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ABSTRACT

Positive limiter biasing on the currentless Advanced Toroidal Facility (ATF) torsatron produces a significant increase in the particle confinement with no improvement in the energy confinement. Experiments have been carried out in 1-T plasmas with ~400 kW of electron cyclotron heating (ECH). Two rail limiters located at the last closed flux surface (LCFS), one at the top and one at the bottom of the device, are biased at positive and negative potentials with respect to the vessel. When the limiters are positively biased at up to 300 V, the density increases sharply to the ECH cutoff value. At the same time, the H_α radiation drops, indicating that the particle confinement improves. When the density is kept constant, the H_α radiation is further reduced and there is almost no change in the plasma stored energy. Under these conditions, the density profile becomes peaked and the electric field becomes outward-pointing outside the LCFS and more negative inside the LCFS. In contrast, negative biasing yields some reduction of the density and stored energy at constant gas feed, and the plasma potential profile remains the same. Biasing has almost no effect on the intrinsic impurity levels in the plasma.

1. INTRODUCTION

Biasing experiments on tokamaks have been very successful in improving the global confinement parameters (to H-mode–like values) by setting up a radial electric field at the plasma edge [1, 2]. Experiments on the B-3 stellarator [3] also showed that a radial electric field induced by edge biasing resulted in rapid plasma rotation and improved particle confinement. These experiments have been extended to the current-free Advanced Toroidal Facility [4] (ATF) for further study and characterization of the effects of an electric field on plasma confinement. ATF has a torsatron configuration with $l = 2$, 12 field periods ($M = 12$), a major radius $R_0 = 2.1$ m, and an average plasma radius $a = 0.27$ m. The current-free magnetic configuration of ATF, which is produced by external means, has moderate shear; the rotational transform ($\iota/2\pi = 1/q$, where q is the safety factor) at the last closed flux surface (LCFS) is $\iota/2\pi \approx 1$, which is about a factor of 3 higher than the central value. Initial biasing experiments have been carried out in plasmas with electron cyclotron heating (ECH). ECH plasmas are created at a magnetic field $B = 0.95$ T using a 53-GHz gyrotron source with heating power up to $P_{ECH} \sim$ 400 kW. In these ECH plasmas, a representative line-averaged plasma density is $\bar{n}_e \sim 5 \times 10^{12}$ cm^{-3}, and the plasma stored energy $W_p \approx 2$ kJ. A pair of rail limiters [5], which are normally floating, one at the top and one at the bottom of the device, can be biased at positive and negative potentials with respect to the vacuum vessel.

2. EXPERIMENTAL SETUP

Most of the experiments for this study have been carried out by inserting the limiters, which are not on the same field line, slightly inside the internal separatrix defining the LCFS, where the normalized radius in flux coordinates is $\rho = r/a \approx 1$. The poloidal cross section of the plasma varies with the toroidal angle φ. At the locations of the limiters, $\varphi = 0°$ and 30°, the plasma cross section is vertically elongated (almost elliptical); at $\varphi = 15°$, it is horizontally elongated [4]. For these experiments, the limiters are simply considered as electrodes for providing the biasing because their particle flux coverage is only ~18%, owing to their small physical size and to the low q value, $q \sim 1$, at the edge [5]. The limiters do not affect the edge plasma potential profile when they are floating, which they typically do at about −40 V with respect to the vacuum vessel. For biasing the limiters, a 300-V dc power supply that can deliver a maximum output current of 200 A is used. The locations of the limiters on ATF, the biasing setup, and the diagnostics used for this study are shown in Fig. 1. The limiters are kept under bias

