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Observation of hydrogen pellet ablation material flow by tomography

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An Hα emission measurement array with 25 detection channels has been built on HL-1M tokamak. Reconstruction maps of Hα emission distribution in plasma cross-section have been obtained by using tomography, with a hydrogen pellet injected into the plasma. The dimension, the shape and the rotation characteristic of the cross-section of the pellet ablation material flow tube have been observed. These results have been analysed and explained tentatively by using the 'tail' model and the linear expansion model.

Keywords: hydrogen pellet, Hα emission, ablation rate, tomography

PACC: 5270

1. Introduction

At present, the injection of a hydrogen pellet is used to fuel tokamak plasma and it is expected to be a possible refuelling method for a steady-state fusion reactor. By using the method, a high electron density with a strong peak can be obtained, and the particle confinement and energy confinement can also be improved. The key problem in the pellet refuelling is the local deposition distribution of the pellet ablation material. The distribution is controlled by the dynamics of pellet ablation in high temperature plasma. In order to analyse and study the pellet ablation process, several theoretical models have been created.[1] Among these models, the neutral gas shielding ablation model (NGSM) has been widely used to describe the ablation process and calculate the ablation rate and penetration depth.[2] The NGSM describes the process in which the high energy electrons around plasma bombard the pellet surface and build up a neutral gas cloud around pellet in a very short time. The thickness of cloud is essentially of spherical symmetry. Reasonable agreement between this model and experiment data was found. Later, some other new models based on the NGSM were developed. For example, Lengyel[3] and Gerdin[4] described the ionization and expansion dynamics of high density cloud in magnetically confined plasmas and analysed the evolution of the ionization radius of the ablation cloud. However, none of these models can provide a description in all-round agreement with the ablation data of hydrogen pellet experiment. Therefore, it is important to develop a more accurate model to analyse or simulate the pellet ablation process in order to find the variation rule of ionization radius with plasma parameter in the pellet ablation process. On the other hand, it is necessary to improve and build up new diagnostic methods to provide more accurate experimental data. In this paper, some characteristics of the flow of ablation material in a pellet ablation process are investigated and also tentatively analysed by using 25-channel Hα emission signals and tomography.

2. Measurement equipment and condition

The hydrogen pellet injection experiments are carried out on HL-1M. The HL-1M is a tokamak with a circular cross-section. Its major radius is 102 cm and minor radius is 26 cm. In ohmic heating discharge, the routine operating parameters and plasma parameters are as follows: $I_{\rm p} = 100 - 200$ kA, $B_{\rm T} = 2 - 3$T, $\bar{n}_{\rm e} = 0.5 - 4 \times 10^{13}{\rm cm}^{-3}$, and $T_{\rm e} = 500 - 1500$ eV. A hydrogen pellet is injected into the plasma along the horizontal direction. The pellet diameter is 1 mm or 1.2 mm. Each pellet contains 4×10^{19} – 7×10^{19} atoms. Pellet speed ranges from 500 to 1200 m/s. The pellet injector may inject 1 – 8 pellets into the tokamak during one discharge.[5]

In the research on the pellet ablation process, the main diagnostic methods include high speed photography,[6] soft-x ray radiation measurement and Hα emission measurement. Among these methods,

the measurement of Hα emission intensity is the best method to research the evaporation and ionization process of hydrogen pellet, because the ionization energy and the energy needed for hydrogen atom to be excited into the third exciting level are similar to each ether. In addition, the spectroscopy is not required to have the Hα measurement array, so this method is a cheap diagnostic method and makes it easy to perform a multichannel measurement on Hα emission.

We have built up a 25-channel photoelectric measurement system on the HL-1M device (see Fig.1). The spatial resolution of the system is 2 cm. Each channel in the system consists of an alignment tube, an interference filter, a small lens, a PIN diode and a preamplifier. The central wavelength of the interference filter is 656.3 nm. Acquisition frequency is 100–500 kHz. The system is calibrated relatively. Figure 2 shows the geometric locations of the pellet injecting port and the measurement port on the HL-1M tokamak. The arc length between the two ports is 2 m.

