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Determination of q=1 surface by the variation of pellet ablation rate on the HL-1M

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Strong drop of $H\alpha$ emission has been observed on the HL-1M tokamak by means of a detector array while a pellet crosses the q=1 surface. In this article, the q=1 surface has been determined precisely by the interval and the shape of the $H\alpha$ emission striations on the pellet trajectory due to the variation of pellet ablation rate. The q-profile and current density distribution at the plasma centre region have been calculated according to the pellet ablation rate and the magnetic shear feature.

Keywords: q=1 surface, pellet, $H\alpha$ emission, ablation rate
PACC: 5270

1. Introduction

In tokamak research, the current density profile and the safety factor profile are two important plasma parameters. They will directly influence plasma transport processes and plasma instability. Reliable measurement of the q-value is needed especially for controlling the bootstrap current with respect to an advanced tokamak, for active control of plasma instability and for the improvement of plasma confinement.

On many tokamak devices, the q-profile is usually determined with an equilibrium code based on magnetic measurement. With the development of fusion research, other diagnostic techniques for measuring the q-profile have been developed. For example, the Zeeman effect,[1,2] Faraday rotation [3] and motional Stark effect,[4–6] and so on. In particular, motional Stark effect polarimetry has played and continues to play an important role in current density measurement and stability and current drive studies. In pellet fuelling experiments, a method for determining the q-profile by means of the inclination angle of the magnetic field lines along the pellet path has been used in the ASDEX-U, TEXT and T-10 tokamak.[7,8]

In all large tokamaks (JET,[9], TFTR [10] and JT-60 [11]), a striation phenomenon for pellet ablation cloud has been observed and used to measure the q=1 surface. This suggests that the local limitation of the ablation rate at the dark region of the striation could be related to the crossing of resonant magnetic surface by the pellet. A quantitative analysis of this mechanism [12,13] has pointed out that the width and the depth of the observed striations might be connected with local flattening of the q-profile around the rational q-value. This interpretation is strongly supported by observation of a very dark striation when the pellet crosses the q=1 surface. In order to observe and research the phenomenon further, a detector array for $H\alpha$ emission is set up on HL-1M. The phenomenon exhibits that the pellet ablation rate is reduced abruptly when the pellet crossing the q=1 surface has been observed. The q=1 surface has been determined and compared with the result obtained from a soft x-ray sawtooth.

2. Experimental condition

The pellet fuelling experiments were completed in the HL-1M, which is a tokamak device with circular cross-section (major radius R=1.02m, minor radius a=0.26m, toroidal magnetic field $B_{\rm T}$=2–3T and plasma current $I_{\rm p}$ $\leq$350kA) and with two full graphite limiters at a distance of 180° in the toroidal direction. Figure 1 shows the experimental arrangement for pellet injection on the HL-1M. In the pellet fuelling experiment, pellets of solid H_2 with a diameter of 1–2mm

were injected into the plasma on the mid-plane along the major radius from the weak field side.[14] The pellet had a velocity about 1km s^{-1}. It contained an atomic inventory of about 4.5×10^{19} (when the pellet diameter was 1mm). Pellet ablation duration was less than 400μs. The pellet ablation pattern was obtained by an optical measurement technique. A detector array with 20 PIN diodes was located on the top port above the pellet injection lines and on the same poloidal cross-section. The detector system consisted of the slit, interference filter, detectors and preamplifiers and made up a pinhole camera for $H\alpha$ emission. The centre wavelength of the interference filter was 656.3 nm. The lines of sight for the detector array covered the whole plasma cross-section.

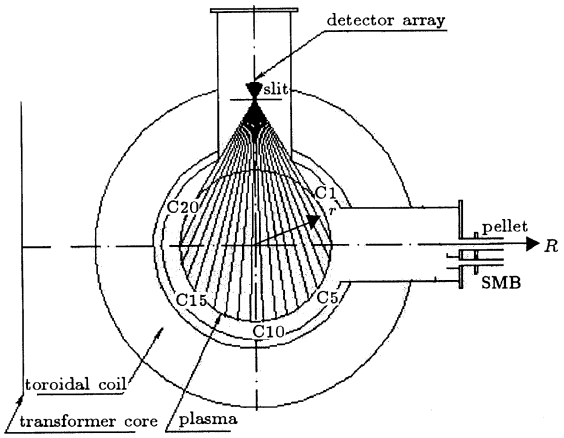


Fig.1. The experiment location for pellet injector and detector array.

