

Experimental studies of plasma production and transport mechanisms in the toroidal device TORPEX

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Introduction

Magnetised laboratory plasmas generated by microwaves (μw) in the electron cyclotron (EC) frequency range represent an interesting tool for investigating instabilities and related phenomena of relevance to fusion, such as turbulence-induced transport. A good knowledge of the mechanisms regulating the background plasma profiles is required to understand the contribution of the turbulent transport to the total particle and energy flux. Results from experiments on plasma production and particle transport in a simple magnetised plasma are presented here. The processes leading to ionisation of the neutral gas are investigated in order to characterise the spatial profile of the particle source using techniques based on the modulation of the μw power. These techniques are then applied to study the particle transport and estimate the transport coefficients. Finally, a comparison with measurements of the turbulence-induced flux is presented.

Experimental setup

The experiments are performed in TORPEX, a toroidal device with major and minor radius of 1 and 0.2m. The helical magnetic field results from a toroidal component $< 100\text{mT}$ and a vertical component $\sim 1\text{mT}$. Plasmas are produced from Hydrogen and Argon by waves at 2.45GHz, in the EC range. Up to 20kW of power is injected from the low field side and can be modulated at frequencies $\leq 120\text{kHz}$. Typical densities, temperatures and plasma potentials, measured by electrostatic Langmuir probes, are $n \sim 10^{17}\text{m}^{-3}$, $T_e \sim 5\text{eV}$ and $V_{pl} \leq 20\text{V}$.

Ionisation processes and particle source profile

The ionisation of the neutral gas occurs by impact of electrons with energies higher than the ionisation potential, W_{iz} . Firstly, a contribution to the particle source comes from the electrons in the tail of the thermal distribution, $S_{th}(\mathbf{x}) = n_g n(\mathbf{x}) \langle \sigma_{iz}(v) v \rangle_{T_e}$, where n_g is the neutral density, $\sigma_{iz}(v)$ the velocity-dependent ionisation cross-section, and the average is calculated assuming the local values of T_e . S_{th} can directly be estimated from the experimental profiles of n and T_e . Second, electrons can be accelerated to energies larger than W_{iz} by interacting with the injected waves at the EC and upper-hybrid (UH) resonant layers. The nature of the interaction is different for the two cases [1]. At the EC layer there are no fluid resonances

and a kinetic model must be used to describe the resonant particle acceleration. At the UH layer, where the waves encounter a fluid plasma resonance, the enhanced wave electric field can also lead to significant particle acceleration. The total particle source term can be written as $S(\mathbf{x}) = S_{th}(\mathbf{x}) + S_{ec}(\mathbf{x}) + S_{uh}(\mathbf{x})$. The profile $S_{ec}(\mathbf{x})$ and $S_{uh}(\mathbf{x})$ can be inferred from experiments with modulation of the injected power. An example is shown in Fig. 1 for a Hydrogen plasma. Here the μw power is modulated with square pulses between two values, $P_{abs} = 0.2\text{kW}$ and 1.8kW , and the density variation following an increase of the absorbed power is derived from the ion saturation current measured by Langmuir probes across the poloidal section.

Fig. 1 also highlights the strong coupling between the density and the power, due to the dependence of the UH resonance on n . More quantitative information on the value of $S_{ec}(\mathbf{x})$ and $S_{uh}(\mathbf{x})$ can be obtained from the dependence of the total number of plasma particles upon the injected μw power (Fig. 2), from which the two contributions can be separated on the basis of a phenomenological model [2]. Once the source term is reconstructed, it can be modelled by a convenient analytical formula and used as input for numerical simulations of plasma turbulence in specific experimental situations.

