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Spectroscopic studies of stationary MARFEs in TEXTOR-94

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Abstract

Long living stationary multi faceted radiation from the edge (MARFEs) have been produced in TEXTOR-94 by gas puff feed-back controlled via the impurity radiation (CII line emission) from the MARFE zone. The stabilization of the MARFE opened a possibility to investigate this phenomenon in detail on a longer time scale. The population densities of excited state of deuterium in the MARFE were estimated from Balmer series line emission. The spectrum of the continuum radiation from the MARFE core has been measured in the spectral range 450–740 nm. The plasma parameters $T_e = 1.1$–1.5 eV and $n_e = 2 \times 10^{20}$–2.1×10^{20} m^{-3} have been estimated from the measurements of the Balmer line emission, Balmer line Stark broadening and continuum radiation.

Keywords: Spectroscopy; Deuterium emission; Line radiation; MARFE; TEXTOR

1. Introduction

Operation of tokamaks at the highest density close to the density limit is often accompanied by a multi faceted radiation from the edge (MARFE) formation. In many cases, the MARFE development is a precursor of a major disruption. Such MARFEs demonstrate a non-stationary behaviour: they move along the inner wall of a tokamak, change size and brightness, can also disappear and appear again. The lifetime of these MARFEs without any feed-back stabilization is in the range of 100 ms. The MARFE acts as a pump by accumulating particles injected by the gas feed system which are ionized in the plasma layer and flow along the magnetic field lines to the MARFE zone. For this reason, gas injection does not increase the bulk plasma density but leads to a growth of the MARFE size. Therefore, the threshold for the appearance of a MARFE limits also the maximum achievable plasma density. The subsequent disruption results from an inappropriate gas feed leading to a growth of the MARFE up to an unstable size. The MARFE size can be stabilized by a feed-back controlled gas puff via the impurity radiation from the MARFE zone. The feed-back system to control the MARFE formation has been developed in TEXTOR-94 and stationary MARFEs have been produced with life times of few seconds (several tens of τ_p) [1]. The stabilization of the MARFE opened a unique possibility to investigate this phenomenon in detail, in particular, to verify the interpretation of the MARFE as a result of localized plasma recycling on the inner wall [2]. The results of such investigations by means of optical methods are presented.

2. Measurements

The MARFE investigation has been performed on the tokamak TEXTOR-94 with a siliconized wall for the following discharge parameters: $B_T = 2.24$ T, $I_p = 285$ kA, $R = 1.75$ m, $a = 0.46$ m (toroidal limiter ALT-II is a main limiter), $\overline{n_e} = 4 \times 10^{19}$ m^{-3}. The measurements

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were done in deuterium discharges with 1.3 MW NBI heating (hydrogen injection). To produce a 'fat' MARFE (the definition for 'fat' and 'thin' MARFE is given in [1]) the plasma column was shifted 1 cm with respect to a normal centred position towards the bumper limiter. To increase the plasma density the gas puffing starts at 1.21 s. The MARFE appears near the midplane of the bumper limiter at 1.3 s; then the gas puffing is feed-back controlled by the intensity of a CII (426.7 nm) line from the MARFE region. The threshold type of the feed-back was used. The line of view of the CII line detector was oriented in the toroidal direction, tangentially to the bumper limiter. The MARFE stays at the midplane position until 2.5 s; then it moves downwards and disappears at about 3.6 s. Owing to the feed-back control, such MARFE behaviour was reproducible.

Tangentially viewing CCD-cameras (color and black-and-white) were used in combination with interference filters to observe a full poloidal cross-section at the location of the poloidal limiters. Spectral measurements in the MARFE region were performed by means of a grating spectrometer with an image intensified CCD-camera sensitive down to 200 nm. The viewing optics collected light along a tangential chord passing through the region near the bumper limiter. The image of the entrance slit of the spectrometer has been oriented radially along the equatorial plane of the torus. The spectral interval covered by the CCD-camera was about 21 nm (0.03 nm per pixel), the instrumental half width was 0.17 nm for these measurements. The radial resolution was about 0.3 cm. The CCD-cameras had a standard video output – 20 ms per half frame, integration time for colour and black-and-white cameras was, respectively, 20 and 1 ms. The image intensified CCD-camera has 40 ms integration time. The video data were digitised and stored on PC equipped with a 8 bit video grabber.