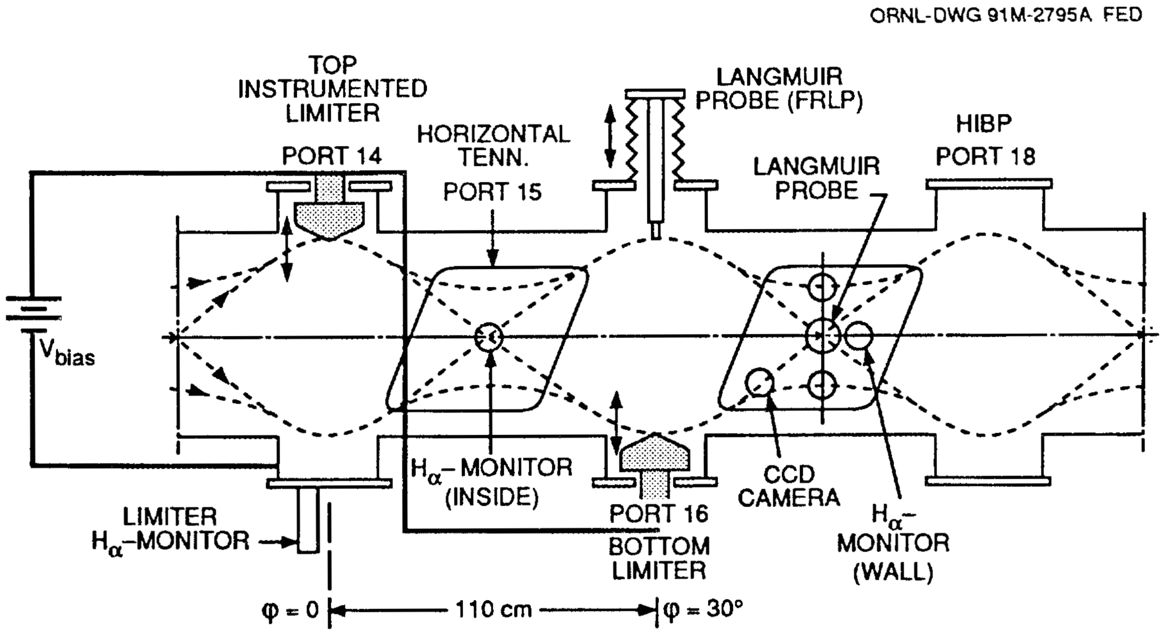

Fig. 1. Locations of the limiters on ATF, the biasing setup, and the diagnostics used for this study.

throughout a discharge. To characterize the effects of limiter biasing on confinement, comparison experiments with and without biasing were performed using either a constant gas feed or a constant density obtained with feedback control.

3. EXPERIMENTAL OBSERVATIONS AND RESULTS

The first comparison experiment was carried out with a constant gas feed and a positive biasing voltage of V_{bias} = +120 V with respect to the vacuum vessel applied to the limiters (Fig. 1). After the plasma discharge was initiated, the line-averaged plasma density increased rapidly, as shown in Fig. 2(a), by about a factor of 3 from the value when the limiters were floating and reached the cutoff density of the ECH at the second harmonic resonance, $\sim 10^{13}$ cm^{-3}; this occurred at time $t_c \sim 0.125$ s. At the same time, the particle recycling, as indicated by a number of H_α monitors around machine, was significantly lower than in the nonbiased case. For example, as shown in Fig. 2(a), a drop in the intensity of the H_α radiation, I_{H_α}, from both the limiter and the wall indicates reduced particle recycling as a result of improved particle confinement with the positive biasing. Similar results are observed on the Texas Experimental Tokamak (TEXT) [6],

