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Edge plasma study using a fast VIS camera in the COMPASS tokamak

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I. INTRODUCTION

A Tokamak is a device that uses magnetic field in a toroidal configuration to confine hot plasma ($\sim 10^8$ K) in order to produce self-sustainable controlled fusion reaction.

As the energy released by instabilities and other plasma transportation processes can have severe impact on the life time of the plasma facing components, it is essential to study these processes and methods to diagnose them.

While the core plasma only provides X-ray radiation due to its high temperature and full ionization, the edge plasma radiates also in the visible light spectra thanks to the presence of neutral gas and its excitation by hot electrons. Various transport processes and oscillating modes in the edge have a local effect on electron density and temperature, which can be observed as a variation of the intensity of the emitted visible light. Since typical time scales of the changes of the light intensity can be in the order of microseconds, camera with a very high frame rate ($\sim 10^6$ fps) is needed to detect such changes.

This paper presents an initial assessment of possibility of detection of transport processes and oscillating modes in the COMPASS tokamak using a fast Photron SA5 camera operating in the visible range. In addition, the effect of RMP (Resonant Magnetic Perturbations) coils on the strike point splitting was studied.

II. SPECIFICATION OF THE TOKAMAK COMPASS AND THE PHOTRON SA5 CAMERA

Tokamak COMPASS [1] is a medium sized tokamak with D-shaped divertor configuration similar to ITER (International Thermonuclear Experimental Reactor). Ohmic heating and two NBI (Neutral Beam Injection) beams are used as sources of heating of plasma. The toroidal magnetic coils may provide up to 2.1T of magnetic field.

The technical parameters of COMPASS are:

- Major radius 0.56 m
- Minor radius 0.2 m
- Plasma current <400 kA
- Magnetic field < 2.1T
- Length of pulse ~ 1 s

The stainless steel vacuum chamber is equipped by carbon plasma facing components. The most important of them is the so-called divertor (see Fig. 1) which receives the energy and particle flux leaving the confined plasma by transport processes. Most of this flux is delivered along the separatrix (magnetic surface defining the edge of plasma) which intersects the divertor surface at the so-called strike points (Fig. 3).

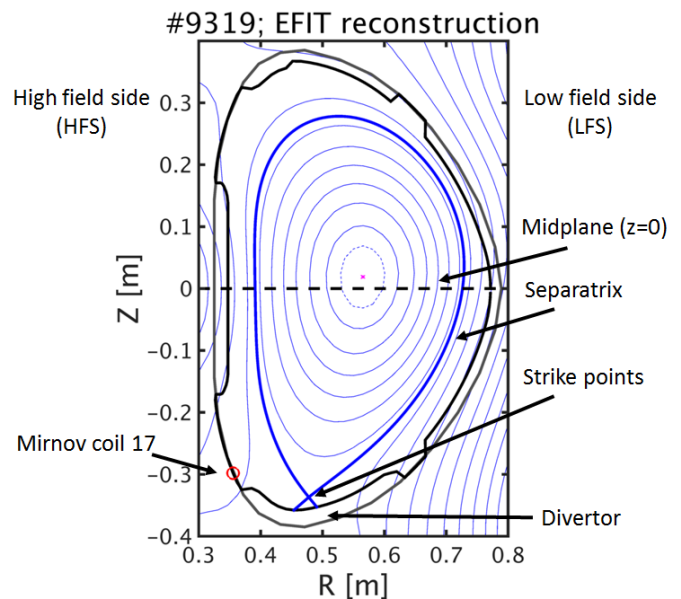


Figure 1. Poloidal cross section of the COMPASS vessel (black) with the reconstructed magnetic surfaces (blue) by EFIT [2]. Separatrix (thick blue line) represents the boundary of the confined plasma. Divertor is located at the bottom of the vessel. Midplane is located at $Z=0$.

Photron SA5 is a 12-bit ultrafast camera with 1024x1024 pixels operating in the visible range. The speed of imaging depends on the resolution which can be reduced to a small region of interest (ROI) in order to increase the frame rate. The imaging speed is 7000 fps at maximum resolution and up to 1 Mfps at 64x16 pixels. The camera has pixel width of 20 μm and high quantum efficiency (50%). Another advantage is low thermal noise (rms~23).

