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

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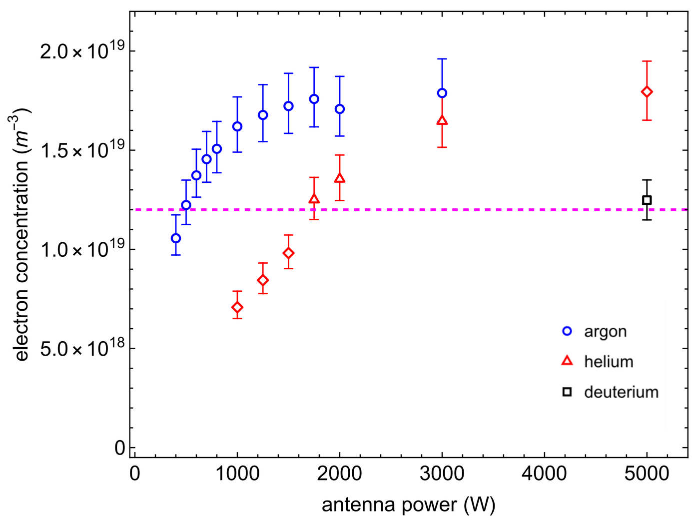
Abstract

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.

Interpretation of experiments conducted on RAID require plasma diagnostics which provides reliable values of electron density n_e (~ 10^{18} to few 10^{19} m^{-3}) and electron temperature T_e (1 – 10 eV). For this, an incoherent **T**homson **s**cattering (TS) setup has been developed similarly to that of the **A**dvanced **WAK**efield **E**xperiment (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 presenterd experiment have reached the same axial electron density (~1.4×10^{19}) for plasma generated in different gases (see **figure**) and we have compared radial scans for those conditions.

Introduction to helicon waves

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

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

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

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

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 cylidrical tube as a plasma vessel) imposes the bondaury condition

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

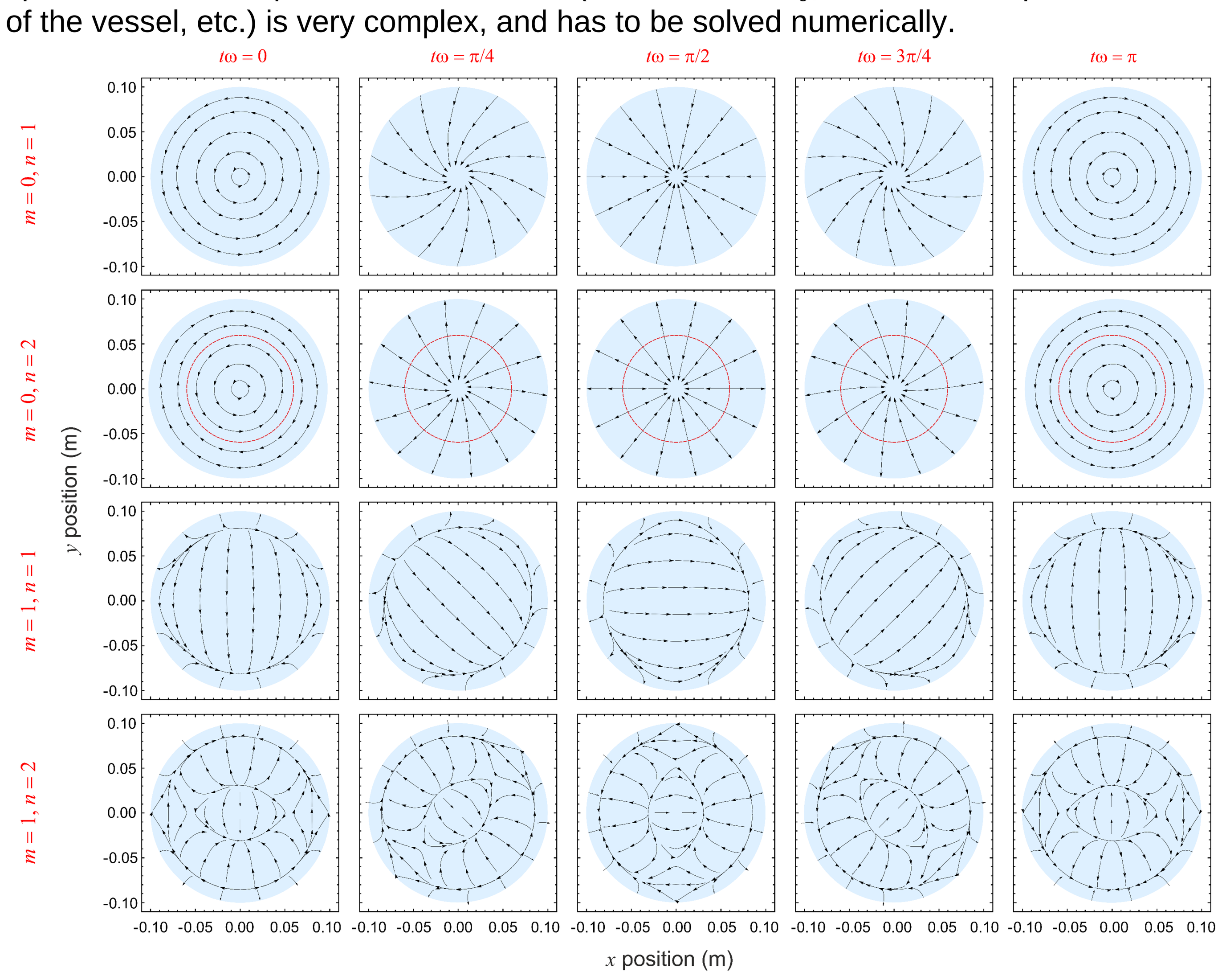
where a is the radius of the vessel (or radius of the plasma column).

