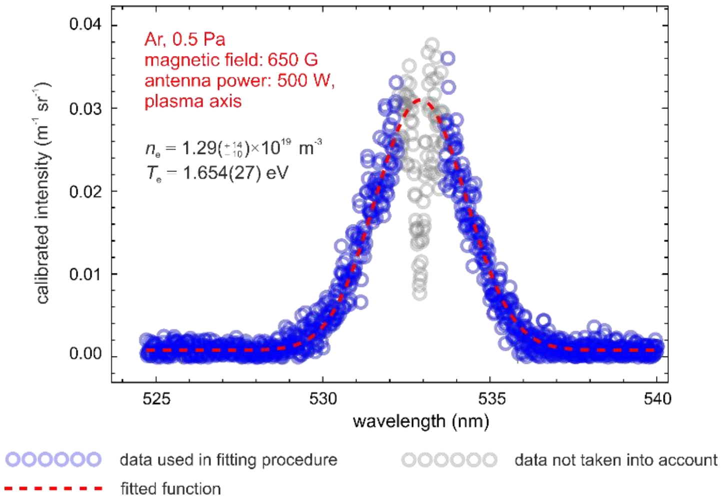

Figure 3. An example of the experimental spectrum.

Results

The resultant plasma profiles has been comapred with simulations of the plasma column made by **Philippe Guittienne** in the COMSOL® environment. Those are first-principles simulations. Namely, both Maxwell equations and transport phenomena were taken into account to obtain a self-consistent solution. In the **Figure 4** you could see example of the 2D map of electron temperature and electron density for argon plasma produced in 0.5 Pa gas, with 650 G magnetic field and 500 W of the birdcage antenna. In the **Figure 5** you could see comparison of 1D plasma profiles originating from the simulation (red line) and from the experiment (blue circles).

Conclusion

The crucial features of the experimental plasma column have been reproduced in the simulations. The hot, so-called “blue core” of the plasma column, has been observed for argon and helium plasma. The existence of the core is believed to be a sign of helicon wave heating of the plasma. Differences between electron density and its temperature obtained for different gases could be reproduced by the simulation.

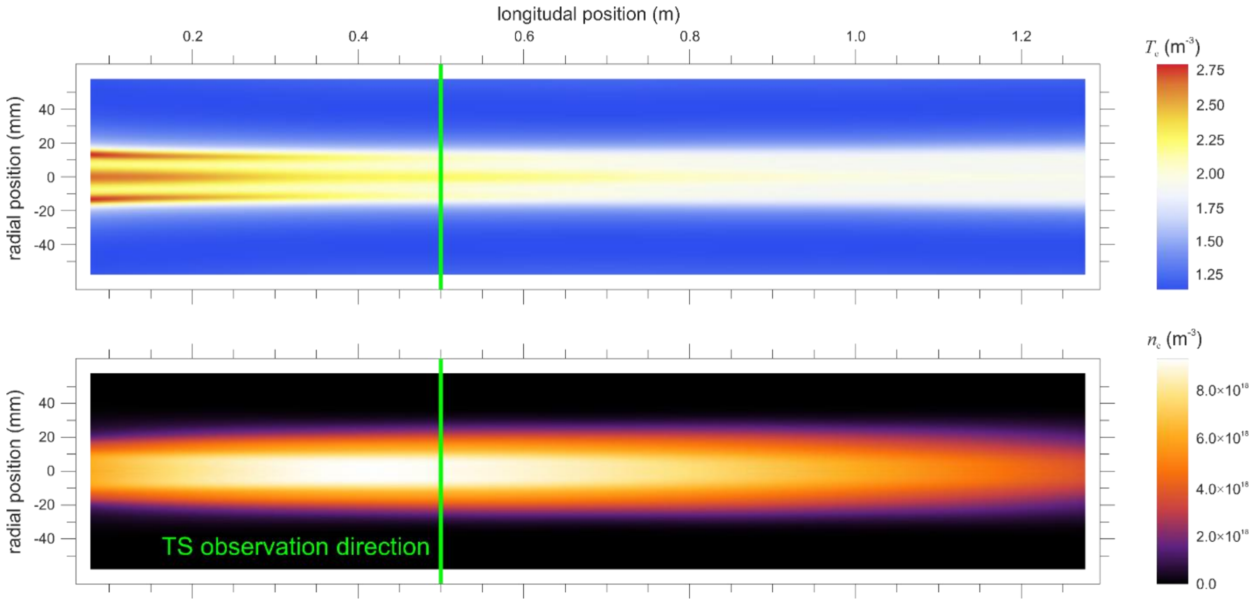

Figure 4. Simulated plasma 2D maps.

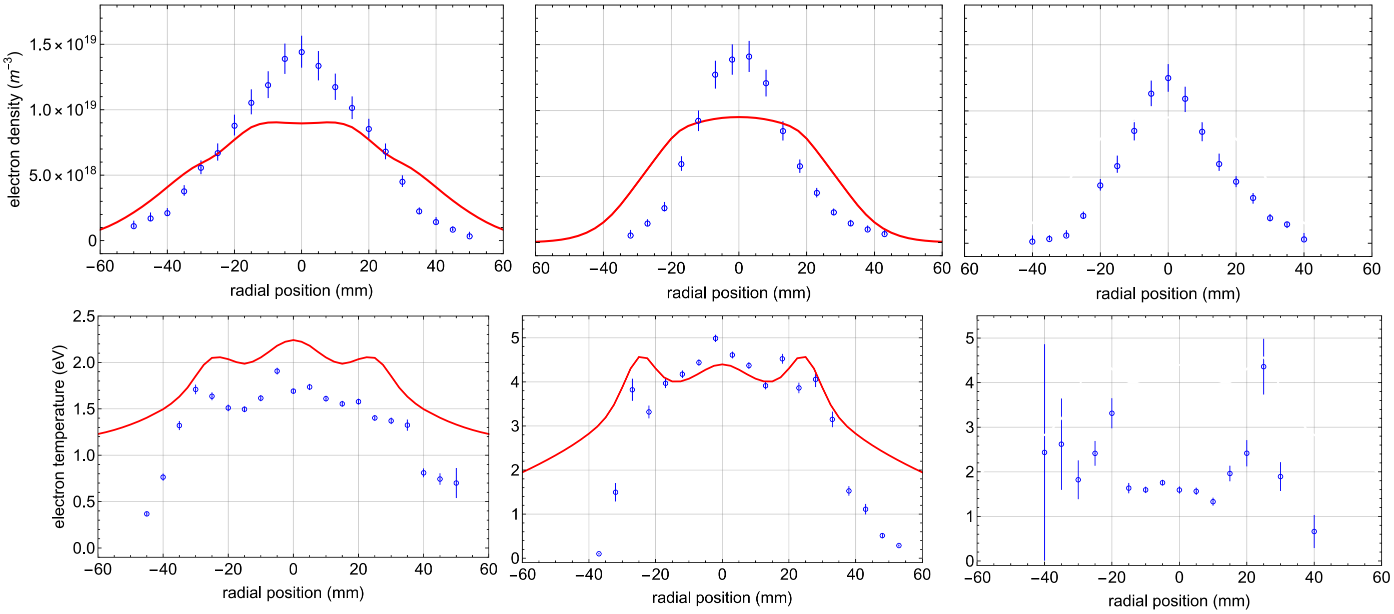

Figure 5. Comparison of experimental and simulated plasma profiles. The first column represents argon, the second helium, and the last one hydrogen.

References

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