Brazilian Journal of Physics, vol. 25, no. 1, March, 1995

Experimental Study on Recycling Source Profiles in **TBR-1**

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Received October 12, 1992; revised manuscript received August 30, 1993

Distribution of particle recycling from limiter ancl wall in all olimically heated tokamak plasma was investigated by hydrogen alfa line ($A = 6562.8$A) ineasurements in TBR-1. The results show tliat tlie intensity profiles are toroidally and poloidally asymmetric. The peak value of H, emission occurs in the limiter ancl tlien decays exponentially along the toroidal direction. The decay angle is less than 20'. Tlie poloidal asymmetry, at the plasma edge can be represented by a factoi $(1+ p\cos 0)$, witli h being about 0.8 in tliis expeiiment. A linear relation between recycling source and electron density is coiifirmed. Particle confinement times and recycling rates are also discussecl.

I. Introduction

H, emission is a useful indicator of hydrogen ionizations, siiice tlie energy required to excite liyclrogen to the $n = 3$ level is approximately the same as to ionize the liydrogen atoni. Other aspects of H, spectral research, sucli as the rate of recycling and tlie global particle confinement time, τ_p, can be inferred from measuring spatial distributions of H, emissivity. In 1962, Bates and others discussed in detail the recombination between electrons and atomic ions in optically thin ancl thick plasma using statistical theory and presented accurate calculations of tlie collisional - radiative recombination coefficients[1,2]. The ionization and recombination coefflcients for the populations of excited levels were obtained from the solution of transition rate equations for atomic liydrogen by Johnson and Hinnov in 1973[3].

The study of transport at tlie edge of a toliamali plasma is important per se, and the base of this study is to get details of plasma recycling source profiles ancl diffusion parameters. Tlie existence of H-mode and its strong connection to edge transport as well as the differences between limiter and divertor plasma, and plasma edge rotation, all suggest tbat tlie transport near tlie edge where the recycling source exists, can lead to different profiles in different tokaniaks, and can affect global plasma confineinent. Previous metliods of transport study considered only poloidally localized source. As tliere is some experimental evidence that the theoretically calculated parallel transport coefficients are incorrect[4-8], a traditional assumption of toroidal symmetry is broken. Toroidally asymmetric sources can modify tlie theoretical prediction, and possibly provide a better fit to tlie experimental data[9]. Therefore, it is necessary and helpful to investigate in detail the particle recycling source for studyiiig transport.

Tlie experimental evidence for toroidal and poloidal asymmetries of the source has been obtained by measuring tlie briglitness profile of H, radiations in some tokamaks[10,11]. In those experiments, a cornplex profile structure was measured, along with new scaling relations of total transport aiid global particle confinement time with plasma current and electron density.

Recycling source profile in TBR-1 is little understood up to now. The experimental study presented in

*Instituto de Física, Universidade Estadual de Campinas, Campinas, São Paulo, Brazil tions of total transport and global particle confinement time with plasma current and electron density.

Recycling source profile in TBR-1 is little understood up to now. The experimental study presented in this paper is organized as follows. First, a descriptions of the tokamak and its operations, and the diagnostics relevant to this experiments are presented in section II. Second, the experimental results ancl analysis are reported in section III. Next, estimate values of global particle confinement time and rate of recycling is introduced in section IV. The results, are compared with other tokamaks, and a summary is presented in section V.

II. TBR-1 and H, spectral diagnostics

The experiments were carried out in TBR-1, a small ohinically heatecl tokamak, with a major radius of 30.0 cm and with a minor radius limited to 8.0 cin by a poloidal stainless steel liniiter. Three ports for H, monitoring are located at 0°, 45° and 135° respectively from the poloidal limiter on the outside of the vacuum vessel, and another one is on the top of vessel at 135° from the limiter. plasma is fuelled continually from a single fast gas valve located at the bottom of the torus below the limiter. A typical discharge signals are presented in Fig. 1. For these experiments, plasma currents (I_p) is fixecl at 10 kA, toroiclal field (B_t) at 0.5 T, and electron density under these conditions is about several 10^{12} cm^{-3}. The measurements reported here are taken cluring the plateau regime of the plasma current.