3. Ablation feature and shear on the q=1 surface

According to the linearity relationship between pellet ablation rate and $H\alpha$ emission intensity, the pellet ablation rate can be represented directly by the variation of the $H\alpha$ emission intensity. When a pellet is injected into the plasma, the pellet ablation rate pattern, as shown in Fig.2, is usually obtained. Figure 2 shows the evolution of $H\alpha$ emission intensity observed from the pellet injection direction. There is a strong drop for $H\alpha$ emission appearing between A_1 and A_2, which represent two $H\alpha$ emission striations for the pellet ablation cloud. They are caused by the change of ablation rate when the pellet is crossing the region of the q=1 surface. According to the limited influence of magnetic shear, the q-value should be less than 1.0 at $r < r_1$ (r_1 is the radius for the q=1 surface). After the magnetic line turns one circle along the toroidal direction, simultaneously it rotates more than one circle around the poloidal direction. In contrast, the rotation around the poloidal direction will be less than one circle for $r > r_1$. The case corresponds to the two $H\alpha$ emission peaks (A_1 and A_2) appearing in Fig.2. If the q=1 surface is located at $r = r_1$, the magnetic shear at r_1 can be represented as follows:[12]

$$\left(\frac{\mathrm{d}q}{\mathrm{d}r}\right)_{r1} \approx \frac{r_{\mathrm{P}}}{\pi r_1 \Delta}, \qquad (1)$$

where r_{P} is the radius of the pellet ablation cloud and Δ is the distance between A_1 and A_2, which is relative to the width of magnetic shear at the q=1 surface in the major radius direction.

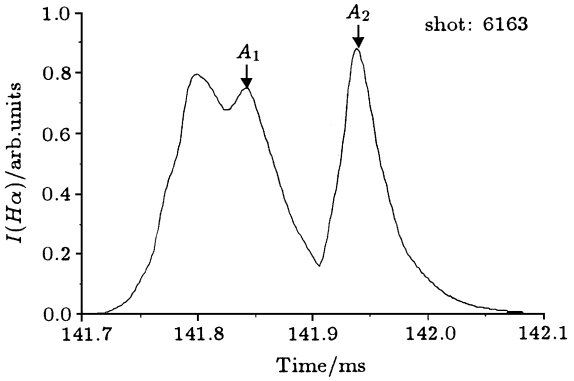


Fig.2. The temporal evolvement of $H\alpha$ emission signal from pellet ablation cloud when a pellet crosses the q=1 surface.

The magnetic lines around the q=1 surface form a magnetic flux tube. When a pellet is passing through the flux tube, only a limited amount of electrons in the closed flux tube can interact with the pellet ablation cloud. So the pellet ablation rate becomes a little weaker. However, the magnetic lines on a non-rational magnetic surface are not closed, hence the thermal flux obtained by the pellet will be much larger than that on the rational surface. In practical measurement, we have noted that the reduction of the pellet ablation rate around the q=1 surface is very obvious, but the variation of the pellet ablation rate on other rational surfaces excluding the q=1 surface is not obvious. Possibly this is due to the spatial resolution for the detector array being 3cm, such that the variation of the ablation rate within the range of 3 cm cannot be detected. On the other hand, the magnetic shear on other rational surfaces is larger than that on the q=1 surface, and as a result the width of the magnetic surface is narrower. In this case, it is not easy to detect the variation of the ablation rate by the detector array.

However, the magnetic shear near the q=1 surface is smaller, i.e. $\frac{a}{r_1}\frac{\mathrm{d}q}{\mathrm{d}r} \ll 1$, it follows that the width of the magnetic surface is wider, and the variation of the pellet ablation rate becomes remarkable.

