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L.D. Horton 1), A.V. Chankin 1), Y.P. Chen 1), G.D. Conway 1), D.P. Coster 1), T. Eich 1), B. Kurzan 1), J. Neuhauser 1), I. Nunes 2), M. Reich 1), S. Saarelma 3), J. Schirmer 1), J. Schweinzer 1), E. Wolfrum 1) and the ASDEX Upgrade Team 1)

1) Max-Planck-Institut für Plasmaphysik, EURATOM-Association, D-85748 Garching, Germany
2) Associação EURATOM/IST, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
3) Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon OX14 3DB, U.K.

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3) Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon OX14 3DB, U.K.

e-mail of contact main author: Lorne.Horton@ipp.mpg.de

Abstract. The scaling of the edge transport barrier (ETB) that sustains H-mode plasmas is crucial for the performance of next step tokamaks. At ASDEX Upgrade, the suite of edge diagnostics has been significantly improved so as to address this issue. High spatial resolution profiles of most of the key edge plasma parameters necessary to determine the MHD stability are now available. New high temporal resolution measurements give clear indications of the nonlinear evolution of the ELM crash. The correlation lengths of edge turbulence have been shown to be correlated with the edge radial electric field shear using a new correlation Doppler reflectometer system. The measured pressure gradient in the ETB is found to be consistent with ideal MHD stability limits, both for Type I and II ELMs. In addition, the edge electron temperature and density gradient lengths are found to be strongly correlated, leaving only the ETB width as a free parameter. In ASDEX Upgrade, the ETB width does not vary significantly over the entire edge database. Comparison of dedicated hydrogen and deuterium discharges where the ionisation depth is calculated to vary due to the mass difference also show no significant difference in the ETB width. Modelling of the transport of these discharges requires a transport barrier in both the energy and particle channels.

1. Introduction

The scaling of the edge transport barrier (ETB) that sustains H-mode plasmas is crucial for the performance of next step tokamaks. The strength of the barrier and, in particular, the temperature at the top of the barrier provide the boundary condition that determines the level of turbulent transport in the plasma core. On the other hand, the large ELM relaxations that are typical of the highest confinement edge barriers result in energy pulses that may have serious consequences for the lifetime of reactor divertor and first wall components.

The understanding of the edge barrier region and the ability to test models in this region are strongly limited by the difficulty in making profile measurements with sufficient spatial and temporal resolution. Resolving the ~2 cm pedestal width on ASDEX Upgrade requires spatial resolution of a few mm. The entire ELM crash occurs in a few 100 µs so that diagnosing the dynamics of the crash requires bandwidths of the order of 100 kHz or more. For these reasons, a significant effort has been made at ASDEX Upgrade to improve the diagnosis of the edge barrier. These diagnostic improvements are now providing insight into the physics of the ETB, both during the inter-ELM phase and during the ELMs.

2. Inter-ELM Transport in the ETB

The electric field shear is thought to play a key role in suppressing turbulent transport in the plasma edge barrier. The radial electric field in the plasma edge region is measured at ASDEX Upgrade using a Doppler reflectometer system [1]. By using a dual channel Doppler reflectometer, it is possible to measure the density fluctuation level, the radial correlation length of the fluctuations and the radial electric field shear and to correlate the reduced turbulence parameters with the field shear [2]. An example of a measured radial electric field profile for an Ohmic discharge is shown in Fig.1. Using the SOLPS5 code [3,4] with the inclusion of drift terms [5], it is possible to reproduce both the shape and the magnitude of the measured profile. The discrepancy between measurement and model in the transition region near the separatrix is thought to be due to the omission of a perpendicular viscosity term in the model. For the present modelling, the effect of the perpendicular viscosity term is simulated using an anomalous perpendicular conductivity. Work is underway to improve the stability of the code when the viscosity term is included.

