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Summary of the Workshop on Electric Fields, Structures and Self-organisation in Magnetized Plasmas (EFTSOMP) 2009.

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** See annex of F. Romanelli et al, "Overview of JET Results", (Proc. 22nd IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).*

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This 2-day workshop was held as a traditional satellite meeting of the 32nd European Physical Society Conference on Plasma Physics, in Sofia Bulgaria. 20 participants attended the meeting which was organized as invited talks and oral presentations in six sessions covering plasma turbulence, self organisation, H-mode and ELMs.

The timeliness of the workshop was underlined by the presentation of *Carlos Hidalgo, chairman of the European Fusion Development Agreement (EFDA) Transport Topical Group, on the TG's pilot project on* Long-range correlations and transport barrier physics. This is a focused action of the TG to address the question of understanding the role of long-range correlations when approaching plasma conditions in which the edge transport bifurcation develops.

The project has three elements: shear flow and long range correlation measurements in Ohmic (L-mode) and biased plasmas, study of the development of long-range correlations during spontaneous H-mode transitions and simulations. The experiments are supported by special diagnostic developments, including probes, Beam Emission Spectroscopy (BES), reflectometry, fast visible cameras and Heavy Ion Beam Probe (HIBP). Several of these developments aim at duplicating systems to perform measurements at remote locations on the same device.

Several results have already been obtained in 2008 not only on EU fusion devices but in China (HL-2A) and Japan (CHS) as well, which underlines the international collaboration of the effort. Experiments on several devices have shown that long-range correlations in potential fluctuations are present during the development of the edge shear flows and how these correlations are amplified by externally imposed radial electric fields . Further diagnostic developments progress steadily (e.g. BES) with the aim of getting first measurements in 2010. A discussion was held after the presentation which focussed on how to compare the experimental results against theory under the present circumstances when no first principles model can generate an H-mode transition. Some element is missing from present theories and experiments could help pinpointing where theorists should look.

An invited talk was presented by *A. Kendl on the theoretical aspects of edge turbulence* in fusion plasmas. Three basic scales have been identified and discussed: micro (drift waves), meso (GAMs and ELMs) and macro (low frequency zonal flows, MHD and the L-H barrier). The similarity to atmospheric dynamics has been emphasised, where large scale flows (jet streams) are also known to be able to stabilise the otherwise turbulent weather conditions for some time. Several of the above multiscale elements and their interactions in fusion edge plasmas have already been studied in detail. Various cascades in 2D turbulence are seen in low temperature plasma experiments, basic properties of GAMs are now characterized in fusion plasmas. The calculated plasma shape effects on zonal flows seem to be consistent with transport tendencies. There is evidence for the role of the Reynolds stress in the generation of zonal flows and the shear suppression of turbulence.

The H-mode barrier and the ELM element of the story and its connection to turbulence is much less understood. Presently there is no first principle code which can generate the necessary spin up for an L-H transition. On the other hand ELM-like phenomena are found in both MHD and fluid simulations when the initial H-mode conditions are entered into the codes. E.g. in gyrofluid simulations by Kendl and Scott the instability of an ideal ballooning mode triggers strong ITG turbulence, but no explosive growth of the mode is seen. The H-mode and its link to turbulence is still one of the hardest problems in fusion plasma physics.

A. D. Gurchenko reported on groundbreaking experiments on electron Larmor scale (ETG) turbulence. In the vicinity of the Upper Hybrid resonance the wavenumber of X-mode microwaves increases and therefore backscattering experiments on ETG scale turbulence become possible. At present three fusion devices have such microwave scattering systems: FT-2, DIII-D and NSTX. A double frequency correlation version of the diagnostic on FT-2 enables the study of radial wavenumbers as well. The experimental results show that ETG turbulence is indeed present in these devices under certain conditions, consistently with linear ETG simulation results.