A 4-channel photodiode system with interference filters viewed radially a 570×110 mm^2 area of the bumper limiter and measured simultaneously the absolute intensities of D_α (656.1 nm), D_β (486.0 nm), D_γ (433.93 nm) and CII (426.7 nm) lines with a time resolution of 0.1 ms. The longer side of the observation area was oriented in poloidal direction.

Both the spectrometer and photodiode system were absolutely calibrated with the help of a standard light source (Ulbricht sphere equipped with a halogen lamp).

There are also channels of the electron cyclotron emission (ECE) diagnostic (time resolution 0.1 ms) which received electron cyclotron radiation from the high-field side by means of an antenna mounted inside the bumper limiter. The signal of the 130 GHz ECE was used for the detection of the MARFE onset owing to a cut-off signature when the electron density in the region between antenna and emission volume ($R = 168.5$ cm) reached a critical value of about 1.8×10^{20} m^{-3}.

3. Experimental results and discussion

3.1. Line ratios and particle densities

The 130 GHz ECE signal, CII (426.7 nm) line intensity, D_α intensity and intensity ratios of D_β/D_α and D_γ/D_α are shown in Fig. 1. First the ECE signal drops at 1.3 s within 8 ms, then the line intensities and their ratios start to increase and reach their maximums at 1.35 s. Both ratios increase when the MARFE develops: the ratio for D_β/D_α grows from 0.13 to 0.24 and for D_γ/D_α from 0.02 to 0.09. Then the ratios decrease slightly and stabilize at 1.37 s. The D_α intensity strongly varies in time during the MARFE but the ratios are practically constant

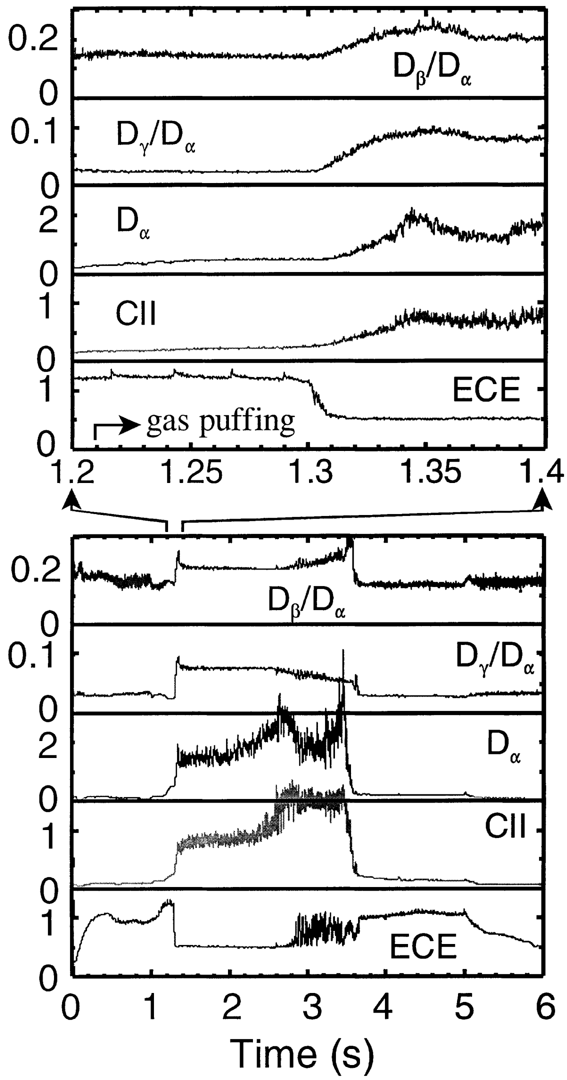

Fig. 1. Time trace of ECE (a.u.), CII (426.7 nm) line intensity (a.u.), D_α intensity (10^{19} photon/m^2 sr s), D_γ/D_α and D_β/D_α intensity ratios (#82306).