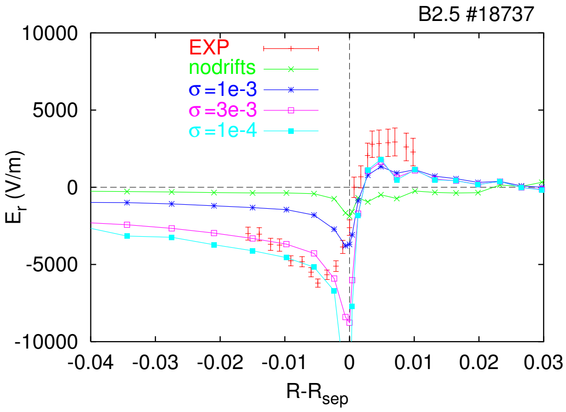


Fig.1. Profiles of radial electric field in an Ohmic discharge measured using a Doppler reflectometer (red points). Modelling of the same discharge using SOLPS with (green) no drift terms included and with drift terms and various values of an anomalous radial conductivity σ.

Edge ion temperature profiles can now be measured on ASDEX Upgrade with a 5 mm spatial resolution using charge exchange spectroscopy on a diagnostic lithium beam [6]. The H-mode ion temperature profiles are found to be similar to the electron temperature with perhaps a factor of two higher separatrix ion temperature (Fig.2(left)). The separatrix ratio of ion to electron temperature, while important for SOL power balance studies, leaves little uncertainty in the total pressure gradient required as input for magneto hydrodynamic (MHD) stability studies. Using SOLPS5, the transport coefficients for ions and electrons can be derived by fitting the measured upstream profiles (Fig.2(right)). The electron and ion temperature profiles can be reproduced with the assumptions that the ion and electron heat flux entering the edge region are equal and that the ion perpendicular thermal conductivity inside the separatrix χ_i is 40% of χ_e. The ion thermal conductivity in the ETB is, on these assumptions, approximately a factor of 3-5 above that predicted by neoclassical theory. Work is ongoing to

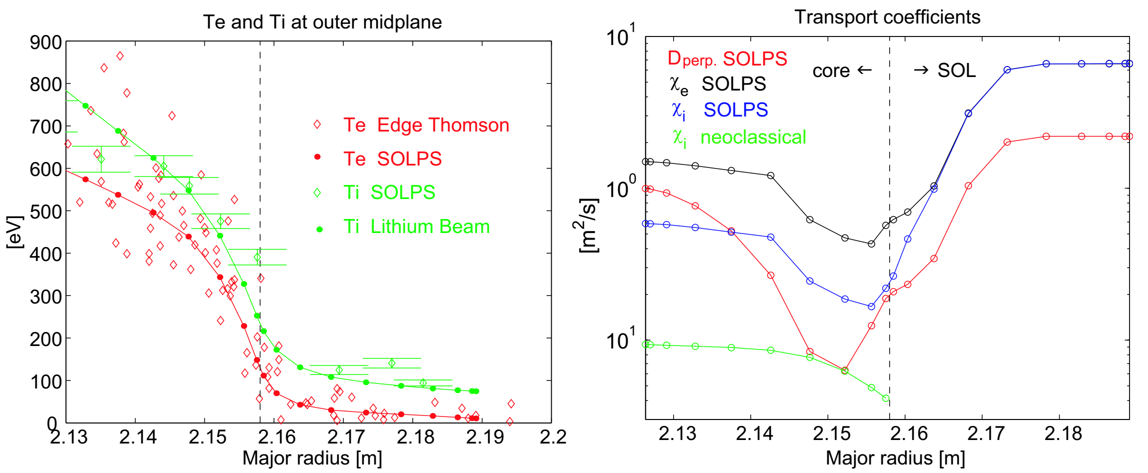


Fig.2. (left) Profiles of electron and ion temperature at the outer midplane during a Type I ELMy H-mode plasma. (right) The transport coefficients used in SOLPS5 to reproduce the experimental measurements and a calculation of the neoclassical ion heat conductivity for the measured profiles.

determine how generally one observes anomalous ion conductivity and, in particular, the sensitivity of this conclusion on the equipartition of heat fluxes between the ion and electron channels.