4. Determination of q=1 surface

Figures 3 and 4 show the multi-channel $H\alpha$ emission signals from the pellet ablation cloud, which come from the same pellet as shown in Fig.2. They represent the evolution of $H\alpha$ emission intensity with the different channels and different times. The q=1 surface can be determined by the position at which the $H\alpha$ emission drops sharply in Figs.3 and 4. The q=1 surface is located at about r=4cm. In addition, the connected line between the tops of $H\alpha$ emission peaks obtained from the different detector channels in Fig.4 displays the pellet moving track. The average pellet velocity after the pellet enters the plasma can be estimated from the moving track; it is about 1km s^{-1}. Figure 5 shows the multi-channel sawtooth signals from soft x-ray emission. The q=1 surface can be estimated by the sawtooth reversed surface. The reversed radius is about 5.5cm from Fig.5, therefore the q=1 surface is located at about $\frac{5.5}{\sqrt{2}} \approx$3.9cm. The results from the two kinds of measurements are consistent with each other. This indicates that the method of determining the q=1 surface by means of the variation of pellet ablation rate is simple and feasible.

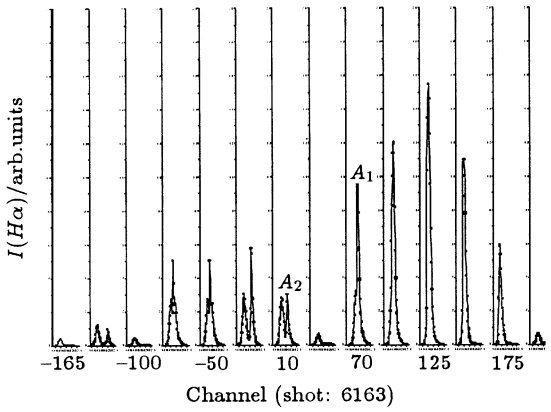


Fig.3. Evolution of $H\alpha$ emission with different detected channels.

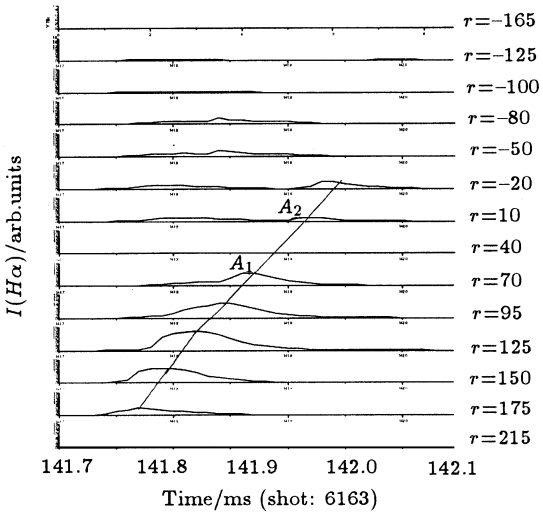


Fig.4. Evolution of $H\alpha$ emission observed in different channel with time.

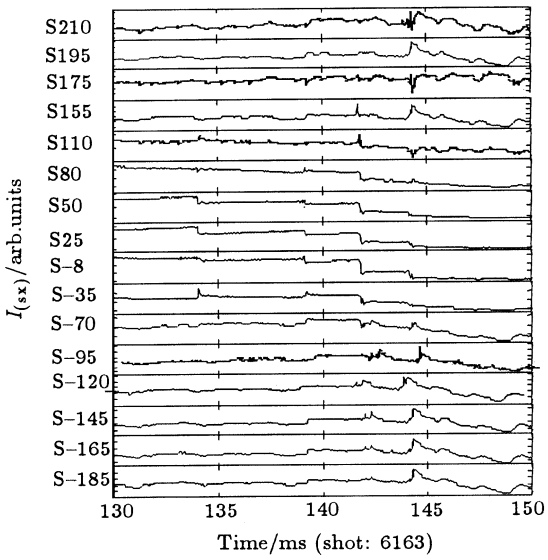


Fig.5. Evolution of soft x-ray sawtooth signals with time.

