Recent Results From Divertor Operation in ASDEX Upgrade


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Abstract. The results of divertor studies on ASDEX Upgrade, at currents of up to 1.2 MA and heating powers up to 10 MW are described, with emphasis on the ELMy H-mode. The spatial and temporal characteristics of their heat load, and the simulation of ELMs by a time-dependent scrape-off layer code are described. High gas puff rates were found to lead to a large increase in divertor neutral pressure, at modest changes in $n_e$, and to a strong reduction in time-averaged power flow and complete detachment from both target plates in between ELMs. Using pre-programmed puffs of neon and argon, the radiative power losses could be raised to 75% of the heating power, in H-regime discharges, and the regime of enhanced divertor neutral pressure was found also to lead to an improved pumping of recycling impurities.

1. Introduction:

ASDEX Upgrade is a mid-size tokamak with non-circular cross-section (major radius $R_0 = 1.625\text{m}$, horizontal minor radius $a = 0.5\text{m}$, elongation $b/a = 1.6$), purpose-designed as a poloidal divertor device (Figure 1). Further distinguishing features of it are the poloidal field coils placed outside the toroidal ones, and the presence of a saddle coil ("PSL"... passive stabilising loop) inside the vacuum vessel for stabilising the vertical displacement instability. Together, these two features provide a relatively large space between the vacuum vessel and the X-point of the poloidal field lines, although the present divertor configuration, selected to optimise the heat load distribution, places the target plates relatively close to the X-point.
The analyses of the ITER team during the conceptual (CDA) and engineering design activities (EDA) have identified the problems of power handling, impurity control and helium pumping as the most crucial ones for the successful operation of a fusion reactor (ITER JCT, 1993). The efforts directed towards their solution constitute also the primary aim of ASDEX Upgrade, with further objectives being the study of discharge control and disruption dynamics (GRUBER et al., 1993) and contributions to core plasma physics.

2. Extent of present operational regime:

In non-circular cross-section discharges, ASDEX Upgrade has so far operated with toroidal fields in the range $1 \, \text{T} \leq |B_t| \leq 3 \, \text{T}$ and flattop currents between 0.3 MA and 1.2 MA, at safety factor values down to $q_{95} = 2.1$. The plasma current has up to now been limited by the forces exerted on in-vessel structures by halo currents during vertical-displacement events. Following further reinforcements to be implemented during the next opening of the vessel, access to the full design range of plasma currents ($I_p \leq 1.6 \, \text{MA}$) should become possible. Operations have also been affected by the appearance of arcing in the toroidal gap of the PSL conductor during hard disruptions. In previous campaigns, with energetically conducted disruption studies, this had led to progressive copper contamination of the discharges, ultimately necessitating opening of the vessel. During the present campaign - which included high-performance (10 MW heating power) discharges at 1 MA - these arcing phenomena could, however, be well tolerated. It is hoped that a major refurbishing of the gap-region of the PSL in autumn 1994, which will include substitution of the Vespel by Mica-based insulating materials, and bridging of the gap by a low-resistance shunt (0.15 mΩ), will definitely eliminate this problem.

ASDEX Upgrade is at present equipped with ICRH and NBI as additional heating systems. The ICRH system has a broad frequency range ($30 \leq f \leq 120 \, \text{MHz}$) and a power capability of each of its four generators of up to 2MW; each generator, individually, has so far achieved 1.1 - 1.4 MW. The injected power of the neutral beam system (at acceleration
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voltage of 55kV for H^0, and 63kV for D^0-injection) exceeded the design specifications in both hydrogen (7 MW rather than 6 MW) and deuterium (10 MW rather than 9 MW). The system has now also the capability of chopping the power with different frequencies and a variable duty cycle, allowing to fine-tune or feed-back control the injected power (VOLLMER et al., 1994).