($D_\beta/D_\alpha = 0.2$ and $D_\gamma/D_\alpha = 0.075$). Similar values for the D_γ/D_α ratio have been obtained on JET [3]. The observed fluctuations of the Balmer line intensities is the result of the MARFE volume variation because the poloidal extension of the MARFE (about 300 mm) was essentially less than the observation area in poloidal direction. These fluctuations correlate with operation of the gas feed system. When the deuterium gas feed is switched on, the intensity of the Balmer line increases, when it is switched off, the Balmer line intensity decreases.

The spectra of the plasma radiation in the MARFE have been measured in the spectral range of 240–740 nm by the spectrometer mentioned above in series of reproducible discharges. The relative line intensities of the Balmer series from D_γ to $D_{9\to 2}$ have been deduced from the spectra. The typical spectrum of D_ε, $D_{8\to 2}$ and $D_{9\to 2}$ Balmer series lines is shown in Fig. 2. These intensities measured for the chord intersected bumper limiter and those intensities measured by the photodiode system were used for the population density calculation. The population densities were estimated using an observed MARFE size of 2×30 cm^2 and are shown in Fig. 3 as a function of principal quantum number. They have been evaluated at 1.1, 1.28 and 2 s which correspond to periods before gas puffing, before the MARFE with gas puffing and during the stationary MARFE. It is clearly seen that the population is remarkably different inside the MARFE. The population densities decrease with principal quantum number before the MARFE onset but they increase inside the MARFE. Such behaviour directly indicates that these levels are populated through a recombination process [4,5]. For this reason, the lines of the Balmer series cannot be used for the flux measurement of neutral deuterium into a MARFE.

The deuterium flux estimated from D_α line intensity shown in Fig. 1 for the time of 1.28 s (before MARFE onset) is 1.2×10^{21} m^{-2} s^{-1}.

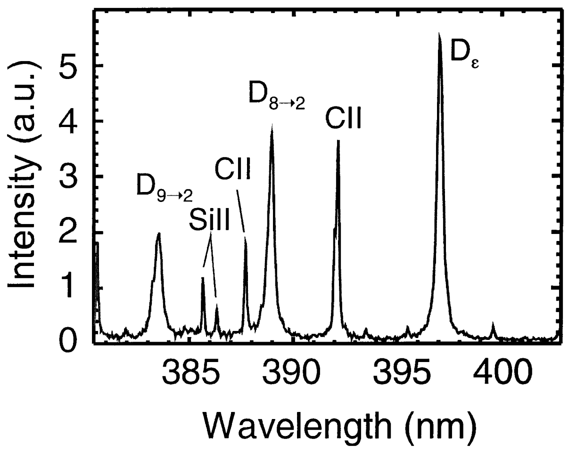

Fig. 2. Spectrum of the Balmer series lines in MARFE ($t = 2$ s, #82304).

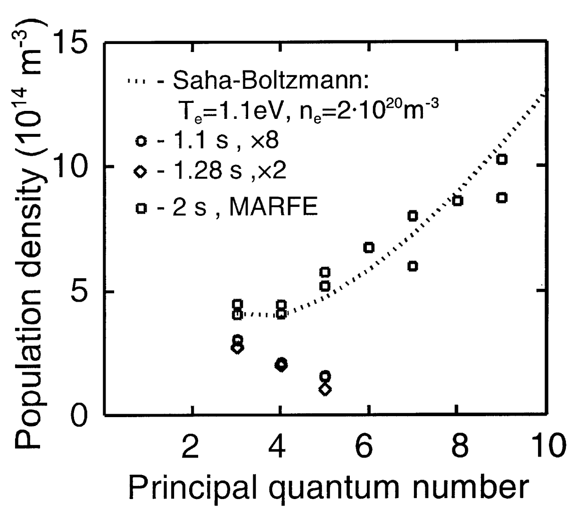

Fig. 3. Population densities of atomic deuterium levels at the bumper limiter region. The symbols indicate the measurement, dotted line – Saha–Boltzmann equation with $T_e = 1.1$ eV, $n_e = 2 \times 10^{20}$ m^{-3}.