Y. Xu reported on long-range correlation measurements with probes in the edge of TEXTOR plasmas. Data from two probe systems located at nearly 180 degrees toroidally are analyzed for correlation properties. In low-density Ohmic plasmas, long range correlation appears in the floating potential fluctuations if the two probes are around the same radii, whereas for the ion saturation current no correlation is seen. The cross-phase of the potential mode in the two probe systems is close to 0, indicating zonal flow-like structures. Two coherent modes are identified: 1kHz and 10kHz. This latter is shown to be a GAM by Li-beam measurements, while the 1kHz mode is similar to JFT-2M zonal flow results. With the increasing of plasma density, a damping effect on the coherent modes and the long-distance correlations has been observed.

In the electrode biasing experiment, the insertion of the electrode modifies the boundary conditions and suppresses the coherent modes and long-range correlations. However, in the biasing H-mode phase significant long-distance correlations are present in potential fluctuations. It is found that with biasing the *dc* E×B shear flow triggers low-frequency (~ 1.6kHz) zonal flows and consequently the long-range correlation. The time-varying zonal flow shear rate could amplify and complement the fluctuation suppression linked to the *dc* E×B flow shear. These findings support the critical role of multi-scale physics in the L-H transition process, as proposed in the TG's pilot project.

In his second talk *A.D. Gurchenko reported on GAM-like flow modulation measurements on FT-2* using the electron-scale microwave UHR backscattering system in Doppler mode. He emphasised that, unlike on some other devices, no GAMs have been seen with the normal (ion scale) Doppler reflectometry system. This might be caused both by insufficient spatial resolution and by the effect that the ITG wave velocity overcomes the E×B speed and therefore the turbulence cannot track the plasma flow. The situation is different for small-scale waves were the plasma flow is always expected to dominate the wave velocity. In the actual experiment indeed peaks appear in the Fourier spectrum of the Doppler shift. One such peak is identified as MHD wave, but another (close) one might be a GAM. In the discussion it was mentioned that such satellite MHD peaks are also seen in TEXTOR reflectometry measurements.

S. Zoletnik reported on GAM measurements using Lithium BES on TEXTOR. This system measures a light signal roughly proportional to plasma density at 16 radial locations. Poloidal flow velocity modulations can be measured by 400kHz poloidal beam hopping, when virtually each measurement point is split up into two poloidally offset points and correlation analysis is done. Alternatively, distortions of the autocorrelation function of singe poloidal measurement points can reveal relative velocity modulations. Different numerical methods have been tested for the above situation and it was found that the autocorrelation function based method is the most suitable. Indeed GAM-like peaks appear in the Fourier spectrum of the poloidal flow velocity modulation. Coherency of the modulations with GAMs measured by correlation reflectometry is found. The GAM frequency appears to drop from 17kHz at about 5cm depth inside the LCFS to 10kHz at the LCFS. Clear sensitivity on edge q is observed. The results are perfectly consistent with both reflectometry and Langmuir probe measurements and complete the TEXTOR GAM studies from the edge of the plasma to the core.

C. Maszl spoke about the comparison of cold and emissive probe turbulence measurements on ISTTOK. In most probe measurements cold probes are used in floating mode to approximate the plasma potential. This approach is known to be inaccurate as the potential drop between the probe and plasma depends on the electron temperature. Heated (emissive) probes overcome this problem, therefore comparative measurements have been done on ISTTOK with a probe head mixing heated and cold probes. From the difference even the temperature fluctuations can be calculated.
Substantial differences have been found between the cold and hot probe measurements: the blobs appear to be more structured and composed of shorter pulses. The plasma potential profile determined from the two probes is quite different. A 20kHz peak in potential fluctuations is seen inside the LCFS but not in the SOL. This has already been identified previously as GAM.

