ELSEVIER

Journal of Nuclear Materials 241-243 (1997) 857-860

journal of nuclear materials

Effects of an RF limiter on TEXTOR's edge plasmas

J.A. Boedo [a,*], T. Shoji [a,b], Y. Sakawa [a,b], D.S. Gray [a], J.G. Schwelberger [a], R.W. Conn [a], K.H. Finken [a,c], G. Mank [a,c], N. Noda [a], TEXTOR team [a]

[a] *UCSD, Fusion Research Program, San Diego, USA*
[b] *Department of Energy Engineering and Science, Nagoya University, Nagoya, Japan*
[c] *KFA-IPP, Juelich, Germany*

Abstract

Studies directed towards the reduction of particle and heat fluxes to plasma facing components by the application of ponderomotive forces generated by radio frequency (RF) are being conducted in TEXTOR. A modified poloidal limiter is used as an antenna with up to 3 kW of RF power; the data obtained show that the plasma is repelled by the RF ponderomotive potential. The density is reduced by a factor of 2–4 and the radial decay length is substantially altered. The density near the limiter decays exponentially with RF power. The electron temperature profile changes, with the decay length becoming longer (almost flat) during the RF. The temperature in the scrape off layer (SOL) increases and its increase is roughly proportional to the RF power until it saturates, suggesting that the heating efficiency drops with power, and that improved performance is to be expected at higher powers.

Keywords: TEXTOR; Tokamak; Limiter

1. Introduction

Experiments using a limiter as an RF antenna have been performed in the TEXTOR tokamak. The RF current along the magnetic field produces an evanescent RF field near the limiter if the frequency and antenna size is properly chosen and this near field wave creates a ponderomotive potential barrier. For values of the potential of the order or above the electron temperature kT_e, the electron flux to the limiter is suppressed and the resulting ambipolar potential also suppresses the ion flux. The objective of the experiments is to use the ponderomotive force exerted by the RF field to:

(1) Modify the particle fluxes and decay lengths in the plasma edge and SOL.

(2) Reduce the heat load on the limiter.

Proof of principle experiments were successfully performed in the PiSCES facility [3] and later in JIPP-TIIU [4] and the CHS stellarator [5] which showed that with a modest amount of RF power, the recycling and heat flux at the limiter are reduced and that a dc potential forms around the limiter as expected in order to reduce the ion and electron fluxes.

The ponderomotive potential Ψ_{RF} [1,2] can be written as a function of the parallel E_{par} and perpendicular E_{perp} electric fields, the particle mass m, the RF frequency ω and the cyclotron frequency ω_c as:

$$\Psi_{RF} = \frac{1}{4m}\frac{e^2E_{perp}^2}{\omega^2-\omega_c^2} + \frac{1}{4m}\frac{e^2E_{par}^2}{\omega^2}. \quad (1)$$

Notice that the second term in Eq. (1) is larger for the electrons than for the ions due to the m as dependence and is the dominant term as long as $\omega \neq \omega_c$ so that the first term is small, this is the term used to produce the ponderomotive potential. The frequency and size of the antenna-limiter have to be chosen carefully to assure that the fast wave is evanescent and does not propagate in the plasma. The power transmitted to the plasma by the RF field E_{RF} can be written in terms of the electron–ion collision rate ν_{ei} and local electron density n as:

$$P_{abs} = n\frac{e^2E_{RF}^2}{m_e}\frac{\nu_{ei}}{\omega^2+\nu_{ei}^2} \approx n\frac{e^2E_{RF}^2}{m_e}\frac{\nu_{ei}}{\omega^2}; \quad \nu_{ei} \ll \omega. \quad (2)$$

* Corresponding author. Tel.: +49-2461 613 554; fax: +49-2461 613 331; e-mail: j.boedo@kfa-juelich.de

