Experimental Study on Recycling Source Profiles in TBR-1

M. Machida*, A. C. P. Mendes, E. I. Sanada, C. R. M. Rincoski

Instituto de Física Universidade de São Paulo
Caixa Postal 20516, 01452-990, São Paulo, SP, Brasil

Y. D. Meng
Academia Sinica, Beijing, PRC

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

Distribution of particle recycling from limiter and wall in all ohmically heated tokamak plasma was investigated by hydrogen alfa line (\(\lambda = 6562.8\) Å) measurements in TBR-1. The results show that the intensity profiles are toroidally and poloidally asymmetric. The peak value of H\(_{\alpha}\) emission occurs in the limiter and then decays exponentially along the toroidal direction. The decay angle is less than 20°. The poloidal asymmetry at the plasma edge can be represented by a factor \((1 + p\cos\theta)\), with \(p\) being about 0.8 in this experiment. A linear relation between recycling source and electron density is confirmed. Particle confinement times and recycling rates are also discussed.

I. Introduction

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

The study of transport at the edge of a tokamak plasma is important per se, and the base of this study is to get details of plasma recycling source profiles and diffusion parameters. The 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 that the transport near the edge where the recycling source exists, can lead to different profiles in different tokamaks, and can affect global plasma confinement. Previous methods of transport study considered only poloidally localized source. As there 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 the theoretical prediction, and possibly provide a better fit to the experimental data\([9]\). Therefore, it is necessary and helpful to investigate in detail the particle recycling source for studying transport.

The experimental evidence for toroidal and poloidal asymmetries of the source has been obtained by measuring the brightness profile of H\(_{\alpha}\) radiations in some tokamaks\([10,11]\). In those experiments, a complex profile structure was measured, along with new scaling relations 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...
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 description of the tokamak and its operations, and the diagnostics relevant to these experiments are presented in section II. Second, the experimental results and 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\textsubscript{\alpha} spectral diagnostics

The experiments were carried out in TBR-1, a small ohmically heated tokamak, with a major radius of 30.0 cm and with a minor radius limited to 8.0 cm by a poloidal stainless steel limiter. Three ports for H\textsubscript{\alpha} monitoring are located at 0\degree, 45\degree, and 135\degree respectively from the poloidal limiter on the outside of the vacuum vessel, and another one is on the top of vessel at 135\degree 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 fixeled at 10 kA, toroidal field ($B_t$) at 0.5 T, and electron density under these conditions is about several $10^{12}$ cm\textsuperscript{-3}. The measurements reported here are taken during the plateau regime of the plasma current.

![Image](image_url)

Figure 1: Typical discharge condition signal. The experiment was conducted during plasma flat-top (2.7 ms). 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. 1e is H\textsubscript{\alpha} emission brightness. The toroidal field for this hydrogen discharge was 0.5 T.

A single channel of the photodiode monitor with an interference filter with a passband centered on the hydrogen H\textsubscript{\alpha} line is used for shot by shot measurements of H\textsubscript{\alpha} emission distributions. The spectral line radiation from the 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, photodiode and an operational amplifier are housed all together inside a metallic cylinder. The experimental results are obtained during flat top of plasma current when a totally ionized plasma is formed. At the beginning of the discharge the appearance of a peak value for the H\textsubscript{\alpha} line is considered as hydrogen molecular continuum radiation, as can be seen on Fig. 1-e. The continuum can be omitted during the plasma current plateau. A high gain amplifier is applied at the entrance of the acquisition system.

