ADVANCED TOKAMAK OPERATION ON ASDEX UPGRADE

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Abstract

Discharges with improved core confinement by a modification of the current profile using additional heating in the current ramp-up phase have been investigated. In plasmas with internal transport barriers and L-mode edge central ion temperatures up to 15 keV, corresponding to ion thermal conductivities at neoclassical values, have been achieved transiently. Stationary discharges with H-mode edge and internal transport barrier with central values of T_i = 10 keV and T_e = 6.5 keV could be maintained for 6 s, only limited by the given duration of the neutral beam injection, which corresponds to 40 confinement times or 2.4 resistive time scales for internal current diffusion. In this regime of operation not only the ion thermal conductivity is approaching neoclassical value but also the electron transport is significantly reduced.

1. INTRODUCTION

Improved confinement related to the modification of the current profile was observed in several tokamaks. Common to these regimes of operation is the flattening of the central current profile corresponding to a zero or even negative value of the central magnetic shear ($s = \frac{r}{q}\frac{dq}{dr}$, where q is the safety factor). There is increasing evidence that, in addition to magnetic shear stabilization, a combination with $\mathbf{E} \times \mathbf{B}$ shear stabilization is required for the initiation of internal transport barriers (ITB) [1,2]. In most experiments additional heating in the current ramp phase is used to reduce current diffusion and hence generate a broad or hollow current profile with q > 1 [3,4,5,6]. Two types of discharges with ITBs can be distinguished: (1) By avoiding an early H-mode transition ITBs are established with edge plasma parameters comparable to L-mode [7]. (2) The second regime of operation combines improved core confinement with an H-mode edge [8,9].

On ASDEX Upgrade, various operating scenarios have been tested to achieve improved core confinement by modifying the current density profile using early additional heating in the current ramp at low initial density ($\overline{n}_e < 3 \times 10^{19} m^{-3}$). ITBs with plasma edge parameters comparable to L-mode have been obtained transiently. They are distinguished by steep pressure gradients in the barrier region. Discharges with improved core confinement and H-mode edge, which exhibit more moderate gradients, but therefore under steady state conditions, have been produced.

2. IMPROVED CORE CONFINEMENT WITH L-MODE EDGE

Applying 5 MW of neutral beam heating in a current ramp of 1 MA/s, which is the maximum possible at ASDEX Upgrade, and at the same time avoiding the H-mode transition by using a limiter configuration, ITBs have been obtained reaching central values of T_e = 5 keV and T_i = 15 keV. The confinement enhancement factor of $H_{ITER89-P}$ = 1.9 and normalized beta of β_N = 1.6 are limited by the radial extent of the barrier region ($\rho_{tor} \leq 0.5$). The ITBs were only of transient nature, usually terminated by (2,1) modes, radiation collapse due to large impurity influxes, or both. This indicates that, due to the constantly penetrating current, as soon as a q = 2 surface is formed, the large pressure gradients become unstable. In FIG. 1 the profiles of temperature, density, and toroidal rotational velocity of such a discharge with L-mode edge and ITB are shown. Associated with the high ion temperatures are rotational velocities up to 370 km/s.

Transport analysis with the 1–1/2–D ASTRA code gives ion thermal conductivities at neoclassical values in the plasma core (FIG. 2). The plateau in T_i leads to the rise of χ_i towards the plasma center, the uncertainty of which is large (50%), as it sensitively depends on the T_i gradient in the center. The electron thermal conductivity is larger than χ_i, reflected in the large difference between T_i and T_e, which only partially is caused by the stronger NBI heating of the ions. The q-profile, inferred from the transport calculations, exhibits a negative central shear region.

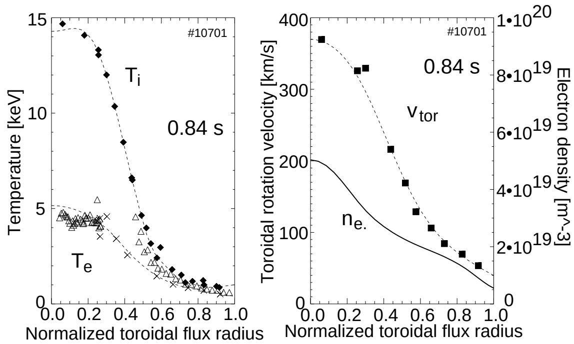

FIG. 1. Radial profiles of ion and electron temperatures (ECE and Thomson scattering), electron density, toroidal rotational velocity (v_{tor}) of discharge with ITB and L-mode edge, and 5 MW of NBI. The time point chosen is at maximum performance just before the termination of the ITB.