III. OSCILLATING MODES AND INSTABILITIES

Out of many kinds of instabilities and oscillating modes regularly observed in COMPASS, we focus in this work on the sawteeth instability, geodesic acoustic mode (GAM), and tearing mode. Sawteeth [3] is an internal instability accompanied by periodic collapses of confinement in the core plasma (so-called sawtooth crashes) resulting in flattening of the temperature gradient and propagation of a heat wave towards the plasma edge. Tearing mode [4] is a resistive magnetohydrodynamic instability developing on rational magnetic surfaces as a chain of magnetic islands, which typically rotates along with the surrounding plasma, i.e. it can be observed as a propagating wave. GAM [5] is a toroidally symmetric electromagnetic oscillation with a standing wave pattern in the poloidal direction. Its typical periodicity in the poloidal direction is $m=2$, which means that two maxima, two minima, and four nodes are distributed along the poloidal cross-section.

IV. METHODS AND ANALYSIS

A. Full frame of the camera

Operating regimes of a tokamak can be divided into two basic categories. The low confinement mode (L-mode) is characterized by a high level of turbulent plasma losses that significantly degrade plasma confinement. The high amount of radial turbulent transport in a form of plasma filaments intermittently released from the confined plasma provides strong visible light emission in the edge (Figure 2). The high confinement mode (H-mode) is characterized by a decrease of turbulent transport suppressed by a transport barrier formed at the edge of the plasma. Consequently, the confinement time, central temperature and energy increase. The light due to turbulent plasma losses considerably decreases in the H-mode (Figure 3) and other sources of the emission visible on the camera, such as the edge plasma near separatrix (mainly at the high field side), strike points in the divertor region and gas puff (when active), become dominant. The low field side edge of plasma is already out of the camera viewing angle.

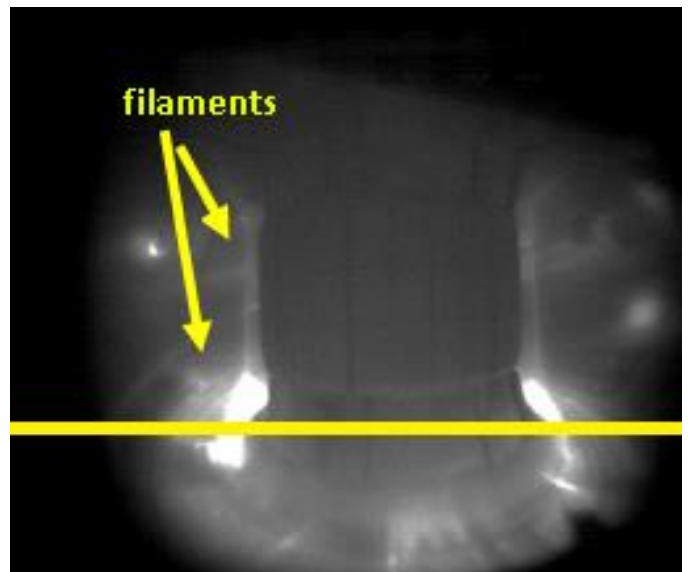


Figure 2. Low confinement mode during the shot #9375. High emission of light due to the turbulent transport. Plasma filaments following magnetic field lines are visible. The marked horizontal line represents the line along which light intensity during RMP is studied (see Fig.4).