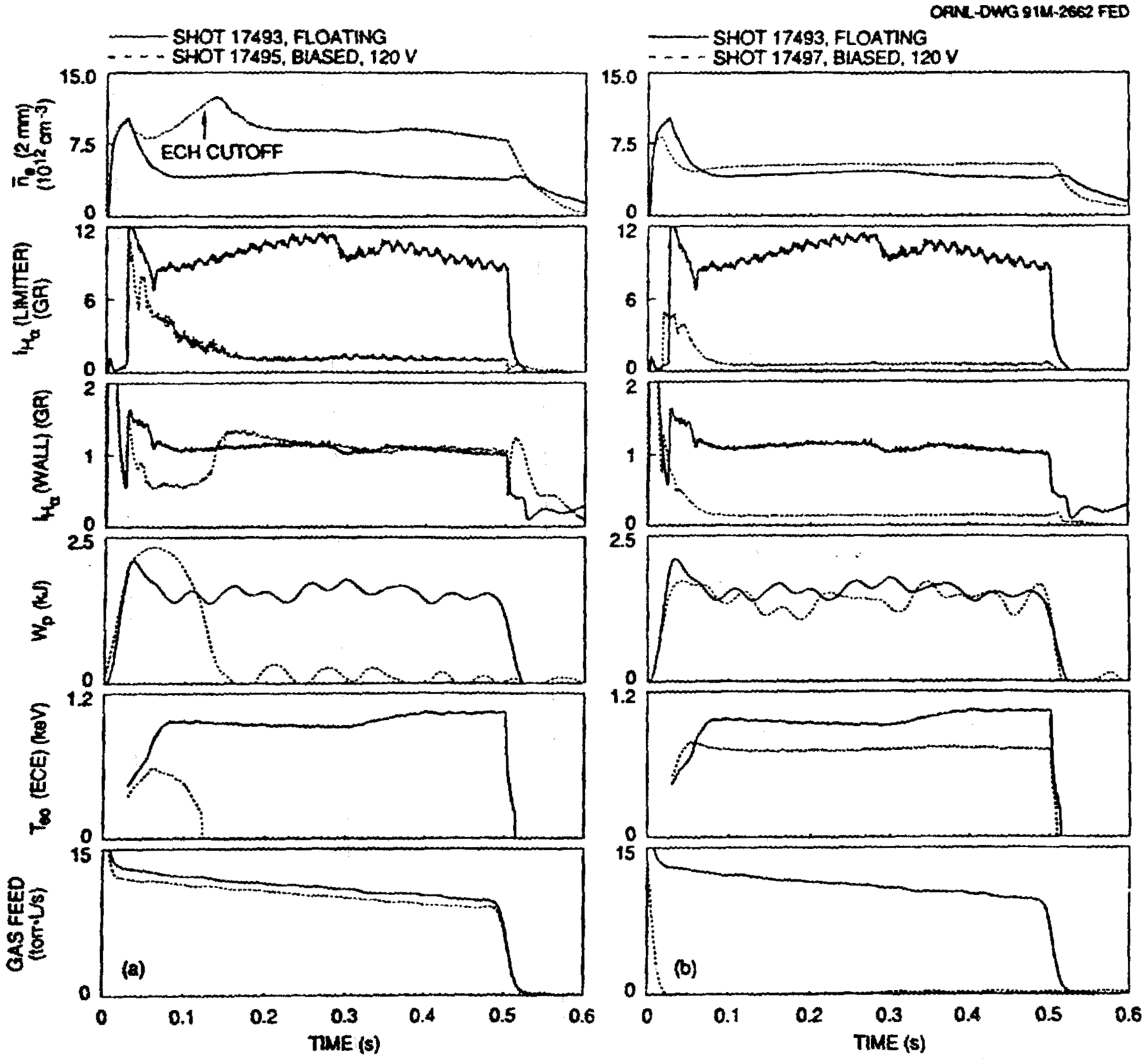

Fig. 2. Time evolution of plasma parameters ($\bar{n}_e$, H_α signals, W_p, T_{eo}, and gas feed) for floating limiter, shot 17493, and positively biased (+120-V) limiter, shots 17495 and 17497, for (a) constant gas feed and (b) constant density. The ECH cutoff for shot 17495 is indicated; at this time, the plasma collapses.

DIII-D [7], and the Tokamak de Varennes [8] but with negative limiter biasing. Again relative to the floating case, the plasma stored energy W_p, measured with diamagnetic loops, initially increased with the density but then collapsed for a time $t \geq t_c$ after the ECH was cut off.

When this experiment was repeated at a constant plasma density, obtained by feedback control of the gas feed, Fig. 2(b), a further reduction of I_{H_α} and almost no change in W_p were observed. With positive biasing, the gas input required to keep the density constant was much lower than that required in the case without biasing—almost zero. This observation again indicates that the particle confinement is substantially higher with positive biasing, and for this case it is as much as an order of magnitude higher. The central electron temperature T_{e0} from the electron cyclotron emission (ECE) measurements shows a drop from 925 eV to about 725 eV at $t = 0.3$ s; this temperature drop was also measured with Thomson scattering (TS). Measurements from the heavy-ion beam probe [9] (HIBP) and the fast reciprocating Langmuir probe [10] (FRLP) indicate that the plasma potential ϕ at the LCFS, $\rho \sim 1$, increased by about +100 V, Fig. 3, as if as a result of the shift in the peak of ϕ from outside the edge, $\rho \sim 1.1$, toward the inside, $\rho \sim 1$. Similar results are also observed on TEXT [6]. This spatial shift in ϕ results in a change in the sign of the radial electric field E_r, which becomes outward-pointing outside the LCFS and more negative inside the LCFS. With positive biasing, the estimated radial electric field changes from $E_r \approx -6$ V/cm to $E_r \approx 25$ V/cm at $\rho \geq 1$.

