*36th EPS Conference on Plasma Phys. Sofia, June 29 - July 3, 2009 ECA Vol.**33E**, P-1.169 (2009)*

Radial and Parallel Transport Fast Camera Observation on LHD SOL Region

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I. Introduction

During 2008 NIFS experimental campaign, a new fast camera system was installed on the LHD stellarator, following previous work performed on LHD with conventional CCD cameras [1],[2] and previous work performed on TJ-II with similar camera systems [3]. On present work, the observation of edge transport mechanics during high β (up to 5%) discharges is described. These high β plasmas (R_{ax}=3.6 m, B_t=-0.425 T, Bq=100%, γ=1.197) are obtained by MHD optimization of the magnetic configuration [4] and their edge is characterized by the presence of the $\iota/2\pi = 3/2$ surface almost outside the LCFS (r_{eff}=0.99) [5]. Fast camera observation shows the strong dependence of SOL and divertor leg surfaces transport, and even wall interaction, on external MHD activity.

II. Experimental Setup and Data Interpretation

The fast camera employed in this experiment is a Photron APX-RS capable of 200 kHz operation, coupled to a 75 mm. objective by a 4.5 m long coherent optical fibers bundle in order to protect it from the intense magnetic fields from LHD. This layout allows the reception of either full spectrum light or, by the use of spectroscopic filters attached to the objective, observe specific line radiation bands. The camera was placed on LHD 6-T tangential port, overlooking a region of almost 90º of the vacuum vessel. For a more detailed description of the camera layout and its position on LHD, see [1] or [2] in which previous CCD camera experiments are outlined. On typical SOL conditions (T_e under 100 eV, $n_e \approx 10^{19}$ m^{-3} near the LCFS), mostly H_α and some Carbon lines radiation are detected. *Fig 1a* shows most of the camera field of view (FOV) where helicoidal illuminated curves corresponding to the toroidal positions of the two X point regions can be seen. Between these and the strike points (SP), two tenuous stripes indicate divertor leg magnetic surfaces. Thanks to LHD configuration and dimensions, edge signal is emitted at quite well determined magnetic regions (either the X point or the divertor leg) which almost never overlap on the camera FOV, allowing to identify the 3D position from a 2D view. At high β discharges sampling rates of 50 kHz were used, limiting the FOV to the highlighted area of *fig 1a*. On *fig 1b*, the projection of Poincare diagram[1] of both the ergodic layer and the edge is displayed, showing the two divertor leg surfaces in different colors. At this high frame rate (20 μs/frame) filaments can be seen propagating along divertor leg surfaces both toroidally, on the direction of the magnetic field, and radially, alternating between inwards and outwards motion.

[1]In this first study, only vacuum magnetic field lines are considered. Future developments will include finite β effects in the analysis.

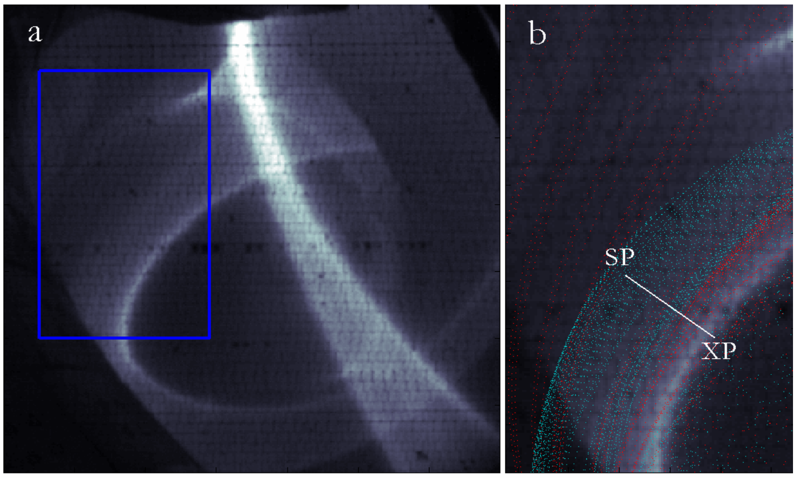

Fig. 1 *Typical images for a high β discharge. On b, Poincare diagram and radial channel with Strike Point and X Point highlighted.*