5. Determination of q-value at plasma centre

First, we assume that the q-profile within the q=1 surface has a form of

$$q(r) = q_0 + (1 - q_0)\left(\frac{r}{r_1}\right)^2. \qquad (2)$$

The relation between the magnetic shear at q=1 surface and the q-value (q_0) at the plasma centre is as follows:

$$\left(\frac{\mathrm{d}q}{\mathrm{d}r}\right)_{r_1} = \frac{2(1-q_0)}{r_1}. \quad (3)$$

An expression of the q_0-value based on Eqs.(1) and (3) can be obtained as

$$q_0 = 1 - \frac{r_\mathrm{P}}{\pi\Delta}, \quad (4)$$

where d_P=1.2mm (pellet diameter) and r_P ≈2.1–3.5 d_P. If we take r_P ≈3.0d_P, and Δ=60mm from Figs.3(a) and (b), then q_0 will equal 0.98 from Eq.(4). Note that Eq.(4) is only used when the sawtooth has not crashed.

6. Determination of $q(r)$ and $j(r)$ in the plasma core region

In the pellet fuelling experiment corresponding to Figs.2 and 3, the plasma parameters are I_p=140kA, B_t=2.1T, T_e=600eV, n_e=2.4×10^{13}cm^{-3} and $q(a)$=3.7. After q_0 is obtained, the q-distribution in the radial direction near the q=1 surface can be calculated according to formula (2). The result is shown in Fig.6.

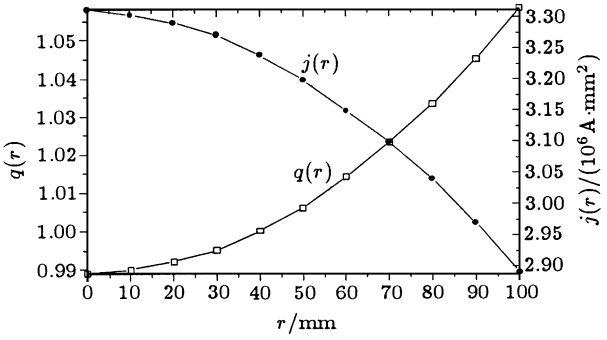


Fig.6. The q distribution and the current density distribution at the plasma core region.

In addition, the current density distribution $j(r)$ can also be expressed by

$$j(r) = \frac{B_t}{\mu_0 R q(r)}\left[2 - \frac{r}{q}\frac{\mathrm{d}q}{\mathrm{d}r}\right] = \frac{B_\mathrm{t}}{\mu_0 R q(r)}[2 - \hat{S}(r)], \quad (5)$$

where the shear value is

$$\hat{S}(r) = \frac{2(1-q_0)\left(\frac{r}{r_1}\right)^2}{q_0 + (1-q_0)\left(\frac{r}{r_1}\right)^2} = 2 - \frac{2q_0}{q(r)}. \quad (6)$$

In the near magnetic axis region, Eq.(5) can be rewritten as

$$j(r) = \frac{2B_\mathrm{t} q_0}{\mu_0 R q(r)^2}, \quad (7)$$

where $\mu_0 = 4\pi \times 10^{-7}$, R=1.02m and B_t=2.1T. The $j(r)$ near the q=1 surface can be calculated by Eq.(7). The result is shown also in Fig.6.

7. Summary

In the pellet injection experiment of HL-1M, we have used a simple method to determine the q=1 surface. We have obtained more data which are similar to Fig.2 under the condition that the q=1 surface exists and the pellet has not been broken during the injection process. In this article, the q=1 surface has been determined by means of the interval between the $H\alpha$ emission striations on the pellet trajectory. The results are consistent with that from the reversed radius for soft x-ray sawteeth. This indicates that this method is feasible. In practical measurement, the spatial resolution of the detector array in the major radial direction is only 3 cm. In order to obtain a more precise result, it is necessary to increase the number of detecting channels. There are already many kinds of methods to measure the q-value and the current density profile on many tokamak devices. They have respective excellence and shortcomings, and their measurement principles and measuring equipment are usually complicated. In particular, in the 1990s, a new diagnostic method (motional Stark effect polarimetry) was developed which, to date, has been the best method for current density distribution measurement. The method for determining the q=1 surface described in this article is simpler. It can produce more data comparable to other diagnostic methods in a q-measurement database.

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