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Measurement of lower hybrid hot spots using a retarding field analyzer in Tore Supra

J.P. Gunn [a,*], V. Petržílka [b], A. Ekedahl [a], V. Fuchs [b], E. Gauthier [a], M. Goniche [a]
M. Kočan [a], J.-Y. Pascal [a], F. Saint-Laurent [a]

[a] CEA, IRFM, F-13108 Saint-Paul-Lez-Durance, France
[b] Association EURATOM-CR, Za Slovankou 3, 18200 Praha 8, Czech Republic

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ABSTRACT

A retarding field analyzer was used to provide direct measurements of the particle and power fluxes of suprathermal electrons in hot spots that are magnetically connected to the region in front of the waveguides of a lower hybrid antenna in Tore Supra. Hot spots can be divided into two regions according to the temporal evolution of the local suprathermal electron flux. Adjacent to each waveguide row is a layer of strong, dc current on which is superimposed strong fluctuations. Deeper into the plasma a second type of electron flux is identified: highly intermittent (∼10 kHz) bursts separated by brief periods of zero flux. Electron bursts occur at least up to 40–50 mm in front of the grill mouth. These observations contradict the standard theory that predicts that hot spots should be at most ∼5 mm wide.

1. Introduction

In magnetic flux tubes passing just in front of the waveguides of lower hybrid (LH) antennas, a few percent of the launched LH wave power is absorbed by the scrape-off layer (SOL) plasma [1]. The strike points of these flux tubes sometimes fall into the field of view of cameras dedicated to the observation of plasma-facing components. Evidence of intense plasma-wall interaction is seen in visible and infra-red wavelengths, and local wall damage can occur. The parallel power flux within these "hot spots" is estimated to be up to several tens of MW/m^2 by infra-red imagery [2], but no information concerning the current density or energy of the particles can be obtained. According to theory [3], Landau damping transfers the power carried by the high refractive indices $n_{//}$ of the wave to thermal SOL electrons with energies of a few tens of eV and accelerates them up to a few keV. The high $n_{//}$ spectral components are expected to be absorbed immediately in front of the LH grill within a few mm [4]. Combined Langmuir and emissive probe measurements in front of a low power LH grill in the CASTOR tokamak demonstrated large sheath potentials in a thin layer, which, although indirect, could be consistent with the existence of suprathermal electrons [5].

We report here on the first direct measurements of the full two-dimensional spatial distribution of suprathermal electron flux in the LH hot spots using a retarding field analyzer (RFA). The design of the Tore Supra RFA [6] is based on one that was used in the JET tokamak [7]. The RFA is mounted on a vertically reciprocating probe drive, situated on top of the torus. The analyzer is biased to collect only suprathermal electrons with energy greater than (eU_{se} + 200 eV) (Fig. 1). In thermal plasmas the potential drop between the sheath edge and the slit plate U_{se} measured with respect to machine ground can be obtained from the ion current characteristic, but the ion current is swamped by the suprathermal electron current in the hot spots, so we have no reliable estimate of this quantity. In order to calibrate the particle and power fluxes carried by suprathermal electrons, we estimate the total transmission coefficient of the RFA $\xi = 0.36$ as the product of the optical transmission factors of the slit and the grids. The width and length of the slit are $W = 30$ μm and $L = 5$ mm.

The RFA was in a vertical port at toroidal angle $\varphi = 40°$. The LH launcher (referred to as "C2") was in a horizontal port at $\varphi = 320°$. The nominal radial position of the leading edge of its lateral protection limiter was $R_{C2} = 3.138$ m at the midplane. A full mapping of the suprathermal electron current was measured by varying the plasma current from $I_p = 0.72$ to 1.18 MA over 20 probe reciprocations on shots 39 547, 39 548, and 39 551. The other main plasma parameters (major radius $R_0 = 2.38$ m, minor radius $a = 0.72$ m, line-integrated density $\bar{n}_e = 3.5 \times 10^{19}$ m^{-2}, LH power $P_{C2} = 1.5$ MW) were held constant. All four waveguide rows were active. A Langmuir probe in another vertical port at $\varphi = 160°$ measured SOL profiles simultaneously on field lines that were not connected to the antenna. The SOL density was observed to be $5 \pm 1 \times 10^{17}$ m^{-3} at the antenna's radial position.

The mapping was calculated by integrating the field line equations in the positive toroidal direction from each point along

* Corresponding author.
E-mail address: Jamie.Gunn@cea.fr (J.P. Gunn).