As observed in earlier edge turbulence studies on ATF, the peak of ϕ is related to the location of the shear layer of the poloidal phase velocity of the electrostatic fluctuations [10]. Therefore, positive biasing affects the location of the velocity shear layer and, in turn, the edge fluctuation characteristics [11,12]. For example, the power

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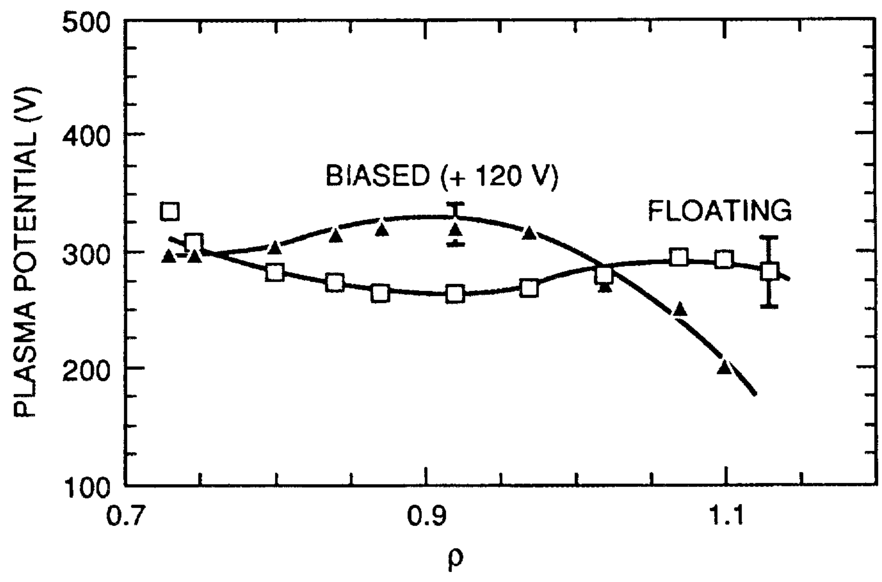

Fig. 3. Plasma potential, ϕ, profile measured with HIBP at the edge for the floating and positively biased limiter cases for constant $\bar{n}_e$. The HIBP measurements have a position resolution of ~5% and a potential resolution of ~10% for $\rho \leq 1$ and ~20% for $\rho \geq 1$.

spectrum of the edge plasma fluctuations in electron density $\tilde{n}$ and plasma potential $\tilde{\phi}$ at the LCFS, as measured with the FRLP, is less broad with biasing because of the quenching of the high-frequency (>100-kHz) components, as shown in Fig. 4. The fluctuation levels (rms) $\tilde{n}_{rms}$ and $\tilde{\phi}_{rms}$ are reduced significantly, Fig. 5, with positive biasing. At the same time, the propagation direction of the electrostatic fluctuations reverses to the ion diamagnetic direction with positive biasing. This result is shown in Fig. 6, which displays the measured wave number k in the poloidal direction as a function of the applied bias voltage to the limiters. Moreover, we see from Fig. 6 that the wavelength and the correlation length (~ $1/k$) of the fluctuations are longer with positive biasing.

As a consequence of these reductions in the fluctuation parameters, the fluctuation-induced particle flux $\tilde{\Gamma}_r \sim (k/B)\tilde{n}_{rms}\,\tilde{\phi}_{rms}$ is also reduced, Fig. 7, by almost an order of magnitude at the LCFS. One explanation for this reduction is decorrelation of the

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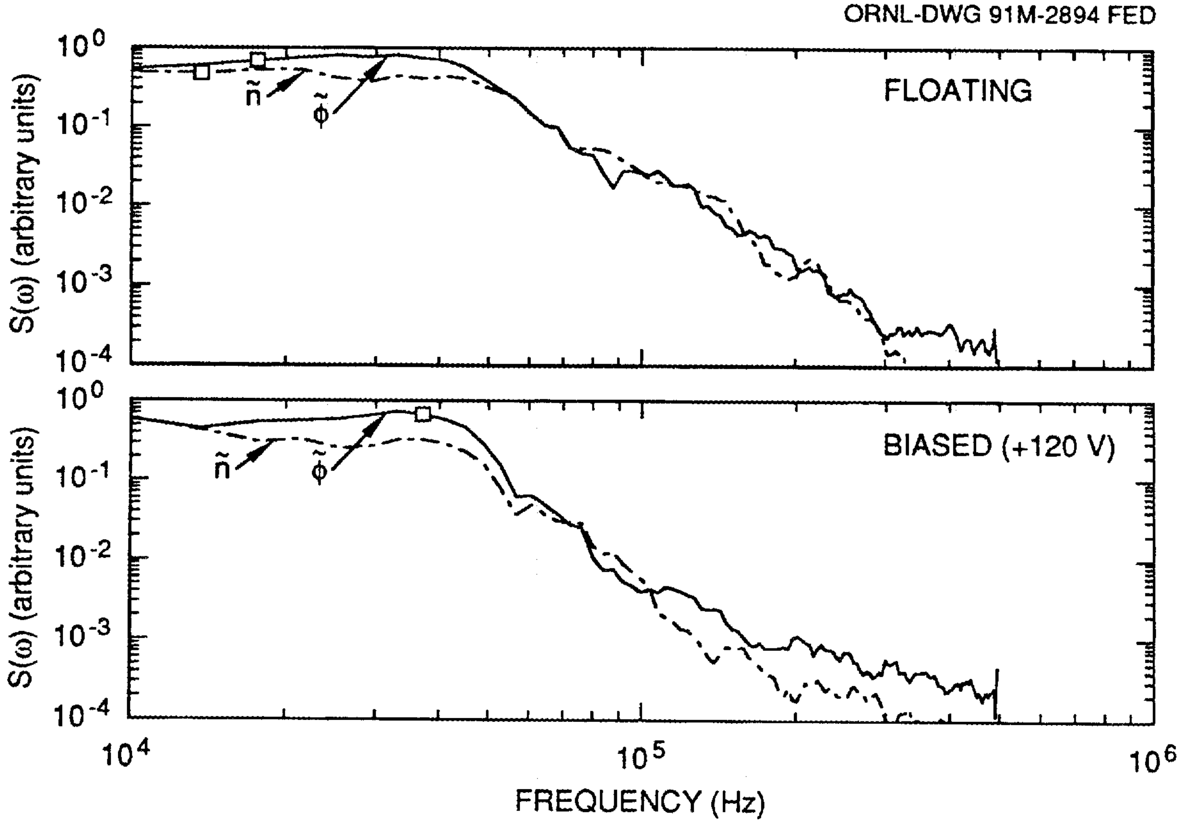