PII S0022-3115(96)00620-4

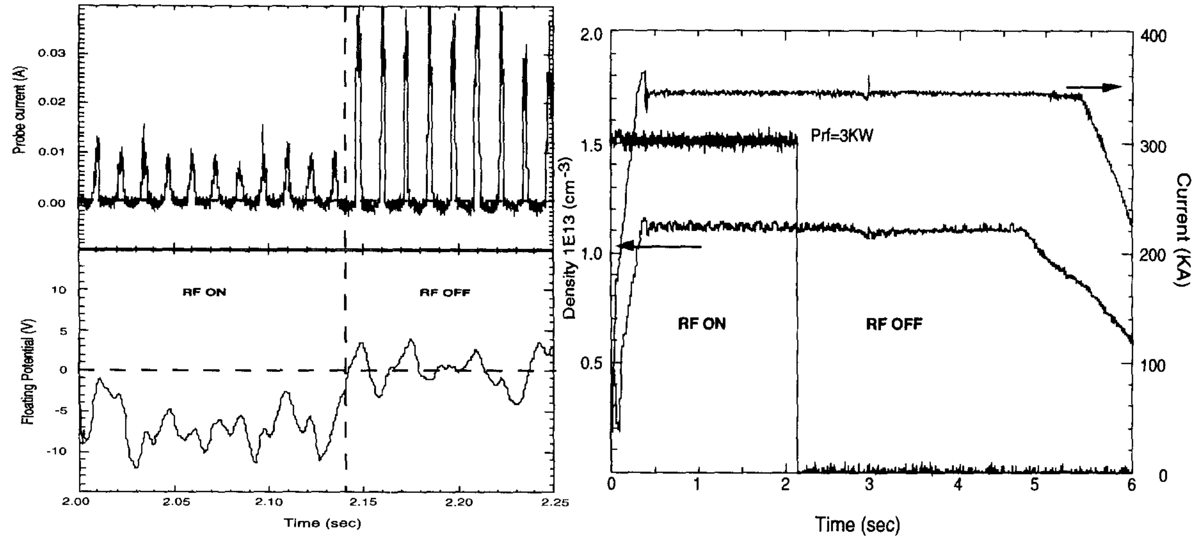

Fig. 1. Traces showing a TEXTOR shot and probe data. The 3 kW RF pulse is applied until 2.2 s. The changes in floating potential and probe characteristic are clearly observed around the turn-off time (2.2 s).

Notice that in our case the RF frequency (13.56 MHz) is much higher than the electron–ion collision frequency. This expression indicates that the heating will depend on the local density squared (since ν_{ei} is a function of n as well) and is a weaker function of temperature.

2. Experimental setup and diagnostics

The experiments were performed in Ohmic (OH) discharges in TEXTOR, which is a medium size tokamak with major radius $R = 1.75$ m, and minor radius $a = 0.46$ m. In the first experiments, RF power levels of 2–3 kW at 13.56 MHz were used (toroidal field $B_t = 2.25$ T, plasma current $I_p = 350$ kA, line averaged density $N_e = 1-3 \times 10^{13}$ cm^{-3}), the RF pulse was started briefly before the discharge and lasted until about 2 s as shown on Fig. 1; the limiter was upgraded later by changing the geometry in order to increase the RF current density at the upper and lower leading edges and the frequency changed to 8 MHz. The data shown here is for a floating, non-upgraded limiter as is shown in Fig. 2.

The limiter was instrumented with two scannable probes located about 3.3 cm above and below of the limiter as seen on Fig. 2; one of the probes consists of 5 tips which are operated as a swept probe for T_e and N_e measurements, an ion saturation probe and two floating potential probes. The second probe contains two loops to detect magnetic fluxes and is located at the bottom of the limiter.

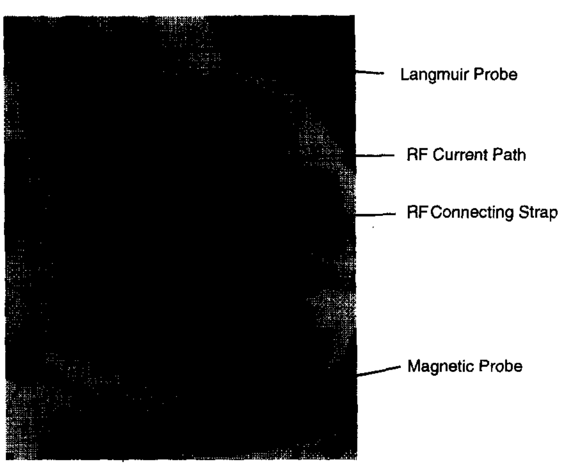

Fig. 2. The RF limiter head is shown after the upgrade to force higher current densities at the top and bottom of the limiter following the marked paths. The scannable probes can be also seen.

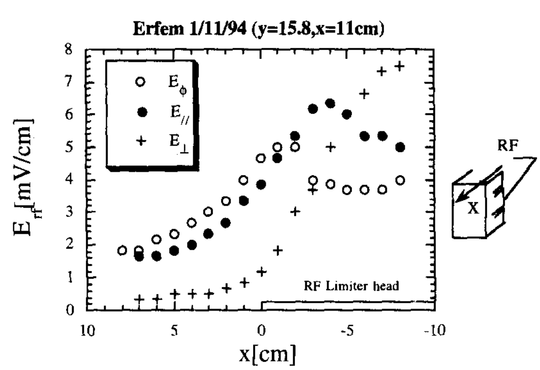

Fig. 3. Mapping of the various RF fields as a function of distance at the position of the probes, in vacuum.