The total heating power with D^0 injection has so far been limited to 12 MW by a regulatory constraint, which will be raised in the near future. Figure 2 shows important global parameters for a high performance shot, with a plateau in heating power at 10 MW, sustained for 2.5 sec (~ 30 energy confinement times) and a total energy deposited in the plasma of close to 30 MJ. Discharges with D^0 injection into D^+ plasmas and additional heating powers in excess of 2 MW are typically in the type-I ELM regime, are stationary, and show an energy confinement time, based on the total particle energy content, in good agreement with the DIII-D/JET ELM-free confinement scaling (SCHISSEL et al., 1991). The agreement with this scaling, originally derived for the thermal energy content of non-stationary, ELM-free discharges, is most probably due to the fact that ELM effects and contributions from non-thermal particles are both small in these cases (in the 5 - 10% range) and oppositely directed. An isotope effect on confinement is also observed, with \( \tau_E(D^0 \rightarrow D^+) = 1.3 \tau_E(H^0 \rightarrow H^+) \).

3. H-mode and ELM physics

H-mode physics studies are an essential part of our ITER-relevant divertor investigations. They include, in particular, mapping of the H-mode regime boundaries (RYTER 1994a), characterisation of the energy deposition on the target plates, and analysis of the impact of ELMs on particle and impurity confinement.

ASDEX Upgrade has a broad access to the H-regime, attaining it under favourable B_\perp-orientation - with the ion VB-drift in the direction towards the X-point (B_\perp < 0 in our device co-ordinate system) - and |B_\parallel| \leq 1.35 T already in Ohmic discharges. All heating methods have been utilised in these studies, with ICRH, in particular, used to fine-tune the heating power under near-threshold conditions, and NBI to get the largest operational range.
In a scan of heating power \(P_{\text{heat}}\), for \(B_t < 0\), the H-mode shows the characteristic sequence of features found in DIII-D (ZOHM et al., 1992): dithering cycles and type-III ELMs immediately above the threshold for the L-to-H transition \((P_{\text{HL}})\), followed by an ELM-free phase, and, ultimately, the appearance of type-I ELMs. The two ELM-types are distinguished, in particular by the response of their frequency \(v_{\text{ELM}}\) to variations in the heating power, with \(dv_{\text{ELM}} / dP_{\text{heat}} < 0\) for type-III, and > 0 for type-I ELMs. The power thresholds for the L-H transition and for the different ELM types are shown in Figure 3 in a scatter plot of discharges in the \(\bar{n}B_t\) vs. \(P_{\text{heat}}\) plane, showing approximately linear behaviour for both signs of the magnetic field, albeit with an \(\approx 2 \times\) larger slope in the case of the ion \(\nabla B\)-drift direction away from the X-point. It is notable that in the latter case dithering cycles and type-III ELMs seem to be absent, with the L \(\rightarrow\) H transition followed immediately by type-I ELMs.

Figure 3 also shows the extent of the power range of H-mode studies on ASDEX Upgrade and of the type-I ELM regime, which is by far the most ubiquitous one in our device. The power threshold for the L-H transition also shows a strong isotope effect, dominated by the background rather than the injected particle species: \(P_{\text{HL}}(\text{D}^0 \rightarrow \text{D}^+) = P_{\text{HL}}(\text{H}^0 \rightarrow \text{D}^+) = P_{\text{HL}}(\text{H}^0 \rightarrow \text{H}^+)/1.8\).

The H-mode transition has a hysteresis character, with the back transition H \(\rightarrow\) L typically occurring at a lower heating power \((P_{\text{HL}})\) than the forward transition. This was studied particularly in experiments in which the separatrix power flux was modified by the addition of neon or argon. Results, reported in more detail by RYTER et al., (1994b) show that \(P_{\text{HL}}\) strongly depends also on the gas-puff history of the discharge, and more weakly on \(P_{\text{HL}}\) on the sign of \(B_t\).