Fig. 4. Power spectrum of the edge plasma fluctuations at the LCFS measured with the FRLP in electron density $\tilde{n}$ and plasma potential $\tilde{\phi}$. The spectrum is less broad with positive biasing because of the quenching of the high-frequency (>100-kHz) components.

turbulence mechanism around the shear layer, resulting in suppression of the fluctuation-induced particle transport [12]. This reduction in $\tilde{\Gamma}_r$ is consistent with the observed improvement in $\bar{n}_e/I_{H_\alpha}$ (I_{H_α} from the wall), which is related to the global particle confinement time, by about an order of magnitude as shown in Fig. 7. The core plasma density profile, Fig. 8, obtained from TS at $t = 0.3$ s shows a higher central value, by about a factor of 2, while the edge density as measured with the FRLP drops, Fig. 9(a), indicating a more peaked density profile. The edge electron temperature profile, Fig. 9(b), with positive biasing, also measured with the FRLP, indicates lower values, by almost a factor of 2. The core plasma pressure, $P_e \sim n_e T_e$, profile from the TS measurements remains approximately the same with positive biasing, consistent with W_p measurements. Power deposition on the limiters is also reduced, by about a factor of 6, as a result of reduced edge plasma density and temperature, since the particle heat flux to the limiters is $\sim n_e T_e^{1.5}$.

