EUROPEAN FUSION DEVELOPMENT AGREEMENT
JET

EFDA–JET–PR(02)27

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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

Preprint of Paper to be submitted for publication in
Plasma Physics and Controlled Fusion

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ABSTRACT.
The statistical properties of the radial propagation of ELMs have been investigated in the Scrape-Off-Layer(SOL) region of the JET tokamak. The shape of ELMs shows evidence of fine high frequency structures propagating radially with effective radial velocities in the range of 1000 m/s. Experimental results suggest a link between the radial velocity and the size of transport events. This shows the importance of the competition between both parallel and radial transport to explain particle losses onto the divertor plates. Parallel flows show a transient increase during the appearance of ELMs, providing evidence of a coupling between parallel dynamics and radial transport.

1. INTRODUCTION

Understanding the impact of edge localized modes (ELMs) induced particle and energy fluxes in the divertor plates remains as one of the major concerns in the fusion community for future devices like ITER. ELMs are repetitive fluctuation activity which appears, in addition to residual small-scale turbulence, near the edge plasma in improved confinement regimes in magnetically confined plasmas. ELMs affect both energy and particle confinement decreasing the plasma energy and particle content [1]. Therefore, ELMs can provide particle control in improved confinement regimes. However, large amplitude ELM might lead to unacceptable power loads in the divertor plates when extrapolated to next step devices [2].

In determining the ELM energy and particle losses to the divertor it is important to clarify the possible link between the amplitude and the radial propagation of ELMs. This effect might have an important consequence in the extrapolation of the impact of ELM in the divertor plates on future devices. Additionally, the radial structure of the SOL region is directly connected with the mechanisms which control the radial propagation of transport events. Recently the investigation of the dynamical coupling between transport and gradients has shown that the resulting radial velocity depends on the size of transport events [3, 4]. The resulting radial velocity of fluctuations is of the order of 20 m/s for transport events implying a small deviation from the most probable gradient but increases up to 500 m/s for large transport events. From these perspectives it is important to investigate the statistical properties of the radial propagation of ELM like transport events.

The aim of this paper is to study the statistical properties of the radial propagation of ELMs in the JET scrape off layer (SOL) region. The paper is organized as follows. In section 2 the experimental set-up is described. In section 3 shows the ratial and temporal structure of ELMs in the SOL region. The radial propagation of ELMs coupling between radial and parallel dynamics are discussed in section 4 and 5 respectively. Section 6 gives the conclusions.

2. EXPERIMENTAL SET-UP

The radial propagation of ELMs and the structure of fluctuations are under investigation in the JET SOL region using Langmuir probes located in the upper part of the device. The experimental set up consists of arrays of Langmuir probes radially separated 0.5cm, allowing a unique investigation of the propagation of ELM events and fluctuations with good spatial (0.3cm) and temporal (2ms) resolution. Also a Mach probe was used to study coupling between radial and parallel propagation of ELMs. Plasma fluctuations are investigated using standard signal processing techniques and 500 kHz digitisers. Plasmas studied in this paper were produced in X-point plasma configurations with toroidal magnetic fields B = 1 - 2.5T, Ip = 1 - 2MA, P_{Total} = 2 - 13MW (H-mode plasmas).

TEMPORAL AND RADIAL STRUCTURE OF ELMS

The frequency spectra of density and potential have been investigated during the ELMs occurrence. Modifications in the frequency spectra of fluctuations have been observed before and after the arrival of the ELM event propagation. In particular, bursts in frequency spectra (50 - 100 kHz) have been detected after the ELM arrival in potential signals but not in density signals.

Figure 1 shows the time evolution of the ion saturation current as measured by two probes radially separated during the ELM propagation in the SOL region (B = 1T, I = 1MA). The response of ion saturation current and potential signals show an increase followed by decay during ELMs. However, it should be noted that the shape of ELMs, as measured by Langmuir probes with high frequency ADCs, shows high frequencies structures. We denote the initial sharp change in the time evolution of the ion saturation current traces by the time of arrival of the ELM event propagation. Typical time delays for the time of ELMs arrival are in the range of 2 - 10µs for sensors radially separated 0.5cm. This implies a radial velocity in the range of 1000m/s. Perturbations in ion saturation current and potential signals induced by the appearance of ELMS are observed up to 7cm beyond the LCFS in the SOL region (Fig.2). This result implies that the ELM convective SOL-width is much broader than the typical SOL-width measured during time intervals between ELMs (about 1 cm).