3.2. Plasma parameters

To measure the plasma parameters in front of the bumper limiter the thermal helium beam installed at the high field side was used [6]. This beam was in the line of view of our spectrometer. The HeI (667.8 nm/706.5 nm/728.1 nm) line intensities were measured. The line ratios at 10 mm in front of the bumper limiter were HeI (667.8 nm)/HeI (728.1 nm) = 9.5 and HeI (728.1 nm)/HeI (706.5 nm) = 0.36 at 1.28 s (before MARFE onset). The accuracy for these values is estimated to be about 10%. So, comparing calculated [7] and measured line intensity ratios the plasma parameters are found to be $T_e = 17$, eV $n_e = 5 \times 10^{19}$ m^{-3} with an error of about +12 eV/−1 eV and $+1.6 \times 10^{19}$ m^{-3}/ $- 2.8 \times 10^{19}$ m^{-3}. The errors are rather large because the line ratio HeI (667.8 nm)/HeI (728.1 nm) is a strong function of the electron density in this density range.

The profiles of the electron density and temperature inside the MARFE were evaluated from Stark broadening and the volume emission of the Balmer series line $D_{9\to 2}$ (383.4 nm). Abel inversion was performed to obtain the volume emission profile from the measured line integrated intensity profile as the MARFE has a toroidal symmetry and the observation chords were perpendicular to the major radius. Then, the electron density was estimated using the expression from [8]:

$$\Delta\lambda_n = 2.5 \times 10^{-14} \alpha^n_{1/2} n_e^{2/3}, \tag{1}$$

were $\Delta\lambda_n$ is the full width at half maximum (FWHM) of the Stark broadened line profile (in nm), $\alpha^n_{1/2}$ – half width of calculated Stark profile and n_e – electron density (in m^{-3}).

The FWHM was determined from the ratio of the total line emission to the emission in the line centre. Due to NBI heating the concentration of hydrogen in the discharge was about 40%. The presence of hydrogen produced an apparent line broadening of about 0.1 nm due to the isotopic shift between the hydrogen and deuterium lines; this effect was taken into account.

An estimation shows that the highest excited states of hydrogen and its isotopes satisfy the conditions for partial local thermodynamic equilibrium inside the MARFE and, consequently, the population density of these states is determined by the Saha–Boltzmann equation. Neglecting impurities and taking into account that the ionization energy of the highest excited states ($n > 8$) is much smaller than the expected electron temperature the Saha–Boltzmann equation can be rewritten:

$$\frac{n_e^2}{n_n} = 3 \times 10^{27} \frac{T_e^{3/2}}{n^2}, \quad (2)$$

where n_n denotes the population density of the level with principal quantum number n, T_e-electron temperature in eV, n_e and n_n in m^{-3}.

The profiles of the plasma parameters in the MARFE evaluated by this procedure are shown in Fig. 4 together with profiles measured on the low field side by a thermal helium beam diagnostic. The electron density inside the MARFE reaches values of about 2×10^{20} m^{-3} whereas the electron temperature drops to about 1.1 eV. This result is in good agreement with the measured population density distribution seen in Fig. 3 where the dash line indicates the population distribution calculated with