In order to find the full structure of the space of solutions of (1) with the boundary condition (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 $n = 1,2,3,\dots$ tells us which zero of the Bessel functrion 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 below** illustrates the mode structure of the full solution of (1) in terms of the electric field distribution.

There are two mechanisms of helicon waves dumping:

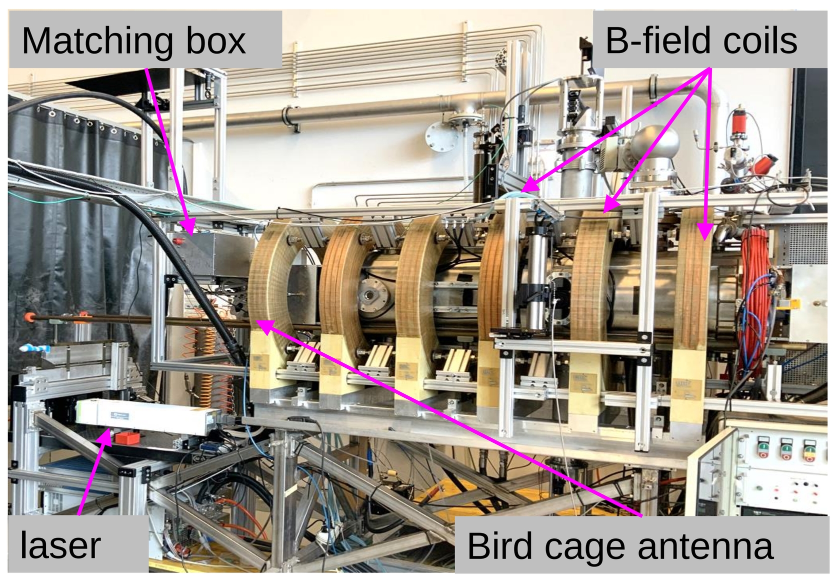
- collisional damping,
- Landau damping.

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



Lines of the electric field corresponding to (n, m) modes of the helicon wave given by the formula (2).
The picture is generated for the cylindrical plasma of the radius 10 cm, electron density 10^{19} m^{-3},
RF frequency 13.56 MHz, and a constant magnetic field 500 G.

