ADVANCED TOKAMAK OPERATION IN ASDEX UPGRADE: First Experiments and Feasibility Study for Stationary Operation

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Introduction. First experiments to investigate improved core confinement by a modification of the current profile using additional heating in the current ramp-up phase have been performed at ASDEX Upgrade. Temperatures up to T_e = 8.5 keV and T_i = 14.5 keV have been attained. Different operating scenarios regarding type, power, and timing of the heating are discussed with respect to their effectiveness in achieving high performance.

Predictive transport simulations have been performed with the objective to explore the feasibility of stationary discharges with a reversed shear (RS) configuration in the tokamak ASDEX Upgrade. Optimization of the discharge parameters to achieve highest possible beta is made. It is found with the model used, not considering MHD stability, that the values $T_i(0) \approx 20$ keV and $\beta_N \approx 3$ can be expected in steady state when the RS region is extended from magnetic axis to 0.5 of minor radius.

Operating scenarios. Various operating scenarios have been tested at ASDEX Upgrade to achieve improved core confinement by modifying the current density profile. The common feature of these scenarios is the early additional heating in the current ramp-up phase at a low initial density ($\overline{n_e} \leq 3 \times 10^{19} m^{-3}$) to increase the electron temperature and thereby reduce the current diffusion and subsequently produce a flat or hollow current profile with q > 1. The global discharge parameters are 1 MA plasma current with a ramp-up rate of 1 MA/sec and a toroidal field in the vicinity of 2.5 T resulting in a q_{95} which approaches 4. The types of discharges can be divided into three groups:

(1) In the first type of plasmas moderate additional heating was applied in the current ramp-up phase, consisting of 2.5 MW neutral beam injection (NI) and in some cases also 800 kW electron cyclotron (ECRH) or 2 MW ion cyclotron heating (ICRH), followed by up to 7.5 MW NI in the flat top phase. The plasma configuration used — a single null (SN) configuration with the divertor at the bottom of the machine, which is the normal case for ASDEX Upgrade — has a low H-mode threshold resulting, for the powers applied, in a H-mode transition as soon as the X-point is formed, which in these discharges is at the end of the current ramp. In the H-mode phase ion temperatures of up to 12 keV and electron temperatures up to 6 keV have been observed. An analysis with the 1.5–D transport code ASTRA shows, that the ion transport is reduced to neoclassical values for q > 1. For q < 1 a strongly enhanced ion heat conductivity was found. The current profile inferred from the ASTRA calculation is broad, but due to the moderate heating power going into the electrons during the current ramp without an obvious region of reversed shear. Though the ASDEX Upgrade Motional-Stark-Effect diagnostic has delivered first profile information recently, a calibration is still missing. Therefore, a more accurate analysis of the current profile will follow at a later stage of the study. However, the occurrence of (3,2) and (1,1) modes is consistent with the evolution of the calculated current profile and agrees with change from neoclassical to anomalous transport at q = 1. With 7.5 MW of NI a $\beta_N \approx 2.6$ was achieved at $\overline{n_e} \leq 3.5 \times 10^{19} m^{-3}$. The duration of the high performance phase was, however, limited

by the occurrence of neoclassical tearing modes. Keeping the NI-power at 5 MW a stationary $\beta_N \approx 1.8$ with $\tau_E/\tau_{ITER92P} \approx 1.2$ could be maintained for 2.5sec only limited by the end of the NI (Fig. 1).

(2) In the second scenario the feasibility of pure electron heating during the current ramp was investigated. The configuration used was the same as in the discharges described above. The only difference was that, instead of applying NI during the current ramp-up phase, a combination of 800 kW ECRH and 2 MW ICRH was used. This resulted in core electron temperatures of 3.5 keV at the end of the current ramp. With 7.5 MW NI during the flat top phase T_e and T_i transiently increased to 8.5 keV and 11 keV, respectively. Again the high performance phase was terminated by neoclassical tearing modes.

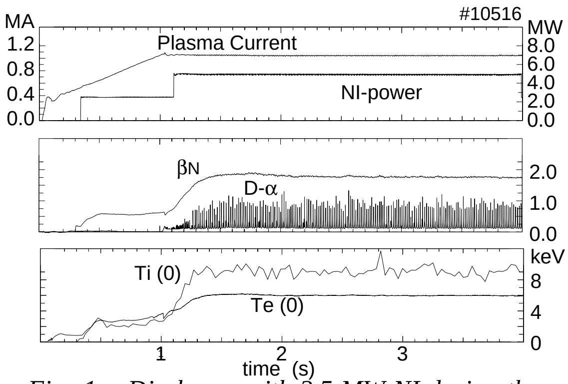

Fig. 1.: Discharge with 2.5 MW NI during the current ramp-up phase. Applying 5 MW NI in the flat top phase stationary high T_i and T_e were achieved at a constant line averaged density of $\overline{n_e} \approx 4 \times 10^{19} m^{-3}$.

