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A note on the radial extent of LH wave – tokamak SOL interaction

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1 Introduction

The lower hybrid antenna (grill) electric field has been previously shown to interact with the tokamak scrape-off (SOL) plasma by means of electron Landau damping **[1,2].** The electron acceleration associated with the power absorption results in high power-flows along magnetic field lines, causing possible damage to tokamak vessel components. It is therefore of practical importance to understand the radial extent of the fast electron population. The present understanding of the tokamak edge LH power absorption is based on the antenna calculations of Jacquet et al **[3],** which self-consistently include the LH-generated hot electrons, and on electron Landau damping results from 2-D simulations of Rantamäki et al. **[4]**. Both these studies **[3,4]** give a radial interaction zone of the order of a few millimeters adjacent to the grill mouth. However, recent results from retarding field analyzer (RFA) measurements on Tore Supra **[5],** as well as infrared measurements from JET **[6],** have indicated the existence of fast electrons as far as a few centimeters from the grill mouth.

The observed fast electrons causing hot spots can be divided into two distinct classes **[4]**. To the first class belong fast electrons generated very near the grill, characterized by electric probe signals, which persist for the duration of LH power. The second class of electrons causing spots on target components further away from the grill mouth - of the order of cm - exhibit temporal intermittency at a rate comparable with the detachment rate of relatively hot and dense plasma “blobs” from the main body of the plasma.

The blobs, driven by the interchange instability **[7,8],** are detached from the last closed flux surface (LCFS) around mid-plane from the low field side of the torus and are observed, in experiment **[7]** as well as in simulations **[8],** to move toward the plasma edge, maintaining a radial extent of typically 1-2 cm. As the blob spreads out along B-field lines, its temperature and density gradually decreases. This decrease is however slower than the temperature and density decrease of the background plasma into which the blob propagates. This essentially leaves a tenuous and relatively cold SOL between blob events. If under such circumstances the background density exceeds the slow wave critical coupling value ($n_e \geq 1.7 \times 10^{17}$ m^{-3} for f_{LH}=3.7 GHz), the wave will propagate and experience very weak damping. It is only when the wave encounters a relatively dense and hot incoming blob, that the damping becomes appreciable. We henceforth refer to a SOL with blobs as “turbulent”. In contrast, we refer to the assumed steady-state situation of Refs **[3,4]** as “quiescent”.

The relevant time scales of the “turbulent” situation are as follows. The blob detachment frequency is typically of the order of 10 kHz, while its lifetime is of order tens of μs. In contrast, the quasi-linear scale time for establishment of the fast electron distribution function is of the order of μs, so that the distribution function with its attributes are formed almost immediately on the "blob" time scale.

We aim here to explain the observed substantial width of the LH-generated fast electron beam on the basis of electron Landau damping in a turbulent SOL with blobs. An alternative non-linear route to explaining fast electrons further away form the grill mouth is being undertaken by Petržílka **[9].**

2 Electron Landau damping of grill spectrum in the SOL

Two important factors influence the spectrum damping. First, the generated hot electron population itself modifies the damping, especially in the lower-$n_{//}$ spectrum range. Second, the high-$n_{//}$ components are progressively removed from the spectrum as the wave propagates inwards. It is therefore essential to find a self-consistent state by iterating between the distribution function, which depends on the acting electric field and the damping, which depends on the electron distribution.

We first consider electron Landau damping occurring in quiescent SOL plasma, described by measured time-averaged plasma profiles from Tore Supra shot #39547:

$$n_e(r) \cong 13\exp[-0.25(6-r)], \quad T_e(r) \cong 45\exp[-0.19(6-r)] \qquad (1)$$

These profiles can be thought of as time averages of the fluctuations associated with the intermittent (≈10 kHz) entry of blobs from the LCFS into the SOL.

We determine the electron distribution function at selected radial positions by PIC-type test electron simulations **[10],** using an electric field determined from the ALOHA coupling code **[11]** for the Tore Supra C2 multi-junction antenna at nominal power density 25 MW/m^2. The resulting fast electron concentrations and temperatures used in the slow wave dispersion relation are given in Table I. Iterations towards a self-consistent solution are carried out as follows. We first calculate the effect of Landau damping on the $E_z(z,r)$ field in the cold background without the fast electron contribution, i.e. we determine the wavenumber $k_\perp(n_{//})$ in the range: $n_{//} \leq |180|$ imposed by the grill. We then calculate the distribution function from a test electron simulation, find Maxwellian fits, solve the dispersion relation, recalculate the electric field and repeat the procedure. To deal with modification of the electric field we introduce a low-pass filter $F(n_{//}, r) = \exp[-r/d_\perp(n_{//})\,]$ at a given position r **[12]**. The electric field $E_z(z,r)$ then applied in a test electron simulation is the inverse Fourier transform of $E_z(n_{//},r)\ F(r,n_{//})$.

Table I Background temperature T_e and density n_e, and fast electron T_h and η_h from test electron simulations, at selected radial positions in the inhomogeneous plasma of Eq. (1). The blob temperature and density in the" turbulent" case is assumed to follow T_e and n_e. S^+ is the fast electron powerflow in the direction of the plasma current.