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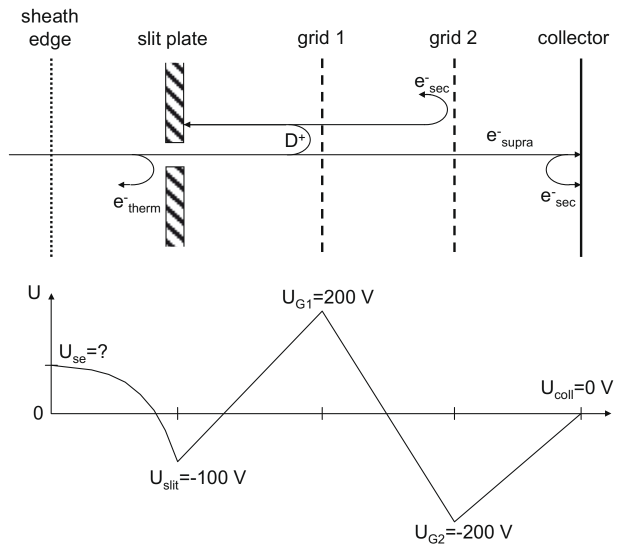

Fig. 1. Schematic of the RFA with applied voltages. Thermal electrons are repelled by the slit plate before entering the cavity. Thermal ions are repelled by grid 1. Only electrons with kinetic energy greater than $-e(U_{se}+U_{G2})$ attain the collector. Grid 2, to which is applied the most negative voltage, also serves to suppress currents of secondary electrons.

the probe trajectory to the poloidal plane that intersects the left-hand edge of the grill as viewed from outside the tokamak (Fig. 2(a)). At each point where the RFA measured electron current more negative than $-100\ \mu A$, a dot was placed on the map (Fig. 2(b)). A hot spot is seen in front of each waveguide row. The leading edges of the hot spots describe an arc that has exactly the poloidal curvature of the lateral limiters, but shifted radially inward by ~1.5 cm. The measurement of the launcher position lacks precision due to deformation of the flange under vacuum, dilation of the antenna under baking at 120 °C, and hysterisis of the sliding contacts. A recent mechanical study of the system concluded that an uncertainty of 1–1.5 cm on the nominal launcher position is to be expected [8].

The suprathermal electron current measured on reciprocation #16 ($q_a = 6.49$) is shown in Fig. 3. Zero collector current is measured when the RFA is behind the leading edge of the lateral limiter (gray shaded region in Fig. 3) indicating that the applied grid volt-

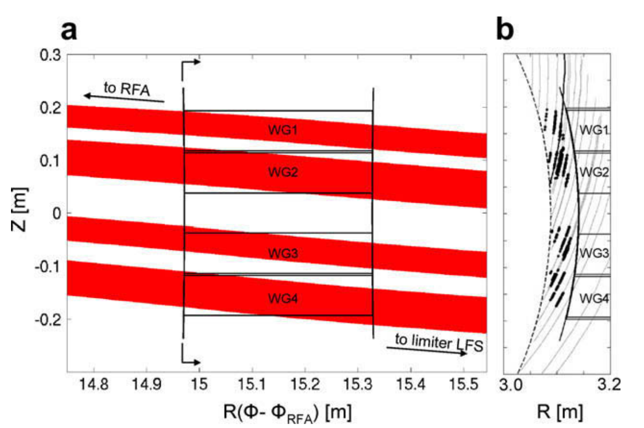

Fig. 2. (a) LH antenna viewed from outside the machine looking inward along the major radius. Shaded regions indicate magnetic flux tubes in which suprathermal electrons are detected by the RFA. The four waveguide rows are labeled WG1–WG4 from top to bottom. (b) Poloidal plane through the left-hand edge of the antenna. The RFA trajectories mapped from the top of the machine are indicated by the thin gray curves, except for the sixteenth reciprocation (thick black curve) for which the raw data are displayed in Fig. 3. Black dots indicate positions at which electron current more negative than $-100\ \mu A$ was detected. The dashed curve is the LCFS.

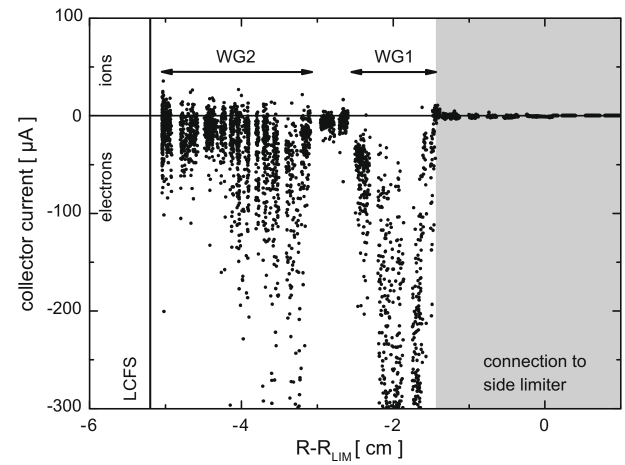

Fig. 3. Current measured by the collector versus midplane major radius relative to the leading edge of the LH antenna side limiter. Electron current is detected when the RFA is magnetically connected to waveguide rows WG1 or WG2 as indicated. The range of radial positions for which we believe the RFA to be connected to the side limiter of the LH antenna is coloured grey.