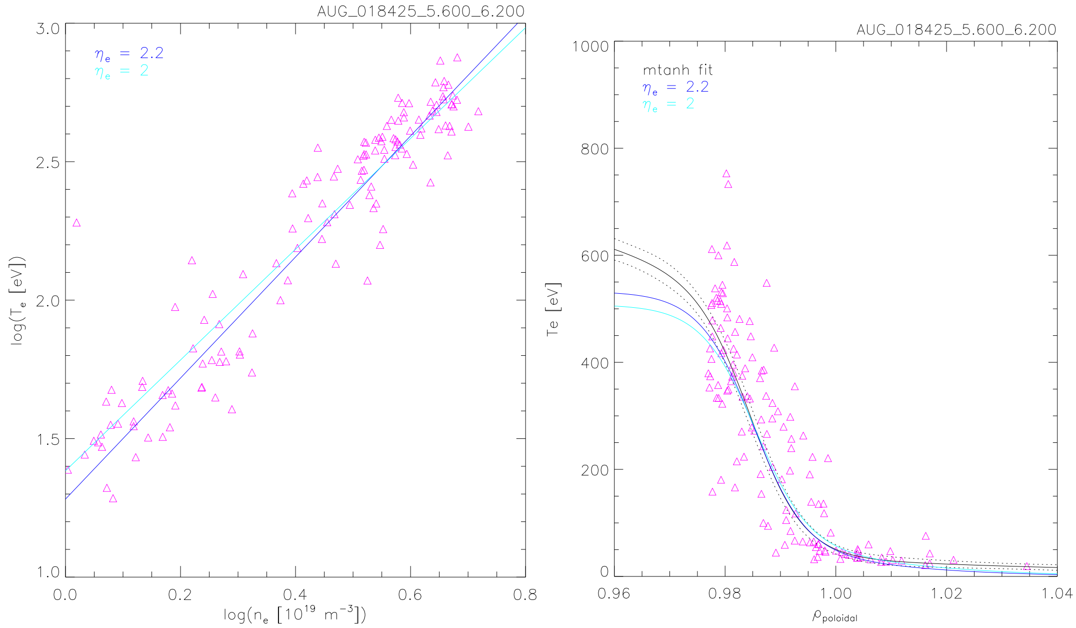


Fig.3. (left) Linear fit of log(electron temperature) versus log(electron density) in the ETB region of a Type I ELMy H-mode. The best fit gives η_e *=2.2;* η_e *=2.0 is shown for comparison. (right) Profiles of the edge electron temperature profile: in black the best modified tanh fit to Te (to a wider range of data than shown); profiles derived from the best modified tanh fit to the electron density profile and, in blue, the assumption that* η_e *=2.2 or, in light blue, using* η_e *=2.*

The confinement which can be achieved in the edge transport barrier is limited by ideal MHD to normalised pressure gradients $\alpha \sim (q^2R/B^2)(\nabla p)$ of order unity. This has been shown not just for Type I ELM plasmas (in most present-day tokamaks) but also for Type II discharges in ASDEX Upgrade [7]. There is in addition an observed correlation between the width of the most-unstable eigenmode and the size of the ELM crash. Thus the small size of Type II ELMs is supposed to be related to the narrow modes which are achieved by operating at moderate safety factor and in near double null magnetic configurations.

In addition to the MHD pressure limit, the ratio of the electron density to temperature scale lengths (η_e=L_{ne}/L_{Te}) is found to be approximately 2 in all ASDEX Upgrade H-mode discharges [8]. This result is particularly robust in that, for diagnostics such as Thomson scattering which measure simultaneously temperature and density, no mapping is required. An example of a fit of η_e is shown in Fig.3. With a hyperbolic tangent fit to the electron density profile and using η_e =2, it is possible to reproduce the measured electron temperature profile in the ETB. The constraint on η_e in the edge barrier is sufficiently robust that deviations from it can be used to determine the width of edge barrier. Indeed, with two separate constraints on the edge density and temperature, the edge barrier width is left as the only unconstrained parameter.