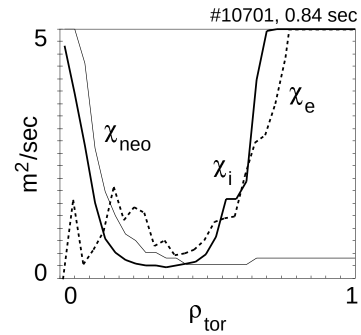

FIG. 2.: Ion and electron thermal conductivity ($\chi_{i,e}$) for discharge of FIG. 1 vs normalized toroidal flux radius. Also shown is the neoclassical ion thermal conductivity (χ_{neo}) [10].

3. STATIONARY IMPROVED CORE CONFINEMENT WITH H-MODE EDGE

A stationary regime of operation has been found which shows improved core confinement of both electrons and ions in combination with an H-mode edge. In FIG. 3 the main plasma parameters of such a discharge are illustrated. During the current ramp of 1 MA/s moderate neutral beam heating of 2.5 MW is applied. At 1 s the X-point is formed and the L-H-transition occurs. After reaching the current flat top, the NBI power is raised to 5 MW and the line averaged density is kept at 4×10^{19} m^{-3}. While during the current ramp at 2.5 MW heating power electron and ion temperatures increase at the same rate, T_i reaches almost twice the value of T_e when the heating power is doubled.

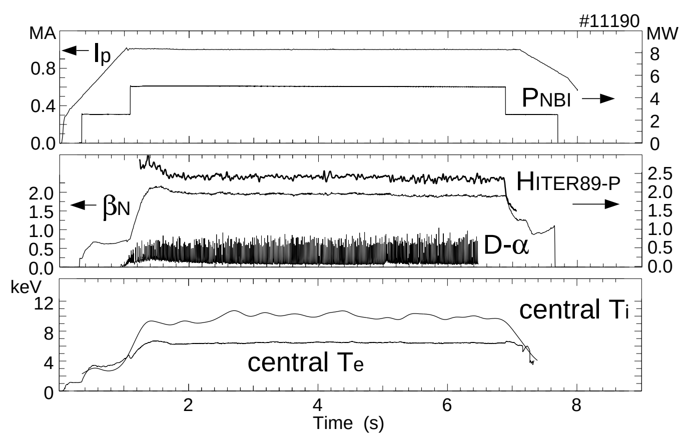

FIG. 3.: Time evolution of plasma current (I_p), neutral beam heating power (P_{NBI}), H-factor ($H_{ITER89-P}$), normalized β (β_N), divertor D_α radiation, and central electron and ion temperatures ($T_{e,i}$) for a stationary discharge with ITB and H-mode edge. The toroidal magnetic field is B_{tor} = 2.5 T.

Central values of T_i = 10 keV and T_e = 6.5 keV, $H_{ITER89-P}$ = 2.4, and β_N = 2 are maintained for 6 s, only limited by the prescribed duration of the NBI. This corresponds to 40 confinement times or 2.4 resistive time scales for internal current redistribution, which here is the time for a current perturbation to diffuse over half of the minor radius. The only MHD activity observed in the core of the plasma are strong (1,1) fishbones which start at 1.1 s and accompany the whole 5 MW heating phase, indicating that the central q is in the vicinity of one. The plasma edge is that of an ELMy H-mode, as seen on the D_α-trace.

The fishbone oscillations seem to behave like a resistive MHD instability [11]. Similar to sawteeth, but on a much faster time scale, the soft X-ray (SXR) profiles from a 1–D deconvolution of the line integrated SXR emissivities show a relaxation oscillation expelling energy and possibly also impurities. This is confirmed by T_e measurements using electron cyclotron emission (ECE). In addition, when increasing the beam power, β_N was limited by the occurrence of (3,2) neoclassical tearing modes, the onset of which was always preceded by a fishbone. Usually the (3,2) modes were followed by (2,1) and (2,1) locked modes. Considering that sawteeth are not present, the second harmonic of a (1,1) fishbone acts as a seed island for the initiation of (3,2) neoclassical tearing modes [12]. The existence of resistive fishbones would also explain that, despite q being in the vicinity of one, sawteeth do not appear, as the fishbones oscillations could serve as a mechanism for keeping q at or just above one. The β-limit is close to β_N=2.2. At 6.25 MW of NBI β_N=2.2 still could be maintained for a duration of 1 s after which, due to the proximity to the β-limit, a (3,2) mode occurred.

The profiles of plasma temperature, density, and rotational velocity (FIG. 4) show, in addition to the H-mode pedestal, an increase starting at ρ_{tor}=0.6, which compared to ASDEX Upgrade transport barriers with L-mode edge is less pronounced. The density peaking is $n_{e0}/\bar{n}_e = 1.5$.