ages are sufficient to fully repel all thermal ions and electrons. There is an abrupt transition to intense suprathermal electron current when the RFA begins to intercept field lines connected to the volume in front of WG1. The sharpness of the transition is consistent with the idea that the electrons are accelerated only on field lines that pass in front of the waveguides, and that they undergo no measurable radial spreading during their 15 m flight to the RFA. Near the grill the signal presents strong fluctuations superimposed upon a dc component. The electron current is sometimes strong enough to saturate the analog-to-digital convertors at $-300\ \mu A$, therefore the flux exceeds $5500\ A/m^2$ and the maximum instantaneous power flux carried by the electrons is at least $(5500\ A/m^2)(200\ V) = 1.1\ MW/m^2$. The true value could be much higher because the electron energy is expected to be as high as a few keV according to theory, and the sheath potential drop, which the electrons must overcome in addition to U_{G2}, is not measured.

Due to magnetic shear, the orientation of the mapped RFA trajectory in the *R-Z* plane is more poloidal than radial. After the first intense layer of electron current, a thin region is observed between WG1 and WG2 where again there is nearly zero signal. Then the RFA connects to the volume in front of WG2. Here, the RFA is already 1.5 cm radially in front of the grill. According to theory, within the first few millimetres, the high $n_{//}$ component of the LH wave should be fully absorbed by Landau damping on the cool SOL electrons. No electron acceleration should occur at these radial positions. It is thus remarkable that strong electron current is observed even at the deepest point of the reciprocation, 3.5 cm in front of the grill, at the LCFS.

The temporal character of the electron current varies radially. To qualify the nature of the signal we take a sample of measurements within a small radial range and calculate its mean $\bar{I}_e$ and its most probable value I_e^{MP}. We equate I_e^{MP} with the dc component. When $\bar{I}_e \approx I_e^{MP}$, the electron current is defined to be "steady" (although fluctuating strongly around the mean). When the distribution of current is strongly skewed towards negative values such that $I_e^{MP}/\bar{I}_e \ll 1$ the signal is defined to be "bursty". The characteristic repetition rate of the bursts is of the order of 10 kHz. It is interesting to note that this is consistent with the observed frequency range of natural SOL density fluctuations [9].

The measurements were shifted vertically to overlay the data and get a composite mapping of a single waveguide row with better spatial resolution (Fig. 4(a)). Two principal regions are identified based on the temporal behaviour of the electron current. We

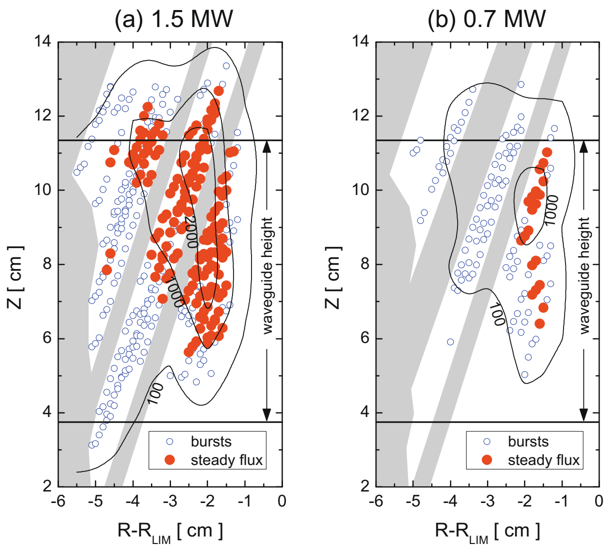

Fig. 4. Composite mapping of the flux of electrons with parallel energy greater than 200 eV for LH power (a) 1.5 MW and (b) 0.7 MW. Radial distance is measured with respect to the leading edge of the antenna's electron-side limiter. All data are shifted vertically to lie in front of the second waveguide row WG2. The horizontal black lines indicate the top and bottom walls of the waveguides. Areas where no data were measured are coloured grey. Full and open circles represent respectively points where the time-averaged electron current was more negative than −50 μA or where 10% of the electron bursts were more negative than −20 μA. Approximate contours of time-averaged electron current density (A/m^2) are shown.

refer to the layer of steady electron current adjacent to the leading edge of the side limiter as the "near field beam". It is defined to encompass all points where $\bar{I}_e < -50$ μA (full circles in Fig. 4). The height of the layer is about the same as that of the waveguide rows (7.6 cm), but it is poloidally asymmetric, about 1 cm radial width across the bottom, and 3–4 cm across the top. Each hot spot is shifted upward ~1 cm with respect to the corresponding waveguide row, consistent with the tilt of the magnetic field lines (Fig. 2(a)).