The width of the ETB is now typically characterised by the width of a hyperbolic tangent function fit to the available experimental data [9,10]. While such fits provide a good characterisation of the data, the regularisation they introduce can produce artefacts which are not present in the original data. In the case of the density profile, in particular, the separation of the ETB region from the SOL can be difficult and can lead to significant uncertainties in the determination of the width of the density ETB that are typically not reflected in the statistical uncertainty of the fit. The hyperbolic tangent model for the density is based on the work of Engelhardt and Feneberg [11], extended to divertor geometries by the DIII-D Team. The original model, based on particle conservation, a constant diffusion coefficient and a uniform, mono-energetic flux of neutrals into a plasma slab, produced a density profile in the shape of a hyperbolic tangent only inside the LCFS with an exponential decay in the SOL. Furthermore, the model assumed that recycling was local whereas the recycling in present divertor tokamaks is localised near the X-point of the active divertor. This has been incorporated into the working model at DIII-D by including an average flux expansion near the X-point into the neutral penetration length. For the purposes of the discussion here, it is sufficient to note that the fact that a hyperbolic tangent function can be used to fit the density profile is not sufficient to conclude that the particle diffusion coefficient across the core, ETB and SOL regions is constant.

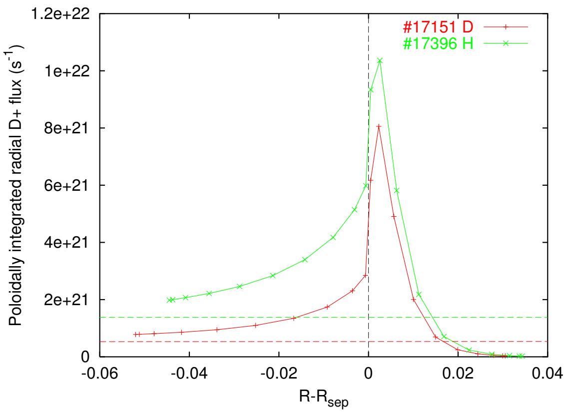


Fig.4. Profiles of poloidally-integrated ionisation sources for two similar ELMy H-mode discharges, one in hydrogen and one in deuterium. The horizontal dashed lines show the level of the particle source provided by the neutral heating beams.

In DIII-D [12] and, more recently, in JET [13], the density width has been correlated to the ionisation depth in the edge plasma. In ASDEX Upgrade, on the other hand, no significant variation in the width of the density barrier has been observed [14,15]. In a further, dedicated experiment, hydrogen and deuterium H-mode plasmas were compared and little difference was found in the measured ETB width. Detailed SOLPS modelling has shown that the naïve assumption that the hydrogen ionisation profile should extend deeper into the core is correct (Fig.4). At the top of the ETB, the particle flux driven by ionisation of recycling particles is about equal to the particle flux from the injected neutral heating beams. The measured density and temperature profiles

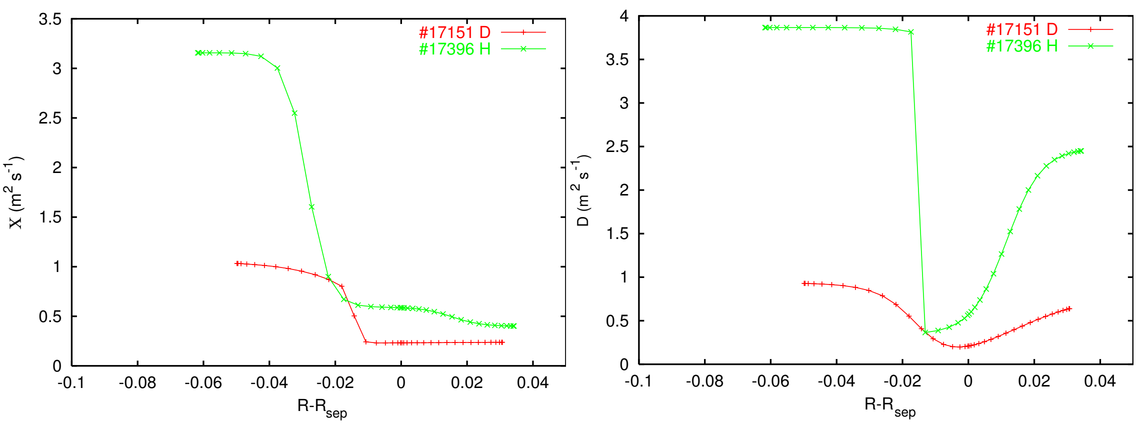


Fig.5. Profiles of anomalous perpendicular heat and particle diffusivities for two similar discharges in hydrogen and deuterium. Fits to the measured profiles require an edge transport barrier in both the energy and particle channels.