RAID



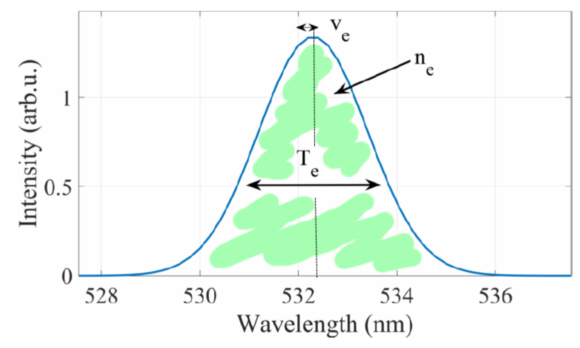
Typical RAID parameters

Vessel $_{radius}$	0.2 m
Plasma length	1.8 m
Magnetic field	0.01 – 0.1 T
Gas pressure	0.15 – 1.5 Pa
RF frequency	13.56 MHz
RF power	0.7 – 3 kW
Density n_e	(1–30)×10^{18} m^{-3}
Temperature T_e	< 1 – 10 eV

RAID enables **steady state operation** by **efficient helicon wave excitation** and plasma generation in **noble gases** by specially designed **birdcage antennas** [1,3]. The RAID device is equipped with an extensive set of plasma diagnostics, which provide high precision and accuracy (gigahertz interferometry), high spatial resolution (Thomson scattering), and the ability to cover the entire volume of the plasma column (movable Langmuir probes). These diagnostics thus allow precise and reliable mappings of plasma parameters, which are fundamental for research on transport phenomena and helicon physics.

Incoherent Thomson Scattering

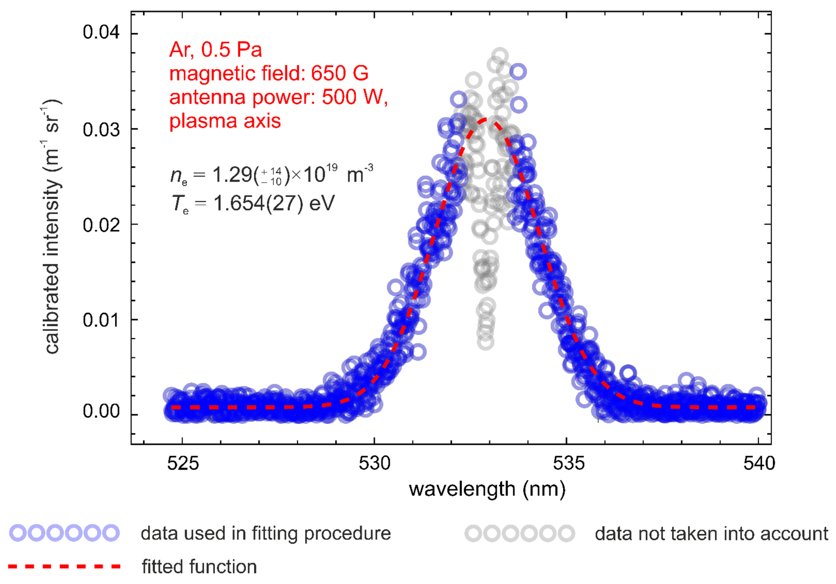
Elastic scattering of light from free electrons with wavelength shift due to Doppler effect