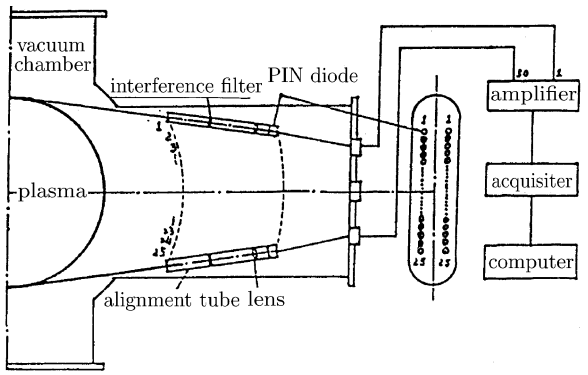


Fig.1. 25-channel photo-electricity measurement system for Hα emission.

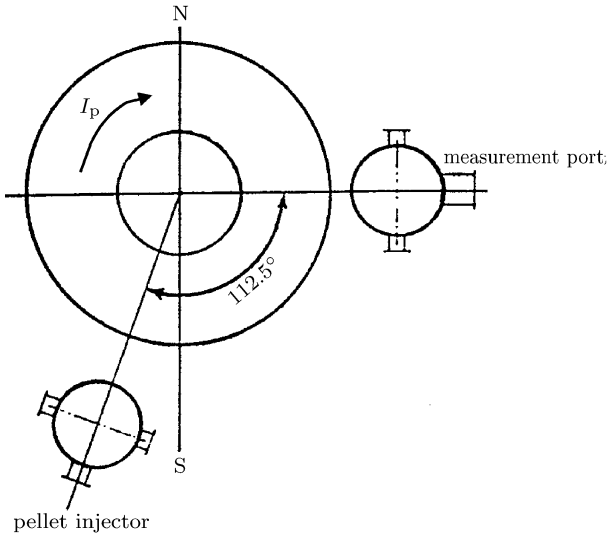


Fig.2. Geometric location of pellet injection port and measurement port on the HL-1M tokamak .

3. Measurement results

In the pellet ablation process, the relationship between Hα emission intensity and pellet ablation rate is as follows:[7]

$$I \propto \dot{N} \frac{\langle \sigma v \rangle_{\rm exc}}{\langle \sigma v \rangle_{\rm ion}}, \tag{1}$$

where I is the Hα emission intensity, $\dot{N}$ is the pellet ablation rate, $\langle \sigma v \rangle_{\rm exc}$ is the excitation rate constant, and $\langle \sigma v \rangle_{\rm ion}$ is the ionization rate constant. When the electron temperature is higher than the ionization potential energy $e\phi_{\rm i}$, the $\langle \sigma v \rangle_{\rm exc}/\langle \sigma v \rangle_{\rm ion}$ is unrelated to the variation in electron temperature, therefore, Eq.(1) can be regarded as

$$I = \dot{N}, \tag{2}$$

Equation (2) indicates that the pellet ablation rate is proportional to the Hα emission intensity, therefore, we can analyse and study the hydrogen pellet ablation process by using Hα emission measurements.

We obtain the temporal and spatial evolutions of the reconstruction maps of Hα emission intensity distribution measured in a cross-section by using tomography (see Fig.3). Hα emission located in a central region in each map comes from the pellet ablation material flow that consists of the pellet ablation particles and low temperature plasma. Height of the map represents the intensity of Hα emission.

In order to better observe the variation in Hα emission from the pellet ablation material flow in a central region of plasma, we give Fig.4 in such a way that the Hα emission from an edge region of plasma in Fig.3 is removed, only the Hα emission from the flow in the plasma central region is retained there. Then a curve is formed by connecting the maximum of each map in Fig.4 (see Fig.5).