STATISTICAL PROPERTIES OF ELMS RADIAL PROPAGATION

Turbulent particle transport and fluctuations have been calculated, neglecting the influence of electron temperature fluctuations, from the correlation between poloidal electric fields and density fluctuations at the inner probe position. The poloidal electric field has been estimated from floating potential signals measured by poloidally separated probes, $E_\theta \, \Delta\tilde{\Phi}_f / \Delta_\theta$ with $\Delta_\theta \approx 0.5$ cm. Fluctuations in the radial component of ion saturation current gradients have been computed as $\tilde{\nabla} I_s\,(t) = [\tilde{I}_s^{inner}\,(t) - \tilde{I}_s^{outer}\,(t)]$ with $<\Delta\tilde{I}_s>=0$, where $\tilde{I}_s^{inner}$ and $\tilde{I}_s^{outer}$ are the ion saturation current fluctuations simultaneously measured at two different plasma locations radially separated by 0.5cm. An effective radial velocity has been defined as the normalized E×B turbulent particle transport to the local density: $v_r^{eff} = <\tilde{I}_s\tilde{E}_\theta> / \tilde{I}_s B_T$ where I_s is the ion saturation current of the inner probe. This effective velocity is not affected by uncertainties in the probe area providing a convenient way to investigate the statistical properties of the radial propagation of ELMs in the SOL region.

In order to study the coupling between Probability Density Functions (PDF) of transport and gradients, we have computed the joint probability P_{ij} of the two variables X and Y. The probability that at a given instant X and Y occur simultaneously, is given by $P_{ij} = P(X_i, X_j)=N_{ij}/N$ where N_{ij} the number of events that occur in the interval (X_i, $X_i + \Delta X$) and (Y_i, $Y_i + \Delta Y$) and N the time series dimension. ΔX and ΔY are the bin dimension of X and Y time series, respectively, where the indices stands for i-th (or j-th) bin average value. The expected value of X at a given value of Y_j is defined as

$$E[X/Y_j] = \frac{\sum_i P_{ij} X_i}{\sum_i P_{ij}}$$

and represents the average value of the probability distribution of X at a given value of Y.

Experimental results show a strong coupling between the time evolution of E×B transport, fluctuations in the radial gradient and ELMs in H-mode plasmas (Fig.3).

The PDF of fluctuations in gradients is strongly affected by the presence of ELM events. They show much stronger non-gaussian features in ELMy plasmas than in L-mode plasmas (Fig.4).

Figure 5a shows the expected value of the radial effective velocity versus fluctuations in the radial gradient ($\nabla \tilde{I}_s$). Radial effective velocities increase up to 2000m/s during ELMs. This radial velocity is consistent with the $E_\theta \times B$ velocity which can be computed from the poloidal electric field shown in figure 5b. The present experimental results suggest that the radial velocity of ELMs increases with the ELM size (i.e. increasing $\nabla \tilde{I}_s$). Large transport events seem to have also an associated poloidal velocity, computed from the $E_r \times B$ velocity (E_r being the radial electric field) (Fig.5c).

The radial structure of radial perturbations and velocities associated with ELMs has been investigated using Langmuir probe signals measured at different radial location in the SOL region (Fig.6). Raw data show that the size of the radial perturbation (s I ~ Ñ) linked to ELMs decreases as increasing the distance to the LCFS. However, experimental results shows that the maximum radial speed of ELMs does not significantly depend to the distance to the LCFS [$r - r_{LCFS} = (1 – 6)$ cm] (fig. 7a), suggesting a ballistic rather than diffusive propagation mechanism in the SOL region. The large radial speed of ELM might partially explain experimental results showing that only about 50 – 80 % of the energy losses due to large type I ELMs arrives to the divertor plates [5].

The effective radial velocity of ELM transport events in JET is rather similar to the radial velocity of ELMs previously reported in spherical tokamaks [6] and of large transport events reported in L-mode plasmas (fig.8). Interestingly this value is rather close to the speed of 200 m/s reported during the evolution of transport through the L-H transition in JET [7] . However, ELMs radial speed in the SOL is much larger than the effective radial velocity of simplified simulations of diffusive transport in the SOL region. These results suggest the existence of different transport mechanisms for small and large transport events (non-diffusive) in the JET plasma boundary region.