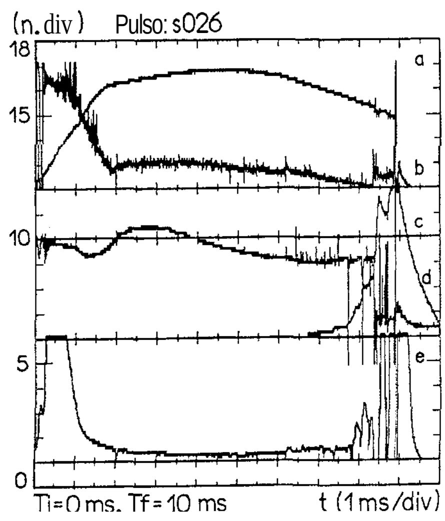

Figure 1: Typical discliarge condition signal. Tlie experiment was conducted during plasma flat-top (2-7ms). Fig. 1a is plasma current (10 kA), Fig. 1b is loop voltage, Fig. 1c is horizontal plasma position, Fig. 1d is hard X-ray and Fig. leis H, emission brightness. The toroidal field for this hydrogen discharge was 0.5 T.

A single channel of the photodiode inonitor witli an interference filter with a passband centered on the hyclrogen H, line is used for shot by shot measurements of H, emission distributions. The spectral line radiation froin tlie plasma column is viewed by an optical system consisting of two plane-convex lenses of focal length 5 cm and 100 cm respectively. All the components, lenses, interference filter, photodiocle and an operational amplifier are housed all together inside a metallic cylinder. The experimental results are obtained cluring flat top of plasma current when a totally ionized plasma is formed. At the beginning of tlie clischarge tlie appearance of a peak value for the H, line is considered as hydrogen moleciilar continuum radiation, as can he seen on Fig. 1-e. The continuum can be omitted cluring the plasma current plateau. A high gain amplifier is applied at the entrance of the acquisition system.

III. H$_\alpha$ spectral profiles

The experimental results show that the hydrogen spectral emissivity distribution is toroidally and poloiclally asymmetric in TBR-1. Both of these asymmetries were seen also in other tokamaks. This complex profile structure can he represented in terms of H, emissivity on the material limiter by:

$$\epsilon(r,\theta,\varphi) = \left[\epsilon_\ell \exp\left(-\left|\frac{\varphi}{\varphi_0}\right|\right) + \epsilon_\omega\right] \epsilon_0(r)(1+\beta\cos\theta)\ . \tag{1}$$

were E is the local emission, r, 0 ancl φ are, respectively, the minor radius, poloidal and toroidal coordinates. *The limiter is localized at* $\varphi = 0°$, *and* subscript ℓ and *w* means limiter and wall contributions. In our experiment the distance from the detector to plasma edge was fixecl in such way to have no dependency on minor radius. The toroiclal component is represented as an experimental decay from a peak value at the limiter $(\epsilon_\ell$, E) to a wall value E. The decay is given by the corresponding toroidal angle, φ_0. Uncler these assumptions Eq.(1), can be replacecl by:

$$\epsilon(\varphi,\theta) = \left[\epsilon_\ell \exp\left(-\left|\frac{\varphi}{\varphi_0}\right|\right) + \epsilon_\omega\right](1+\beta\cos\theta) \tag{2}$$

Eq. (2) can be compared to experimental results once we acquire the toroidal and poloidal brightness distribution in TBR-1.

111.2 Toroidal distribution

The global toroidal brightness profile is show in Fig. 2. It is taken at the midplane during the flat-top part of the discharge (t = 4 ms). It has a peak value, $(\epsilon_\ell, \epsilon_\omega)(1+\beta)$ at the limiter, and then decays exponentially to a constant minimum value $\epsilon_\omega(1+\beta)$ according to Eq.(2). Fig. 3 shows the brightness profiles with discharge time in the four ports mentioned before. Due to limited spatial region for the measurements the global profile curves can not be obtained at other points.