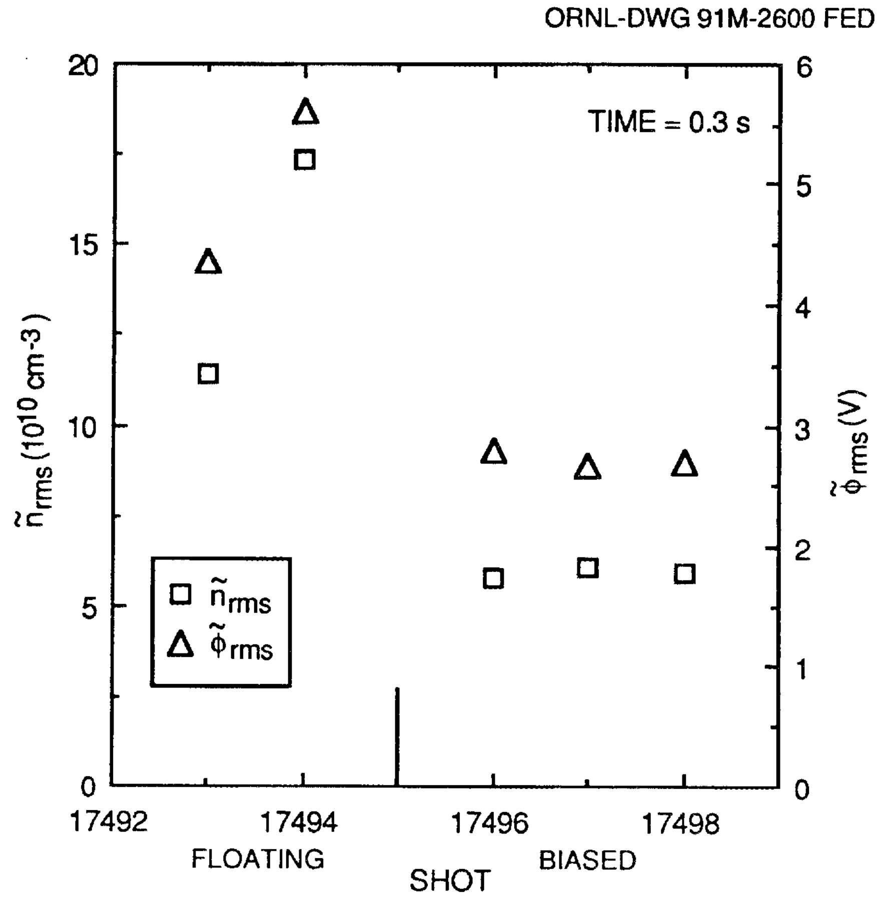

Fig. 5. Fluctuation levels (rms) of density $\tilde{n}_{rms}$ and potential $\tilde{\phi}_{rms}$ for the floating and positively biased limiter cases for constant $\bar{n}_e$.

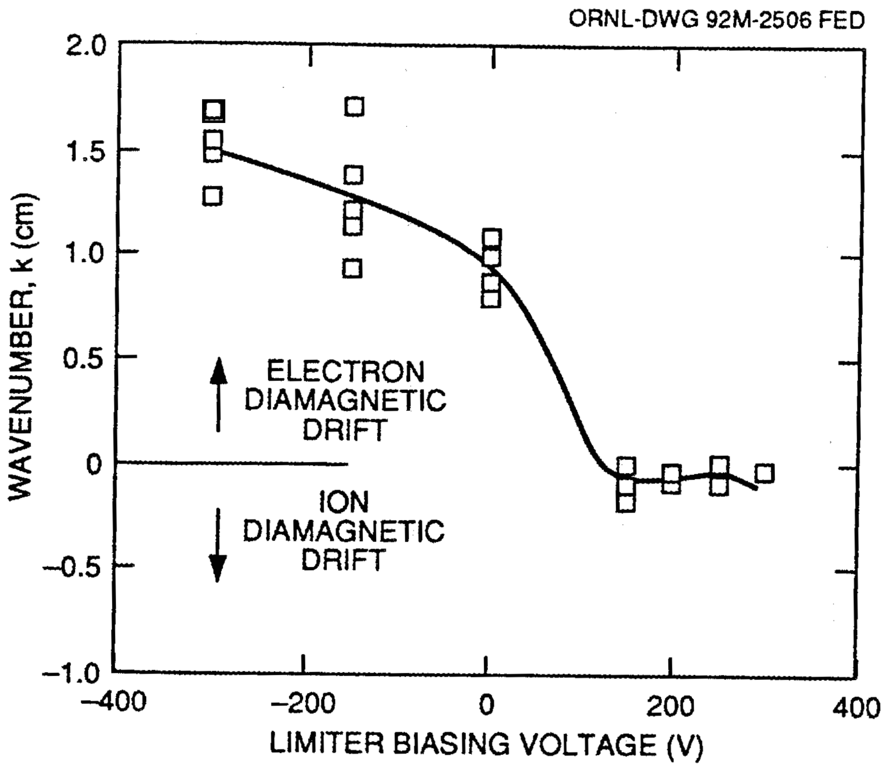

Fig. 6. Measured wave number *k* as a function of the applied bias voltage to the limiters. The propagation direction of the electrostatic fluctuations reverses to the ion diamagnetic direction with positive biasing.

