3 Calibration

Before the measurement it is necessary to calibrate each channel using a high-pressure mercury-vapor lamp with 546.1 nm and 577 nm wavelength of line radiation. The first spectral channel is departure from the central wavelength of 530 nm more than 11 nm so as to avoid the influence of incident radiation upon scattering signal. In addition, the calibration of relative sensitivity of spectral channel also is necessary. The calibration of whole spectral channels were carried out by means of a set of optic system with a tungsten lamp of a СИРШ-6-100 type. In case of calibration, the average value of the calibration data can be obtained through 100 times of measurements in each channel. After the measurement, all of the channels have to be normalized by using anyone as standard channel. The coefficients of calibration are used in account with definition of electron temperature. If the system is also used for measurement of electron density then absolute calibration of scattering intensity need to be done. This system can be used to measure the range of 100 eV $\leqslant T_e \leqslant$ 2 keV with polychromater of 600 lines/mm grating.

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1.4 Investigation of Pellet Shape and Cloud Structure in the HL-1M Tokamak

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Key words Pellet shape Cloud structure CCD photo

Frozen pellet injected into plasma is exposed to direct action of energetic particles, mainly electrons. As gyration radius of electron is much less than pellet radius, electrons can move to the pellet surface. Along the magnetic field lines the cigar-shaped cloud, consisting of neutral and partially or fully ionized particles are formed immediately around the pellet, the latter may follow the local magnetic field [1]. The intensity of H_α radiation from the cloud often infer the pellet ablation rate, so pellet ablation characteristic is usually studied photographically. Various ablation models, such as neutral gas shielding (NGS), neutral gas and plasma shielding (NGPS) and their modification are developed [2].

A great deal of progress in the pellet fuelling experiments has been achieved on the HL-1M tokamak. The aim of this paper is to demonstrate experiment results of pellet shape and cloud structure.

1 Experiment set-up

In order to observe pellet itself and its injection, an experiment set-up was designed on the injecting output window. It consisted of a ruler, a flash instrument, CCD camera, personal computer and related control and trigger unit. The whole arrangement is shown as Fig. 1. One flash shot duration is 0.7 μs, so CCD camera should be exactly opened for taking photo on time. On the window below along the injection direction the ruler was put to indicate dimension in millimeter. The pellet experiment set-up on the HL-1M tokamak was reported (See Ref. [3]).

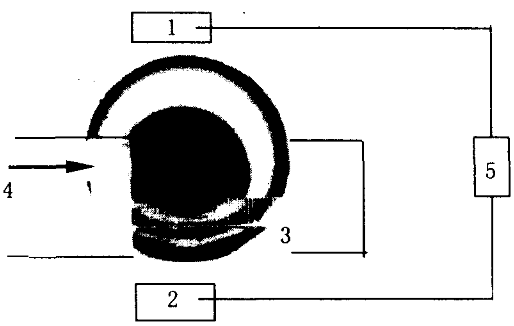

Fig. 1 Experiment set-up for pellet injection
1——flash instrument, 2——CCD & pc, 3——ruler, 4——pellet injection direction, 5——fiber & control unit.

Two kinds of settings were chosen for camera control: (A) multiple and (B) long exposures. Setting A is program control of exposure and delay (between two exposures) times with purpose of observing ablation process in detail. For a cycle of del. time + exp. time, up to 10 cycles can be set. Setting B is for the whole pellet ablation history, its exposure time is greater than pellet ablation duration τ_a (~0.4 ms).

The experiment was carried out on the HL-1M tokamak, which is circular cross-section tokamak with an iron core transformer. The ohmic-heated plasma current $I_p = 120 \sim 250$ kA, toroidal magnetic field $B_T = 2.2 \sim 2.7$ T, target electron density $n_e = (0.3 \sim 3.5) \times 10^{19}\ m^{-3}$ during horizontal injection of 8 hydrogen pellets ($2 \times \phi 1.0$ mm, $6 \times \phi 1.2$ mm) as well as supersonic molecular beam injection.

2 Pellet injection and flight velocity measurement

It is well known the fact that pellet flight velocity is assumed constant before and after entering plasma. Along the injecting tube there was pellet flight velocity (v_p) measurement unit. The v_p measuring unit, being composed of semi-conductor laser and fiber optic interrupter array, was fitted on the injecting tube. v_p can be determined by two of signals from the interrupters. Meanwhile it may be given according to the duration and distance between one of the interrupter and cloud position. In most cases the flight velocity (v_p) range was of 500 ~ 1 100 m · s^{-1}, the error was estimated to be about ± 15%.