RADIAL AND PARALLEL DYNAMICS

Mach probe measurements have shown that during the appearance of ELMs, perturbations in the ion saturation current are larger (about a factor of 3) in the probe facing the outer divertor (e.g. region of bad curvature) than in the probe facing the inner divertor (e.g. region of good curvature) (fig.9). This result implies that ELM events and parallel flows are dynamically linked. This result might reflect the strong ballooning character of ELMs but it also suggests that parallel flows are strongly affected by fluctuations. This conclusion is consistent with recent results in JET showing a dynamical coupling between turbulent transport events and parallel flows.

CONCLUSIONS

The statistical properties of the radial propagation of ELMs have been investigated in the Scrape-Off-Layer (SOL) region of the JET tokamak and the following conclusions have been found:

a) The shape of ELMs shows evidence of fine high frequency structures propagating radially. Effective radial velocities in the range of 1000 m/s have been obtained.
b) Experimental results suggest a link between the radial velocity and the size of transport events. These results imply that ELMs arrival time to the plasma wall can be comparable to, or even smaller than, the characteristic time of transport to the divertor plates (in the range of 0.1–0.5 ms); in these circumstances we have to consider the competition between parallel and radial transport of ELMs to explain and predict particle and energy fluxes onto the divertor plates in ITER.
c) Parallel flows show a transient increase during the appearance of ELMs, providing evidence of a coupling between parallel dynamics and radial transport.

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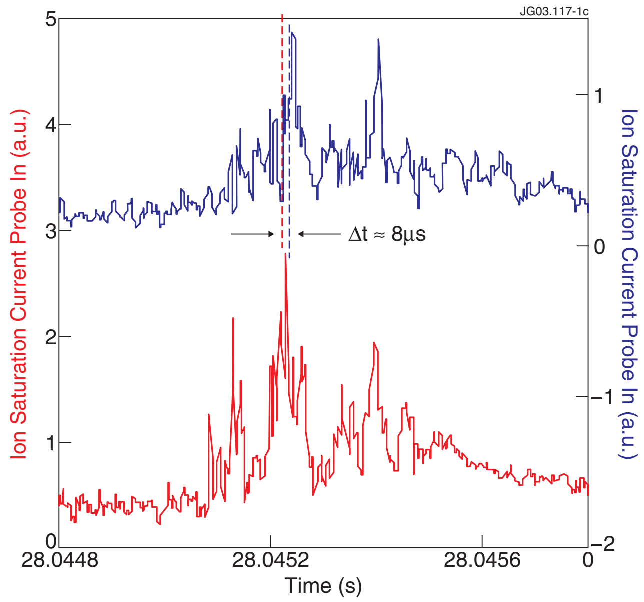

Figure 1: Time evolution of the ion saturation current as measured by two probes radially separated during the ELM propagation in the SOL region (B = 1T, I = 1MA).

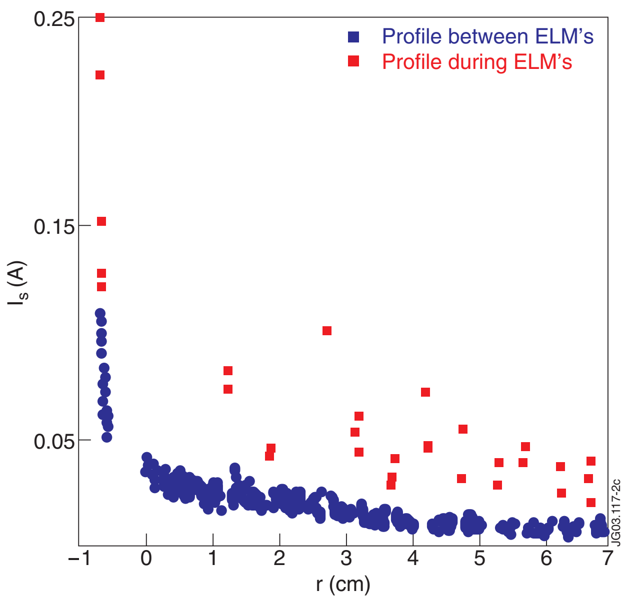

Figure 2: Radial profiles of ion saturation current during and between ELMs.