M. Spolaore presented a study on electromagnetic vortex structures in the RFX mod reversed field pinch (RFP). This device has now an active control system for the magnetic boundary reducing plasma-wall interaction due to MHD activity. Measurements on an RFP might give insight into general characteristics of turbulence processes as the magnetic field structure in a RFP is significantly different from mainstream tokamak experiments. A so-called U probe has been developed which contains 2 toroidally displaced 2D Langmuir probe arrays with an embedded 3-axis magnetic pickup coil system. A He gas-puff imaging diagnostic complements probe measurements.

This set of diagnostics observed blob-like fluctuations in the 50-300kHz frequency range moving with the ExB flow. Magnetic measurements indicate a current filament associated with the toroidally travelling blobs. The experimentally found features of the structures allow to identify them as drift kinetic Alfvén vortices.

S. Spagnolo reported on high frequency magnetic measurements in RFX mod. Data from a large array of magnetic probes has been processed and the toroidal and poloidal mode numbers extracted for the strong activity around 100 kHz. The above mentioned U-probe was inserted into the plasma edge to measure the mode numbers inside the plasma. This way the mode radial eigenstructure could be determined. The result is that these modes are localised at the plasma edge. Several candidates have been considered for the physical interpretation: Toroidal Alfvén Eigenmodes, resistive interchange modes. The clear identification needs some further effort.

At the start of the ELM session *G. Kocsis gave an invited talk on ELM triggering by deuterium pellets*. The injection of pellets is known to trigger an ELM in ELMy H-mode plasmas. A coordinated effort has been done in Europe during the last years to utilize this possibility for modifying the ELM frequency, and through that reduce the ELM energy what is expected to be excessive on ITER. On ASDEX Upgrade, JET and DIII-D various injection directions have been tried and all seen to trigger ELMs. A detailed study on ASDEX Upgrade revealed that the pellet is located at the region from the middle to the top of the edge barrier when the ELM is triggered. In discharges with Resonant Magnetic Perturbations on DIII-D the pellets needed to travel deeper to trigger ELMs. Recent measurements from JET revealed that the ELM starts as a magnetic field aligned perturbation extending from the pellet. MHD simulations has been started but the details of the process are not clear yet. To understand what kind of perturbation is caused by the pellet in the plasma comparative experiments have been done in L-mode, type III ELMy and type I ELMy H-modes by observing the magnetic field perturbations by pick-up coils as the pellet travels into the plasma. It is revealed that these do not depend on the pellet parameters, rather they are a function of the plasma pressure. It seems that the pellet-caused perturbations just amplify the MHD noise already present in the plasma and the ELM-related modes clearly distinguishable from these.

P. Lang gave an overview of pellet ELM pace making (periodic triggering) experiments. Up to now the basic problem in this technique is caused by the additional fuelling from the high-frequency pellet injection and the related confinement drop. In ASDEX Upgrade the price of doubling the ELM frequency is 15-20% confinement degradation. Given the larger volume of the JET plasma only 2-10% degradation is expected for 10 times frequency increase. In ITER the requested frequency is expected to be reachable with less than 1% degradation. These results are quite promising, therefore a new high frequency pellet injector has been built for JET. At present it can work reliably only with larger pellets, therefore the fuelling is still too high. However, pacemaking is demonstrated and a final result is expected as soon as the injector can handle smaller pellets as well. The pellet effect on the plasma has been modelled and the agreement with experiments is good, giving confidence to extrapolations to ITER.

S. Soldatov reported on recent reflectometry measurements during ELMs in JET. The JET reflectometry system for fluctuation measurements operates in X–mode polarization at four distinct frequencies spaced sensibly to cover the H–mode pedestal region. The amplitude and spectral characteristics of reflectometer signals are described in the relationship with the plasma density fluctuations, density profile scale length and turbulence rotation velocity. The H–mode type I ELMy discharges are analysed on the ELM time scale. The width of the frequency spectrum shows gradual change during the ELM cycle indicating gradual change in the plasma poloidal flow velocity. The variation is largest in the middle of the pedestal. During the ELM crash the fluctuation amplitude drops by several times temporary within 200μs in all four channels spaced radially within 40 cm. Two explanations can be considered for this behaviour: either the fluctuation amplitude drops or the plasma flow is quickly braked. The loss of the probing beam due to deflection by the corrupted reflecting layer cannot be excluded as well and requires further exploration. After the ELM crash the profiles recover smoothly, and in some cases the phase run of the probing wave can be followed directly if the cutoff position is close to barrier, where the reduced turbulence level is presumed. This enables the tracking of the radial cutoff position with 1mm accuracy and 100μs resolution.