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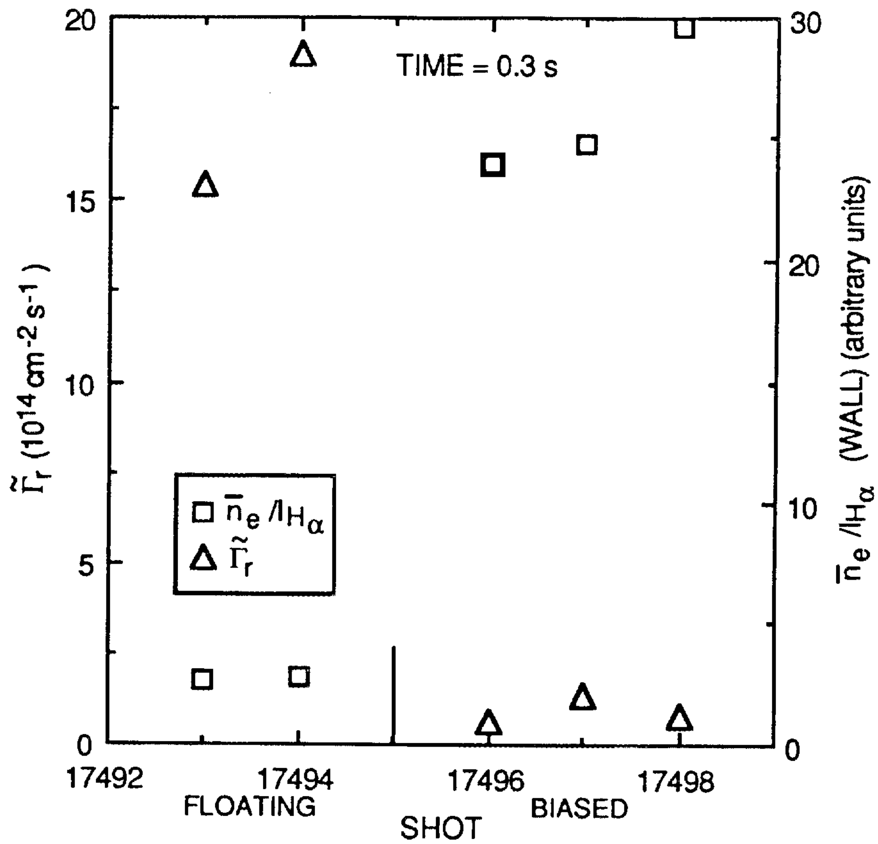

Fig. 7. Fluctuation-induced flux $\tilde{\Gamma}_r$ and $\bar{n}_e/I_{H_\alpha}$(wall) for the floating and positively biased limiter cases at constant $\bar{n}_e$.

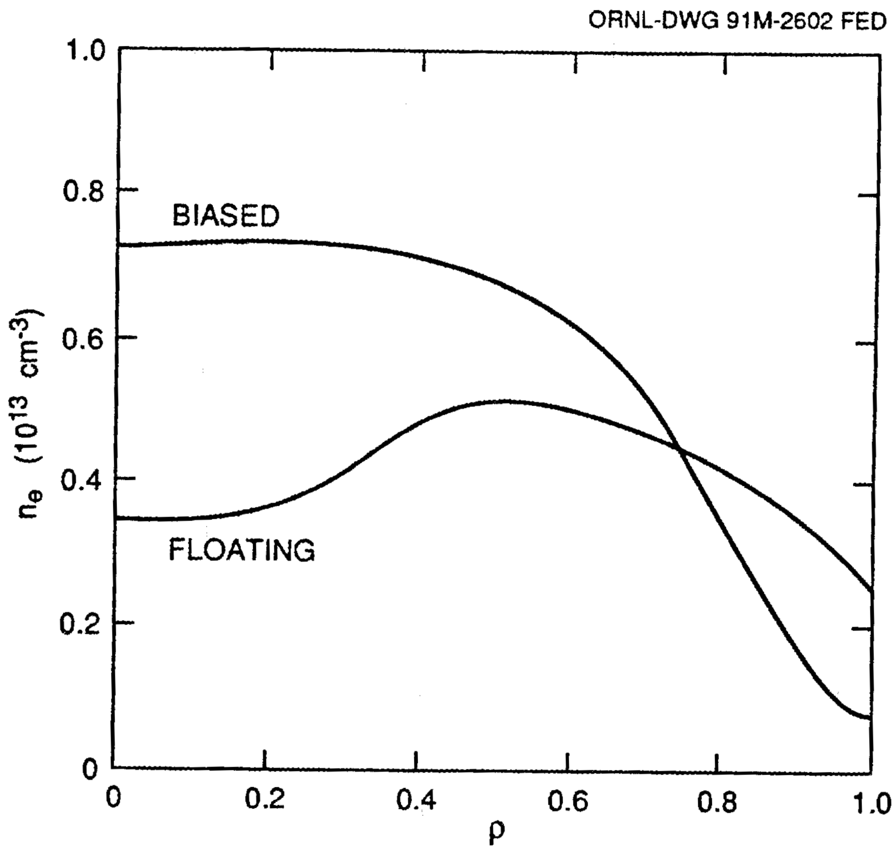

Fig. 8. Density profile obtained from TS measurements for the floating and positively biased limiter cases at constant plasma density.