Further away from the grill, we call the region of isolated intermittent bursts without a significant dc component the "far field beam". We define a point in space as belonging to the far field beam if 10% of the most negative current values are lower than −20 μA. Bursts are observed even at the deepest points of the probe reciprocations on the LCFS, so we do not know how far in front of the LH grill they occur.

Interpolating the mean electron current density $\bar{J}_e = \bar{I}_e/(LW\xi)$ onto a regular grid and integrating over the composite hot spot we obtain 3.4 A, the total current of suprathermal electrons having parallel energy greater than 200 eV. This value underestimates the true value because the slit transmission coefficient is overestimated, the RFA did not go deep enough to fully map out the hot spots, and the electron current in the near field beam saturated the measuring circuit. Multiplying by 8 (assuming that the same current flows in both directions along the field lines from each of the four waveguide rows), we obtain a minimum estimate of the total LH power lost to the SOL electrons: $P_{LOSS} > 5.4$ kW, or 0.35% of the total injected power. The true value could be several times higher, as explained above. Preliminary measurements of the full energy distribution at a fixed point in a hot spot have been carried out by varying U_{G2} down to −1000 V. These results will be presented in future work, but we can already report that despite visible attenuation of the electron flux at the most negative applied voltage, significant currents are still observed in both near field and far field beams, implying that a fraction of the electrons have energies greater than 1000 eV. Finally, it must be noted that the electrons measured by the RFA are accelerated on field lines that pass in front of the antenna side limiters. There is additional power lost in the private flux region between the two limiters, adjacent to the grill mouth. The grill is about 1–3 mm behind the leading edges of the side limiters, depending on the local toroidal field ripple for a given antenna position. Hot spots connected to each waveguide row are systematically recorded by infra-red imagery. The power loss responsible for these hot spots was estimated to be in the range of 1–2% depending on plasma conditions [2]. We conclude that the power losses in the SOL are of similar magnitude as those in the private flux region of the grill.

The mapping was repeated with the antenna firing half as much power (Fig. 4(b)). The SOL density only decreased by 10–20% on unconnected field lines. Both the near and far field beams are strongly reduced in size. The beam retains its poloidally asymmetric shape; the most intense current is displaced upwards with respect to the center of the profile for both power levels. The total current in the beam is 0.8 A, roughly four times less than for full power. The LH power loss fraction appears to have a strong nonlinear dependence on the injected power. These measurements corroborate past findings [1].

2. Conclusion

A retarding field analyzer was used during LH current drive experiments to provide direct measurements of the particle and power fluxes of suprathermal electrons emanating from the region in front of the LH grill. When one of the active wave-guide rows is magnetically connected to the RFA, a strong particle flux due to suprathermal electrons is observed. A fraction of the electrons have energies greater than 1000 eV. Estimates of the power flux carried by the electrons onto hot spots are consistent with past infra-red measurements [2]. A hot spot can be broadly divided into two regions according to the temporal evolution of the local suprathermal electron flux. Adjacent to each waveguide row is a layer of strong, dc current on which is superimposed strong fluctuations. This layer is poloidally asymmetric at high power densities: around 5–10 mm radial thickness at the bottom of the waveguide row, and around 20–30 mm thick at the top (for 1.5 MW injected power). Deeper into the plasma a second type of electron flux is identified: highly intermittent bursts of electron flux separated by brief periods of zero flux. The typical burst rate is in the 10 kHz range, a frequency that is reminiscient of natural density fluctuations in the SOL. Electron bursts occur at least up to 40–50 mm in front of the grill mouth, even at the LCFS. It is not known how deep into the plasma they might be observed because the reciprocation depth of the RFA is limited to the LCFS. These observations cannot be explained by the standard theory of parasitic absorption [3] that predicts that waves with high refractive index should be totally absorbed within at most 5 mm from the grill [4], and that the electron current should be stationary in time.

Acknowledgement

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References

[1] J. Mailloux et al., J. Nucl. Mater. 241–243 (1997) 745.
[2] M. Goniche et al., Nucl. Fusion 38 (1998) 919.
[3] V. Fuchs et al., Phys. Plasmas 3 (1996) 4023.
[4] K. Rantamäki et al., Nucl. Fusion 40 (2000) 1477.
[5] F. Žáček, V. Petržílka, M. Goniche, Plasma Phys. Contr. Fusion 47 (2005) L17.
[6] M. Kocan et al., Rev. Sci. Instrum. 79 (2008) 073502.
[7] H.Y. Guo et al., Contribution Plasma Phys. 36 (1996) 81.
[8] E. Delmas, Private Communication, 2007.
[9] P.C. Stangeby, The Plasma Boundary of Magnetic Fusion Devices, vol. 369, Institute of Physics Publishing, Bristol and Philadelphia, 2000.