III. H\textsubscript{\alpha} spectral profiles

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

$$\epsilon (r, \theta, \varphi) = \left[ \epsilon_{\ell} \exp \left( - \frac{\varphi}{\varphi_0} \right) + \epsilon_o \right] \epsilon_0 (r) (1 + \beta \cos \theta)$$ \hspace{1cm} (1)

where $\epsilon$ is the local emission, $r, \theta$ and $\varphi$ are, respectively, the minor radius, poloidal and toroidal coordinates. The limiter is localized at $\varphi = 0\degree$, and subscript $\ell$ and $w$ means limiter and wall contributions. In our experiment the distance from the detector to plasma edge was fixed in such way that have no dependency on minor radius. The toroidal component is represented as an experimental decay from a peak value at the limiter ($\epsilon_\ell, \varphi_0$) to a wall value $\epsilon_0$. The decay is given by the corresponding toroidal angle, $\varphi_0$. Under these assumptions Eq. (1), can be replaced by:

$$\epsilon (\varphi, \theta) = \left[ \epsilon_{\ell} \exp \left( - \frac{\varphi}{\varphi_0} \right) + \epsilon_o \right] (1 + \beta \cos \theta)$$ \hspace{1cm} (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, \( (\epsilon_T, \epsilon_w)(1 + \beta) \) at the limiter, and then decays exponentially to a constant minimum value \( \epsilon_w(1 + \beta) \) 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 \( H_\alpha \) radiation in the midplane. The value peaks at limiter \( (\varphi = 0^\circ) \) and then decays exponentially to \( \epsilon_w(1 + \beta) \).

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

\( H_\alpha \) 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, \( \Sigma \epsilon_T \), and from the wall, \( \Sigma \epsilon_w \), are presented in Fig. 4 and Fig. 5 respectively. The decay angle, \( \varphi_0 \), is less than \( 20^\circ \) during plasma flat-top as can be seen in Fig. 6. Fig. 7 presents \( \varphi_0 \) profile with electron density taken by Langmuir probe measurements.

Figure 4: \( \Sigma \epsilon_T/\Sigma \epsilon_w \) profile versus electron density.

Figure 5: \( \Sigma \epsilon_T/\Sigma \epsilon_w \) profile versus discharge time.
Figure 6: The decay angle, $\varphi_0$, versus discharge time. It is less than 20°.

Figure 7: The decay angle, $\varphi_0$ versus electron density.

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

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

Figure 10: $\beta$ factor versus electron density.
III.3 Poloidal distribution

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

IV. Global particle confinement time $\tau_p$ and recycling rate $R$.

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

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

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:

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

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

$$R = \frac{\Sigma S_i}{\eta_e} \tau_p.$$  \hspace{1cm} (5)

Therefore, we have

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

The electron source $\Sigma S_i$ can be determined by measuring H$_\alpha$ emission and it is directly proportional to the H$_\alpha$ 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 $\Sigma S_i$ can be obtained from spatially resolved measurements of the electron density and the emission from a hydrogen spectra or H$_\alpha$ measurements. In our case, the electron density at the center is measured by microwave interferometry$^{[12]}$ and a Langmuir probe is used to get $\eta_e$ at the plasma edge. Fig. 12 shows the electron density profile with time in a typical discharge assuming a parabolic spatial profile, $n(r) = \eta_0 n[1 - (r/a)^2]$ with $\eta_0$ as center density.

In the H$_\alpha$ emission measurements, the electron source can be represented by:

$$\Sigma S_i = 2\pi \int_0^{+a} S \frac{\varepsilon_a r}{X_{13} B_{92}} dr,$$  \hspace{1cm} (7)

where $S$ is the electron impact ionization rate coefficient, $X_{13}$ is the collisional excitation coefficient for transition from level 1 to 3, $B_{92}$ is the branching ratio from level 3 to 2, and $\varepsilon_a$ is the emissivity of H$_\alpha$ line. The brightness of H$_\alpha$ line, which is related to measurement value, can be related to $\varepsilon_a$ by:

$$B_\alpha = \frac{1}{2\pi} \int_0^{+a} \varepsilon_a dr,$$  \hspace{1cm} (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:

$$\Sigma S_i = \frac{4\pi^2 r_0 S B_{92} X_{13}}{B_{92} X_{13}} B_\alpha.$$ \hspace{1cm} (9)