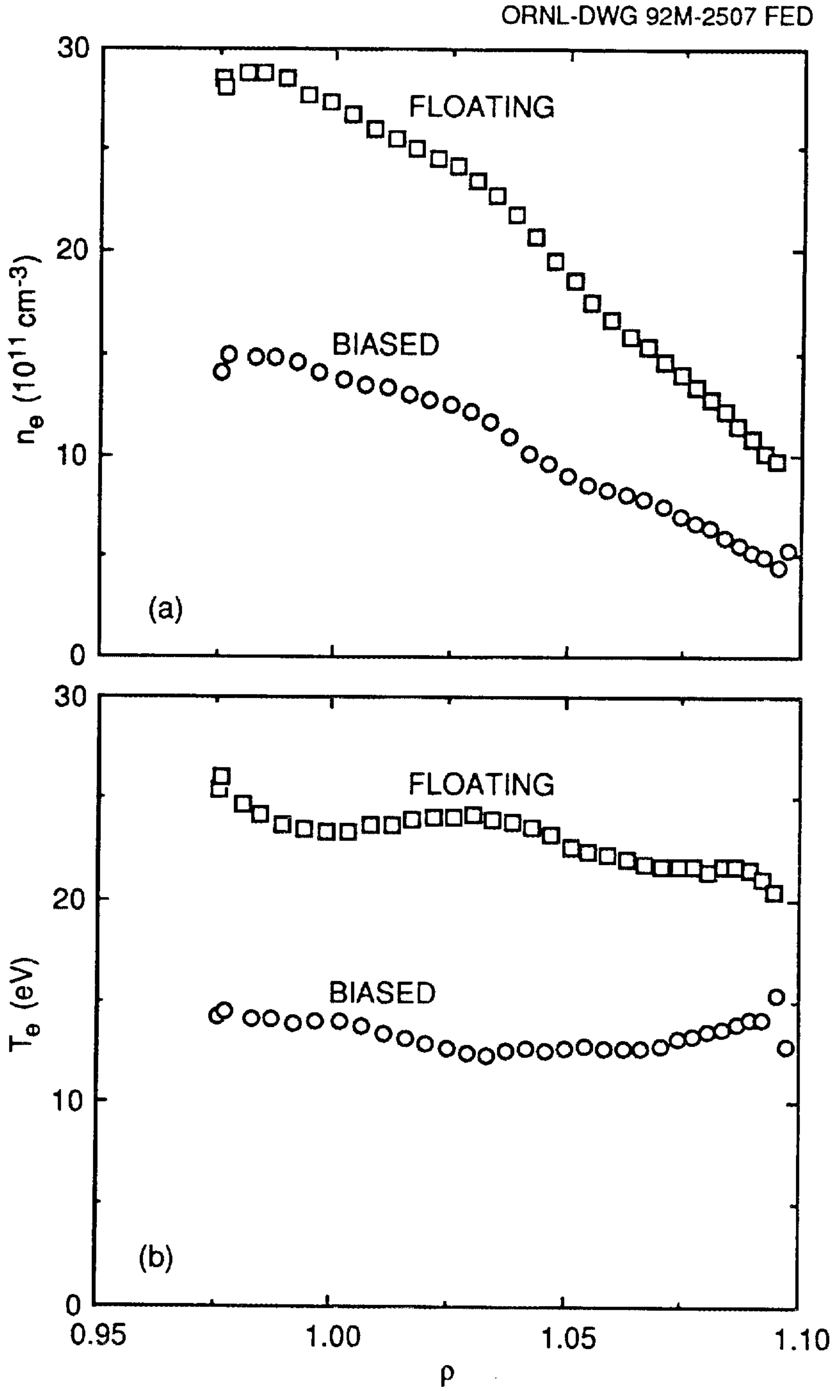

Fig. 9. FRLP measurements of (a) edge density and (b) edge electron temperature profile with positive biasing. The edge density profile is lower, indicating a more peaked profile with positive biasing, and the corresponding electron temperature profile also indicates lower values (almost a factor of 2).

4. CONCLUSION

Even though global particle confinement improves with positive biasing on ATF, so far almost no improvement in the energy confinement is observed. This result strongly suggests that the edge radial electric field affects the fluctuation characteristics by changing the location of the velocity shear layer, which leads to strong decorrelation of the turbulence around it and, in turn, to suppression of the turbulence, which is the dominant mechanism for global particle transport. In contrast to tokamak biasing experiments [1, 2], a strong decoupling of the energy confinement and the particle confinement is found. In experiments with negative biasing, on the other hand, there is some reduction of the density and stored energy at constant gas feed and almost no change at constant density. Simultaneous measurements of the plasma potential profile indicate almost no significant change with negative biasing of the limiters. Biasing causes almost no increase in the iron impurity signal from the plasma center or in the oxygen impurity signal from the edge.

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