	Quiescent SOL				**Turbulent SOL**		
r [cm]	**T_e [eV]**	**n_e [10^{17} m^{-3}]**	**T_h[eV]**	**η_h**	**T_h[eV]**	**η_h**	**S^+[MW/m^2]**
0.0	**15.0**	**3.00**	**900**	**0.06**	**1900**	**0.016**	**10**
0.10	**15.2**	**3.12**	**750**	**0.06**	**1800**	**0.014**	**6.0**
1.0	**17.4**	**3.72**	**100**	**0.17**	**1250**	**0.006**	**2.6**
2.0	**21.0**	**4.78**	**90**	**0.25**	**1250**	**0.0016**	**0.9**
3.0	**25.5**	**6.14**	**90**	**0.29**	**1250**	**0.001**	**0.7**
4.0	**30.8**	**7.88**	**90**	**0.35**	**1250**	**0.001**	**0.9**
5.0	**37.2**	**10,12**	**90**	**0.37**	**1250**	**0.0017**	**2.1**
6.0	**45.0**	**13.0**	**90**	**0.45**	**1250**	**0.0025**	**4.6**

Of interest is the radial damping rate $Im[k_\perp(n_{//})]$ and its inverse $d_\perp(n_{//})=1/Im[k_\perp(n_{//})]$, the slow wave radial e-folding penetration depth required to reduce the power by about 90%. In a homogeneous plasma, the penetration depth is $d_\perp(n_{//})=1/Im[k_\perp(n_{//})]$, but in a inhomogeneous plasma a different expression is required. At the Tore Supra plasma edge WKB we obtain **[12]**:

$$d_\perp(n_{//}) = r_{max}, \quad \text{if} \int_0^{r_{max}} Im[k_\perp(n_{//},\rho)]\,d\rho = 1 \quad \text{for} \quad r_{max} < r_{LCFS} \qquad (2)$$

$$\text{and} \quad d_\perp(n_{//}) \cong r_{LCFS}/\delta, \quad \text{if} \int_0^{r_{LCFS}} Im[k_\perp(n_{//},\rho)]\,d\rho = \delta < 1 \qquad (3)$$

Data from both the quiescent and turbulent Tore Supra SOL situations are given in **Table I**, with the corresponding penetration depths $d_\perp(n_{//})$ shown in **Fig. 1.** The converged quiescent result of **Fig. 1a** indicates a penetration depth, i.e. a power absorption width, of about 5mm, much less than the observed width of at least 4 cm **[5]**, but in agreement with conclusions of earlier studies.

We now therefore turn to the “turbulent” situation. As pointed out before, there are brief periods between “blob” events when the wave can propagate with little damping so that most of the lower-$n_{//}$ spectrum components can easily access the LCFS. As it does, it will intercept a blob and damp. This is represented in **Fig. 1b,** where penetration depths $d_\perp(n_{//})$ for various blob positions are given.

3 Conclusions

We have outlined a computational procedure for a self-consistent model of lower hybrid power deposition in the tokamak SOL and shown that the interchange instability in Tore Supra allows LH power deposition all the way at least to the LCFS. In contrast, with a quiescent, time-averaged plasma profile such as in Eq. 1, power deposition widths of order 5 mm are obtained, in agreement with earlier results **[3,4]**.

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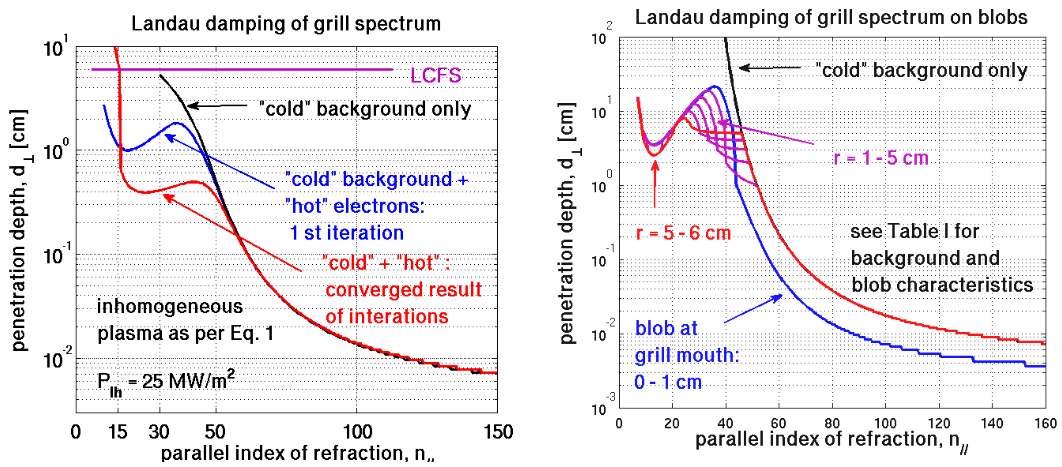

Fig. 1 Grill spectrum penetration depth $d_\perp(n_{//})$ from Eqs. (2,3). a) "Quiescent" inhomogeneous Tore Supra plasma of Eq. 1. b) "Turbulent" Tore Supra plasma with blobs driven by the interchange instability. A break in $d_\perp$ is evident at a blob position. Maxwellian fits to the corresponding distributions are characterised by the concentrations η_h and temperatures T_h of Table I.