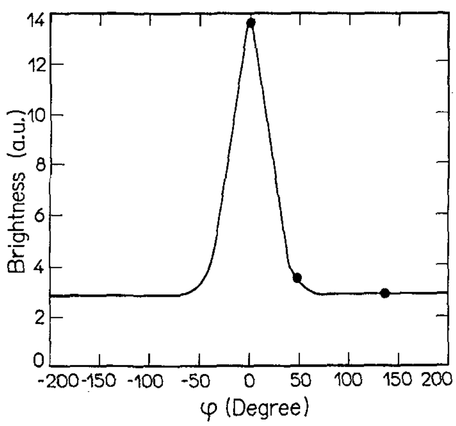

Figure 2: Global brightness profiles of H, radiation in the midplane. The value peaks at limiter ($\varphi = 0°$) and then decays exponentially to $\epsilon_\omega(1+\beta)$.

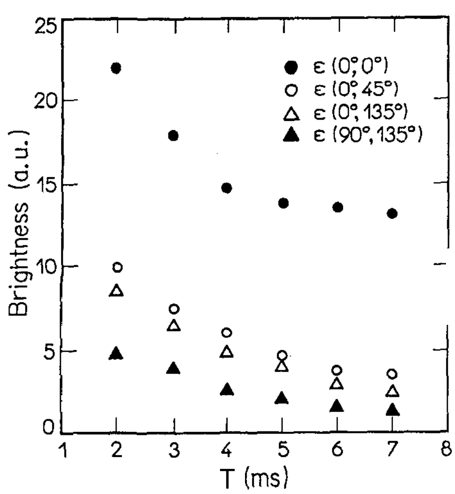

Figure 3: Brightness versus discharge time at different viewing points: **(a)** $\varphi = 0°$, $0 = 0°$, (b) $\varphi = 45°$, $0 = 0°$, (c) $\varphi = 135°$, $0 = 0°$, (d) $\varphi = 135°$, $\theta = 90$".

H, radiation is toroidally asymmetric due to the reaction of the plasma with the limiter, and the fact that the limiter is one of particle recycling sources of the plasma is confirmed again. The peak of emission at the limiter decays exponentially to zero along the torus direction. The density and time variation of the ratios between total recycling source from the limiter, $\Sigma\epsilon_\ell$, and from the wall, $\Sigma\epsilon_\omega$, are presented in Fig. 4 and Fig. 5 respectively. The decay angle, φ_0, is less than 20° during plasma flat-top as can be seen in Fig. 6. Fig. 7 presents φ_0 profile with electron density taken by Langmuir probe measurements.

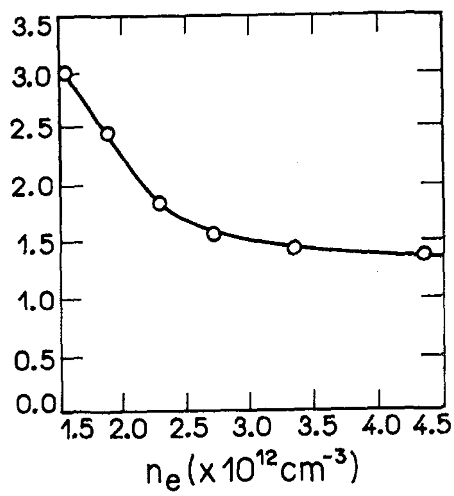

Figure 4: $\Sigma\epsilon_\ell/\Sigma\epsilon_\omega$ profile versus electron density.

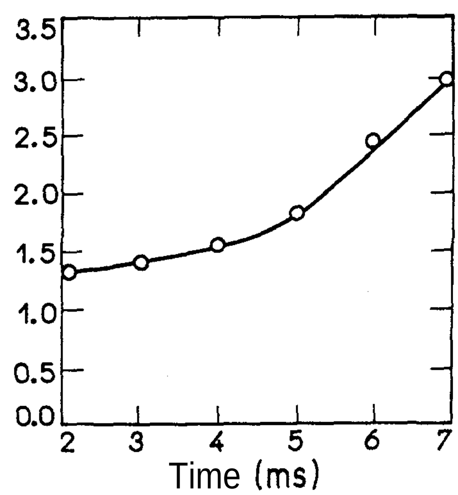

Figure 5: $\Sigma\epsilon_\ell/\Sigma\epsilon_\omega$ profile versus discharge time.

