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Analysis of Pellet Ablation and Penetration in HL-1M Tokamak

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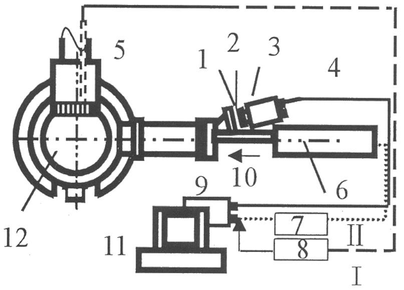
1.Introduction

Pellet injection is proposed as a possible refueling way in steady state fusion reactor, pellet-plasma interactions produce various complex phenomena, The particle and energy confinement are improved during pellet injection.

Frozen pellet injected into plasma is exposed to direct action of energetic particles. During ablation, the H_α light emission accompanies. The local ablation rate is often deduced from the time dependent H_α signal, so usually the penetration depth as an injecting characteristic parameter is detected by the temporal and spatial evolution of H_α line emission intensity and the trajectory and expansion geometry of the ablated cloud are studied photographically. As the inclination angle of elongated cloud is correlated with the magnetic field, it is possible to measure the q(r)-profile (1)



1Interference filter2.Zoom lens 3..CCD camera 4. Optical fiber 40m long 5. H_α detector array 6. Multi-pellet injection system 7.Delay unit 8.Electronics unit 9.Data acquisition system 10.Pellet injection direction 11. PC 12. Plasma

I : Trigger mode H_α /SXR signal

II : Trigger mode from V_p-measuring unit

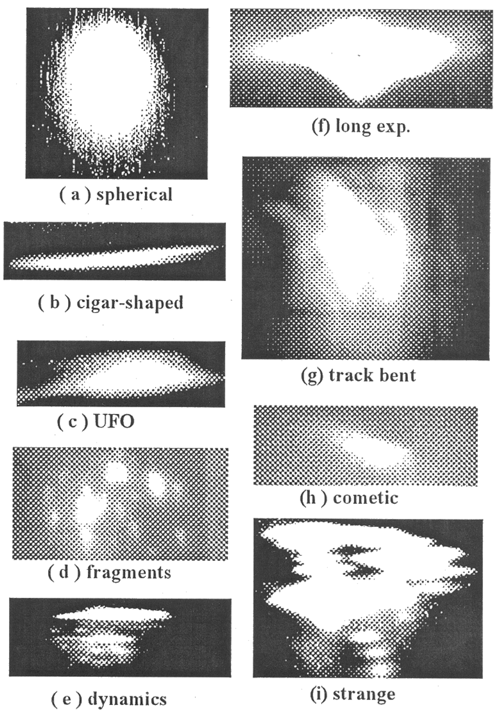
Fig.1. Experiment setup

2 Experimental setup

In pellet injecting experiments on the HL-1M tokamak, the whole experiment arrangement is shown in Fig.1. Hydrogen multiple pellets (2×Φ1.0mm, 3×Φ1.2mm, 3×Φ1.2~1.3mm) are horizontally injected into the plasma. (2) On the top port of the device a H_α emission detector array with 20 channels of PIN diodes is located and on the same cross section with the pellet injecting port. Data acquisition frequency is 100kHz. Sight of the array can cover whole the plasma cross section. Supported by IAEA, the 2D CCD camera (SensiCam 360LF made by the PCO company in Germany (3)) and adjustable support are mounted above the pellet injection path at viewing angle 13.4° to observe pellet ablation. In front of the camera there are zoom lens (f/1.4) and H_α optic filter (λ_0=656.3nm, FWHM=7nm). Signals taking from laser measuring-pellet-velocity unit and from the H_α/SXR emission diagnosis are chosen as. CCD trigger pulses. After electronics disposing, the later is more exact and suitable for CCD timing. As the image file format (b16) in this type of camera is a non-general binary mode to store data, so proper related software is developed for data processing and drawing.

3.Experimental results

3.1 Pellet cloud shape and dimension



(a) spherical (b) cigar-shaped (c) UFO (d) fragments (e) dynamics (f) long exp. (g) track bent (h) cometic (i) strange

Fig2 ablation cloud imagines

HL-1M is a circular cross-section tokamak with an iron core transformer. Its major and minor radii are 1.02m and 0.26m. During the pellet injecting discharge plasma current was 120~250kA, toroidal magnetic filed was 2.2~2.7T, target electron density was $0.3\sim3.5\times10^{19}m^{-3}$. The most typical shapes of the ablation clouds were "spherical", "cigar-shaped", "dynamics", "fragments", "UFO" and so on, as listed in Fig.2. Spherical shape means pellet ablated only in the outer plasma region with slow velocity, while cigar-shape indicates cloud went into deeper area. The typical lengths were 50~90mm along the magnetic field and widths perpendicular to it 5~10mm(Fig2 (b)). Dynamics shape (Fig2 (e)) was very useful to analyze pellet movement. We also observed many fragments dispersed in all directions (Fig 2(d)). They already took place in the gun or traveling in the guide tube.