The influence of Nitrogen seeding on the SOL transport during and between ELMs was presented by H.W. Müller. The experiments were done in ASDEX Upgrade, which is a full Tungsten device now. The lack of Carbon impurities reduced radiation losses in the plasma edge and divertor, and Boronization even further decreased it. To avoid thermal overload of the divertor tiles Nitrogen is puffed by feedback control from the divertor plasma temperature. Gas inlet is done either in the main chamber or the divertor private flux region. The radiation could be increased by this technique up to 40% while the energy content of the discharge increased by 5–10% applying a Deuterium gas puff of $6\text{-}9\times10^{21}\mathrm{s}^{-1}$. The largest radiation increase happened at the X-point.

Besides the beneficial effect of increased divertor radiation N seeding also increased the ELM frequency by 20-50%. and decreased the ELM energy loss normalized to the pedestal energy. In the outer divertor the measured peak plasma temperature also dropped during the ELM crash. Measurements with the special filament probe (special array of Langmuir probes just in front of the outer limiter) indicate that the number of large filaments arriving during an ELM crash is reduced, but the size of the largest ones remained the same. Similarly, between ELMs the number of large filaments is reduced.

At the start of the H-mode session *K. McCormick made an invited overview of the High-Density H-mode (HDH mode) of the Wendelstein 7-AS stellarator.* An HDH discharge is a fairy-tale plasma: combines high energy confinement with reduced particle confinement. This operating mode was unexpectedly found in the last year of W7-AS operation when an island divertor was installed in the device. Before that good energy confinement was observed in ELM-free H-mode but the particle confinement increased with increasing density. This caused impurity accumulation in the centre leading finally to a radiation collapse. With the divertor the plasma spontaneously jumped into HDH mode above a certain density around $2\ 10^{20}\ \mathrm{m}^{-3}$. The particle confinement dropped and impurities were flushed from the discharge. After that the density could be increased safely to a record $4\times10^{20}\ \mathrm{m}^{-3}$ and the discharge smoothly operated over many energy confinement times. Such discharges occur only in the so-called H-mode iota windows. It was also confirmed that the X-point in the plasma is not a prerequisite of the HDH mode: with the X-point pushed behind the divertor tiles it can also be achieved.

Modelling of HDH mode discharges indicated that some outward particle transport (density pumpout) mechanism has to be assumed at the external transport barrier. The density and temperature profiles of the ELM-free H-mode and HDH are very similar, only the collisionality is different. Therefore the particle pumpout should happen in the pedestal only.

The HDH mode can be compared with the EDA mode in Alcator C-MOD and the HRS mode in

JFT-IIM. All appear at high collisionality and some edge instability is presumed to affect particle transport at the pedestal. On DIII-D in similar parameter ranges a small-ELM regime appears.

An attempt to include normal confinement, H-mode and HDH in a unified scaling law fails. However it was found empirically that for all discharge types the plasma energy content scales with the edge (separatrix) density as $W \sim n_e^{0.7}$, the relationship holding even dynamically.

