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# High-speed 2-D image measurement for plasma-wall interaction studies

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**Abstract**

A movable carbon target with a head diameter of 9 cm was inserted into the peripheral region of a Heliotron J plasma. High-speed, two-dimensional images of filtered visible light emission near this target were taken by a C-MOS video camera. In high-density ECH discharges (70 GHz, 0.3 MW, $\bar{n}_e > 1.5 \times 10^{19}$ m$^{-3}$) it was observed that a striped pattern of $H\alpha$ light moved along the poloidal direction. Simultaneously, other diagnostic data (ECE signals, line integral electron density, ion saturation currents of Langmuir probes) showed plasma oscillation at a frequency of 5–6 kHz. Individual signals from pixels of the visible camera images indicate that the oscillation phase is approximately constant along the field line, suggesting that coherent structure phenomena along the field line are present in the high-density plasmas of Heliotron J.


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## 1. Introduction

Fast camera visualization of edge plasma behavior and/or plasma-wall interactions is a common measurement technique for investigating the physics of plasma. Striped patterns were first observed on the inner wall of the TFTR vacuum vessel using a fast video camera, and these observations were attributed to edge plasma turbulence [1]. Recently a more sophisticated way to visualize edge plasma turbulence was developed in C-mod and NSTX [2,3], referred to as Gas Puff Imaging (GPI). In GPI a non-perturbative gas puff is injected into the plasma to enhance emission and highlight the edge plasma behavior. Another method to highlight the edge is to insert a solid target into the edge. Carbon is one of suitable material to insert into the peripheral plasma because of low $Z$ and high sublimation temperature. This method also arose plasma-wall interactions to be studied, especially the recycling process on a controlled surface. A solid carbon target is inserted in Heliotron J to study plasma-wall interaction and edge plasma behavior with a C-MOS fast video camera and spectrometer [4]. In this paper the results of high-speed,

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2-D image measurements using a fast video camera are described.

## 2. Experimental setup

Heliotron J is a medium sized heliotron device with an L = 1/M = 4 helical axis which can form various magnetic configurations [5–7]. The schematic of the experimental setup is shown in Fig. 1. The poloidal cross-section of the standard magnetic configuration [8] is also shown. A movable carbon target with a head diameter of 9 cm was installed and inserted into the peripheral plasma from a bottom port, localizing the observation area for two video cameras. The position of the top of the target is $z = -200$ mm from the equatorial plane of the torus. The last closed flux surface (LCFS) is located at $z = -175$ mm. Retractable Langmuir probes ($\phi 1.5 \times 3$ mm molybdenum probe tips) are embedded in the target. Fig. 2 shows the schematic of the carbon target. A fast video camera (FASTCAM Ultima-SE, Photron; http://www.photron.com/) views this carbon target from the top, while a medium-speed video camera (FASTCAM NET500, Photron) monitors the target from a horizontal port. Both cameras are usually used with optical filters; $H\alpha/D\alpha$ filter (656.3 nm) and/or CII filter (514.5 nm). Normally the fast video camera is operated with the speed of 40 500 frames per second (fps), and the medium-speed video camera is operated at 250 fps.

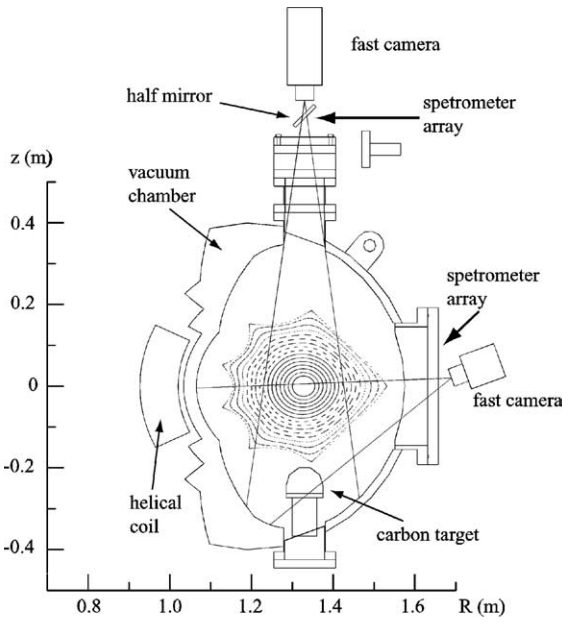


Fig. 1. Experimental setup in Heliotron J for solid carbon target experiments.