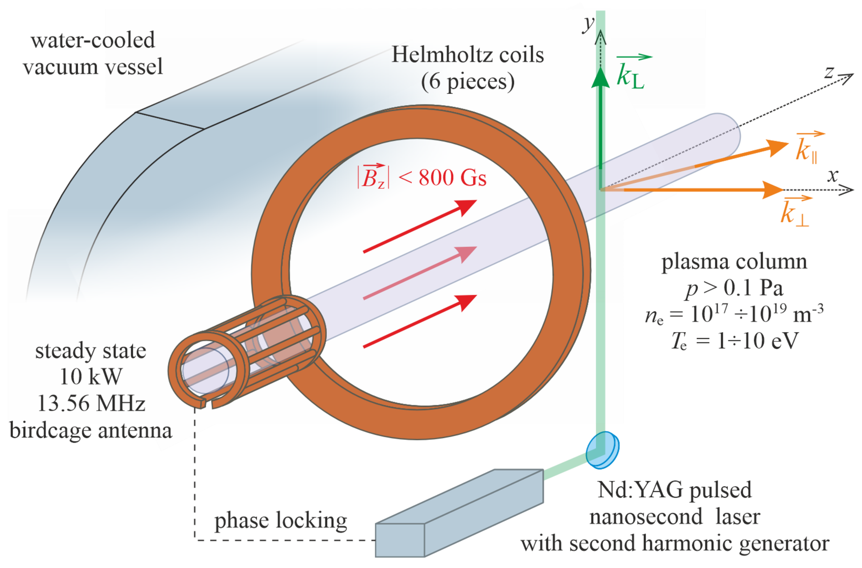


$$\frac{dI_s}{d\Omega d\omega_s} = n_e\,L\,I_i\,\frac{d\sigma_{TS}}{d\Omega}(\vec{e}_s)\,S_k(\omega_s)$$

$$S_k(\omega_s) \propto \exp\left(-\frac{m_e\left(\omega_i-\omega_s-kv_{e,drift}\right)^2}{k_B T_e\,\omega_i^2}\right)$$

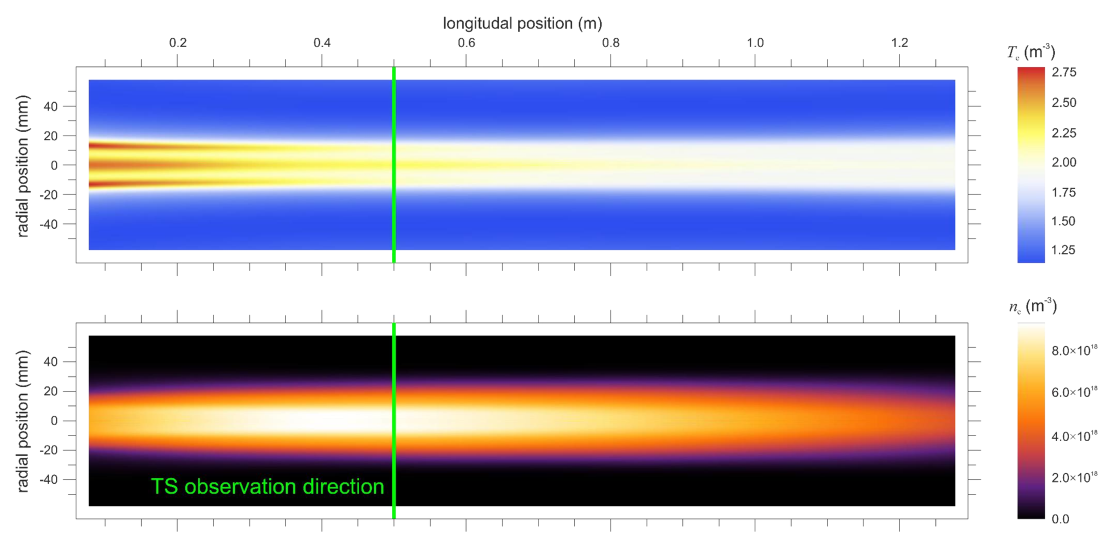
I_s: scattered intensity
I_i: incident intensity
L: interaction length
σ_{TS}: TS cross section
S_k: spectral formfactor

