Internal transport barriers in ASDEX Upgrade

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Abstract This paper gives an overview the experiments on transport barriers performed on ASDEX Upgrade in the 2001/2002 campaign. Strong ($R/L_{Te} = 25$ $T_e(0) = 20$ keV) electron temperature barriers are generated with counter electron cyclotron current drive in low density plasmas. Ion barriers are generated using neutral beam heating in the current ramp up. Correlation with plasma parameters, shows that a sufficiently low density is a necessary condition for barrier formation. A study of the barrier position with respect to the q-profile reveals that the foot of the barrier is always in the positive magnetic shear region whereas the top of the barrier is in the negative shear region. The barrier therefore expands over the region of zero shear. A new scenario with delayed heating in the current ramp has set new ASDEX Upgrade records of central ion temperature (now 21 keV), beta normalised (now 4.0) and H89 (now 3.3). Pre-heating with ECRH delays the barrier formation, which forms at the same radial position. Stronger barriers can be generated with more NBI power.

1. Electron barriers

Electron barriers have previously been obtained on ASDEX Upgrade using on axis counter current drive [1]. These discharges had a moderate barrier and were unstable showing irregular strong collapses of the central electron temperature. Progress has been made in the 2001/2002 campaign through an increase of the plasma current from 400 to 600 kA. This yielded stable discharges while in addition strongly increasing the central temperature. Stable discharges were also obtained through a wider deposition profile of the ECRH power, however, at significantly lower electron temperatures.

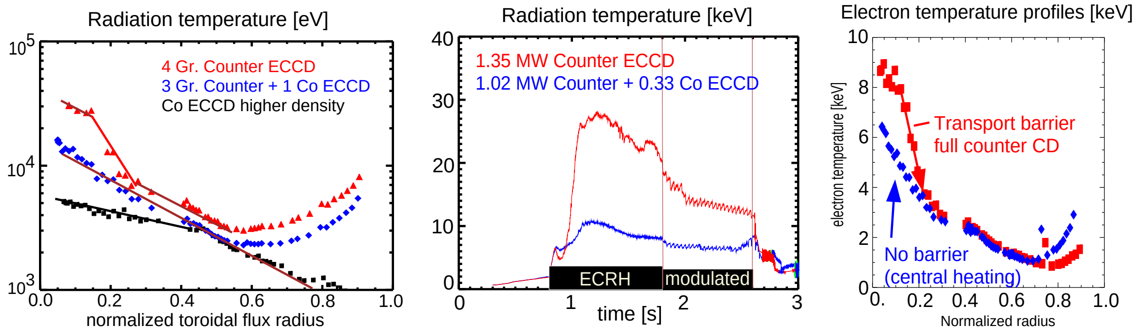

Figure 1: *left temperature profiles of the FC (red) and RC (blue) case, middle the time traces an (almost) central cannel, right temperature profiles at higher density*

Figure 1 shows the temperature profiles and time traces of several discharges. On the left is shown a the case with the highest ECE radiation temperature ($n_e = 1.3 \cdot 10^{19}$ m^{-3}, $B_t = 2.35$ T, $I_p = 600$ kA, $P_{ECRH} = 1.6$ MW, $\phi_{inj} = 20^\circ$ $f_{ECRH} = 140$ GHz, X-mode). Compared are a case with full counter current drive (FC), and a case with the same heating power and deposition profile, but with a 50% reduced current drive (RC) obtained through the changing of the toroidal direction of one of the 4 gyrotrons. At these temperatures the ECRH generates a significant non-thermal electron distribution function which affects the radiation temperature. The latter then no longer represent the true electron temperature, but the difference is calculated (Fokker Planck) to be ’only’ 30%, with the electron temperature estimated to be 20 keV in the FC discharge. The deviation of the radiation temperature from the true temperature is unable to explain the large difference between the two cases. Furthermore, also in the RC case the ECRH heating power is the same and is able to generate a comparable effect. Also the non-thermal population is very sensitive to an increase in density which strongly increases collisionality (since also the temperature goes down), the barrier formation however remains as is shown for a discharge with a line averaged density of $n_e = 2.2\ 10^{19}\ \mathrm{m}^{-3}$ on the right of Fig. 2. Fokker Planck calculations for the latter case give a negligible difference between the two temperatures.