cannot be reproduced with radially constant transport coefficients (in the absence of pinch terms). Profiles of coefficients which do reproduce the measurements are shown in Fig.5. In addition to the reduced heat transport that is required in the ETB, the particle diffusion coefficient is also reduced. We thus conclude that, at least in this case, the ETB width is set both for energy and particles by the width of a region of reduced anomalous transport rather than by the neutral penetration depth.

3. ELM Triggering and Dynamics

In ASDEX Upgrade, the edge electron density profile is measured with a 35 μs temporal resolution and a 5 mm spatial resolution using a swept frequency reflectometer system [16]. With this resolution, it is possible to investigate the dynamics of the density evolution during an ELM event. Using the low field side (LFS) and high field side (HFS) reflectometer systems, it is further possible to study the poloidal variation of the ELM instability. Time traces of divertor Dα emission, pedestal-top density and scrape-off layer (SOL) density are shown for a typical Type I ELM in Fig.6. As in JET and JT-60U, the ELM crash in AUG is observed to occur first on the LFS of the plasma [15,17-19]. The delay in appearance of the ELM instability at the HFS is equal to the delay one calculates if the instability is assumed to propagate poloidally at the pedestal-top sound speed along the length of the unperturbed field lines connecting the LFS and HFS. During an ELM, the electron density on both the LFS and HFS is observed to increase in the SOL and decrease at the top of the ETB with a pivot point at about the location of the separatrix.

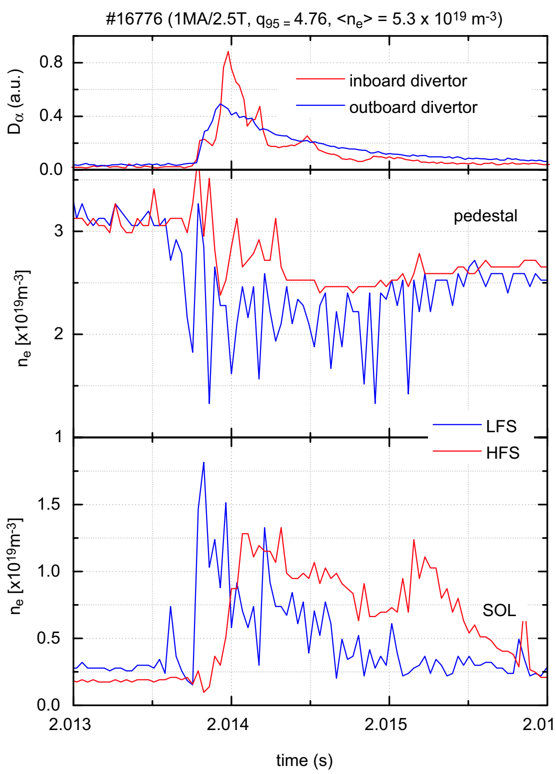


Fig. 6. Time traces of (top) inner and outer divertor Da emission, (middle) pedestal-top electron density and (bottom) SOL electron density during a typical Type I ELM. The observed delay between LFS and HFS is consistent with the instability propagating poloidally at the pedestal-top ion sound speed.