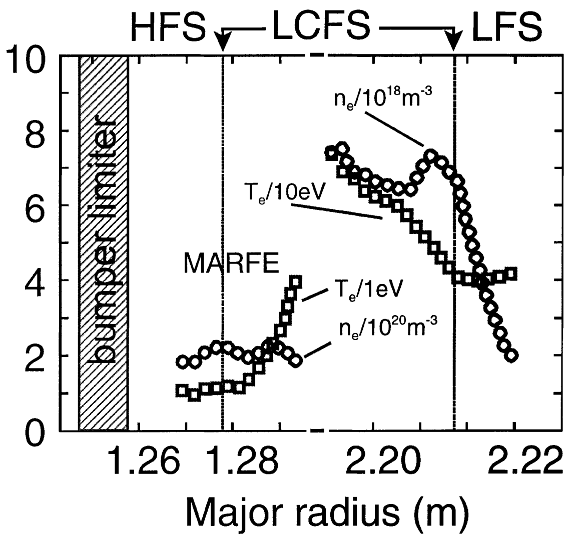

Fig. 4. Measured electron density and temperature profiles at the high field side (HFS) and low field side (LFS) during a MARFE ($t = 2$ s, #82304).

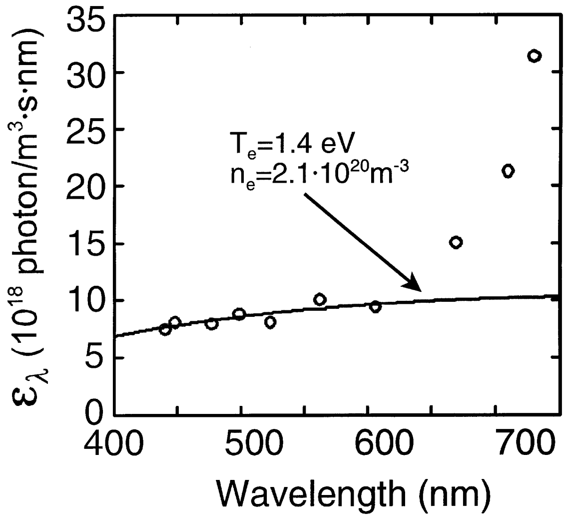

Fig. 5. Spectrum of the continuum emission in the MARFE core ($t = 2$ s, #82308–82319).

the help of Saha–Boltzmann equation for these plasma parameters.

The continuum radiation was clearly seen on the all recorded spectra. A spectral interval of 1.2 nm was used for these measurements. The position of this spectral interval was carefully selected to avoid interference by impurity line radiation. The radial profiles of the continuum radiation were measured and the volume emissivities were calculated by means of an Abel inversion procedure. The continuum intensity in the MARFE core within the visible spectral range from 450 to 740 nm is shown in Fig. 5. The continuum intensity slowly increases with wavelength (an increase of about 30% from 450 to 600 nm), but stronger from 600 to 730 nm by a factor of three. The reason for a sharp increase of the continuum intensity in the near infrared is unknown and is a task for future investigations. The experimental points within 450–600 nm were fitted by a formula for the continuum radiation of a pure hydrogen plasma from [9]. This curve for $T_e = 1.4$ eV, $n_e = 2.1 \times 10^{20}$ m^{-3} is shown in Fig. 5. The D_γ volume emission in the MARFE was measured and shown in Fig. 6 together with CII (426.7 nm), CIII (418.7 nm). The ratio of the D_γ volume emission to continuum volume emission (within a 10 nm band) in the MARFE core is 14 which corresponds to $T_e = 1.5$ eV according to the data of the paper [10]. Thus, the plasma parameters of the MARFE measured by three different methods are in a good agreement within the errors of the measurement.