To understand and extrapolate the effect of ELMs on divertor performance, we are developing a semi-empirical model using a scrape-off layer simulation code (COSTER et al., 1994). The present status of these calculations is illustrated by Figure 4, which shows the measured \(\text{D}_\alpha\)-radiation from the divertor during a discharge with type-I ELMs (Figure 4a) together with a simulated signal (Figure 4b) produced by the B2-Eirene code (BRAAMS 1987, REITER 1992, SCHNEIDER 1992). The latter solves, in full time dependence, the coupled 2-d plasma and neutral particle transport equations, using a combined fluid and Monte Carlo approach. The computational region covers the full scrape-off layer, and a zone of closed flux surfaces inside the separatrix. To model the ELM effect, the perpendicular diffusivities for particles \((D_p)\), electron temperature \((\chi_e)\) and ion temperature \((\chi_i)\) in the
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closed flux surface region are periodically enhanced for a time interval \((\Delta t)_E\) with the values of the diffusivities, the region of transport enhancement, the period length and \((\Delta t)_E\) used as fitting parameters.

This model implies that the impact of ELMs \((\Delta t_{r,E})\) on confinement times \(\tau_c\) will strongly depend on the profiles, and hence on the source distribution of the quantity \(k\) considered, and will be weakest for peaked profiles and central sources and strongest for quantities with sources in the outer plasma regions or the scrape-off layer. Its success in fitting experimental data is therefore in line with the optimistic expectation that the impact of ELMs on confinement will be largest for wall or target-plate produced impurities, less for hydrogen particles, and least for energy.

The most critical parameters for the feasibility and technical layout of a divertor are the fraction of the total heating power arriving at the target plates, and the space and time distributions of the impinging energy fluxes. The most direct information on this, in ASDEX Upgrade, is given by a fast (120 \(\mu\)s) high space resolution (3 mm) infrared thermography system, which monitors both target plates (HERRMANN et al. 1994). Its results have been cross-checked for a variety of discharge conditions against those of target plate calorimetry, and were shown to give, together with our bolometer system, also a satisfactory account of the total energy balance. The case shown in Figure 5 corresponds to a low-q (\(q_\psi=2.7\)) discharge with type-I ELMs, with \(I_p=1.2\) MA, \(B_t=2\) T, and 5.5 MW of \(He^0\) injection into a \(D^+\) plasma. Under these conditions, the power flow between ELMs is narrowly peaked, with strong enhancement on the outer over the inner leg. It accounts, averaged over an ELM cycle, for slightly less than half of the total energy deposited onto the target plates.

Extrapolated along flux surfaces to the mid-plane, the radial decay length of the power flow during this phase corresponds to \(\lambda_{\text{energy}} = 2\) mm. During type-I ELMs this layer

Figure 4: (a) Measured Da-emission in the divertor chamber during a H-mode discharge with type-I ELMs, and (b) simulation of the signal with time-dependent B2-Eirene calculations. For the simulations, all diffusivities in a region of 5 cm depth inside the separatrix were raised to 5 \(m^2s^{-1}\) for a time interval \((\Delta t)_E\) from the values of \(D_0=0.5\ m^2s^{-1}\) and \(\chi_{r}=0.1 \ m^2s^{-1}\) used during the 9 ms between ELMs.
broadens up to $\lambda_{energy}(\text{mid-plane}) = 1 \text{ cm}$ and the maximum of the heat flux shifts to the inner target plate. (In contrast to this, type-III ELMs show a larger power flux to the outer target plates also during the ELMs, as reported in KAUFMANN et al., 1993). For the case shown in Figure 5, the energy lost in a single ELM, within $\approx 0.7 \text{ ms}$, corresponds to about 3% of the thermal energy content. A rise in heating power leads under these conditions to more frequent ELMs rather than a change in the energy carried by each individual one. Even shorter energy decay lengths have been recorded during ELM-free discharges at low powers (pure OH heating), corresponding to $\lambda_{energy} \text{ (mid-plane)} \leq 1 \text{ mm.}$ It is evident that this spatial concentration of the energy deposition in-between and the temporal one during the ELMs constitute formidable challenges for the divertor power handling.

![Diagram]

Figure 5: Power deposition on the divertor target plates during a type-I ELMy discharge with 5.5 MW heating power.