Following basic image analysis techniques frequency band filtering can be used to eliminate the continuous level from the signal, thus isolating its fluctuating component and easing the visualization of structures (*fig 2*). As displayed on *fig 4*, the frequency spectrum of the camera signal, bears a strong resemblance to magnetic probe one, dominated by *m/n=2/3* mode activity (2-3 kHz) and to a lesser exent by *m/n=2/5* (3-5 kHz). This is confirmed by conventional H_α monitors in the sector. In the same figure, some "secondary" activity is found on the range of 4-10 kHz, non being related to the *m/n=2/3* mode. It becomes more important near the X point and less near the wall. This suggests a clear relation between MHD modes and edge transport. If band-pass filtering is done, on the low freq. case, bright and dark stripes alternate propagating on the parallel direction along X and SP regions, although not simultaneously. Between them bright waves can be seen propagating radially -mostly outwards- with no clear toroidal extension. On the high freq. case, less intense "comet" shaped filaments propagate with an apparent "head" following field lines on the X point region and a "tail" stretching radially as it follows the head. In this high band, inwards propagating filaments can also be seen in the outermost part of the channel. *Fig 3a* shows this analysis of the radial channel highlighted in *fig 1b* during 10 ms, while the sequence on *fig 2* shows the full frame superposition of the described effects. Still, this frequency classification is somehow artificial and both phenomena seem strongly related, not being possible to completely separate them.

III. Neutrals and Wall Interaction

On a first approach, outwards moving filaments can be seen as groups of particles ejected at the LCFS, crossing the ergodic layer and finally released on the SOL, travelling towards the wall along the divertor leg surfaces, where the presence of neutrals is high enough to emit in the visible range. As seen in *fig 2* and *fig 3*, they never seem to surpass a certain radial point. This can be explained by a combination of magnetic geometry projection effects (*fig 1b*) and a minimum in the n_0n_e product. Besides, for the given SOL conditions and attached regime, new emissions are produced on the moment of arrival to the wall. LHD wall is made out of

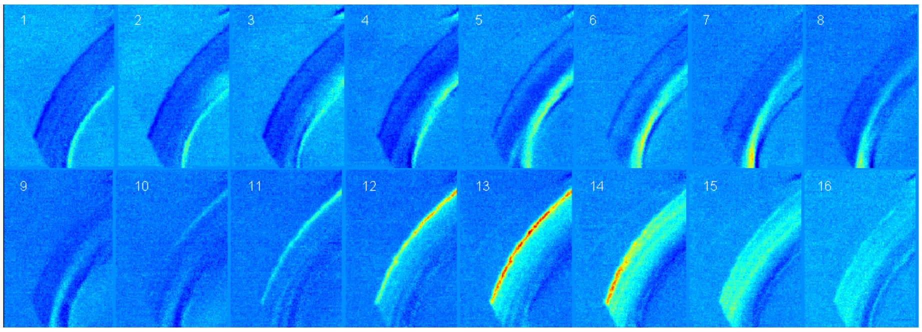

Fig. 2 *50 kHz sequence with continuous component of signal removed (.5-25 kHz employed). Both "comet" like and XP and SP stripes can be appreciated*

stainless steel but can be considered covered by a layer of carbon (as not in nominal conditions, the impact point is on the wall and not in the helical divertor plates). In these conditions, physical sputtering will inject carbon atoms into the SOL which will emit on several visible lines as they ionize. As well, up to 30% of the striking ions [6] can be expected to be reflected with a significant fraction (up to 20%) of the ion energy (after Debye sheath) rather to be implanted in the wall. This is in very good agreement with spectrometric measurements [7], which confirm the existence of reflected neutrals and even observe 22.7 eV neutrals for a typical inward flow velocity of 9.5 km/s on the attached regime.

IV. Radial and Parallel Transport

Radial[2] transport can be observed both on low freq. mode-driven and high freq. filament activity can be distinguished. The slope on *fig 3a* gives velocities around 3 km/s and 6-8 km/s respectively for outwards and inwards travelling filaments (SOL width of some .8 m). Besides, the both high and low freq. outwards trajectory seems to connect the low frequency high states on the XP and SP regions. *Fig 3b* shows the correlation between channels in both regions, being maximum at 250 μs (radial travel time of the filaments). Besides, on *fig 3a* outwards high freq. events seem to be associated to low freq. ones, as if the former took place at the end of the mode high state, with a series of secondary "comets" following the first one, very much like a train of shock waves. Inward events seem to take place mostly after a high state on the strike region. Parallel transport can be observed only in high freq structures (with toroidal extension). For it, a windowed time-dependent fft method is employed [8] to obtain an average velocity for the filaments. Observed velocities range in the order of 10-20 km/s and seem to be directly related to NBI injected power and direction in good agreement with