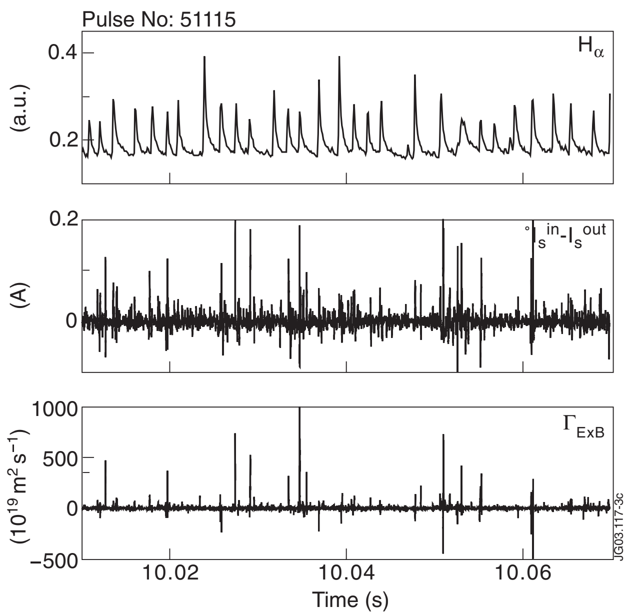

Figure 3: Time evolution of H_α, radial gradients ($\nabla \tilde{I}_s$) and E×B transport signals on H-mode plasmas.

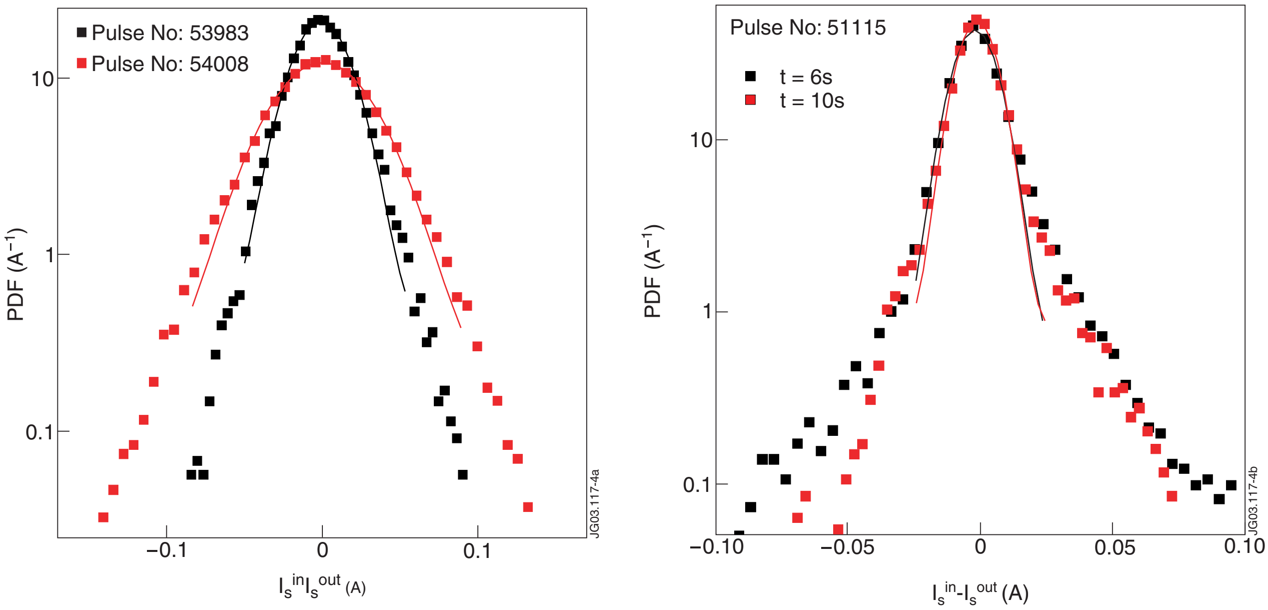

Figure 4: The probability density function of fluctuations in density gradients: a) in L-mode plasmas. The PDF is rather gaussian b) in two different instants in ELMy H-mode. There is a visible departure from the gaussianity due to ELMs.