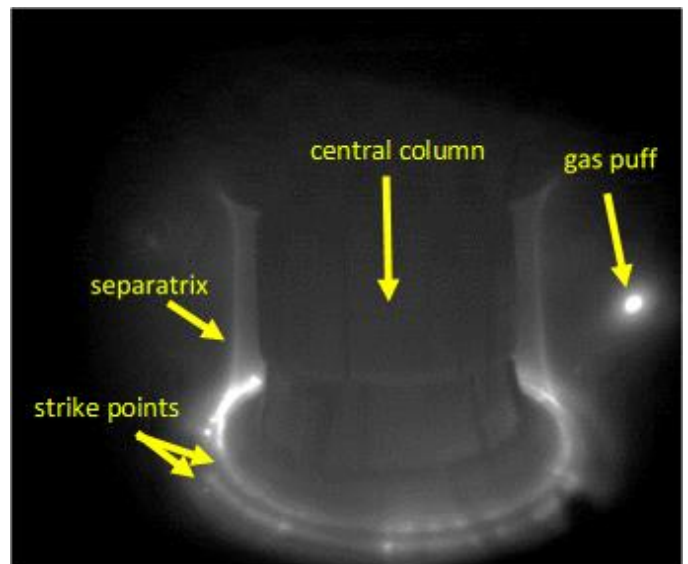


Figure 3. High confinement mode in shot #9375. Background VIS radiation decreases due to reduction of the edge transport. Gas puff (fuelling of the plasma) is visible on the right side of the frame.

B. Strike point splitting by Resonant Magnetic Perturbation

In most of the H-mode scenarios the transport barrier periodically collapses, releasing filaments of hot and dense plasma out of the confined plasma. Such an Edge Localized Mode (ELM) is a potentially dangerous instability that carries large amount of energy and may damage the plasma facing components. Resonant Magnetic Perturbation (RMP) is one of the ELM mitigation methods studied at COMPASS [6]. Application of this method causes a change of magnetic field lines near the separatrix, which may result in a splitting of the strike points at the divertor.

The Photron camera can be used to visualize the evolution of the strike point position in time. Fig. 4 shows time evolution of light intensity along a horizontal line (marked in Fig.2 by a yellow horizontal line) that crosses the divertor region twice (on the left and on the right with respect to the central column). The two strike points are clearly visible as two horizontal regions of increased light intensity. When a current in the RMP coils is ramped-up between times 1100 and 1160 ms, structure of the strike points clearly changes. Their intensity increases accompanied by a development of a well-pronounced secondary strike point. This demonstrates that this method may be used to study the plasma response on RMP coils and change of position and number of strike points present at the divertor.

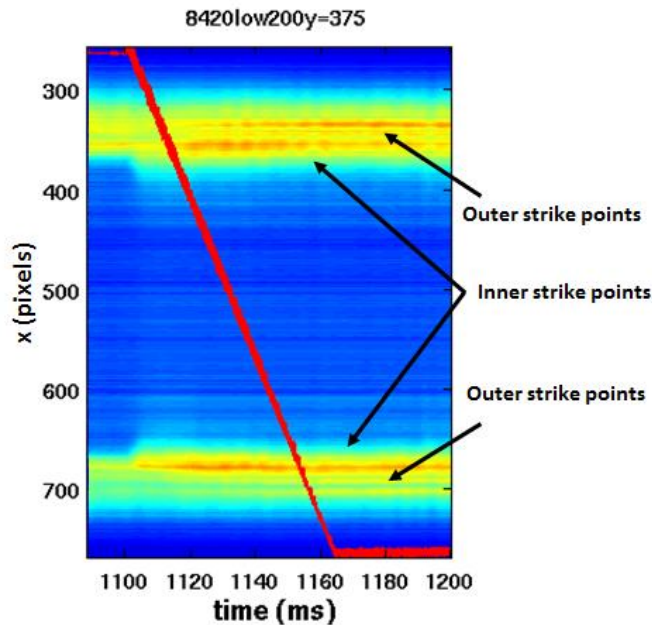


Figure 4. Time evolution of light emission from the divertor strike points in shot #8420. The vertical axis represents the horizontal pixel coordinate within the camera frame (Fig. 2). The current in RMP coils is plotted in red (ranging from 0kA down to -4 kA). Strike points are visible as horizontal lines of increased light intensity. The splitting may be observed since ~1110 ms.

C. Fluctuations of light intensity of individual pixels

In order to obtain light intensity measurement with sufficient frequency, the frame size of the camera must be reduced to a small region of interest (ROI). In the presented case the sampling rate was 232 kfps and the ROI of 128x144 pixels spanned from the gas puff down to the divertor.