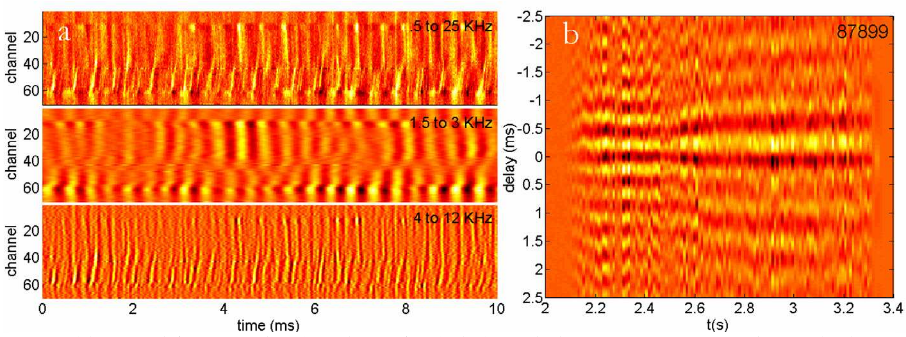

Fig. 3 *(a) Several frequency band analysis of radial channel along t = 2.2 to 2.21 s during discharge 87899 (b) correlation between low frequency band signals on channels corresponding to XP and SP*

[2] Radial and parallel velocities are defined w.r.t. camera view, i.e. "parallel/radial" means "with a projection parallel/perpendicular to the projected field lines"

previous toroidal rotation studies [9].

V. Conclusions

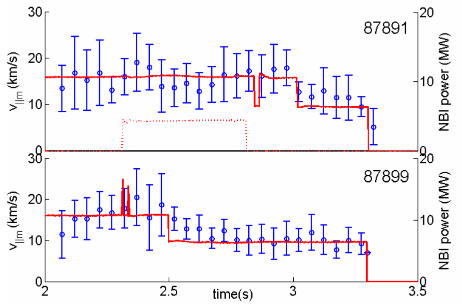

Fig. 5 *Parallel velocities as measured by the camera and NBI power (solid "co"; dotted "counter") on discharges 87891 and 87899*

In conclusion, radial transport across the channel seems to be dominated by low frequency, mode-driven periodical releases of particles still inside the LCFS which give raise to broad waves and, indirectly, to higher freq. "comet" shaped filaments (which, though dimmer, concentrate relevant amounts of particles and might be responsible of a significant fraction both of the ion radial diffusion and neutral penetration). Other structures are created from these as they reach the walls either because of their ions being reflected or carbon atoms in the wall being sputtered. Relation between low freq. structures on the X point and the wall is clear. At high freqs. filaments ejected from the X point region are often (but not always) followed by inwards moving ones. All these structures show a combined radial and parallel motion: the "comet" shape can be seen as combination of perpendicular diffusion and parallel deceleration as particles are released on the tail of the mode rotation (only perceptible in higher freq. filaments due to their limited size). A comparison between velocities (~3 km/s vs. ~10-15 km/s) and distances (some 50-70 cm. width vs. connection lengths of the order of 5-10 m in the observed region) suggest characteristic propagation times for radial and parallel transport are on the same order of magnitude (being the first one slightly faster). This gives a picture with ions hitting the wall in the relative toroidal vicinity of their ejection, rather than travelling several meters following field lines (although often going far enough to leave the FOV, as in *fig 2*). Finally, the ejection pattern of the high frequency structures, and the presence of resistive pressure gradient driven turbulence (characteristic of high β operation in LHD), suggest the possibility of Self Organized Criticality behaviour on the edge. Right now, more detailed statistical analysis is under way.

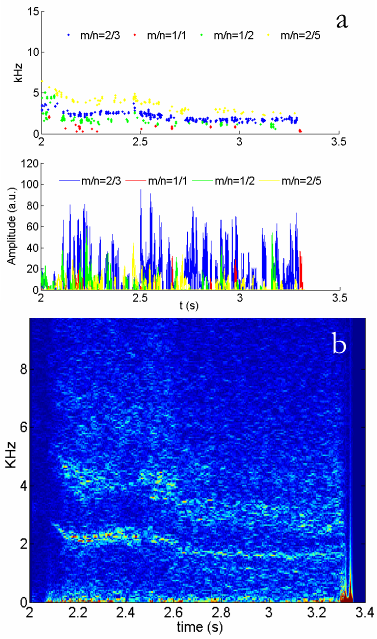

Fig. 4 *a) Magnetic probe data showing several peripheral mode activity (Courtesy of S. Sakakibara) and b) fast camera signal fft spectrum*

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This work is supported by NIFS/NINS under the project of Formation of International Network for Scientific Collaborations