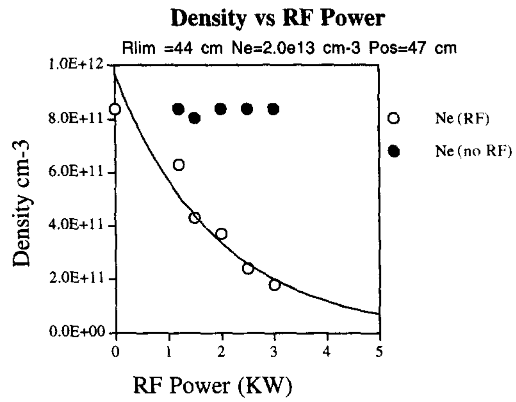

Fig. 4. The density in the vicinity of the limiter (3.3 cm above) as a function of power during the rf pulse (empty points) and after the rf pulse (filled points). The value of the rf potential can be extracted from these data.

Most of the data presented here was obtained with the probes during and after the RF pulse, so that the comparison is done on a same-shot basis as shown in Fig. 1; the current–voltage (I–V) characteristic from the single probe was deformed due to the RF field, but a brief analysis [6] shows that the temperatures and densities measured by the probe should be correct if only the data near the floating potential (V_f) is used. The characteristics were acquired over 20 ms each and then averaged over 1 s. and therefore the errors are low and of the order of 15%. The local value of T_e in the deep SOL is large and the cause is unknown, perhaps large stray fields.

3. Results

The ion saturation current at the probe decreases a factor of 40% with RF power (at 3 kW), suggesting that the local density and/or temperature are reduced in the neighborhood of the limiter, further analysis of the data shows it to be dominated by a local density decrease of a factor of 2–4 over the surface of the limiter despite of an increase in electron temperature, showing the effects of the ponderomotive potential. The local density has an exponential dependence on the RF power as shown on Fig. 4 (as expected form ambipolarity) and given by:

$$n_e = n_{e0} e^{-0.28 P_{RF}} \ (\mathrm{cm}^{-3});$$
$$\text{with } n_{e0} = 9.7 \times 10^{11} \ \mathrm{cm}^{-3};$$
$$P_{RF} \text{ in kW.} \qquad (3)$$

This dependence, which should be in agreement with Boltzmann's relation, implies $\Psi_{RF} = \Phi = 0.28 P_{RF} kT_e$ (where Φ_p is the plasma potential) and allows us to immediately calculate Ψ_{RF} if we know Φ_p, P_{RF} and T_e and also suggests that the RF heating given by Eq. (2) will be reduced significantly at higher powers due to its dependence on n_e^2. According to our measurements, we find Ψ_{RF} to be about 19 V at 1.5 kW and $N_e = 2.0 \times 10^{13}$ cm^{-3} which compares to the engineering value of about 5 V expected using the calibration fields shown on Fig. 3.

The electrons are heated by the RF field to about 1.5–2 times their temperature over a significant volume around the limiter as suggested by the very long decay length for the T_e profile (Fig. 5), the dependence of the electron temperature on the RF power is shown on Fig. 6 and can be fitted within the range of interest by the function:

$$T_e = -0.645 P_{RF}^2 + 3.83 P_{RF} + 4.1 \ (\mathrm{eV}); \quad P_{RF} \text{ in kW.} \qquad (4)$$

The temperatures increase with RF power and seem to saturate at high RF powers; the increase is more pronounced for higher densities and the saturation occurs later than for lower densities as shown in Fig. 6, suggesting a heating and/or dissipating mechanism which is dependent