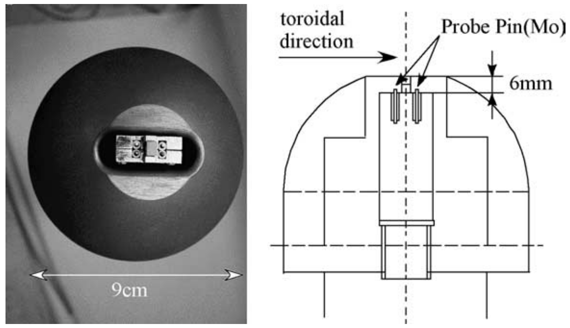


Fig. 2. Top view photograph and schematic of the carbon target.

## 3. Results and discussion

In high density ($\bar{n}_e \geqslant 1.8 \times 10^{19}$ m$^{-3}$) ECH (70 GHz) experiments [9], it was observed that striped patterns of $H\alpha$ emission near the carbon target shifted periodically during a certain period of a discharge. Edge plasma oscillations have already been reported in many machines [10–12], however this oscillation is not always associated with H-mode in Heliotron J plasma.

An analysis of the intensity of each pixel of each frame showed that striped patterns shifted along the poloidal direction with a phase velocity of 460 m/s, corresponding to an oscillation frequency of 5–6 kHz at the target. Fig. 3 shows two-dimensional contour images of the strongest frequency (~5.7 kHz) component obtained by Fast Fourier Transform (FFT) during the fluctuation period. Striped patterns of $H\alpha$ emission moving across the magnetic field lines near the carbon target can be clearly seen.

The waveforms of the line averaged electron density, ECE signals from near the plasma center, ion saturation current of the Langmuir probe in the target top, and pixel data of the camera images at the probe position are shown in Fig. 4.

Magnetic probe signals and the floating potential of the edge plasma, observed by other Langmuir probes at different toroidal sections, were also oscillating with the same frequency during this period (not shown in the figure). These data show that there is a coherent structure in the plasma during this period. The magnetic probe signals suggest that this oscillation is not an electro-static wave. In the main plasma, the oscillation of electron density and that of ECE signal have nearly opposite phases. The poloidal m number of this coherent structure in the main plasma should be even, since the oscillation phases of ECE signals along the measurement points (which are aligned with the minor radius both inside and outside) are almost the same. During this oscillation period the diamagnetic signal increased, thus it is thought that this fluctuation does not degrade energy confinement.