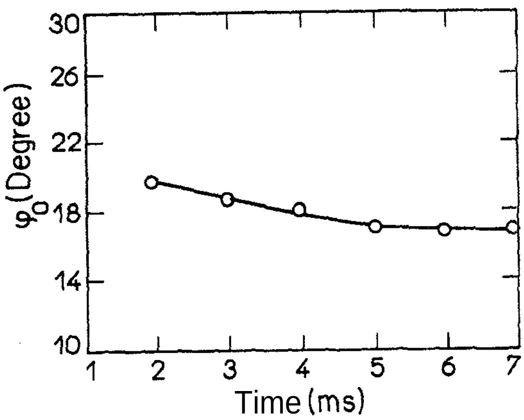

Figure 6: The decay angle, φ_0, versus discharge time. It is less then 20°.

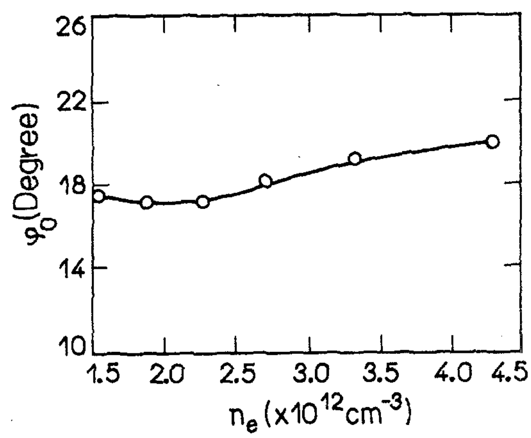

Figure 7: The decay angle, φ_0 versus electron density.

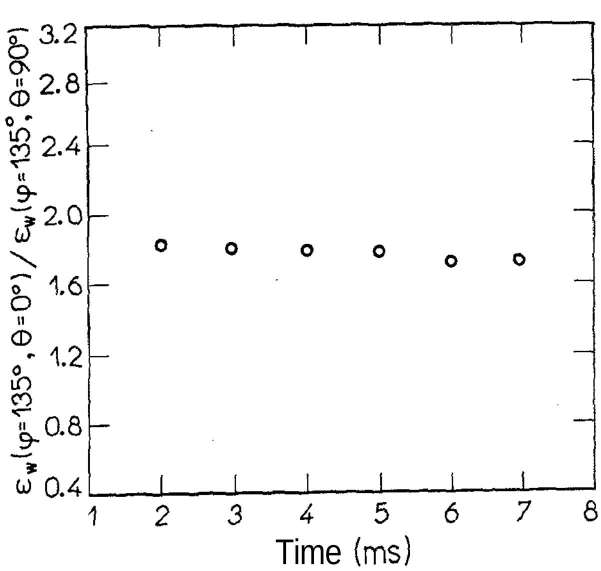

Figure 8: Ratio of $\epsilon_\omega(\varphi = 135°, \theta = 0°)$ and $\epsilon_\omega(\varphi = 135°, 0 = 90°)$ versus discharge time. Note that H, emissivity profile is poloidally asymetric.