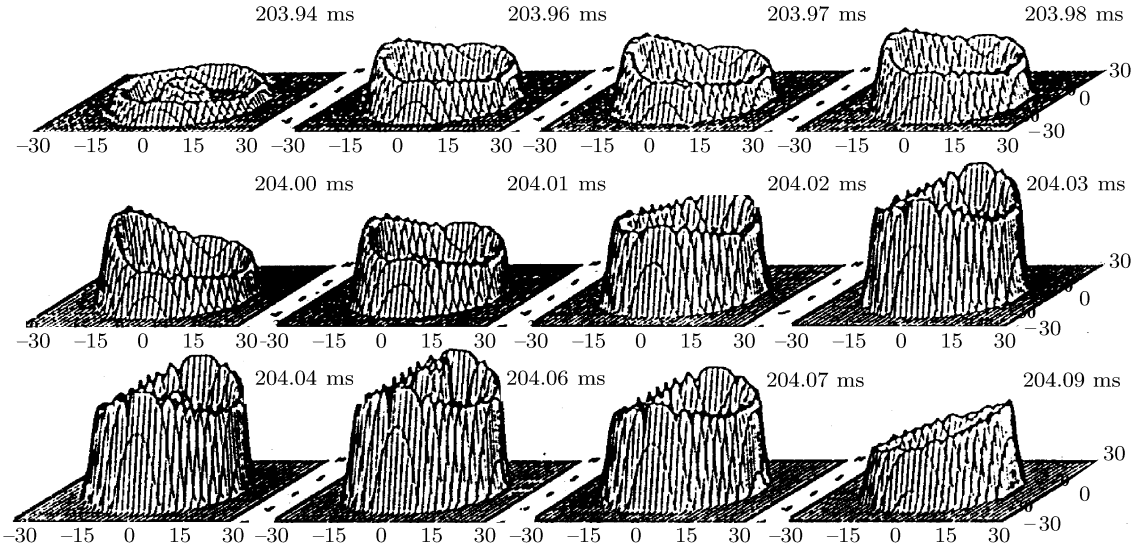


Fig.3. Temporal and spatial evolutions for Ha emission intensity in plasma poloidal Cross-section during pellet ablation, the discharge and plasma parameters are as follows: $I_{\rm p} = 95$ kA, $B_{\rm T} = 2.34$ T, $\bar{n}_{\rm e} = 1.3 \times 10^{13}{\rm cm}^{-3}$ and $T_{\rm e} = 735$ eV.

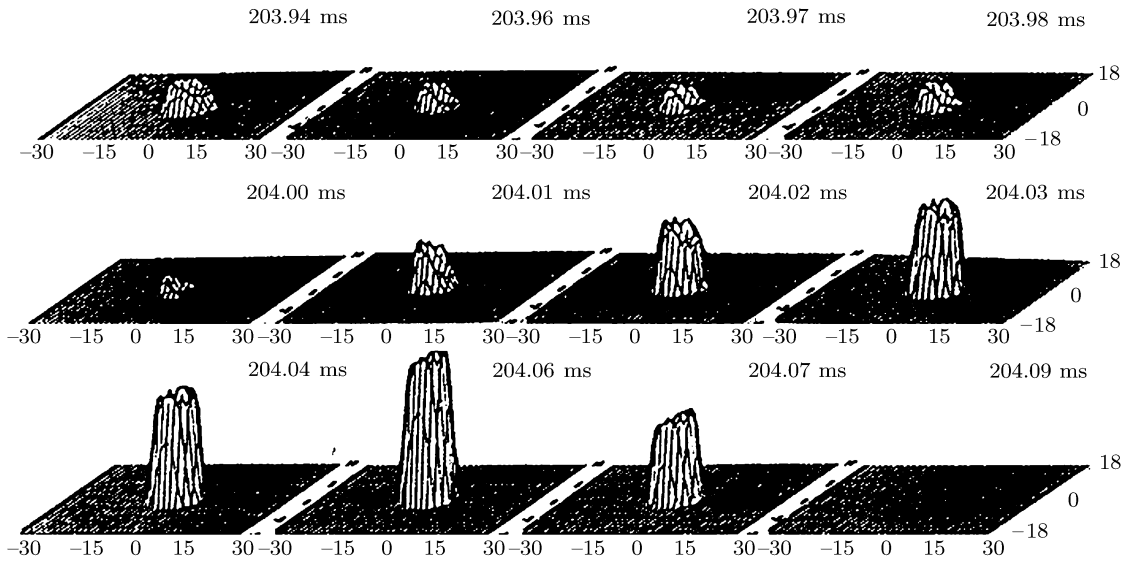


Fig.4. Reconstruction plot with temporal and spatial evolution of Ha emission intensity from the pellet ablation material flow.