4. Recycling, pumping and edge particle transport

The cross-section picture of Figure 1 also shows the features relevant to the particle handling in ASDEX Upgrade. Three toroidally continuous baffles, together with the divertor plates and segments of the separatrix flux surface, effectively define two separate chambers in the divertor region, one below the PSL conductor and one below the X-point. A third region, limited by the inner divertor plate and the inner separatrix leg, is to a large extent open to the bulk plasma region on the high-field side. In each of the two closed divertor regions we monitor the neutral gas pressure with several neutral pressure gauges, which in the case of the PSL chamber can separately measure also the helium pressure. The PSL chamber is connected through 14 ports to turbo-molecular pumps, giving a total measured pumping speed of 15 000 l/s for D$_2$ or He. Both divertor chambers have a large area opening to one divertor fan, thereby resulting – as underlined also by SOL modelling calculations – in a similarity of the recycling pattern to that of a so-called "gas-bag" configuration.

For a simple, global description of the particle balance in a divertor tokamak it is useful to consider two reservoirs of free particles in the plasma vessel, with total atom contents $N^\ast$ (the charged) and $N^0$ (the sum of neutral atoms and of twice the number of molecules), respectively, with interchange terms $N^\ast / \tau_p$ and $N^0 / \tau_{ion}$ giving the respective rates of conversion from one to the other type through recombination at target plates or wall structures, and volume ionisation, respectively. In addition, gas puffing ($S_{gas-puff} > 0$),
neutral beam injection \((S_{\text{NBI}} > 0)\), pumping by external pumps \((S_{\text{pump}} < 0)\) and absorption or out-gassing from wall elements or target plates \((S_{\text{walls}} > 0 \text{ or } < 0)\) constitute source or sink terms for the total content of free particles. Typically (though not always) \(|N^+ / \tau_p|, |N^0 / \tau_{\text{ion}}| >> |S_a|\) holds, making it useful to distinguish processes on two time scales, with the total particle content changing on a slow one, in accordance with

\[
d(N^+ + N^0) / dt = S_{\text{gapoff}} + S_{\text{NBI}} + S_{\text{pump}} + S_{\text{walls}}
\]

and processes on the fast time scale determining the distribution of the particles between the two reservoirs, approximately in accordance with

\[
N^+ / \tau_p = N^0 / \tau_{\text{ion}}...
\]

The global particle balance for a discharge with neutral beam injection is shown in Figure 6, which gives the time traces of \(N^+\) and \(N^0\), and of the source and sink rates due to external sources \((S_{\text{gapoff}} + S_{\text{NBI}})\), wall fluxes \((S_{\text{walls}})\) and the turbo-molecular pumps \((S_{\text{pump}})\). The last contribution is determined from the molecular density measured by pressure gauges in the PSL chamber, in front of the pumping ducts, and the known pumping speed.

Equation (1) was then used to derive the quantity \(S_{\text{walls}}\), which is not directly measurable. During the early phase of the discharge the wall pumping constitutes the main loss mechanism for free particles, which has to be balanced by gas puffing. It diminishes gradually, however, during the discharge. After the onset of NBI, when, for the case shown, the gas puff was switched off, the external pumping by the turbo-molecular system even overcompensates the beam fuelling, indicating also that outgassing exceeds wall pumping during this phase.

The turbo-molecular pumps of ASDEX Upgrade can also pump noble gases - and in particular helium - for which wall pumping and outgassing are expected to play a minor part. This was demonstrated in a series of experiments in which, following a short He-puff, the time variation of a helium recycling signal (He II emission from the proximity of the inner heat shield) was studied for cases in which 1, 7 and 14 turbo-molecular pumps were activated under otherwise identical conditions (with, in particular the electron density controlled by feedback). Figure 7 shows the results for such a set of H-mode discharges, with 3.8 MW of NBI power, and type-I ELMs. Whereas the case with 1 pump leads to no perceptible change during the time interval considered, the rate of decay of the recycling signal in the 14-pump case (= 0.4 s\(^{-1}\) is nearly twice that in the case with 7 pumps and, in fact, larger than in Ohmic discharges.
According to eqn. 2 the ratio between $N^*$ and $N^0$ is primarily determined by the particle confinement time $\tau_p$ and the effective ionisation time $\tau_{\text{ion}}$, where the latter depends in a complex way on the geometrical details of the divertor chamber and plasma parameters. In Ohmic discharges in ASDEX Upgrade, this relation, as monitored by the neutral pressures measured in the X-point and the PSL divertor chambers and the line-averaged plasma electron density, tends to be of a fairly universal form $p_e \sim \bar{n}_e^2$.