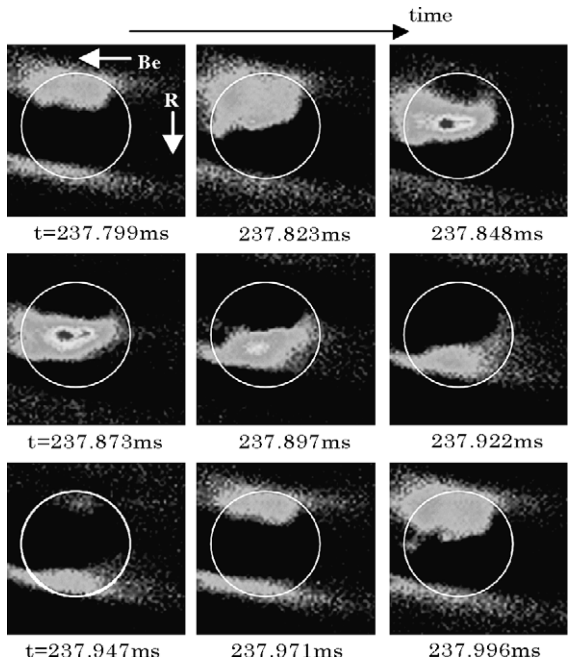


Fig. 3. Contour images of coherent oscillation near the carbon target using fast video camera. From the video image, each pixel data is decomposed to the different frequency sinusoids and their respective amplitudes by FFT, and are reconstructed from the component at the frequency of 5.7 kHz, which is the strongest during the coherent oscillation period.

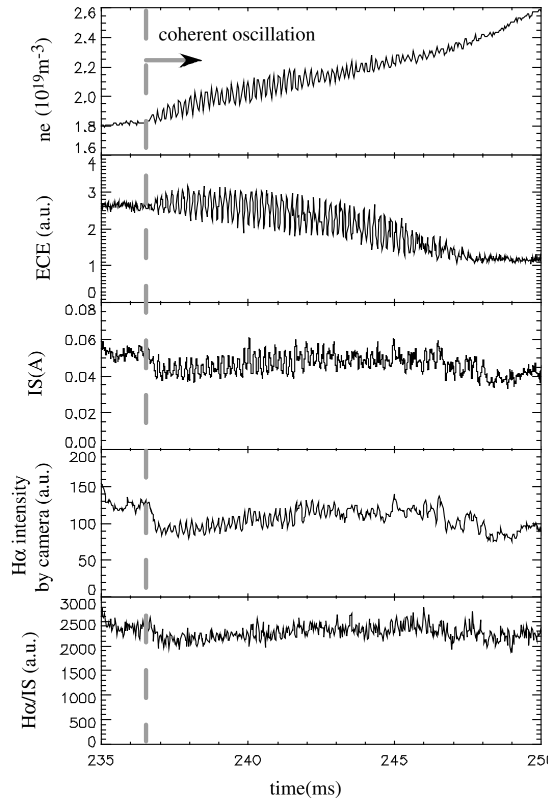


Fig. 4. Plasma parameters corresponding to the coherent oscillation. From top to bottom, Electron density, ECE signal from the plasma central region, ion saturation current of the Langmuir probe on the limiter head, $H\alpha$ signal of pixel data at the probe position in the fast camera images, Ratio of $H\alpha$ signal and ion saturation current.

The waveform of the ion saturation current ($I_{sat}$) measured by the Langmuir probe at the target top and the intensity of $H\alpha$ emission ($I_{h\nu}$) in the pixel corresponding to the probe position in the fast camera images are shown in Fig. 4. Time behaviors of both signals are quite similar. The observed visual images suggested that the flux from the peripheral plasma moves across the poloidal direction. In this shot the oscillation began at 237 ms, and ended at 244 ms according to $I_{h\nu}$ signal. However, the oscillations of the electron density and ECE signal lasted until 248ms. These oscillations started concurrently within the time resolution of the measuring system.

The $D\alpha$ emission profile [13] is radially narrow due to the electron collision excitation of Frank–Condon dissociated atoms. The $D\alpha$ emission region of deuterium discharge is near the target surface. The analysis on $H\alpha$ emission has not been done, however the images from the medium-speed camera show the emission region of $H\alpha$ for a hydrogen discharge is around 1 cm thick near the target surface. Fig. 5 shows a typical side-view image of the target with $H\alpha$ emission. Most likely the $H\alpha$ emission is due to electron collision excitation of Frank–Condon dissociated atoms. $I_{sat}$ is proportional to the product of the ion density at the sheath edge and the sound speed.