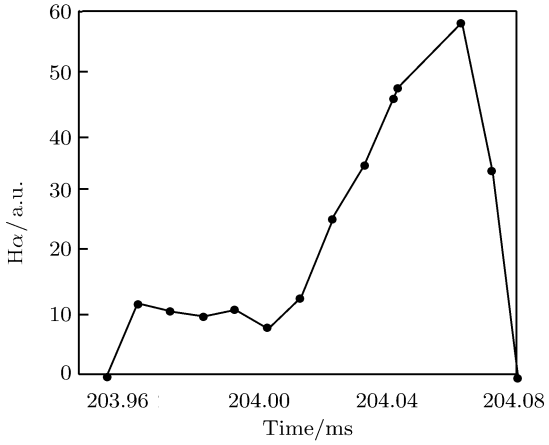


Fig.5. Temporal variation in Ha emission intensity from the flow tube (shot 4002) obtained in the measurement port.

In order to observe the pellet ablation process directly, we have built another detector array on the pellet injection port. The temporal evolution of Hα emission intensity from this array has been obtained during pellet ablation (see Fig.6). Because the Hα emission from the flow tube is proportional to the number of atoms in the flow and the Hα emission intensity observed from the pellet injection port is proportional to the pellet ablation rate according to Eq.(2), a comparison between Fig.5 and Fig.6 in the corresponding time interval shows that variation rules in the two figures are similar, therefore, we can think that variation in Hα emission intensity from the pellet ablation ma-

terial flow is directly related to the variation in pellet ablation rate. The fact that we can observe Hα emission from the flow in the measurement port implies that the length of the flow tube is already equal to or bigger than the arc length between the pellet injection port and the measurement port.

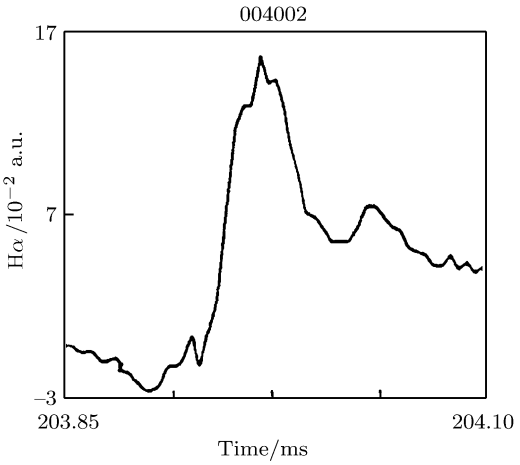


Fig.6. Temporal variation in Ha emission intensity from pellet ablation cloud obtained in the pellet injection port.

The shape, location, dimension and rotation characteristic of the flow tube in the plasma cross-section can be observed from Fig.7. The shape looks like a kidney, its diameter is about 5–10 cm, and the diameter varies slightly and gradually with the recovery of the plasma temperature. At the initial stage of pellet ablation, the flow tube is located near the plasma edge, and then it is gradually moved to the plasma core; meanwhile, it rotates clockwise at a lower speed along the poloidal direction as shown in Figs.7(a)–(d), and the phenomenon in which the movement direction is suddenly reversed is also observed from Fig.7(e). This phenomenon may be due to an increase in pellet ablation rate, the quickening of ionization and more and more charges being deposited in the flow tube so that the local potential distribution in the plasma is changed. The sudden change of the local potential distribution was observed from the measurement signals of Mahe probe[7] and electrostatic probe. The length of flow tube is gradually shortened; thereby the pellet ablation rate turns lower but the ionization rate becomes large. As a result, the plasma temperature around the flow tube is gradually recovered. When the flow length is shorter than the arc length between pellet injection port and the measurement port, we cannot observe Hα emission in the maps.