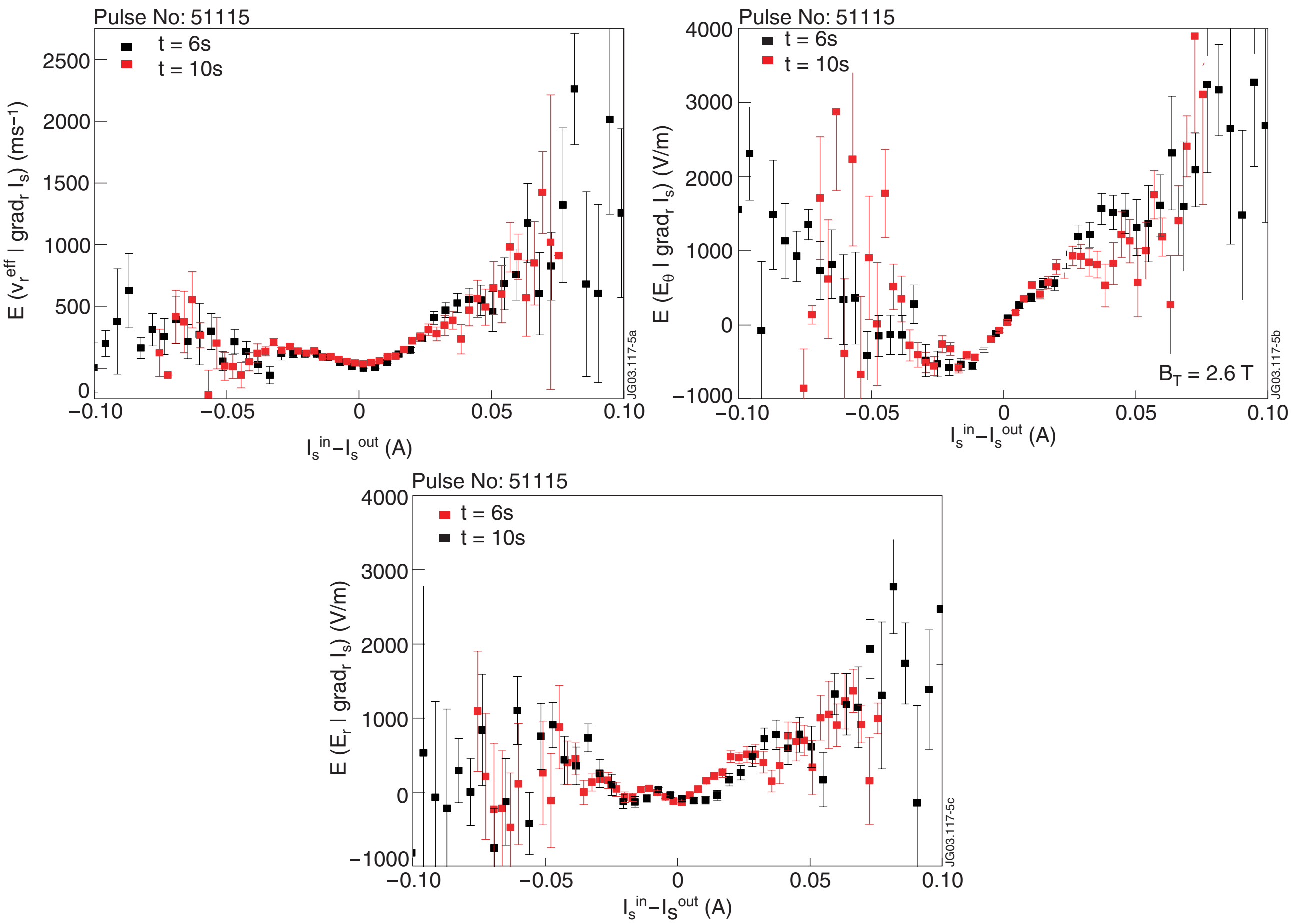

Figure 5: (a) Effective radial velocity versus fluctuations in the radial gradient; (b) Poloidal electric fields versus radial gradient. Measurements were taken at r-r_{LCFS} ≈ 1cm; (c) ErxB radial propagation is larger than EqxB poloidal propagation.