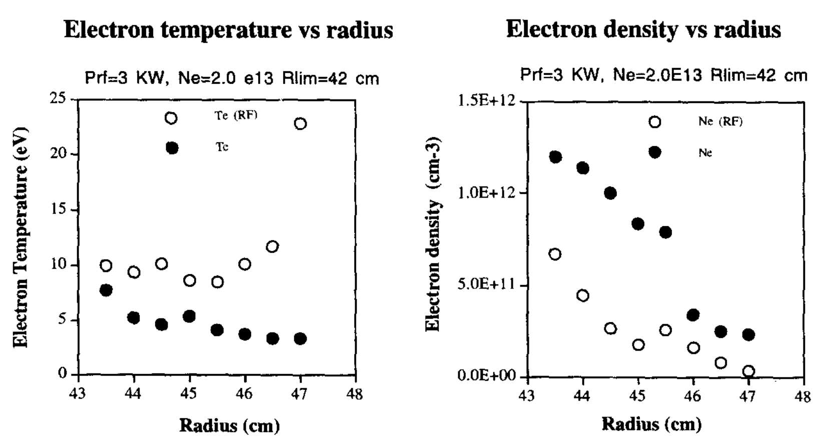

Fig. 5. Profiles of temperature and density with and without RF. The RF limiter face is at 42 cm. The profiles are altered over a large extent of the limiter face and the heating is higher for lower densities. The errors in the measurements are below 15%.

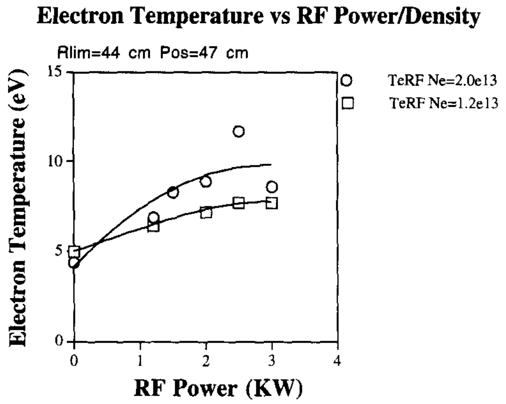

Fig. 6. Dependence of the electron temperature on RF power and density. The heating mechanism is more efficient at higher densities.

on local density. Possible mechanisms are sheath heating or direct RF heating as given in Eq. (2), which is density dependent and predicts losses of roughly 70 W for $N_e = 2 \times 10^{13}$ cm^{-3} at 3 kW, which are consistent (within the uncertainties on the volume heated of a factor of 2–4) with an RF power balance showing 95% of the injected power being dissipated on the limiter head and the rest (150 W at 3 kW injected RF power) disappearing into the plasma. This RF power is negligible compared with the plasma power convected/conducted to the limiter (200 kW) and should be dissipated by conduction or convection to the limiter in such a way that allows for the observed local plasma heating, yet detailed power balance, which depends on the 3D structure of the fields and plasma parameters, which are unknown, is outside the scope of this paper.

The floating potential measured at the probe (on top) is lowered by the RF field, yet the plasma potential, estimated by adding $3.5T_e$ actually increases, the increase is linear with RF power and consistent with the formation of a potential barrier for the ions, this barrier is at the probe location of the order of $1.5-2T_e$. The limiter dc potential is reduced by the applied RF, so it would be beneficial to ground the limiter in future experiments. Note that the measured potentials are of the order of 5–19 V where as those calculated from the engineering estimates are about 4–5 V (in vacuum and not plasma).

Based on the ion saturation current measurement and assuming it to be representative of the behavior near the top of the RF limiter, the particle flux should be reduced by 50% where the field is maximum, at the top of the limiter, unfortunately this reduction is on a small flux (2% of the total flux on the limiter, i.e. 1% drop) and not measurable due to lack of resolution in our H-alpha detectors. The heat fluxes should drop slightly (about 20%) but these are also undetectable at the moment. Higher RF powers should allow us to resolve these issues.

4. Conclusions

We have obtained data which shows that a significant local density reduction can be achieved in the neighborhood of a surface by means of RF induced ponderomotive potential as shown by Eq. (1) (just the ambipolar condition), but the local electron temperature is increased by the RF. The local changes in density and temperature result in lower particle fluxes but slightly reduced (20%) heat fluxes. The local RF electron heating decreases with density and increases with RF power suggesting a local heating mechanism as that in Eq. (2). The electron temperature saturates at the highest RF powers, suggesting that, combined with the still decreasing densities (exponential according to Eq. (3)) it will eventually result in lowered heat flux densities. The density and temperature decay lengths are also changed and therefore this could be a tool for profile modification.

References

[1] L. Pitaevskii, Sov. Phys. JEPT 12 (1961) 1008.
[2] T. Hatori and T. Watanabe, Nucl. Fusion 15 (1975) 143.
[3] T. Shoji, A. Grossman, R. Conn et al., J. Nucl. Mater. 176–177 (1990) 830–836.
[4] T. Shoji, personal communication.
[5] T. Shoji, A. Sagara, N. Noda et al., J. Nucl. Mater. 196–198 (1992) 824–828.
[6] A. Boschi and F. Magistrelli, Nuovo Cimento 29(2) (1963) 487–499.