Although in the two scenarios described so far the ion thermal conductivity was reduced to neoclassical values in the plasma core, internal transport barriers (ITB) in terms of steep ion temperature gradients have not been observed. A possible explanation is that the power to the electrons is not sufficient to produce sustainable hollow current profile which in combination with an H-mode transition at the beginning of the current flat top phase leads to a broad current profile with q > 1, but with no reversed shear region, which seems to be a prerequisite for the formation of an distinct ITB.

(3) In the third scenario 5 MW of NI was applied early (at 300 msec) in the current ramp-up phase. Similar to the DIII-D approach [1] the H-mode was avoided by limiting the plasma on the inner wall. Immediately after switching on the NI, ion temperature gradients started to build up at ρ_{tor} = 0.4. Although compared to scenario (2) the central electron temperature was not higher at this time of the discharge, the T_e increase was much broader, apparently sufficient to produce inverted q-profiles. With 5 MW NI T_i close to 15 MW was reached.

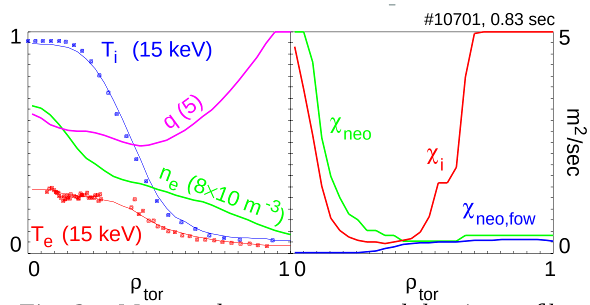

Fig. 2.: Measured temperature and density profiles are shown together with the ion thermal conductivity (χ_i) and q-profiles derived from ASTRA. $\chi_{neo,\,fow}$ and χ_{neo} denote the neoclassical χ's with and without finite orbit width correction [4,5], respectively.

The toroidal rotation profiles are similar to the T_i profiles with maximum values reaching 370 km/sec. Transport analysis with the ASTRA code shows a reduction of the ion thermal conductivity to neoclassical values up to radii, where the maximum of the ITB gradient is located. In Fig. 2 the measured temperature and density profiles are shown together with the derived ion thermal conductivity for a discharge with ITB and L-mode edge. The plateau in T_i leads to the rise of χ_i towards the plasma center, the uncertainty of which is large (about 50 %), as it sensitively depends on the T_i gradient in the center. The formation of the T_i plateau is related to the rise of the central electric field [2].

As the inner wall of ASDEX Upgrade is not compatible with high power limiter operation, increasing the NI-power causes a strong carbon influx from the inner wall, leading to a collapse of the ITB. Therefore, future scenarios for suppressing the H-mode will be SN discharges with the X-point at the top of the machine and hence, due to the inverted ion-∇B-drift, an increased H-mode power threshold.

Transport model. The experimental results described above were compared with the transport modeling including the thermal transport of electrons and ions, poloidal field diffusion, neutral beam (NB) and ion cyclotron (IC) heating and current drive (CD). The radial profiles of n_e, Z_{eff} and radiated power P_{rad} were prescribed according to the typical experimental conditions. An empirical mixed Bohm/gyro-Bohm model for anomalous heat conductivity [3] was employed. Recently derived corrections to the neoclassical electron and ion heat conductivities [4,5] were included and found to be very significant near the magnetic axis. The simulation of ASDEX Upgrade additionally heated plasmas with a monotonic safety factor q shows that the model of [3] describes the experiments reasonably well, although the Bohm–like part of the transport seems to be reduced in ASDEX Upgrade by about a factor of two in comparison with the value used at JET [3]. A confinement improvement observed in many experiments in the region of low or negative magnetic shear, $s \leq 0$, was described by the additional factor in front of the Bohm term $F_{e,i}(s) = \{1 + \exp[20(s_{cr,e,i} - s)]\}^{-1}$ similar to that used in [6]. The dependence of the results on $s_{cr,e}$ and $s_{cr,i}$ has been studied. The best fit for ASDEX Upgrade data with reversed shear suggest a rather optimistic critical shear parameters $s_{cr,e} = s_{cr,i} = 1$. In self–consistent transport modeling this means that the distance between the boundary of improved confinement zone and the location of q_{min}, or $s = 0$, is always about 20% of the minor radius. In what follows, we adhered to more conservative values $s_{cr,e} = s_{cr,i} = 0.3$.

Feasibility of steady state RS configuration. The transport model discussed above was used to assess requirements for a steady state RS operation in ASDEX Upgrade. Firstly we consider the capabilities of the NB system alone.

Up to 20 MW of NB power will be available in ASDEX Upgrade. One fourth ($P_{NB} = 5$ MW with 100 keV of the main beam component) of this power is injected quasi–tangentially producing off-axis current drive with a maximum at half of the minor plasma radius, $\rho_N = 0.5$. The amount of total current driven by this NB component, is shown in Fig. 3 with a dashed line. The remaining three quarters of the NB power (5 MW with 100 keV and 10 MW with 60 keV) are injected nearly perpendicular, resulting in central heating and providing a transition to the high confinement regime in the plasma core. Other curves presented in Fig. 3 show the behavior of the plasma pressure according to the transport model adopted when the plasma density $\bar{n}_e$ is varied.