We chose ice methane as test pellet. A lot of photos were taken as indicated in Fig. 2. In general cryogenic pellet was injected through

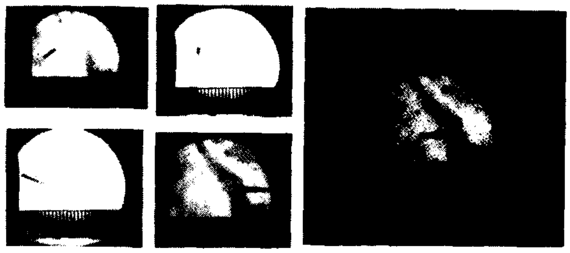

Fig. 2 Pellet injection shapes

the injecting tube of cylindrical form, occasionally in bullet shape. On the exit region of injecting tube, out-injected pellet position was not all centralized, sometime they might be away from the central position. During their flight most of them injected out were found tumbling. The CCD observation proved the extruder could work in sequence satisfactory, therefore continuous pellet production (up to 8 or more pellets were injected for one injecting gun) realized. For the cryogenic cylindrical pellet the typical diameters from 0. 5 to 1. 2 mm and lengths from 3 to 8 mm were observed. In a word, these photos suggested that before going into plasma, initial pellet almost formed in the cylindrical shape [for example, $r_{po} \times (3 \sim 10)\, r_{po}$] with tumbling frequently.

3 Pellet cloud investigation

The most cloud shapes were spherical, cigar-shaped, dynamics, fragments. Spherical shape demonstrated that pellet entered plasma with slow velocity in more cases in our experiment, for example, $v_p = 210$ m · s^{-1} and ablated only in the outer plasma region ($q > 2$). The particles in the cloud were nearly neutral particles, its expansion was unaffected by the magnetic field, so the cloud expanded spherically and H_α intensity had a gaussian-peaked profile, darker central region was not seen [Fig. 3(a)].

The cigar-shape indicated pellet went into deeper area ($q \leq 2$), apart from neutral particles in the cloud, its outer region contained ionized particles. There ions dragged neutral particles to move along the magnetic field [Fig. 3(b)] . Owing to collision, the cloud evolution underwent two clearly distinguished phases: (a) radial flow confinement (μs time-scale), (b) free expansion along the magnetic field (ms time-scale) . As soon as outer cloud layer became ionized, cloud expansion dropped until full stops of the radial expansion. In normal case, lengths were 50 ~ 90 mm along the magnetic field and the ra-

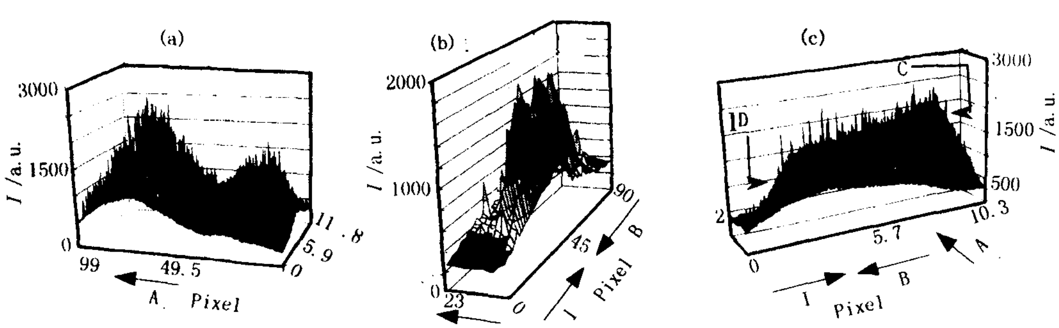

Fig. 3 H_α profile of pellet cloud intensity
A——pellet flight direction, I——plasma curret, B——toroidal magnetic field, C——ion drift side, D——electron drift side.
(a) spherical, (b) cigar-shaped, (c) track bending.

dial widths were 5 ~ 10 mm, expansion rates were nearly $(2.5 \sim 5) \times 10^4$ m · s^{-1}, almost two order higher than v_p.

Concerning the structure of cigar-shaped cloud ablated in the deeper region of plasma, usually there existed a plateau with approximately constant emission intensity and hollow in the central. The plateau seemed to be straight, the plateau was much larger than plateau radius that was obviously larger than pellet radius r_p. Outside the plateau light intensity decayed exponentially with a characteristic length. The longitudinal decay length was greater than that across the magnetic field[3].

Time-integrated image illustrated the whole pellet ablation process. First in the boundary the cloud radiation intensity was very weak due to lower n_e and T_e, the shape became spherical, at ablating beginning cloud often expanded symmetrically. Later cigar-shaped, the cloud freely expanded along the local magnetic field and changed its shape to sharp cigar-shaped. The maximum length reached 174 mm. Then the pellet dimension dropped, accordingly cloud length decreased, finally disappeared.

A lot of fragments dispersed in all directions. We considered they already existed before entering plasma. In some photos we can see instead of being straight the pellet trajectory always bent towards the electron drift side of plasma I_p.

Asymmetry of H_α emission on the ion and electron side of plasma [Fig. 3(c)] showed unequal heating flow, resulting from rocket effect driven by the superthermal electrons (10 ~ 150 keV), the presence of which was observed in the experiments by hard X-ray diagnosis[4].

4 Summary

CCD photography (exp. 100 ns) provided a good deal of information for pellet injection and ablation. Pellet shape just injected out from the injecting tube exit was obtained. Cloud shape, structure, ablation process and trajectory bending were analyzed. These observation results will be of benefit to the further pellet fueling experiments.

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