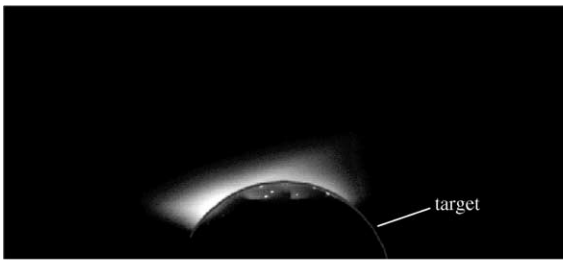


Fig. 5. Side view of the carbon target with $H\alpha$ filter during discharge

$$I_{sat} \propto n_i\sqrt{T_e}.$$

Assuming the corona model, $I_{h\nu}$ is proportional to the product of the electron density, the neutral density, and the excitation rate.

$$I_{h\nu} \propto n_e n_0 \langle\sigma v\rangle_{ex}.$$

The electron density is equal to the ion density at the sheath edge (quasi-neutrality assumption) in left equation. Since the $H\alpha$ emission region is near the target surface and $I_{h\nu}$ is the light intensity at the probe position from the top view, then $n_e$ in both equations is approximately the same value, leading to the following equation,

$$I_{h\nu}/I_{\rm sat} \propto n_0 \langle \sigma v \rangle_{\rm ex} / \sqrt{T_{\rm e}}.$$

Typical peripheral electron temperature is 30 eV in Heliotron J, therefore, $\langle \sigma v \rangle_{\rm ex}/\sqrt{T_{\rm e}}$ is almost constant (6–7) at 15–80 eV. Thus, the ratio of $I_{\rm sat}$ to $I_{h\nu}$ shows the neutral density fluctuation. During the oscillation period shown in Fig. 4 this ratio increases from 0% to 10% at the peak of $I_{\rm sat}$ and decreases 1–8% at the bottom of $I_{\rm sat}$. The scattering of the data is due to the different time resolutions of the probe measurements and cameras, and the line integral effect of the camera. The sampling frequency of the probe signal is 1 MHz and the frame rate of the camera is 40.5 kHz. The deviation of $I_{h\nu}/I_{\rm sat}$ is 5% during 237–242 ms, while the deviations of $I_{\rm sat}$ and $I_{h\nu}$ are 11% and 10%, respectively. The fluctuation of the neutral density is smaller than that of the ion saturation current and the $H\alpha$ emission during the oscillation period in the peripheral plasma. Therefore, it is suggested that electron density increases when the electron temperature decreases, and vice versa in the peripheral plasma. The above inference does not contradict the behavior of the line-averaged electron density and the ECE signals in the main plasma.

The electron diamagnetic frequency $\omega_{*\rm e} = -k_y T_{\rm e}/eBL_n, L_n = {\rm d}\ln n/{\rm d}n$), using $k_y$ from the camera image $\lambda \approx 8$ cm in Fig. 3) and 30 eV of electron temperature, is on the order of the 5.7 kHz frequency of this coherent oscillation. However as was mentioned before, this coherent oscillation does not agree with the simple density fluctuation model. For ExB plasma rotation induces the poloidal-shifting $H\alpha$ patterns, the necessary radial electric field, Er, must be negative in the peripheral region [14]. However, it is difficult to account for the main plasma behavior under these Er conditions.

At present, we do not have a good model for this coherent oscillation. In the near future we will have toroidal and poloidal rotation measurements using Doppler spectroscopy, getting the information for the ion fluid motion. This will allow us to compare with the fluctuation model.

## 4. Summary

Striped patterns of shifting $H\alpha$ emission in the poloidal direction were observed near a solid carbon target in high density ECH plasma. Using FFT analysis, a frequency of 5.7 kHz is the strongest component of this motion, agreeing with main plasma parameters (electron density, ECE signals), which also oscillated at the same frequency during corresponding period. Thus, we concluded that a coherent plasma oscillation has been found in Heliotron J. This was demonstrated that a combination of a small solid target, a Langmuir probe, and a fast video camera are very powerful tools to visualize edge plasma behavior and plasma-wall interactions.

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