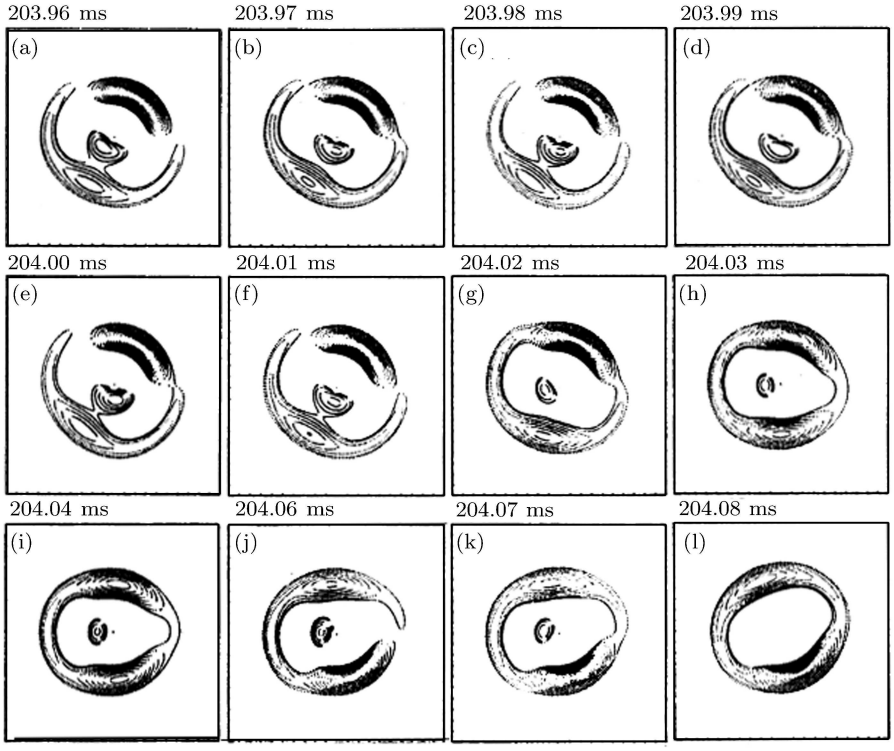


Fig.7. The contour plot of Ha emission intensity from the flow tube in plasma poloidal cross-section during pellet ablation (shot 4002).

4. Preliminary analysis

According to NGSM, when electrons bombard the pellet surface, an ablation cloud is formed around pellet, which is composed of neutral particles. These particles are expanded under electron bombardment, and undergo complex atomic or molecular processes, finally, they are ionized in the region with an ionization radius $r_{\rm i}$. The equation for $r_{\rm i}$ is as follows:

$$r_{\rm i} \approx 1.48 r_{\rm p}[4.56 \times\ 10^{-6} \cdot r_{\rm p}^{0.67} \cdot n_{\rm e0}^{0.67} \cdot T_{\rm e0}^{-1.82} \cdot B_0^2]^{-2/11}, \tag{3}$$

where $r_{\rm p}$ is the pellet radius, $n_{\rm e0}$ and $T_{\rm e0}$ are electron density and electron temperature in a plasma centre respectively, and B_0 is the plasma toroidal field. We know from Eq.(3) that the ionization radius varies with plasma parameter that is time-dependent. The low temperature ions together with neutral particles gradually leave from the pellet cloud and move along magnetic field lines and form a tube-shaped flow that looks like a long tail. The diameter of the flow varies slightly and gradually with the extension of the flow. In the JIPPT-IIU pellet injecting experiment,[8] a long helical tail of ablation light has been observed at an injection angle smaller than a certain value. The direction of helical tail rotation is independent of the direction of magnetic field lines of the tours (see Fig.8). They suggested that the tail-shaped phenomena could be a consequence of plasma rotation under the condition of charge exchange equilibrium of hydrogen ions and neutral particles in a high density state. Sato presented a 'tail model' based on the above-mentioned phenomena. Comparing with this model, we think that the pellet ablation material flow tube obtained on the HL-1M very resembles the long helical tail in shape. Once the length of the tail equals or exceeds the arc length between pellet injection port and measurement port, the long tail composed of pellet ablation material and low temperature plasma will be observed.