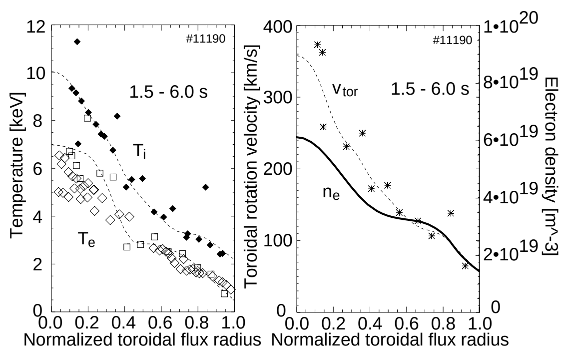

FIG. 4.: Radial profiles of ion and electron temperatures, electron density, toroidal rotational velocity (v_{tor}) of the discharge presented in FIG. 3. The profiles are the average from 1.5 to 6 s covering most of the 5 MW heating phase.

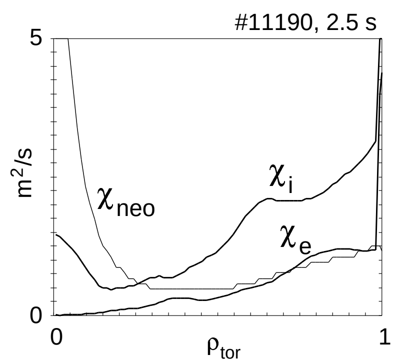

FIG. 5.: Ion and electron thermal conductivity at 2.5 s of the discharge of FIG. 3 vs normalized toroidal flux radius. Also shown is the neoclassical ion thermal conductivity [10].

Energy transport has been analyzed using the 1–1/2–D ASTRA code. In FIG. 5 the resulting ion and electron thermal conductivities are shown. In the central regions of the plasma χ_i drops to neoclassical values, but also χ_e is at a low level, indicating that the transport reduction is not limited to the ions.

Considering that no sawteeth have been observed, a mechanism associated with the fishbones is required to keep q at or just above one. In the ASTRA calculations this has been simulated using Kadomtsev reconnection, which redistributes the central current as soon q drops below one. The resulting q-profile is flat in the center with $q \approx 1$ inside ρ_{tor} = 0.2, which is consistent with the location of the (1,1) fishbone mode derived from the SXR oscillations. Without this mechanism q drops to 0.85 in the transport calculation. The total current profile is flat in the center, but still monotonic, which is supported by the bootstrap current having its maximum close to the center due to a smaller pressure gradient as compared to internal transport barriers with L-mode edge. The total plasma current consists of 68% ohmic current, 10% current drive from NBI, and 22% bootstrap current, the small bootstrap current fraction corresponding to a relatively moderate β_N.

A major concern regarding stationary plasma operation with improved confinement is the behavior of the impurity content. From spectroscopic data the main impurities have been identified as helium (5%), carbon (2.5%), oxygen (1.2%), and silicon (0.3%) after siliconization of the vacuum vessel [13], from which, using corona equilibrium and SXR profiles, Z_{eff} is inferred. Both, the resulting Z_{eff} and deuteron densities are peaked in the plasma center. The time evolution of the SXR data shows that, despite the central peaking of Z_{eff} (≤ 3), no temporal accumulation of impurities is observed. Possibly this is caused by the strong fishbone activity expelling impurities from the plasma core.

Both, raising the density at constant beam power and reducing the heating power resulted in a deterioration of the confinement, which is accompanied by the appearance of sawtooth oscillations when T_i approaches T_e. The loss of the ITB due to a drop of the NBI power suggests a power threshold. Associated with the increase of the density was the increase of the neutral particle flux in the divertor and a simultaneous reduction of the density peaking. The central ion temperature and the toroidal rotation velocity decreased by more than a factor of two, also observed in a reduction of the fishbone frequency. On T_e the effect is less prominent. The confinement drops, which means, as the power is kept constant, that the temperature decrease is stronger than the corresponding density increase. Both, power threshold and confinement reduction due to a density increase could be explained by a requirement of a minimum fast particle population needed for sufficient fishbone activity. The observed density dependence would also be consistent with a critical ∇T_i or $T_i - T_e$ value necessary to sustain the ITB.

4. SUMMARY

Different scenarios with improved core confinement due to a modification of the current profile by neutral beam heating have been attained on ASDEX Upgrade.

ITBs with L-mode have edge show steep pressure gradients and mainly reduced ion transport at neoclassical levels in the plasma core ($\rho_{tor} < 0.5$). $H_{ITER89-P} = 1.9$ and $\beta_N = 1.6$ are limited by the radial extent of the improved confinement region. The ITB is terminated by the occurrence of (2,1) modes.

A stationary H-mode discharge with improved core confinement, where both ion and electron transport are reduced, has been produced. $H_{ITER89-P} = 2.4$ and $\beta_N = 2$ could be maintained for 6 s, corresponding to 40 confinement times or 2.4 time-scales for internal current redistribution. These discharges resulted in the highest $n_{D,0}T_{i,0}\tau_E$ so far observed on ASDEX Upgrade (7.5×10^{19} keV s m^{-3} for 6 s and 8×10^{19} keV s m^{-3} for 1 s). Fishbones, acting like a resistive MHD instability, seem to play a dominant role in the sustainment of a current profile required for the stability of the ITB.

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