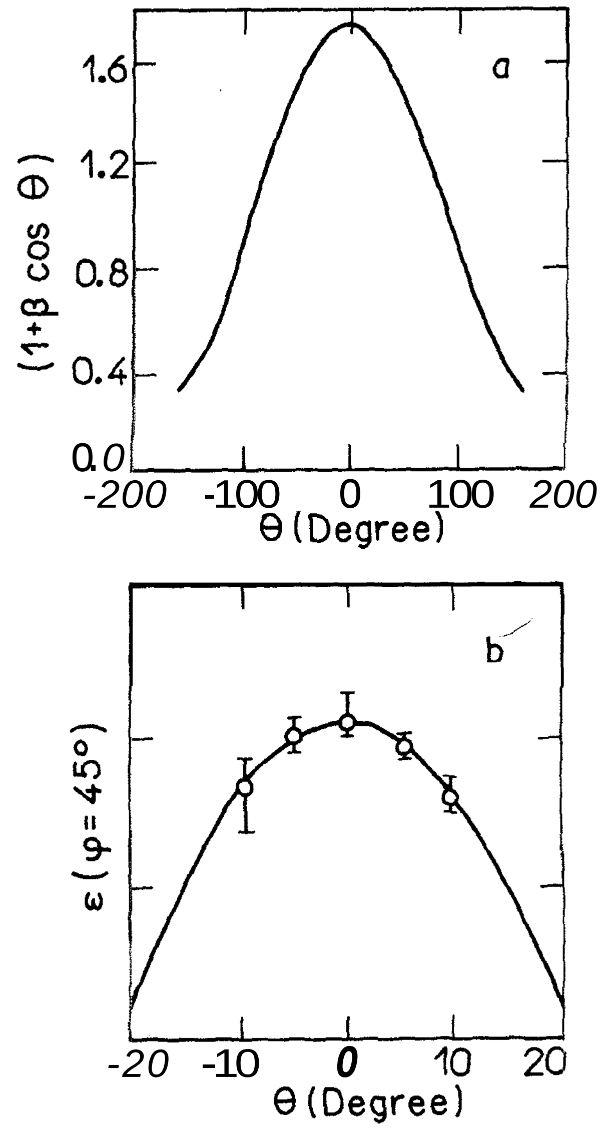

Figure 9: Poloidal asymetric factor, $(1 + \beta\cos\theta)$, profile versus poloidal angle (Fig. 9a). Fig. 9b shows the poloidal local brightness profile made in $\varphi = 45°$.

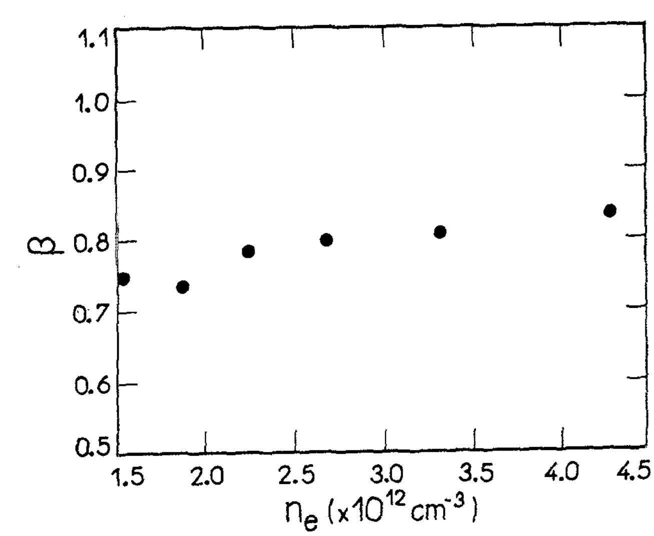

Figure 10: β factor versus electron density.

III.3 Poloidal distribution

According to our model, the H, emissivity far from limiter, $\varphi = 135°$, is assumed to have contribution solely due to pure wall recycling, E to plasma. The H, emissivity time variation at different window locations is given in Fig. **3.** The ratio of $\epsilon(\theta = 0°)$ and $\epsilon(\theta = 90°)$ is presented in Fig. 8. The curve which describes poloidal asyinmetry, $(1+\beta\cos\theta)$, is illustrated in Fig. 9, together with some data points. In the Fig. 10, the β profile with η_e shows that its variations with electron density is a negligible quantity.

IV. Global particle confinement time τ_p and recicling rate R.

Using absolute spectroscopic measurements of hydrogen radiation and electron density rneasurements, it is possible to reduce the global particle confinement time, τ_p, and recycling rate, R, from the continuity equation.

$$\frac{d\eta_e}{dt} = \Sigma S_i - \frac{\eta_e}{\tau_p} \tag{3}$$

where the first term in the right side is the production or total ionization rate and the second term is the loss rate. During the equilibrium phase, production and loss terms are the same, and we can write:

$$\Sigma S_i = \frac{\eta_e}{\tau_p} \tag{4}$$

In the case where the equilibrium is not met, we may represent the source term by a factor R called recycling rate R, given by