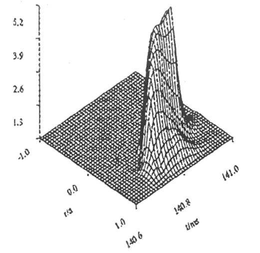


Fig.3a Evolution of radial profile. for $H\alpha$ emission

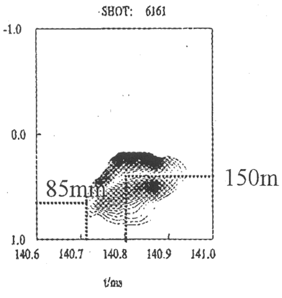


Fig.3b Contour plot for Fig.3a

In Fig.2 (f) (exposure>ablation duration), time-integrated image illustrated the whole pellet ablation process: first in the boundary the cloud radiation intensity was very weak due to small n_e and T_e, then spherical shape, and then sharp cigar-shaped, finally disappeared. In some photos (Fig2 (f) (g)), we can see instead of being straight the pellet trajectory bent towards the ion current side. The reason of track bending is a rocket effect driven by the superthermal electrons that were detected in hard X-ray diagnosis.

3.2 Measurement of pellet penetration depth

The radial profile for H_α emission intensity along the pellet injecting direction has been measured (see Fig.3). Fig.3b is the contour plot. According to the neutral gas shield model, during ablating the pellet is always surrounded by the neutral gas cloud. The H_α emission peak from the neutral gas cloud is moved with the pellet, and then it will indicate the position of the pellet. It is shown in Fig.3b that the pellet entered into the plasma at about 140.6ms and reached the position of 85mm from the plasma edge at 140.71 ms, finally, it was ablated completely in the position of 150mm at 140.8ms. The 150 mm was considered to be the pellet penetration depth (that was 0.6 normalized by the minor radius). The penetration depths under different discharge conditions were between 110mm and 260mm on the HL-1M tokamak.

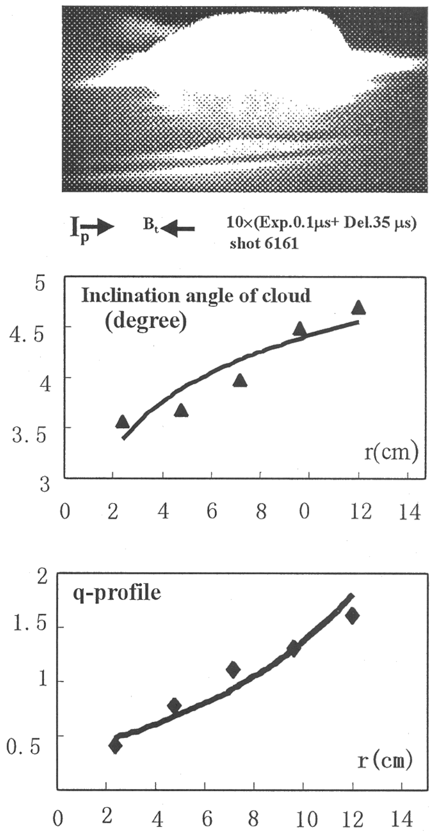


Fig.4 q-profile estimation

3.3. Q-profile estimation in HL-1M device

The safety factor q (r) is defined as

$$q(r)=\frac{d\Phi_T}{d\Phi_p}=\frac{1}{2\pi}\oint\frac{B_T}{R\cdot B_\theta}ds_p \qquad (1)$$

where Φ_p, $B_\theta(r)$ and Φ_T, $B_T(r)$ are the poloidal and toroidal magnetic fluxes, inductions, R is the major radius, ds_p is the poloidal section on the flux surface.

The inclination angle $\alpha(r)$ is a local quantity whereas the safety factor q(r) is an integrated quantity.

t(ms)	100	119	143	175	220
$N_e(10^{13}cm^{-3})$	0.2	2.3	3.27	1.83	0.48
T_e(ev)	620	400	500	560	650
ξ	9.1	18	20	16	9.6
τ_{p2}/τ_{p1}	1	1.72	2.04	2.64	2.12

Table1.Relative variation of global particle confinement times

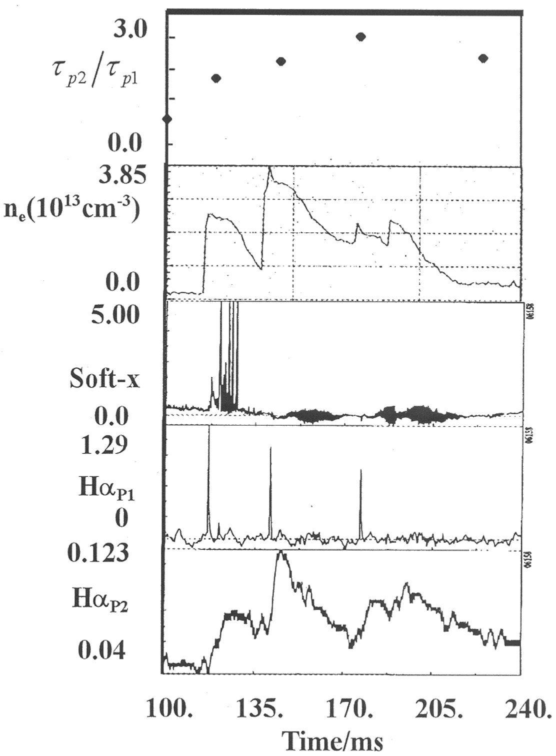


Fig 5 Evolution of the electron density, soft-x-ray and H_α emission during the pellet injection