Significantly different behaviour is, however, observed in H-modes with type-I ELMs (Figure 8), where even strong gas puffing leads only to a modest increase of $\bar{n}_e$, but an accumulation of neutrals in the divertor region (in the case shown corresponding to $d \log(p_e) / d \log(\bar{n}_e) = 3.8$). At the same time, the baseline in the $D_\alpha$ signal, corresponding to the emission in between ELMs, remains closely proportional to $p_e$. Assuming the $D_\alpha$ signal to remain strictly proportional to the ionisation rate, this would clearly prove a deterioration in particle confinement to be the cause of this behaviour. As, however, this regime also coincides with a reduction in the divertor electron temperature (which will raise the ratio between the emitted $D_\alpha$ quanta and the ionisation events), this observation requires further analyses and measurements. The strong enhancement of $N^0$ with respect to $N^*$ is accompanied (and perhaps caused) by a change in the appearance of the ELMs, which increase in frequency, assume a less regular structure, and show a reduced amplitude of the individual $D_\alpha$ spikes, compared with the baseline signal. Comparison shots in which the gas-puff was suddenly interrupted show a return to the more regular ELM structure only on the time scale on which also the divertor neutral pressure changes, thereby excluding a direct influence of the strong gas puff. This is also in agreement with the observation of little hysteresis in the $p_e(\bar{n}_e)$ curve between the density rise and the density fall phases in such cases.

5. Approach to the cold divertor and detachment

The ultimate aim of present divertor experiments is to attain a situation in which the power flow to the target plates constitutes only a small fraction of the total heating power. This requires conversion of conducted power into volumetric losses (predominantly radiation), which, in order not to impair the total energy confinement time, have to originate from the outer layers of the bulk plasma or from the scrape-off layer. In a given divertor
configuration, and at given plasma heating power, the experimental path to this regime is either through a rise in plasma density, or controlled addition of impurities with an appropriate radiation characteristic.

This aim has been achieved in L-mode discharges on JET over a range of NBI and ICRF-heating powers up to 22 MW (JANESCHITZ et al. 1992), by a pre-programmed, strong gas-puff ($S_{\text{gas puff}} = 1 - 2 \times 10^{22} \text{s}^{-1}$). Langmuir probe measurements showed a concomitant strong decrease in the target-plate plasma pressure, which could be explained by momentum loss due to neutral particles (STANGEBY 1993), and should be intrinsically connected to the near-vanishing of the power flow. Using a target-tile temperature as an input to a feedback control system acting on the gas-puff, a similar reduction in the time-averaged heat-flux to the target plates could also achieved in an ELM-H-mode, albeit with rather poor confinement.

Results of density rise experiments on ASDEX Upgrade conducted with purely Ohmic heating have been previously reported (MERTENS et al. 1994a, PITCHER et al. 1994). Starting at intermediate densities, they typically showed the formation of axisymmetric high-density, low-temperature plasma blobs (Marfes) in front of the target plates. Concomitantly, a reduction in the heat flux onto the target plates was observed, caused by radiation losses emanating primarily from the X-point region. Radiation form the near-target plate regions was found to contribute only a modest amount to the total losses ($= 15\%$). At somewhat higher densities, detachment was observed at the inner target plates (drop of the power flow, as measured by infrared thermography, to values below the detection limit). A still further rise of density resulted in migration of the Marfe first from the inner target plate to the X-point region and the high-field-side plasma boundary, and ultimately in its penetration onto
closed flux surfaces, followed by disruption. Intermediate stages of this sequence could be congealed as stationary states by controlling the plasma density at the corresponding level.