Transport mechanisms

Two mechanisms are mainly responsible for the transport of particles, diffusion and convection, quantified by the coefficients D and V . The values of D and V can be estimated by interpreting with a convenient transport model the measured density response to a sinusoidal perturbation of the injected power [3]. Let us assume that D is uniform across the profile, that $\nabla \cdot V = 0$ and that the plasma response is dominated by a single time constant, τ . In the 1-D case along the generic coordinate x , the continuity equation for the perturbed density n_1 , externally induced by the modulation of the μw power, is then $\partial n_1 / \partial t = -n_1 / \tau + S_1(x, t)$, and $n_1 \ll n_0$ (n_0 is the

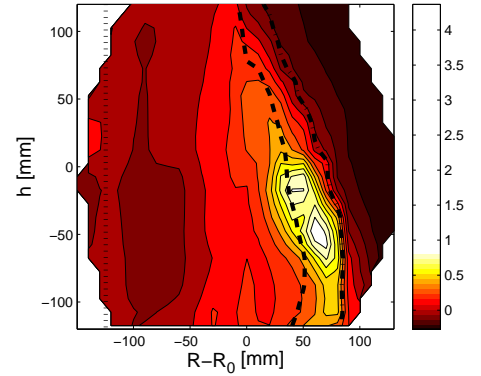


Figure 1: *Relative density variation following a pulse of the injected power. Lines indicate the position of the EC (dot) and UH (dash: before pulse, dot-dash: end of the pulse) layers.*

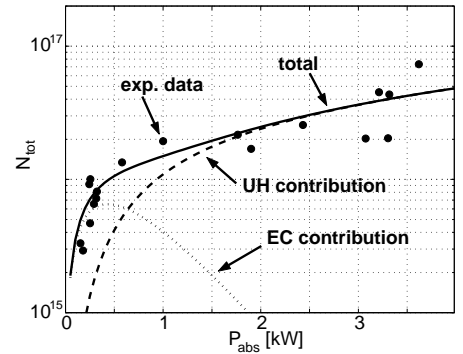


Figure 2: *Dots: total number of plasma particles Vs absorbed power. Lines are a fit to determine the contributions to $S(\mathbf{x})$ from electrons accelerated at the EC and UH layers.*

unperturbed density). In Fourier space we obtain for the amplitude and the phase of n_1 :

$$|n_{1,\omega}| = \frac{|S_{1,\omega}|}{\omega_0} \frac{1}{\sqrt{1 + \omega^2/\omega_0^2}}, \quad \angle n_{1,\omega} = \arctan\left(\frac{\omega}{\omega_0}\right) \quad (1)$$

Assuming that for small perturbations the same time-constant τ characterises the dynamics of both the perturbed and stationary profiles, we have for the unperturbed density:

$$\omega_0 = \frac{1}{\tau} \doteq - \left(\frac{D}{n_0} \frac{\partial^2 n_0}{\partial x^2} - \frac{V}{n_0} \frac{\partial n_0}{\partial x} \right) \quad (2)$$

From Eqs. 1 the complex transfer function between the injected power and the density, T , can be derived and used to fit the experimental data to obtain ω_0 , as shown in Fig. 3. The density response is measured at the EC resonant layer. The injected power is 1 kW, with a sinusoidal modulation with peak-to-peak amplitude ≤ 0.1 kW. The measured transfer function is compatible with a single time constant at frequencies < 30 kHz, but other poles (visible in $\angle n_{1,\omega}$) appear at higher frequencies. These poles are not taken into account in the model, and the data at high frequencies are excluded from the fit.

If the unperturbed density profile is known, from Eq. 2 one obtains a value for D and V , by setting $V = 0$ and $D = 0$, respectively. They are therefore upper limits, also considering the 1-D assumption made in the model. Results for different vertical positions are shown in Fig. 4. Excluding the region $h < -75$ mm, the estimated values are $D_{max} \approx 15$ m²/s and $V_{max} \approx 400$ m/s. The maximum convective velocity is in the range of the ExB plasma velocity, $v_{ExB} \leq 1.5 \cdot 10^3$ m/s, evaluated from the background profiles of T_e and floating potential. The simple model represented by Eqs. 1 does not fit all the data well (cf. Fig. 4, region $h < -75$ mm). One of the weakest points is

the 1-D nature of the model, inappropriate to describe correctly the plasma dynamics in regions where the profiles are intrinsically 2-D. The model will be extended to the general 2-D case in order to include all the regions in the analysis. Moreover, there are regions where poles at