Considering the injection geometry, safety factor q (r) may be approximately expressed as

$$q(r) = \frac{r}{R}\left(1+\frac{r}{R}\right)\bullet\frac{\cos\beta}{tg\alpha'} \qquad (2)$$

with R and r being the major and minor radius, β and α' (r) being CCD viewing angle and cloud inclination angle respect to the torus midplane. So long as the torus midplane line is determined, the pitch angle α of different radial position, and thus q-profile is estimated.

In order to obtain q-profile from photograph, the following procedure was applied: Firstly took the background picture before pellet injection. The torus midplane line of the HL-1M tokamak was determined from the horizontal welding line in the picture. Secondly, set proper exposure and delay time for CCD camera and took photo. Fig.4 shows the multi-exposure photo of ablation cloud corresponding to shot 6161 with I_P=150kA, B_T=2.5T, $n_e=1.3\times10^{19}m^{-3}$ and Vp=686m/s. In this shot the pellet ablated and penetrated deeply, so the center of the plasma was reached. The cloud light intensity in the photo was converted into a two-dimensional imagine by means of the related software. By linear regression, the points of maximum intensity were fitted into a straight line that was considered the cloud inclination line. In this way α' (r) was determined. The 0.1μs exposure was far below the time order $\frac{r_p}{V_p}\approx 0.7\,\mu s$, so each cigar-shaped cloud actually reflected pellet motion and ablation process in detail On the assumption of constant Vp in the radial direction, the time interval 35 μs was transferred to the radial position 2.4 cm.

It was impossible to observe the beginning part of the pellet ablation as the trigger pulse should reach the threshold voltage enough to trigger the camera. Along 12~16cm distances the inclination angles of the cloud varied gradually smaller toward the core plasma. The typical length along the magnetic field was 90 mm and the width perpendicular to the field was 7mm,the ratio of (90/7) was greater than those measured by other tokamak devices (for example 0~60mm/8~10mm, ASDEX Upgrade (1) and TEXT(4)), so it was favorable for inclination angle measurement. In this discharge the SXR sawtooth inversion was observed in the SXR diagnostic, whose characteristic radius of the magnetic surface q (r)=1 was near r = 5cm.

We notice that q (r)=1 radius in the pellet injection observation was consistent with this inversion radius and the reconstructed results of the equilibrium code calculation(5).

3.4 Relative measurement of global particle confinement time

Global particle confinement time can be improved during the pellet injection. This subject is paid closely attention. The H_α emission intensity is proportional to the electron source [4]. In our case, H_α detectors are only calibrated relatively. Therefore, we can only obtain the relative variation for global particle confinement time by means of multi-channel H_α emission signals and multi-channel HCN measurements. The global particle confinement time is defined by (in the case of stationary state)

$$\tau_P = \frac{N_e}{S} \qquad (3)$$

where Ne= $\int_0^a \int_0^{2\pi} n_e(r,\theta) r dr d\theta$ is the electron number per unit length plasma column, $S = \int_0^a \int_0^{2\pi} \xi . I_{H\alpha}(r,\theta) r dr d\theta$--- the H_α emission intensity per unit length plasma column, $I_{H\alpha}(r,\theta)$ --- H_α emission intensity distribution, ξ --- average number of ionization acts per one H_α photon(6) .

In order to avoid impurity effects, we selected first set shots after siliconization vacuum chamber to analyze the experimental results. Because ξ is an insensitive function to electron density and temperature, the relative variation of global particle confinement time for different moments can be expressed by

$$\frac{\tau_{P2}}{\tau_{P1}} = \frac{N_{e2} / \xi_2 I_{H\alpha 2}}{N_{e1} / \xi_1 I_{H\alpha 1}} = \frac{N_{e2} \xi_1 I_{H\alpha 1}}{N_{e1} \xi_2 I_{H\alpha 2}} \qquad (4)$$

In Tabel 1 listed are the physical parameters and ratio τ_{p2}/τ_{p1} for five moments. It is obvious that the global particle confinement time is improved after the pellet is injected. We can see from Fig.5 that the activity of soft x-ray sawteeth has been impaired after the pellet is injected. It might be due to the density peaking. The transport processes before and after pellet injection were simulated in ASDEX-U tokamak(7) . It was discovered that the ratio of the toward particle convection velocity to the particle diffusion coefficient was increased by 2 times or even more after pellet injection. Thus the global particle confinement characteristic was improved.

Summary

The CCD photographic technique and H_α emission detector array provide a good deal of information for pellet injection, the improved global particle confinement characteristic was observed. The penetration depths 110~260mm were obtained on the HL-1M tokamak. From ablation photos exp. 0.1μs, H_α intensity profile , cloud structure, trajectory (and its bending),and Vp, were measured, in particular primary q(r)-profile estimation of HL-1M plasma .

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