Previous attempts on ASDEX Upgrade to achieve detachment in H-mode plasmas with strong additional heating, however, resulted in a back-transition into the L-mode prior to detachment, and a generally very similar sequence of events as observed on D-III D by PETRIE et al. (1992). Significant progress has been obtained, however, recently in the discharges described in the preceding section, where strong gas puffing during the whole phase of additional heating \( (S_{\text{puff}} > 10^{22} \text{ s}^{-1}) \) led to high divertor neutral pressure conditions (MERTENS et al. 1994b). Figure 8 also shows the signals relevant to the global energy balance. As for this particular campaign phase the thermography system was not available, a signal, proportional to the instantaneous charged particle power flow onto the inner and outer target plates was evaluated from the ion saturation current and electron temperatures measured by Langmuir triple probe arrays. The single dots give the maximum and minimum values observed during each ELM cycle, with the solid lines corresponding to the time averages. Clearly, in between ELMs, the scrape-off fan completely detaches, first from the inner but later also from the outer target plate. Also the time-averaged power flow decreases by a factor of approximately 3 over the pulse length of the neutral beam injection, with no evident sign yet of levelling-off with time. This decrease is accompanied by an increase in the radiation losses. The total energy content and hence the global confinement time also decrease by about 20 %, this probably being due, primarily, to the confinement changes accompanying the changing ELM activity rather than the increase in radiation losses. This energy confinement deterioration seems, moreover, to saturate in the later phase of the divertor pressure ramp.

6. Controlled enhancement of plasma radiation

The above experiments prove that, even in the H-mode, the power flow to the target plate can be significantly reduced by enhancing the neutral gas pressure in the divertor chamber. Greater freedom in parameter space could be gained, however, if radiation from externally controlled rather than intrinsic impurities were to be used to unload the heating power. This has been successfully demonstrated in TEXTOR, for L-mode discharges in a limiter configuration, using feedback-controlled addition of neon (SAMM et al., 1993). We have started similar experiments, using so far, however, only pre-programmed pulses of neon and argon. As, in this case, the radiation losses originate primarily from the closed flux surface region, they also reduce the power flow across the H-mode confinement barrier, making the limits given by the compatibility with the H-regime rather than those for stable discharge operation the most critical issue.

Experiments conducted so far, with \( P_{\text{heat}} \leq 8 \text{ MW}, B_{\perp} = \pm 2 \text{T}, \) and various Ne and Ar puff scenarios, resulted in a maximum fraction \( P_{\text{rad, int}} / P_{\text{heat}} \) of 0.75 prior to back-transition into the L-mode, and a maximum value 0.9 under L-mode conditions. The major contribution to these radiation losses originates, as in the TEXTOR limiter discharges, from the bulk plasma \( (P_{\text{rad, bulk}}) \). The limit to this contribution in H-mode, is expected to be given by \( P_{\text{rad, bulk}} / P_{\text{heat}} \leq 1 - P_{\text{fil}} / P_{\text{heat}} \) and should therefore increase with the further increase of heating power. In a divertor tokamak, an additional contribution to the radiation losses - supposedly not affecting the H-to-L transition - comes from the divertor region: for the
above-mentioned H-mode case in ASDEX Upgrade this contribution amounted to $P_{\text{rad,div}}/P_{\text{neut}} = 0.18$. The confinement time in these H-mode discharges with boosted radiation losses remained in the range $\geq 0.8 \, \tau_{\text{jet-DIID}}$.

Figures 9a and b show the time development of global plasma parameters for two discharges with identical neon pulses, but different deuterium puff scenarios during the NBI-heating phase. The neon pulses were adjusted so as to give rise to a transient plateau in the Ne-recycling signal in the case without deuterium puffing during the NBI-heating phase (9a). Apart from the changes in the baseline and ELM signature of the divertor $D_\alpha$ signal, the most conspicuous difference between the two cases is in the rate of change in the recycling signal of neon and in the radiation enhancement presumably associated with its content in the plasma.

**Figure 9:** Enhancement of radiation losses in H-mode discharges through a pre programmed neon gas puff. Case 9a with and 9b without strong gas puff during the neutral beam injection phase.