3.3. Molecules

Usually, an increase of plasma flux to the surface is accompanied by the enhancement of the molecular re-emission [11]. An increase (about 4–5 times) of emission

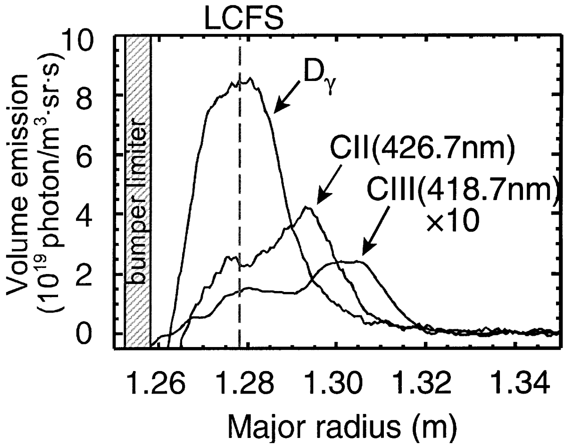

Fig. 6. Volume emission profiles of D_γ, CII (426.7 nm) and CIII (418.7 nm) lines from HFS during MARFE ($t = 2$ s, #82302, #82306).

from CD (CH) and C_2 molecules was observed in a narrow layer about 0.5 cm close to the bumper limiter surface during the MARFE. This observation confirms the increase of the plasma-wall interaction in the vicinity of the MARFE. The CD bands have an essentially higher brightness in comparison with C_2 bands. In contrast to the hydrocarbons, the molecular deuterium emission strongly decreases just 20 ms prior MARFE formation and could practically not be seen during the MARFE. To distinguish the reasons for this reduction of molecular deuterium emission, molecular hydrogen was puffed through the hole at the midplane of the bumper limiter. The spectra recorded in the range of the Fulcher band of molecular hydrogen during gas puffing without and with MARFE are shown in Fig. 7. The Fulcher band emission drops strongly (at least 10 times)

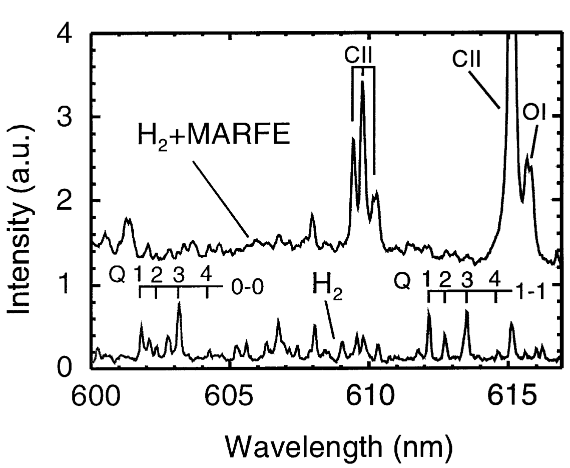

Fig. 7. Spectra measured during hydrogen puffing from the bumper limiter side without and with MARFE ($t = 4$–4.5 s, #82633, #82634).

inside the MARFE and is practically invisible on the continuum radiation. The reduction of the Fulcher band emissivity under such plasma parameters is in a good agreement with a prediction of a collisional-radiative model for molecular hydrogen developed by [12]. Additionally, charge-exchange between hydrogen (deuterium) molecules and ions can also essentially reduce the photon emission of these molecules.

4. Conclusions

In a core of the 'fat' MARFE $T_e = 1.1$–1.5 eV and $n_e = 2 \times 10^{20}$–2.1×10^{20} m^{-3} have been estimated from the measurements of Balmer line emission, Balmer line Stark broadening and continuum radiation.

The deuterium flux from the bumper limiter and plasma parameters in front of the bumper limiter 20 ms prior to the MARFE formation were, respectively, 1.2×10^{21} m^{-2} s^{-1}, $T_e = 16$–29 eV and $n_e = 2.2 \times 10^{19}$–6.6×10^{19} m^{-3}.

In the MARFE the excited levels of deuterium atoms with principal quantum numbers $n > 2$ are mainly populated via recombination and cannot be used for measurements of the neutral particle flux.

The emissivity of the Fulcher band of molecular hydrogen strongly reduces for MARFE plasma conditions so that the molecular hydrogen (deuterium) flux could not be measured due to the strong continuum background. The enhancement of the hydrocarbon emission confirms the increase of a plasma-wall interaction in the vicinity of the MARFE.

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