Johnson and Hinov$^{[8]}$ show that the ratio $X_{13} B_{92}$ is approximately independent of $\eta_e$ and $T_e$ as long as $\eta_e \leq 10^{13}$ cm$^{-3}$ and $T_e \geq 5$ eV, and it is independent of $\eta_0$. Table I shows the ratio as a function of $\eta_e$ and $T_e^{[18]}$. For the plasma parameters of TBR-I, this ratio is about 10. Now, using Eq.(4) and (9), we can write $\tau_p$ as:

$$\tau_p = \frac{\eta_e}{\Sigma S_i} = \frac{\eta_e B_{92} X_{13}}{4\pi^2 r_0 S B_{92}}.$$ \hspace{1cm} (10)

Using the values of $\eta_e$ given by Fig. 12 and $\Sigma S_i = 3.2 \times 10^3 C \cdot B_{92}$, where $C$ is the calibration factor of the detector which is determined by an absolute calibration procedure, and $B_{92}$ (from Fig. 3) in the limiter region, we can show the relationship between the global ionization rate, $\Sigma S_i$, and the electron density in Fig. 13.
According to Eq. (10) and Eq. (4), \( \tau_p \) should be independent on \( \eta_e \) if the equilibrium conditions are satisfied, but the measurements using Langmuir probe and analysis of linear relationship between the global ionization rate, \( \Sigma S_i \), and the electron density, as can be seen in Fig. 13, show that \( r_e \) increases with electron density, as shown in Fig. 14. Therefore, arbitrarily assuming steady state is unwarranted and a recycling value \( R \) should be introduced.

The global particle recycling rate, \( R_e \), is derived from the measurements of \( \eta_e(t) \) 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 temperature, \( (T_e) \) and \( Z_{eff} \) profiles with discharge time. Fig. 11a and Fig. 11b, are the profiles in the center and in the position \( r = 3.8 \) cm respectively. Fig. 11c shows the \( Z_{eff} \) profile.](image)

![Figure 12: Electron density profile versus discharge time.](image)

![Figure 13: Variation of global ionization rate versus electron density.](image)

<table>
<thead>
<tr>
<th>( T_e ) (eV)</th>
<th>( n_e ) (cm(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>10(^{11})</td>
<td>1.4  0.69  0.92  1.70  2.79</td>
</tr>
<tr>
<td>10(^{12})</td>
<td>2.8  2.06  2.58  4.24  17.98</td>
</tr>
<tr>
<td>10(^{13})</td>
<td>5.5  4.54  5.24  9.17  34.03</td>
</tr>
<tr>
<td>10(^{14})</td>
<td>11   6.98  8.09  13.19 47.75</td>
</tr>
<tr>
<td>10(^{15})</td>
<td>22   8.83 10.11 15.80 56.11</td>
</tr>
<tr>
<td>10(^{16})</td>
<td>44   10.12 11.30 16.84 54.38</td>
</tr>
<tr>
<td>10(^{17})</td>
<td>88   10.76 11.82 16.83 51.39</td>
</tr>
<tr>
<td>10(^{18})</td>
<td>177  10.54 11.84 16.19 45.28</td>
</tr>
</tbody>
</table>

Table 1: Ratio of Ionization to H\(_2\) emission (\( S/B_2 X_{13} \)) for different density and temperature.
V. Summary and conclusion

A simple technique of measuring H, radiation profiles for the 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 with 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 $\tau_p$ and $R$ with those parameters. Relative measurements of global recycling source indicate that the $H_\alpha$ emissivity is directly proportional to electron density in the range of discharge of TBR-1. It means that a linear relation of $\tau_p$ and $R$ is confirmed. This scaling relation needs to be further studied in an extensive operation parameters.

Acknowledgements

We would like to thank the 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 $H_\alpha$ detector used in the experiment. This work was supported by FINEP and CNPq.

References