$$R = \frac{\Sigma S_i}{'Ve}\tau_p \ . \tag{5}$$

Therefore, we have

$$\frac{d\eta_e}{dt} = \frac{(R-1)\eta_e}{\tau_p} \ . \tag{6}$$

The electron source ΣS_i can be determined by measuring H, emission and it is directly proportional to the H, emission brightness. The proportionality factor has a negligible dependence on the electron temperature for $T_e > 5$ eV. Fig. 11 shows a nearly constant profile with discharge time[12] for the electron temperature T_e. The quantity ΣS_i can be obtained from spatially resolved measurements of the electron density and the emission from a hydrogen spectra or H, measurements. In our case, the electron density at the center is measured by microwave interferometry[12] and a Langmuir probe is used to get η_e at the plasma edge. Fig. 12 shows the electron density profile with time in a typical discharge assuming a parabolic spatial profile, $n(r) = \eta_{0e}[1-(\frac{r}{a})^2]$ with η_{0e} as center density.

In the H, emission measurements, the electron source can be represented by:

$$\Sigma S_i = 2\pi \int_0^{+a} \frac{S}{X_{13}B_{32}}\epsilon_\alpha r dr \ , \tag{7}$$

where S is the electron impact ionization rate coefficient, X_{13} is the collisional excitation coefficient for transition from level 1 to **3,** B_{32} is the branching ratio from level 3 to 2, and E, is the emissivity of H, line. The brightness of H, line, which is related to measurement value, can be related to E, by:

$$B_\alpha = \frac{1}{2\pi}\int_0^{+a} \epsilon_\alpha dr \ , \tag{8}$$

where a is the plasma minor radius since the detector views along a minor diameter. Combining Eq.(7) and Eq.(8), we can rewrite the electron source term **as:**

$$\Sigma S_i = \frac{4\pi^2 r_0 \bar{S}}{B_{32}X_{13}} B_\alpha \tag{9}$$

Johnson and Hinnov[3] show that the radio $X_{13}\tilde{B}_{32}$ is approximately independent of η_e and T_e as long as $\eta_e \leq 10^{13}$ cm^{-3} and $T_e \geq 5$ eV, and it is independent of η_0. Table I shows the ratio as a function of η_e and T_e[13]. For the plasma pararneters of TBR-I, this ratio is about 10. Now, using Eq.(4) and (9), we can write τ_p as:

$$\tau_p = \frac{\eta_e}{\Sigma S_i} = \frac{\eta_e B_{33}\bar{X}_{13}}{4\pi^2 r_0 \bar{S} B_\alpha} \ . \tag{10}$$

Using the values of η_e given by Fig. 12 and $\Sigma S_i = 3.2 \times 10^3 C \cdot$ B,, where C is the calibration factor of the detector which is deterinined by an absolute calibration procedure, and B_r (from Fig. 3) in the limiter region, we can show the ralationship between the global ionization rate, ΣS_i, and the eletron density in Fig. 13.

According to Eq.(10) and Eq.(4), τ_p should he independent on η_e if the equilibrium conditions are satisfied, but the measurements using Langmuir probe and analysis of linear relationship between the global ionization rate, ΣS_i, and the electron density, as can be seen in Fig. 13, show that r, increases with electron density, as shown in Fig. 14. Therefore, arbitrarily assuming steady state is unnarranted and a recycling value R should be introduced.

The global particle recycling rate, R,, is derived from the measurements of $\eta(t)$ and $\tau_p(t)$ according to Eq.(6). In Fig. 15 it is shown the time behavior of R during the discharge. In this figure, the value of R is still increasing during the discharge. Note that this results is one more confirmation that the steady state of this discharge is not yet well defined.

