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Progress from ASDEX Upgrade experiments in preparing the physical basis of ITER operation and DEMO scenario development

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Plasmas in the ASDEX Upgrade (AUG) tokamak can match a large number of fusion relevant parameters simultaneously. With a tungsten wall and ITER-like magnetic and divertor geometries, high values of the plasma β, the normalized confinement time, Greenwald fraction, and power densities P/R are reached under detached divertor conditions. The synopsis first addresses the integration of a detached divertor into improved confinement regimes while avoiding large ELMs. Secondly, it summarises the work relating to core confinement and stability, and to the physical understanding required for modelling ITER and DEMO plasmas.

Small or no ELM regimes have in common, that the H-mode transport barrier is modified by weakly or quasi coherent modes or changes in turbulence regime such that the peeling-ballooning (P-B) limit is not reached:

(i) The \emph{I-mode} has a number of attractive features with regard to a reactor plasma. The characteristic weakly coherent mode is linked to bursty transport and divertor heat loads which are, according to recent infra-red measurements, smaller than those of ELMs but could still be a threat for the targets [1]. Making use of AUG's flexible heating systems, realtime β control helped to develop stationary I-mode phases with an H-factor of about 0.9. Gyro-fluid simulations indicate that the L-I transition is caused by the stabilisation of ITG turbulence [2]. From the simulations a larger I-mode operation window at higher B field and problems in combining it with a detached divertor would be expected.

(ii) The plasma edge of the recently discovered \emph{stationary ELM-free H-mode} [3] is similar to Alcator C-Mod's \emph{EDA H-mode}. It avoids ELMs by residing close to the ballooning but far from the peeling limit. The regime is favoured by higher triangularity; it has an H-mode like pedestal, an H-factor of above 1 and appears at high density. The transition to an ELMy H-mode at higher heating power could be avoided by introducing radiative edge cooling by argon seeding for powers up to 5\:MW. In both regimes, (i) and (ii), a mode is made responsible for transport limiting the pressure gradient and avoiding impurity accumulation.

(iii) In a similar way, but as a \emph{high-power L-mode}, a new scenario is being developed, where radiative losses from argon in the pedestal region keep the power flux through the separatrix below the L-H threshold value. H-factors of 0.9–1 and a $\beta_N \approx 1.2$ were reached [4]. The core energy increases with power; this leads to a growing H-factor in the parameter range achieved by this high power L-mode scenario. The edge has similarities to that in I-mode, with pedestals in electron and ion temperatures and only a weak one in density. The divertor temperature drops to low values and compatibility with detachment can be expected.

(iv) The active suppression of ELMs by eroding the density pedestal by means of \emph{resonant magnetic perturbations} (RMP) is investigated in low collisionality discharges [5]. Full suppression of ELMs is accompanied by the onset of quasi-coherent fluctuations, radially and toroidally localised in the pedestal. ELM suppression is maintained in a large range of heating powers, which can be understood by a threshold behaviour of the transport-inducing mode. These observations solve a problem of previous models, which invoke classical radial diffusion around magnetic islands or in an ergodised region and therefore predict a dependence of access to ELM suppression on the edge heat flux.

(v) A \emph{H-mode regime with small ELMs} develops when the separatrix pressure and local shear approach the ballooning limit. Small and for the divertor benign pressure gradient relaxations modify the pedestal in the vicinity of the separatrix, where the dimensionless parameters are DEMO-like, leading to a P-B stable edge. At high triangularity this is the most promising scenario at AUG to integrate high performance plasmas with protection of the divertor even against transiently unacceptable heat loads. When approaching the H-mode density limit a transition from drift-wave to interchange turbulence occurs in the vicinity of the separatrix [7]. This transition can also be caused by intense radiation losses from above the X-point (\emph{X-point radiator}). The location of the X-point radiator can now be actively controlled via realtime AXUV measurements and the nitrogen seeding rate as actuator [9]. Based on this ITER-relevant scenario, a discharge was developed without any type-I ELM and a divertor temperature below 8 eV throughout. With 14 MW total heating power, flattop values with H-factors of 0.9 and $\beta_N \approx 2.0$ were reached [6]. Density limit disruptions were avoided by active control.

Where parameters of ITER or reactor plasmas cannot be met in present tokamaks, physics models are developed to predict the performance. The progress in integrated modelling provides increasingly validated physics elements to be included in the new AUG flight simulator [10]. With only global and engineering parameters as input, an integrated transport model was able to reproduce AUG discharges without input from experimental profiles. For this, the ASTRA code was used with a new pedestal model, that allows simultaneous development of the kinetic profiles of core and pedestal, and a simple SOL model, setting the boundary conditions [11]. For reactor projections, discharges aiming at reaching reactor-relevant core transport properties were analysed with the theory-based turbulence model TGLF. It was shown that density peaking is mainly sustained by turbulence, where electromagnetic effects are relevant, while the fueling profile only plays a minor role. Because of the strong link between electron temperature and density, steepening the electron temperature gradient in the confinement region seems the only meaningful way to increase density peaking in a reactor [12].

The prediction of the L-H power threshold for ITER is an important issue. In contrast to recent observations at JET, the threshold in H plasmas did not change when the concentration of helium was increased up to 20\:\%. According to power balance analyses, the ion heat flux through the edge at the L-H transition is independent of the helium concentration [13], being consistent with the finding that neoclassical \exb\ shearing rate triggers the transition. The impact of the isotope mass has been investigated by a new experimental approach, which, by an increase of plasma triangularity in hydrogen, allows core and edge effects to be consistently separated [14]. Nonlinear gyrokinetic simulations have revealed that edge turbulence in L-mode is dominated by electron drift waves, strongly destabilized by collisionality, stabilized by an increase of isotope mass and influenced by electromagnetic effects, providing predicted heat fluxes which are significantly larger in hydrogen than in deuterium, consistent with observations [15,14].

A fusion reactor would benefit from advanced plasma scenarios. Even tiny error fields can grow close to MHD limits, constraining β_N. CAFÉ calculations showed that the correction of the AUG (2,1) and (3,1) field errors can improve the achievable β_N from 3 to 3.2–3.3 [16]. Elevated core q-profiles are instrumental for advanced scenarios. IMSE measurements of the core current profile in discharges with strong ECCD confirmed the predicted beneficial radial current outward transport, introduced by an (1,1) mode, as well as the threshold behavior [17]. Finally, the effect of fast ions on core transport was studied by varying the rotational shear at constant T_e/T_i ratio. Thus the improvement of core ion confinement could be attributed to the fast ion content while rotational shear turned out to have little impact on it [18].

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