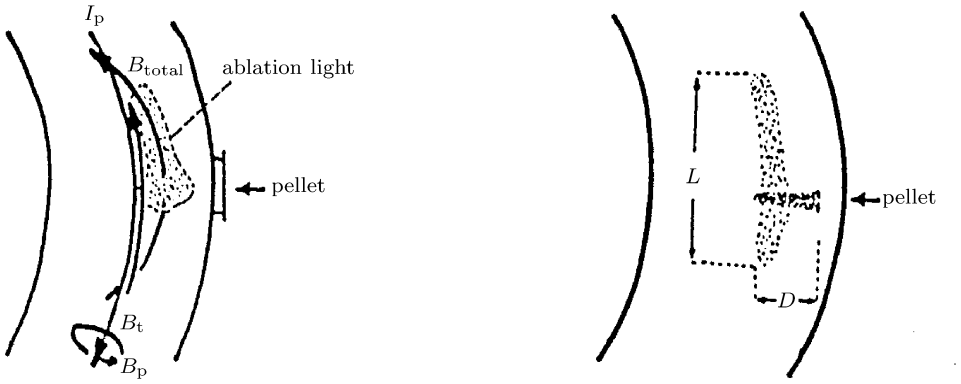


Fig.8. 'Tail Model' On the JIPPT-IIU.

Caufmann observed Hα emission band and dark stripes to be parallel to the magnetic field from photograph of the ablation cloud in ASDEX, then he presented a model of linear expansion of low temperature and high density pellet plasma in a closed toroidal magnetic flux tube.[9] In the model the band structure is perhaps related to cold plasma. Movement of initiated ions along the magnetic field line may be in the form of a flow along a channel (see Fig.9). At $t = 0$, the channel is filled with plasma, after $t > 0$, a particle source is activated, and a low temperature and high-density plasma flows into the channel at a rate of $\dot{N}_{\rm abl}/2$, which is described as follows:

$$\dot{N}_{\rm abl} = 2\pi r_{\rm i}^2 \int_0^r \dot{n}_{\rm abl} {\rm d}x, \tag{4}$$

where $\dot{N}_{\rm abl}$ is pellet ablation rate, $\dot{n}_{\rm abl}$ is cold particle yield per unit volume. The pellet ablation rate calculated from the model is smaller than these rates from other models. It indicated that the shielding effect of the long channel, which is composed of the high density and low temperature pellet plasma, is enhanced. According to the model, our reconstruction results may be explained by using the Caufmann flow.

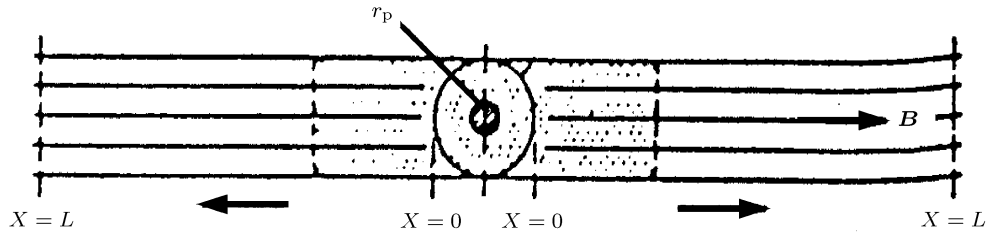


Fig.9. Model of linear expansion of low-temperature and high density pellet plasma in a closed toroidal magnetic flux tube.

5. Summary

In the pellet injection experiment of HL-1M, we have built up two detector arrays for Hα emission measurement: one is located at the pellet injection port for investigating pellet ablation process, the other is located at the measurement port for researching the pellet ablation material flow. The arc length between two ports is 2 m. We reconstruct the distribution of Hα emission intensity in the plasma cross-section located at the measurement port by using tomography. The dimension, the shape and the rotation characteristic of a cross-section of the pellet ablation material flow tube have been observed. These results are analysed and explained tentatively by using the 'tail' model and the linear expansion model.

At present, research of the pellet ablation process is mainly by using high speed photography. The camera is usually located at the place nearly the pellet injection port. It can clearly observe the pellet movement track, but due to the restriction on the visual angle, it is difficult to observe the scenarios of the ablation material at some other places. Multi-channel Hα emission detector arrays may be located at more ports, so as to observe and monitor the pellet ablation process.[10] If high speed photography and multi-channel Hα detector array can be jointly used to observe the pellet ablation process at the same time, we will obtain more experimental information. These results will be more significant to further study of the shielding effect in the pellet ablation process, deposition distribution and ionization state of the ablation cloud.

Acknowledgments

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