E. Belonohy continued along the previous line by presenting *a study on the expected impurity flushing mechanism in HDH discharges*. The quest for such phenomena was unsuccessful for a long time. However, in a series of large volume discharges a Quasi-Coherent (QC) mode activity was found in Mirnov coil signals. It was assumed that they are observable due to the closeness of the separatrix to the coils. Analysing a measurement where a small magnetic probe was inserted into the SOL on a reciprocating drive confirmed the existence of such quasi-coherent modes with m~40, thus undetectable for wall mounted magnetic probes in most of the discharges. The characteristics of these oscillations were studied in detail and several similarities were found to the QC modes observed in the Alcator C-MOD EDA mode. The mode amplitude was clearly seen to correlate with impurity radiation: as soon as the mode amplitude drops impurities start to accumulate in the plasma. Several other modes in the same frequency band were analysed but only one is seen to be related to the HDH mode and impurity flushing. Attempts to find further indications to this mode in existing W7-AS data remained unsuccessful: the Li-beam can measure at these high densities only in the SOL, therefore the QC mode must be localised inside the separatrix. From the available data it is assumed that the QC mode is present in a narrow radial region somewhere around the top of the steep part of the pedestal.

An interesting H-mode related work was presented by *E. Solano on observation of a confined current ribbon in the Hot Ion H-mode of JET*. The motivation of her recent measurements was to study strongly heated plasmas with low gas puff rate where the edge collisionality is low. This reduces resistivity and the higher edge current is expected to stabilise ballooning modes. The difference in ELM behaviour might give information on ELM physics. In the JET hot-ion H-mode high electron and ion temperatures are observed as expected for ITER therefore the study is also highly relevant for ITER. After the H-mode transition and before the first ELMs the confinement of these discharges is transiently very good (H98 ~ 1.4). It is observed that a perturbation called Outer Mode (OM) appears, delaying ELMs. This stops the rise of the pedestal temperature and can cause some reduction of confinement back to H98 ~ 1.

To understand these phenomena the OM was studied in detail. Its magnetic signature contains a series of harmonics similarly to the DIII-D EHO. Magnetic probe measurements were modelled by assuming a rotating closed current filament in the plasma. The mode structure cannot be clearly determined, but observations are most consistent with a co-rotating, co-current filament aligned on the q=4 surface. No evidence of tearing mode is seen in the ECE measurements. In the divertor a heat pulse is seen at the 6 kHz base frequency of the mode, therefore it contributes to the loss from the plasma.

Although a fully developed theory is not available for these observations work has started along the following lines. A closed current filament exists inside a magnetic field vortex in the plasma following field lines. This may act as an in-plasma resonant magnetic perturbation and open up the flux surfaces especially around the X-point, leading to heat and particle loss. If the current filament could be controlled it would open up a possibility of replacing ELMs and controlling plasma confinement.

As the closing talk of the H-mode session *S. Soldatov presented an invited talk about reflectometry study of turbulence and ELM dynamics in the limiter H-mode of TEXTOR*. The limiter H-mode represents a small (about 40%) confinement improvement in TEXTOR with a pedestal mostly seen in the density profile. ELMs appear with 300-1300Hz, their typology has not been studied yet. Fluctuations and poloidal flow profiles are studied during the L-H transition and the ELM cycle. The H-mode pedestal is characterized by the enhanced turbulence rotation shear detected which exceeds the turbulence decorrelation time by several times. Several quasi-coherent modes appear in the H-mode with poloidal mode numbers m~4-5, 19 and 43. They are located around the pedestal top. After the ELM crash within the relaxation stage the fluctuation amplitude drops below ohmic level and this quiet period is kept for a few hundred microseconds. Before the ELM the turbulence level increases again.

The Dynamic Ergodic Divertor generates a Resonance Magnetic Perturbation at the edge of plasma, therefore its effect on the H-mode and ELMs has been studied. With increasing amplitude of the RMP ELMs are reduced in size. However, this is accompanied by a degradation of the pedestal and the plasma falls back to L-mode at higher RMP amplitudes. The poloidal rotation profile was also seen to change in response to the RMP: the flow shear layer is shifted inwards and reduced in strength. QC modes disappear and mean turbulence level increases with amplitude of RMP.