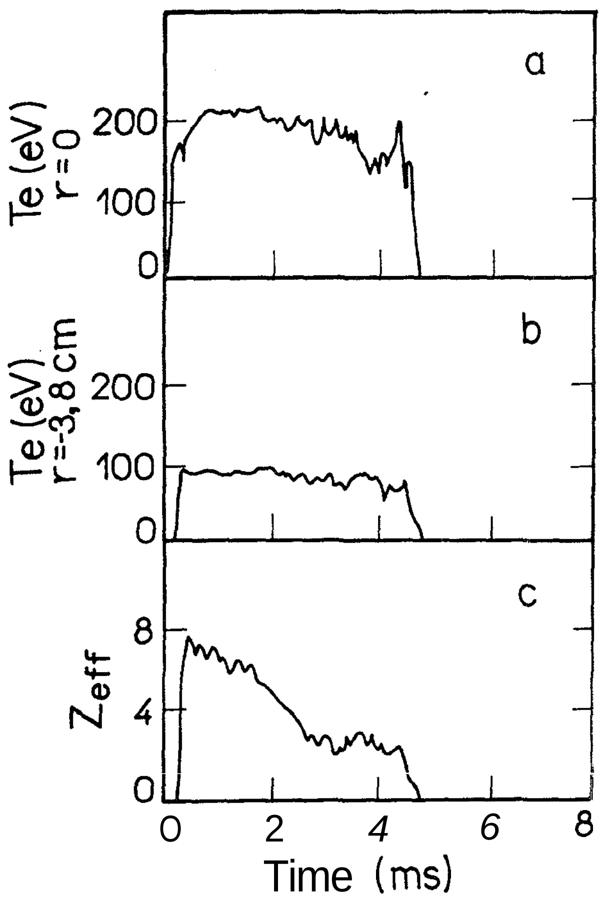

Figure 11: Electron ternperature, (T_e) and Z_{eff} profiles witli discharge time, Fig. 11a and Fig. 11b, are tlie profiles in the center and in tlie position r = 3.8 cm respectively, Fig. 11c shows the Z_{eff} profile.

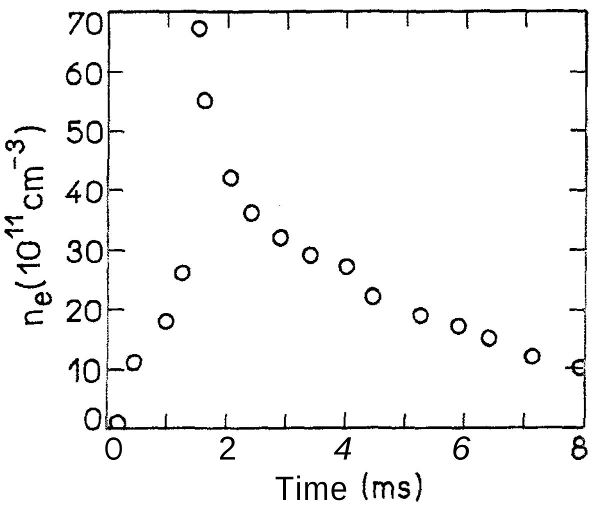

Figure 12: Electron density profile versus discliarge time.

T_e (eV)	$n_e(cm^{-3})$			
	10^{11}	10^{12}	10^{13}	10^{14}
1.4	0.69	0.92	1.70	2.79
2.8	2.06	2.58	4.24	17.98
5.5	4.54	5.24	9.17	34.03
11	6.98	8.09	13.19	47.75
22	8.83	10.11	15.80	56.11
44	10.12	11.30	16.84	54.38
88	10.76	11.82	16.83	51.39
177	10.54	11.84	16.19	45.28

Table 1: Ratio of Ionization to H, emission ($\bar{S}/B_3 2\bar{X}_{13}$) for different density and temperature.

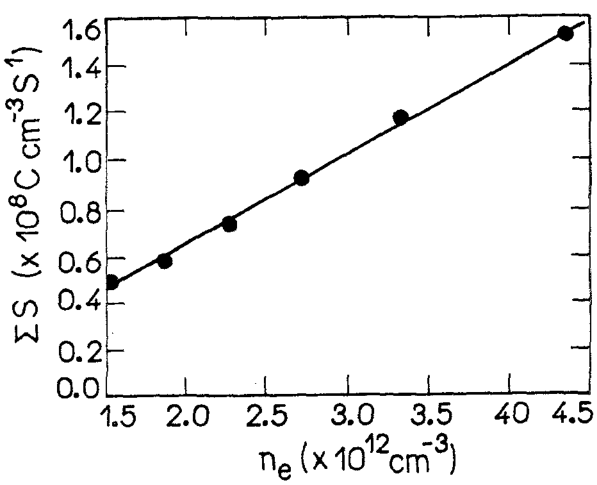

Figure 13: Variation of global ionization rate versus electron density.