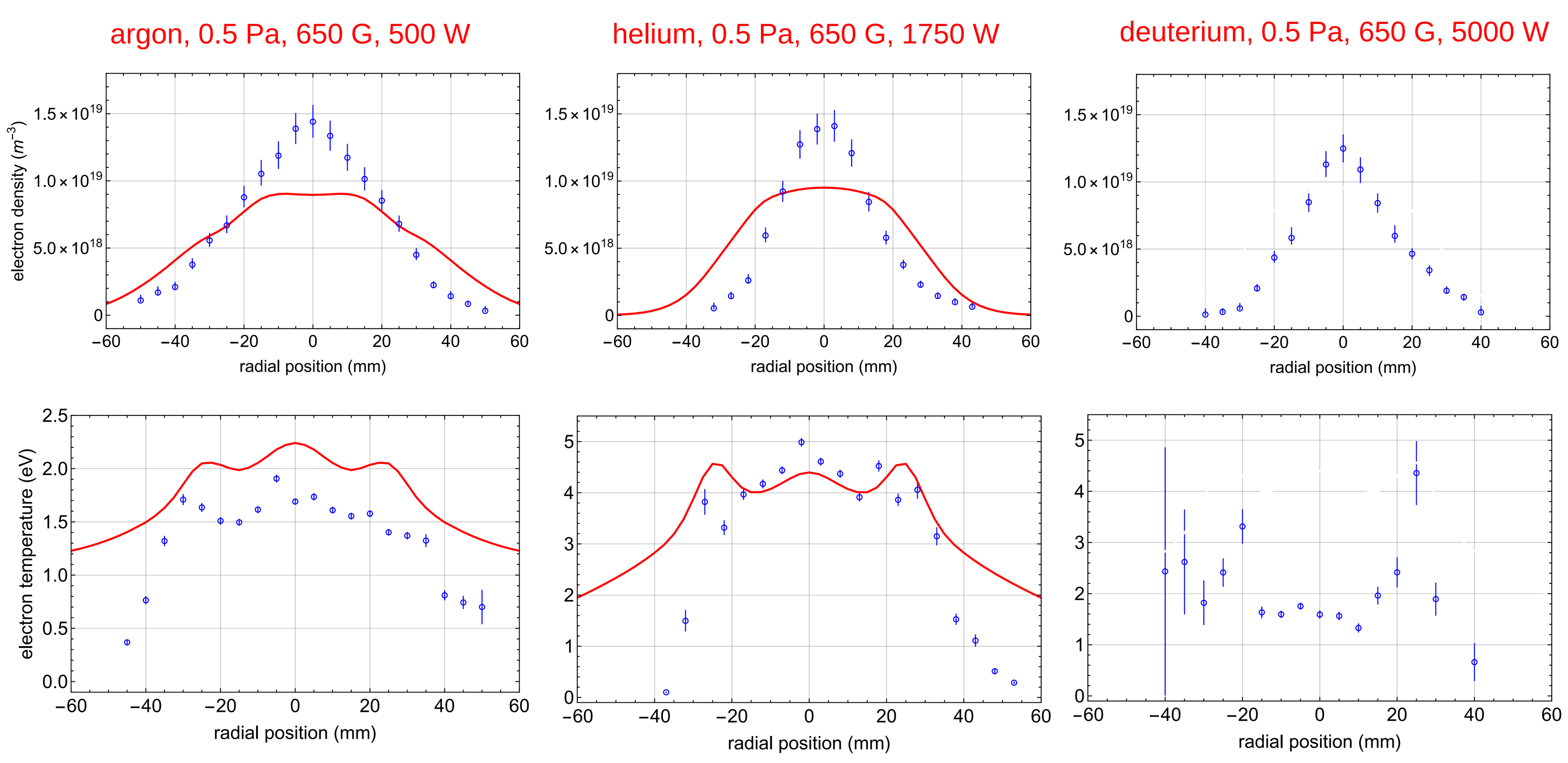




Comparison of experimental and simulated profiles

Simulations of the plasma column made by **Philippe Guittienne** in the COMSOL® environement. Thes are first-principles simulations. Namely, both Maxwell equations and transport phenomena were taken into account to obtain a self-consistent solution.
In the **top figure** 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 **bottom figures** 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 colum, has been observed for argon and helium plasma. The existence of the core is belived 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.

References

[1] P. Guittienne, A. Howling, I. Furno, Resonant Network Antennas, IOP Publishing, 2024.
[2] I. Furno et al., EPJ Web Conf., **157** (2017) 03014.
[3] C. Stollberg, et al., Plasma Phys. Control. Fusion, **66** (2024) 115011.
[4] C. Stollberg, et al., Rev. Sci. Instrum., **97** (2026) 063501.
[5] F.F. Chen, Plasma Phys. Control. Fusion, **33** (1991) 339-364.

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Swiss Plasma Center

EUROfusion

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