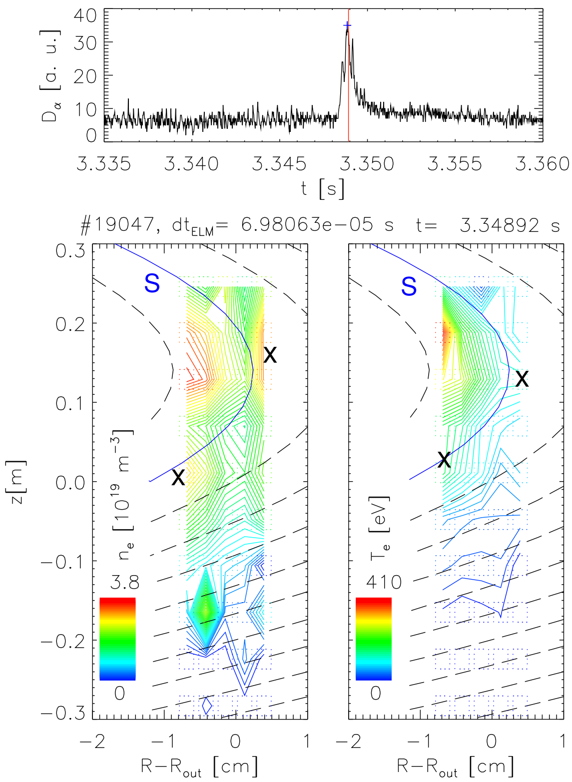
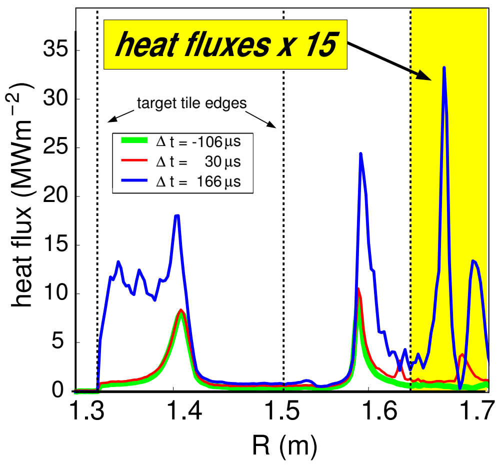


Fig. 7. Two-dimensional profiles of electron density (lower left panel) and electron temperature (lower right panel). The profiles are obtained by firing five Nd-YAG lasers in a burst of total duration 2 μs, centred in this case at the peak of the D-alpha emission caused by an ELM (upper panel). Local maxima of both density and temperature are observed in the near SOL (marked by X in the contour plots),

Edge electron temperature and density profiles are routinely measured in ASDEX Upgrade every 8.3 ms using a Thomson scattering (TS) system. The quality of these profiles has recently been improved using transient recorders and a new signal-processing algorithm [20]. This improved quality has allowed the investigation of deviations of the electron density and temperature profiles from one-dimensional symmetry. By using the Nd-YAG lasers in a burst of 2 μs and taking advantage of the 2.7 mm radial separation of the scattering volumes for each laser, it is possible to map out an essentially instantaneous snap shot of a two-dimensional region of the edge plasma. Strong, local variations (blobs and holes) of plasma are observed during ELMs [21], both inside and outside the separatrix. In Fig.7, an example of such a profile is given for a snapshot near the time of the peak divertor Dα emission due to a Type I ELM. Toroidal mode numbers of ~8 to 20 are derived from the observed spacing between maxima (marked with an X in Fig.7). Due to the limited field of view of the TS system, toroidal modes numbers less than 8 would not be resolvable (only one maxima would be observed). With the limited data so far available, a tendency is observed for the toroidal mode number of the perturbation to increase during the ELM evolution.

Complex power deposition structures are measured on the divertor target plates during Type I ELMs using a fast framing infrared camera [22]. These structures are thought to be the footprints of the field aligned, helical perturbations that are observed upstream in one poloidal plane using the TS diagnostic. Similarly to the TS measurements, the deduced toroidal mode number of this perturbation is in the range of 3-14. Furthermore, the infrared system is fast enough to measure the evolution of this quasi-mode number during the ELM [23]. An example of a profile of the divertor heat flux during a Type I ELM and a statistical evaluation of the number stripes observed on a remote tile during the ELM evolution are shown in Fig.8. Since the poloidal extent of the remote tile maps, along SOL field lines to the outer mid-plane, to cover 100° of the toroidal circumference of the tokamak, this evolution is consistent with an increase of the toroidal mode number from 3-5 during the early phase of the ELM to 12-14 at the time of the maximum power deposition on the divertor.