Excluding the cases with a very high anomalous heat conductivity and, consequently, very flat temperature profiles near the magnetic axis, the typical bootstrap current density profiles are rather flat with a slightly pronounced maximum at $\rho_N = 0.2$. The residual ohmic current as well as the rest of NB current are centrally peaked. Thus, only that current component which is driven by the quasi–tangential NB has a favorable radial distribution and contributes to the formation of the RS configuration. Therefore, in order to extend the region of RS and improved confinement, it is beneficial to maximize this current component. The obvious way to do it is by decreasing the plasma density. However, a further reduction of $\bar{n}_e$ would simultaneously decrease the absorbed NB power and reduce the stored plasma energy. As seen from Fig. 3, the maximal pressure is achieved at a density $\bar{n}_e = 4 \div 6 \times 10^{19}$ m^{-3}. In what follows, the line average density was fixed at $\bar{n}_e = 4 \times 10^{19}$ m^{-3}. The dependence of the β–values on the plasma current is shown in Fig. 4. The dashed line here shows the radial position of q_{min}. Fully non–inductive steady state can be achieved only at a total plasma current $I_{pl} \leq 0.65$ MA with $\geq 45\%$ of bootstrap fraction. The region of improved confinement is then limited to 30% of the minor radius. Such a narrow region of RS does not allow to find a significant improvement in a global confinement. However, the central values of electron and ion temperature can be noticeably higher than in the case of monotonic q. At $I_{pl} = 0.8$ MA, about 20% of the total plasma current is ohmically driven, while the region of RS is reduced to 20% of the minor radius. With a further increase of I_{pl} the fraction of off-axis driven current decreases, $q(\rho)$ becomes monotonic, and the RS configuration disappears.

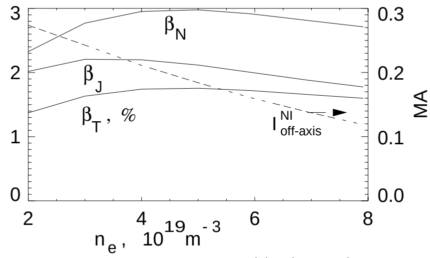

Fig. 3.: β_J, β_T, $\beta_N = \beta_T/(I/aB_T)$ as functions of line average plasma density. The dashed line shows the amount of current driven by the quasi–tangential beam component. The total plasma current is $I_{pl} = 0.7$ MA.

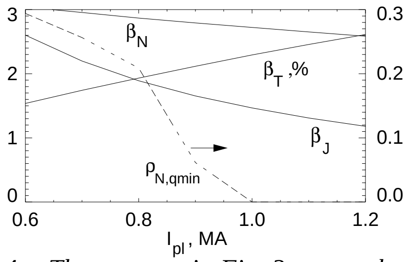

Fig. 4.: The same as in Fig. 3 versus the total plasma current I_{pl}. The dashed line shows the radial position of q_{min}. Here $\bar{n}_e = 4 \times 10^{19}$ m^{-3}.

We conclude, that creating a pronounced RS configuration requires about 30% of the total plasma current to be driven off–axis. Leaving aside non–monotonic ohmic current profiles obtainable transiently during current ramp–up, we now consider additional current drive which can be provided by the ICR system. Up to 6 MW of ICR power is available in ASDEX Upgrade which can delivered to electrons by conversion to the Bernstein mode with the possibility of off–central current drive. Fig. 5 shows various plasma parameters as functions of absorbed ICR power.

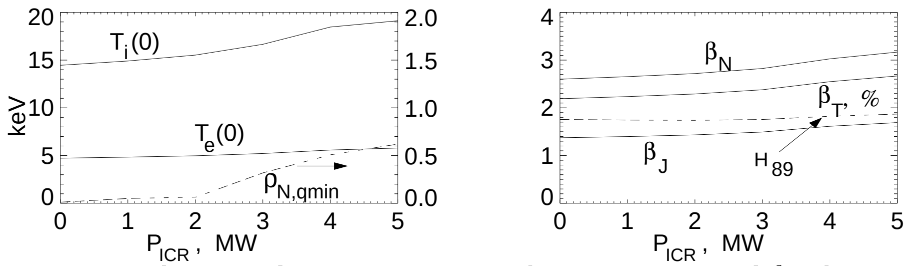

Fig. 5.: Electron and ion temperatures on the magnetic axis and β–values as functions of ICR power deposited around $\rho_N = 0.5$ for $I_{pl} = 1$ MA.

An optimization with respect to the radial location of the power deposition was made here. It is seen that a well pronounced RS configuration with $T_i(0) = 20$ keV, $\beta_N \approx 3$ can be obtained with the future heating and CD systems of ASDEX Upgrade.

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