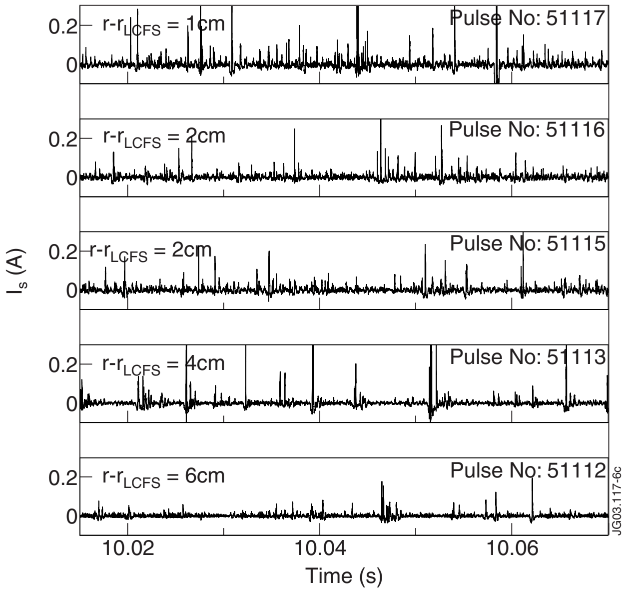

Figure 6: Time evolution of the ion saturation current at different radial locations. The ELMs amplitude decrease as far on the SOL is the observation point

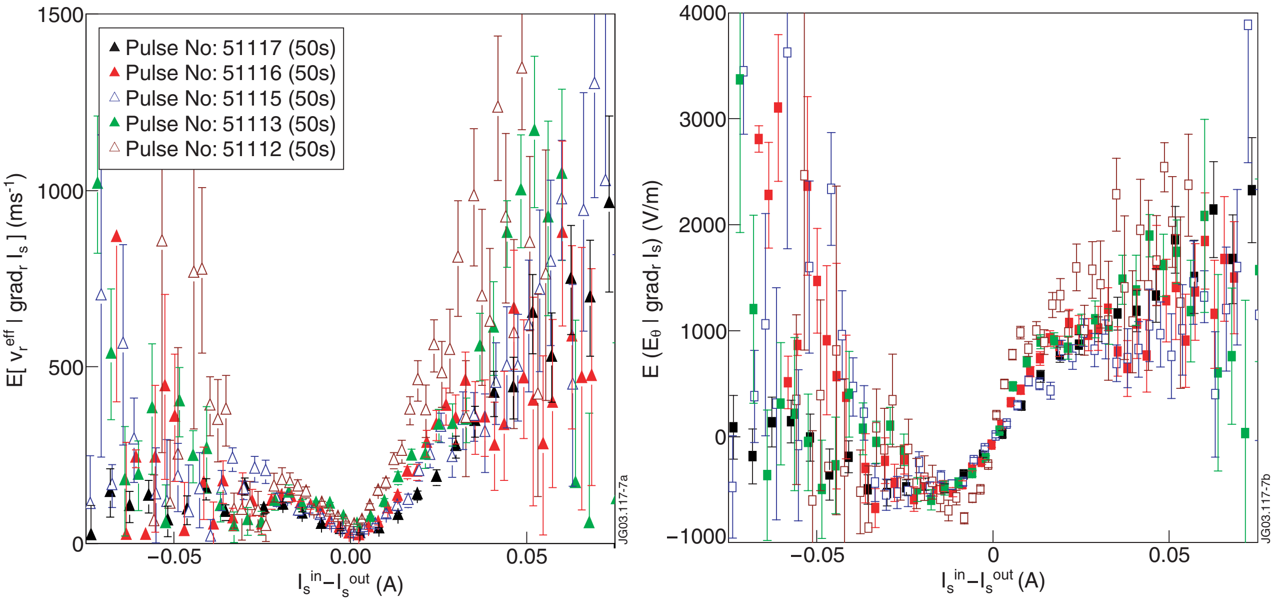

Figure 7: Expected value of the radial effective velocity (a) and poloidal electric field (b) for a given density gradient. The maximum effective velocity and poloidal electric field linked to ELMs seems to be independent of the distance to the LCFS.