Generally, some types of periodic oscillations are visible directly on the signal of individual pixels (see Fig. 5), but most of them need further processing in order to be revealed. Fig. 6 shows spectrogram of a pixel signal (using short time Fourier series), which reveals a tearing mode with frequency ~10 kHz and a low-frequency ~1 kHz oscillations generated by periodic sawtooth crashes. Even more can be revealed by a coherogram of the pixel signal with the Mirnov magnetic coil signal (see its spectrogram in Fig. 7) located outside the vessel at HFS near the divertor (depicted in Fig. 1). This method filters out all fluctuations but those coherent between the two signals. As seen in Fig. 8, it reveals also the presence of 30 kHz GAM oscillations that are weak and hidden in the background noise in the single pixel spectrogram in Fig. 6.

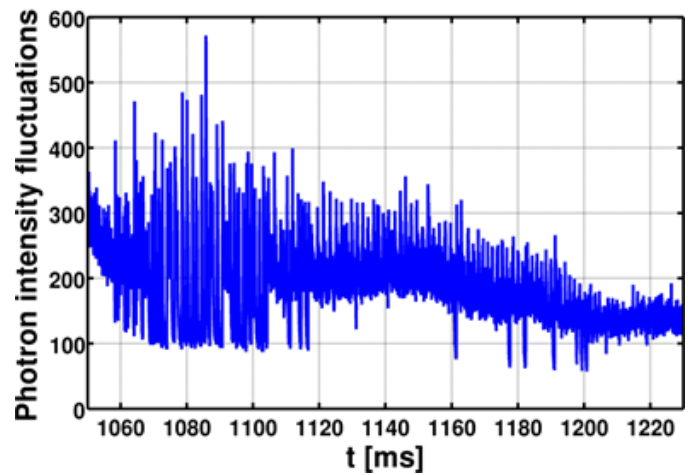


Figure 5. Single pixel intensity fluctuations in shot #9319. The pixel [621,570] is located at divertor.

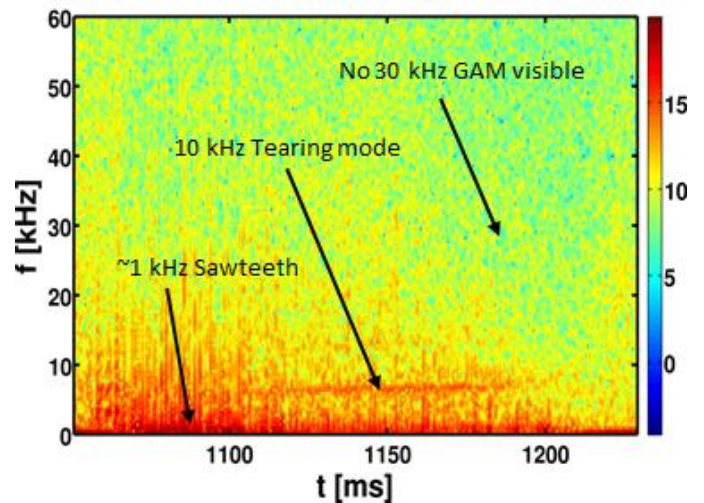


Figure 6. Spectrogram of light intensity fluctuations of the pixel shown in Fig. 5 in the discharge #9319. 10 kHz tearing mode is clearly visible, no distinct line is present at 30 kHz GAM frequency.

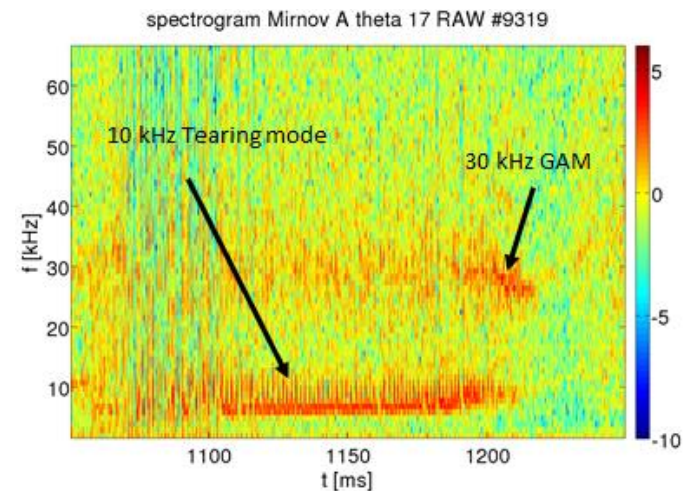


Figure 7. Spectrogram of the poloidal magnetic coil Mirnov A theta 17 (see Fig. 1). 30 kHz GAM and 10 kHz Tearing mode are visible.