The last session of the workshop was devoted to turbulence and related MHD phenomena. *M. Agostini presented a work on turbulence at the edge of RFX mod*. Here modes exist with m=1 and different toroidal mode numbers at different q=1/n rational surfaces. Two states are distinguished: a stochastic regime characterised with multiple modes and a Quasi Single Helicity (QSH) state with a single mode dominating the others. The helium Gas-puff Imaging (GPI) diagnostic is used for studying the plasma fluctuations in plasma discharges where the QSH is present. This diagnostic measures the line radiation of three emission lines of the neutral He puffed into the edge and can unfold the density and the temperature at the same time with 3 microsecond time resolution, with the line intensity ratio technique. The edge profiles are seen to be modulated with modulation of the magnetic field by the modes, the profile modulation is consistent with the change of the connection length. Blobs are studied in this turbulent system by conditional averaging. The density and the temperature structure of the blobs shows different shapes: the density has single peak while the temperature a double-peak structure. The plasma confinement increases with decrease of the magnetic fluctuations and at the same time the edge pressure profile steepens.

P. Garcia-Martinez presented numerical simulations of the dynamics of spheromaks. These calculations are not directly related to plasma turbulence, but they are employed to study the dynamics of a self-organization process. The applied numerical methods are quite relevant for ELMs and other cases. The spheromak plasma is characterised by the Taylor state: rot $\mathbf{B} = \lambda \mathbf{B}$. The configurations are made kink unstable by allowing the parameter λ to depend on the poloidal flux. Such configurations are dynamically modelled by the public domain VAC code developed by G. Toth. Several aspects are studied: relaxation of the configuration through a kink mode, MHD dynamo, the effect of the Lundquist number, etc. The flux-core spheromak formation from an unstable screw pinch is also studied. The code provides reliable solutions to these problems, it might be applicable to other phenomena in fusion plasmas.

An interesting turbulence measurement technique was presented by *G. Bonhomme on fast imaging as a diagnostic tool for plasma turbulence*. Fast visible cameras are mounted on the Tore Supra tokamak and the Mirabelle linear low temperature plasma experiment. The images are processed first with wavelet technique for denoising then blobs are identified. The motion of these is followed using a so-called Minimum Quadratic Distance (MQD) method and the two-dimensional velocity space is calculated. The technique is named Turbulence Imaging Velocimetry (TIV). The results compare well with Doppler backscattering. On the Mirabelle linear device the same technique is applied and compared to probe measurements. These measurements even enable detailed studies of nonlinear couplings in plasma turbulence by calculating bicoherency spectra both from the camera and probe data. An important result is that the nonlinear coupling to the $m = 3$ mode precedes the appearance of the mode itself. A limitation of TIV is the low light level for fast imaging therefore some further technical developments are considered.

The last talk of the workshop was presented by *D. Dunai on the properties of edge plasma turbulence in TEXTOR as measured by Lithium BES*. The Li-beam system has been optimized for fast measurement by maximizing the light collection and detection efficiency, and through that, the Signal to Noise Ratio (SNR). Typically the SNR reaches 30–50 at 500kHz bandwidth. At the plasma edge typically a kind of Quasi Coherent Mode is indicated by a broad peak in the spectrum at 50–100kHz mean frequency. Its amplitude drops from 5% at the plasma edge to 0.5% at $r/a = 0.85$.

A fast beam chopper (250kHz) enables proper measurement of the background light, therefore the Li-beam light profile and the plasma density evolution can be followed on a 5-10μs timescale. This opens up the possibility for many applications including study of the L-H transition, ELM precursors and the ELM crash. A few examples were presented showing that the H mode pedestal develops on a ms timescale and it collapses in less than 100μs during an ELM. Some growing amplitude MHD modes are seen at the steepest part of the pedestal before and sometimes after the crash.

In conclusion the Workshop was a successful meeting and enabled conversation between researchers working with different techniques on different devices. The participants and the International Advisory Board agreed to organise this event again after the next EPS Plasma conference in Dublin, Ireland.