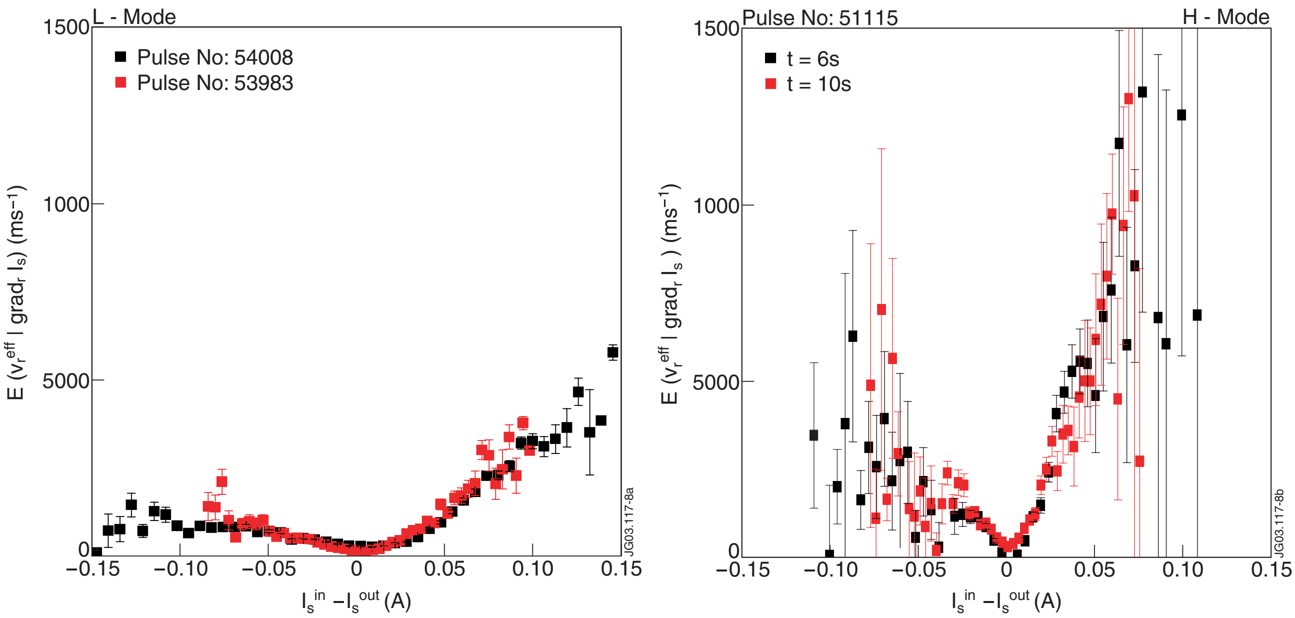

Figure8: Comparison between the radial effective velocities for L and H-mode. Large transport events in L-mode plasmas have radial velocities rather similar to ELMs radial speed. The dynamical link between fluctuations in gradients and turbulent transport is affected by heating power and sheared radial electric fields, in L-mode plasmas.

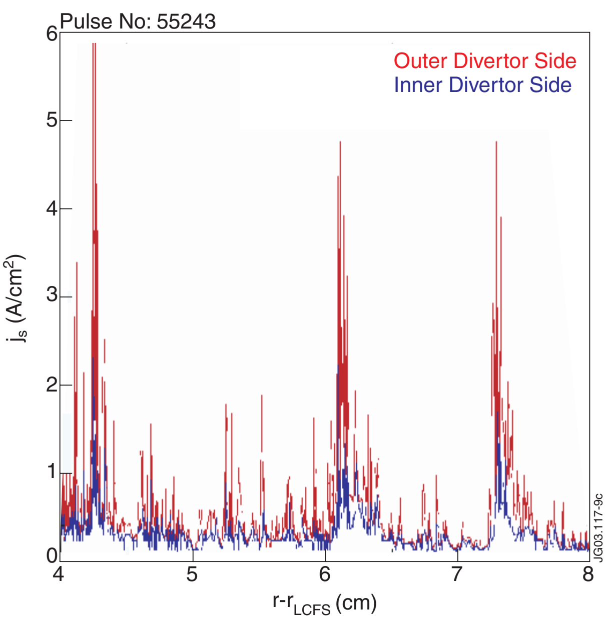

Figure 9: Time evolution of ion saturation current on the ion and electron drift sides of a Mach probe. During the appearance of ELMs, perturbations in the ion saturation current are larger (about a factor of 3) in the probe facing the outer divertor (e.g. region of bad curvature) than in the probe facing the inner divertor (e.g. region of good curvature). This result implies that ELMs have strong ballooning character.