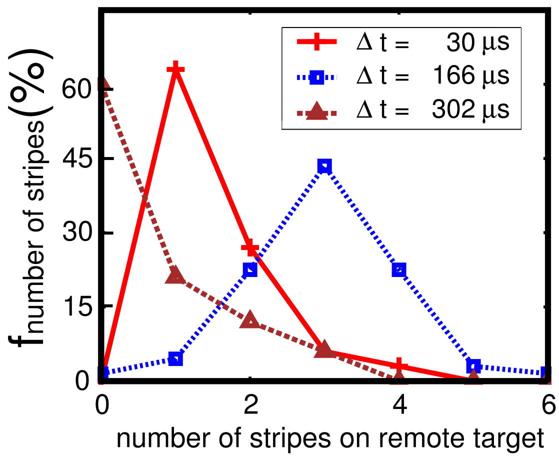


Fig.8. (left) Profiles of heat flux to the upper divertor in ASDEX Upgrade during a Type I ELM. The times of the profiles are relative to the rise of the divertor Dα emission due to the ELM. The yellow region has increased sensitivity due to deposited layers on the remote tile at this location. (right) The distribution of the number stripes observed on the remote tile as a function of relative time during the ELM.

Measurements of the precursor to Type I ELMs in ASDEX Upgrade are difficult as, in the usual case of co-neutral beam injection, the precursors are normally phase locked to the wall [24,25]. In discharges with counter-injection, toroidal mode numbers of 5-10 have been measured, in good agreement with the values inferred from the new, fast profile measurements during the early phase of the ELM evolution. Linear MHD stability analysis of Type I ELMs [7] in ASDEX Upgrade suggests that low (n~3) modes are responsible for the large ELM losses observed, either by being directly destabilised by the inter-ELM edge pressure gradient or because an intermediate n mode (8 was considered in [7]) removes plasma from the outer edge of the ETB thus steepening the gradient and triggering the larger, lower n mode. In the latter case, one might expect to observe an intermediate n precursor followed by a low n mode during the initial ELM crash phase. Further measurements to clarify this issue are planned for the next ASDEX Upgrade experimental campaign.

8. Summary

The suite of edge diagnostics on ASDEX Upgrade has been improved so as to allow resolution of the edge transport barrier on the required spatial and temporal scales. These new measurements have led to an improved understanding of the physics of the ETB, both in the quiescent phase and during ELMs.

The ELM trigger has for some time been modelled as an ideal linear MHD instability driven by a combination of high edge current and pressure gradient. Measurements of the perturbed plasma parameters at the ELM onset confirm this picture of the ELM as a field-aligned helical perturbation occurring in a small number of locations toroidally around the LFS of the tokamak. These perturbations are observed as local increases of both electron temperature and density, propagating from the ETB out in the SOL. The toroidally separated perturbations appear with an apparently random spacing and are not, therefore, one coherent mode. Nevertheless, several perturbations inevitably appear together at least on a time scale of a few tens of μs. The quasi-mode numbers one derives from the average spacing between perturbations is consistent with the linear MHD theory. As the ELM evolves, the number of perturbations increases, providing information on the non-linear evolution of the ELM.

The transport of particles and energy across the ETB is observed to be coupled in such a way that the ratio of electron density to temperature scale lengths remains always approximately constant. This, combined with the calculation that the ion transport in the ETB while low does not seem to be at the neoclassical level, suggests that residual turbulence which is not stabilised by the strong radial electric field shear still controls the transport through the ETB. Work is underway to identify this turbulence mechanism and make direct comparisons with the observed profiles and fluxes.

The combination of a critical pressure gradient associated with the ideal MHD instability and a coupling between energy and particle transport leaves only the width of the ETB as a free parameter when trying to predict the confinement associated with the H-mode edge barrier. No evidence has so far been found that the ETB width in ASDEX Upgrade scales with the neutral penetration depth into the core plasma. On the contrary, dedicated experiments using hydrogen and deuterium suggest that reduced regions of both thermal conductivity and of particle diffusivity are required in order to reproduce the measured profiles.

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