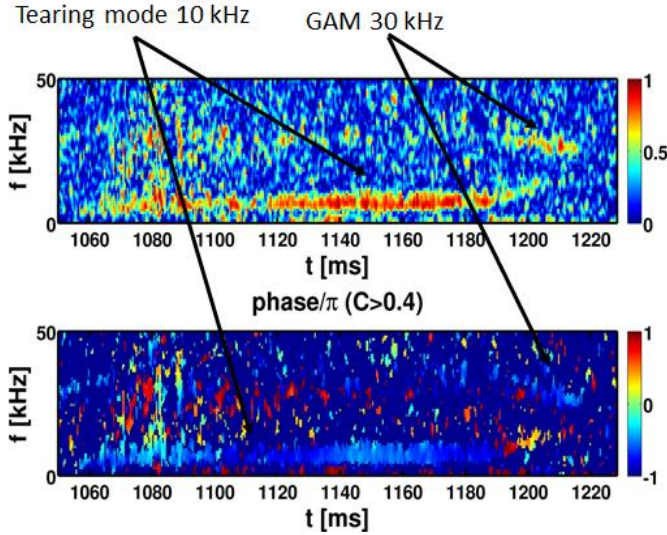


Figure 8. Coherence of a single pixel signal (shown in Figs. 5 and 6) with a magnetic coil. Mirnov A theta 17 in the discharge #9319. The figures show amount of coherent oscillations (top) and the phase between them (bottom). In both figures, 10 kHz tearing mode and 30 kHz GAM are identified.

D. Spatial structure of a mode

In the previous sections we have shown how to use cross-coherence with a magnetic coil to detect specific frequencies and exact times when oscillating modes are present in the intensity signal obtained from a single pixel. Such analysis can be further extended to infer also spatial structure of the mode. Therefore, band-pass filter with a frequency window around frequency of the mode is applied in the selected times on a signal of all pixels in the frame. Afterwards, the frames are again composed from all pixels for each time. Consequently, a video containing only oscillation of light intensity due to the mode under consideration can be created. This is demonstrated in Fig. 9 showing several time snapshots for the case of a rotating ~ 10 kHz $m/n=2/1$ tearing mode. The reconstructed spatial structure verifies the expected poloidal periodicity $m=2$.

We note that for the modes whose signal is not purely harmonic, such as sawtooth crashes, all significant Fourier harmonics should be preserved during the filtering phase.

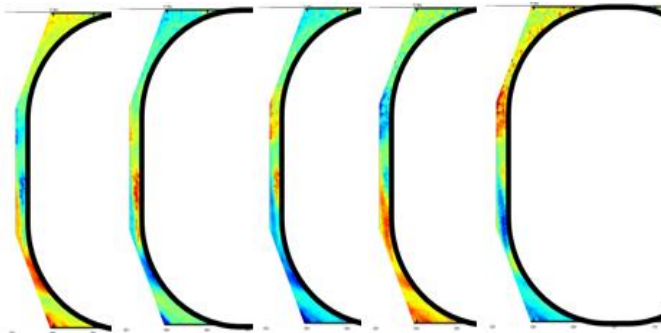


Figure 9. Time snapshots of band-pass filtered 10 kHz oscillations associated with rotating $m/n=2/1$ tearing mode in shot #9301. For simplicity only high-field side part of the last closed flux surface region is plotted.

V. SUMMARY

The work proved that fast imaging camera is an important tool that can be used for further studies of various oscillatory modes on COMPASS. During the initial phase of the analysis, four different types of modes summarized in the Table 1 were detected and a method for visualising their spatial structure has been proposed and tested on the case of a rotating tearing mode.

TABLE OF OBSERVED MODES

Mode name	Frequency
Sawteeth	~ 400 Hz
Unknown	~ 6 kHz
Tearing mode	~ 10 kHz
Geodesic acoustic mode (GAM)	~ 30 kHz

a. Oscillating modes in COMPASS observed by the fast visible camera

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