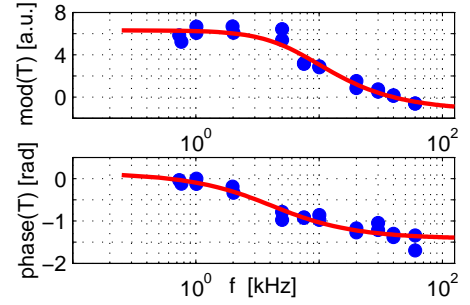


Figure 3: Dots: measured amplitude and phase of T from ion saturation current measurements Vs frequency. Solid line: fit based on a single time constant response model.

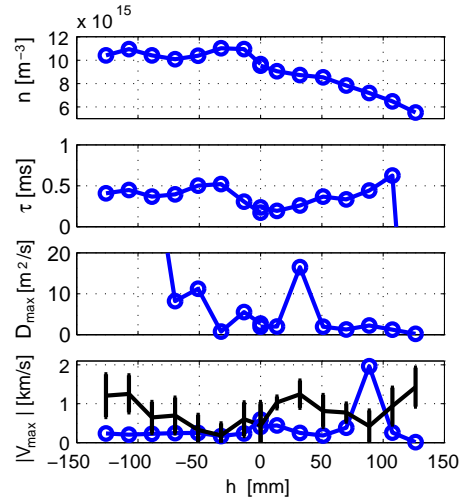


Figure 4: Values of n , τ , D_{max} and V_{max} Vs vertical position. The convective velocity V_{max} (blue line) is compared with the plasma ExB velocity (black line).

$\approx 30\text{kHz}$ dominate the behaviour of the transfer function. This may be due to the dependence of the ion saturation current upon parameters such as V_{pl} and T_e , which might change on relatively fast time-scales during the modulation of the μw power.

Fluctuation-induced particle flux

Instabilities leading to correlated fluctuations of density and electric fields induce a turbulent particle flux, Γ_{turb} . Experimentally, Γ_{turb} can be estimated from measurements of density and floating potential fluctuations made with Langmuir probes, in the approximation $\tilde{E} \propto (\tilde{V}_{fl,1} - \tilde{V}_{fl,2})$ [4]. The time-averaged flux can then be compared with the measured total particle flux. An example is shown in Fig. 5 where the flux evaluated from modulation experiments is compared with Γ_{turb} measured with a three-tip Langmuir probe. Here the total flux is obtained from D_{max} and V_{max} . A more rigorous procedure would involve the integration of Eq. 2, giving $\nabla \cdot \Gamma$. The turbulent flux is separated into two contributions, depending on the frequency range over which it is integrated.

Usually, most of the coherent spectral features are observed below 10kHz [5]. Note that, due to its geometry, the probe used here is only sensitive to the flux directed along the major radius, while the flux from modulation experiments is in principle integrated over all directions. It can be seen that the turbulence-induced flux is smaller than the derived total flux, except close to the edge where the two values are in qualitative agreement. More quantitative conclusions will only be possible once the experimental reconstruction of the plasma response and the transport model used to interpret it will be extended to the 2-D case.

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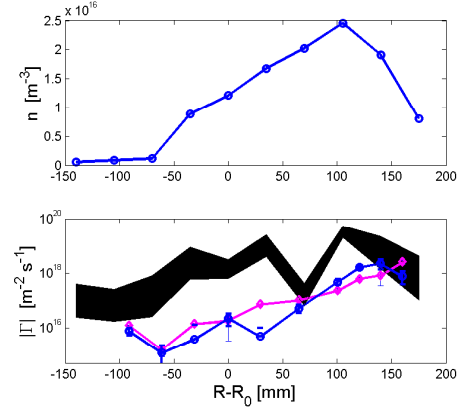


Figure 5: *Top: density radial profile. Bottom: flux Γ from modulation experiments (dark region between maximum and minimum values estimated from D_{max} and V_{max}), and from direct measurements of the turbulent flux integrated below (diamonds) and above (circles) 10kHz.*