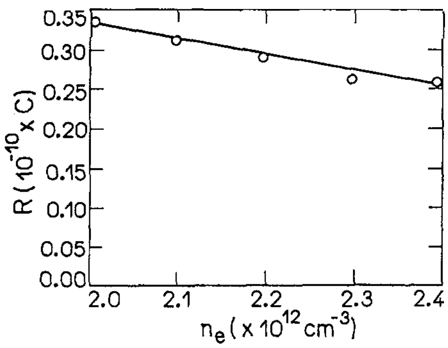

Figure 14: Rate of recycling, R, versus electron density, assuming the τ_p profile sliown in Fig. 15.

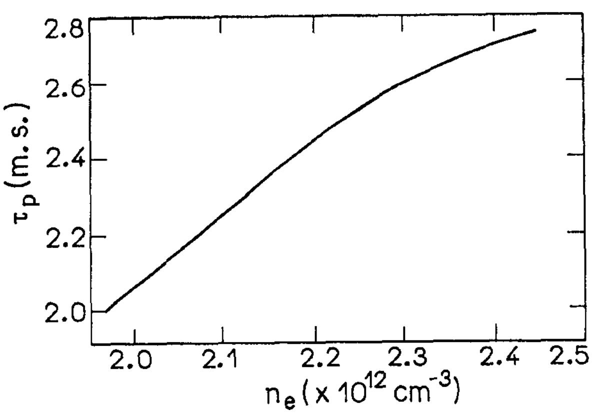

Figure 15: Global particle confinement time versus electron density. Tlie value of C has been set arbitrarily to see the curve beliavior.

V. Summary and conclusion

A simple technique of measuring H, radiation profiles for tlie study of recycling on tokamak TBR-1 is studied. H, spectral profiles observed on this device are similar to those collected from other tokamaks. From this experiment, it is found that the limiter plays an important role in the particle dynamics of the discharge. Comparison witli the particle source distributions yields two interesting results. First, the particle source due to wall and limiter recycling is a good indication that edge transport in TBR-1 is poloidally asymmetric, as well as an assumption of toroidally symmetry should be reconsidered when discussing transport in the plasma periphery. Second, from the experimental results, we observed that a more complex asymmetric profile is needed to give realistic value of τ_p and R witli those parameters. Relative measureinents of global recycling source indicate that the H, emissivity is directly proportional to electron density in the range of discharge of TBR-1. It means that a linear relation of τ_p and R is confirmed. This scaling relation needs to be further studied in an extensive operation parameters.

Acknowledgements

We would like to thank tlie TBR-1 team for all the information on the plasma parameters. In particular, discussions with all of the Lab Staff were very helpful. We would like to acknowledge Dr. W. L. Rowan of the Fusion Research Center, Univ. of Texas, who provided us with the H, detector used in the experiment. Tliis work was supported by FINEP and CNPq.

References

1. D. R. Bates et al., Proc. Royal Soc. of London (A), 267, 297 (1962).
2. D. R. Bates et al., Proc. Royal Soc. of London (A), 270, 155 (1962).
3. L. C. Johnson and E. Hinnov, J. Quant. Spectronic Radiat. Transfer, 13, 333 (1973).
4. K. H. Burrel, Phys. Fluids, 19, 401 (1976).
5. S. K. Wong, Phys. Fluids, 21, 299 (1978).
6. W. M. Stancey Jr., Phys. Fluids, 21, 1404 (1978).
7. W. M. Stancey Jr., Phys. Fluids, 22, 2000 (1979).
8. K. H. Burrel, Phys. Fluids, 23, 1526 (1980).
9. E. R. Solano et al., DOE/ER-53266-29 Fusion Researcli Center, Report No. 353, (1990).
10. A. J. Wootton, Nuclear Fusion, 27, 1105 (1987).
11. A. T. Ramsey and S. L. Turner, Rev. Sci. Instrum., 58, 1211(1987)
12. R. P. da Silva and I. C. Nascimento, III Latin American Worltshop in Plasma Physics, Santiago, (1988).
13. Notes of P. D. Morgan, JET(1986).