As noble gases are primarily pumped by the turbo-molecular pumps, their decay rate will be determined by their partial gas pressure in the divertor chamber, so that the deuterium gas puff, shown in section 3 to lead to a strong enhancement in the neutral compared with the charged deuterium particle content, must also cause a similar change in the distribution between charged and neutral neon particles. This is more quantitatively demonstrated in Figure 10, where for a set of H-mode discharges (with type-I ELMs, and restricted to a narrow interval of heating powers and plasma densities), the observed decay rates of Ne and
Ar recycling signals are plotted versus the divertor neutral pressure. The observed trend is particularly encouraging, since the H-mode with high divertor neutral pressure, favourable for attaining detachment, thus appears favourable also for controlling the recycling impurities used for radiation boosting, and, presumably, also for pumping the helium ash in a reactor.

7. Summary and Outlook

During its present operational phase, ASDEX Upgrade has carried out divertor physics studies at plasma currents of up to 1.2 MA, and heating powers of up to 10 MW, with an increase of the latter limit to 12 MW still planned before the next break. In these experiments, the H-mode has been found to be a very robust operating regime, attainable at lower fields \((B_\parallel \leq 1.35 \, \text{T})\) already with Ohmic heating. Over most of the operating range - covering, e.g. at \(B_\parallel = -2\, \text{T}\), a factor 5 variation in heating powers - it assumes the form of type-I ELMy discharges. The available diagnostics have allowed us to characterise the power deposition onto the target plates and the dynamics of the ELM phenomena with high time resolution, and a fully time-dependent version of the B2-Eirene code is available to simulate their impact on the scrape-off layer and divertor behaviour. In conjunction with the high neutral densities achieved in the divertor region, the available turbo-molecular pumps have been shown to be capable of compensating the particle inflow from NB injection, and also pumping noble gases.

The present prime aim of the divertor investigations on ASDEX Upgrade is to demonstrate the feasibility of a strong reduction in the power flow to the divertor target plates under H-mode confinement conditions, with only modest dilution of the bulk plasma by impurities. Two roads - enhancement of the neutral particle pressure in the divertor chamber by strong gas puffing and controlled addition of noble gases to boost radiation losses - have been successfully followed. With strong gas puffing, full detachment between ELMs, and a reduction in the time-averaged power flow by a factor of 3 on both target plates have been observed. With the addition of pre-programmed neon pulses, radiation power losses could be increased up to 75 % of the total heating power, prior to a drop-back into the L-mode. Strong indications of synergy between the two approaches exist, with the divertor neutral pressure enhancement being accompanied also by an increased pumping rate for recycling impurities and hence an improvement in the capability of controlling their contribution to the radiation losses.
These investigations will be extended during the remainder of the present operating period (till July 1994) over an increased range in heating power, and with the addition of feedback control on the impurity pulses. For the following operating period (starting late autumn 1994) additional edge diagnostics (fast manipulators with exchangeable heads for probing the mid-plane scrape-off region and the outer leg of the divertor plasma, an edge Thomson scattering system, a lithium beam system, a Lena Ti measurement system, two additional bolometer cameras directed at the target plates, and a near-UV and visible light spectrometer system with universal viewing capability) will become available and others (reflectometry systems on the high and low-field sides) will be brought into routine operation. A 0.5 MW/140 GHz ECRH system will also come into operation, to be used primarily for heat pulse propagation studies, probing, in particular the H-mode barrier and scrape-off layer.

In early 1996 we plan to start a limited operation phase for which the present divertor tiles (with slight modifications to the shape of the individual tiles, but identical arrangement) will be substituted by tungsten-covered ones. A major rebuild of the divertor chamber (NEUHAUSER et al. 1994), taking account of recent experimental results, modelling calculations and ITER design studies is planned thereafter, with a scheduled restart of operation in early 1997. At that time, also further additional heating systems will be available, adding approximately 2 MW in the form of ECRH (at 140 GHz) and 10 MW in the form of a second neutral injector box to our system.

References:

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