The FC case shows a localised steepening of the electron temperature profile, with an inverse gradient length as high as $R/L_{Te} = 25$, whereas the RC case has a relatively constant gradient length, i.e. the case with full counter current drive clearly shows the formation of a localised transport barrier. The barrier formation is expected to be related to the formation of a reversed shear in the FC case, and not or significantly less in the RC drive case. This is in agreement with modelling gyro-kinetic stability calculations which show that the trapped electron mode is sensitive to the shear, but can not be confirmed with current profile measurements which are not available.

From the time traces of the central channel of the electron temperature (Fig. 1) one can see that the 600 kA discharges are stable. Furthermore, it takes 100-200 ms for the barrier to form, after which it degrades on a timescale of roughly one second. This effect is interpreted as being due to the current evolution which after the formation of the barrier increases on a long timescale due to the very peaked temperature profiles.

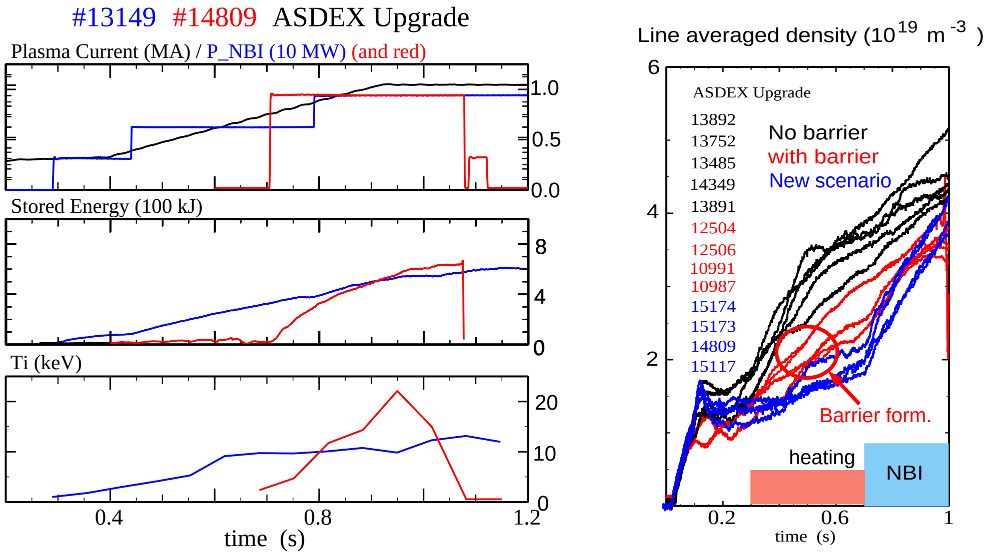

Figure 2: *left: Comparison of old and new scenario right: Correlation of barrier formation with line averaged density*

2. Ion barriers

Ion barrier are generated through neutral beam heating in the current ramp [2,3,4]. Compared with previous campaigns on ASDEX Upgrage, significant progress has been made. For the ion barriers this is obtained mainly by a change in scenario, heating the plasma later in the current ramp. This paper discusses some physics analysis based on the old scenario (see Fig. 2 the blue curves), as well as the performance obtained in the new scenario (Fig. 2 the red curve). The difference lies in the timing of the beams, the applied heating power (significantly more in the new scenario), and the plasma shape (lower single null in the new, upper single null in the old scenario)

3. Physics studies of the old scenario

In the old scenario no reproducible barrier formation was obtained. Therefore, at the start of the 2000/2001 campaign an investigation was initiated to determine under what conditions barriers form. To this extend a number of discharges in which a barrier was formed were compared with similar discharges in which no formation was observed. Correlations with global plasma parameters just before the barrier formation were investigated.

It is found that the density plays an important role in the formation criterion (see Fig. 2). The plasmas in which a barrier was formed all had lower densities compared with the cases without a barrier. Also it was found that barrier formation in the earlier campaign occurred only shortly after a boronization. Again pointing at a low density as a necessary condition. No clear correlation with other global parameters has been found. In terms of local parameters, it is found that the low density is also correlated with a smaller density gradient length, but $R/L_n < 6$, and no clear explanation can be given in terms of instability thresholds.

Unfortunately, no measurements of the current profile in the 2001/2002 campaign are available, due to diagnostic problems. Investigations of the barrier position against the q-profile are therefore available only for the previous campaign in which barriers were generated with 5 or 7.5 MW of neutral beam heating early in the current ramp up. Fig. 3 reports the findings of the barrier position at the time point when a strong barrier is present. It can be seen that the barrier foot is always in the region of positive shear and the barrier top is always in the region of negative shear. The barrier therefore extends over the region of zero shear and has roughly its strongest gradient at this position.

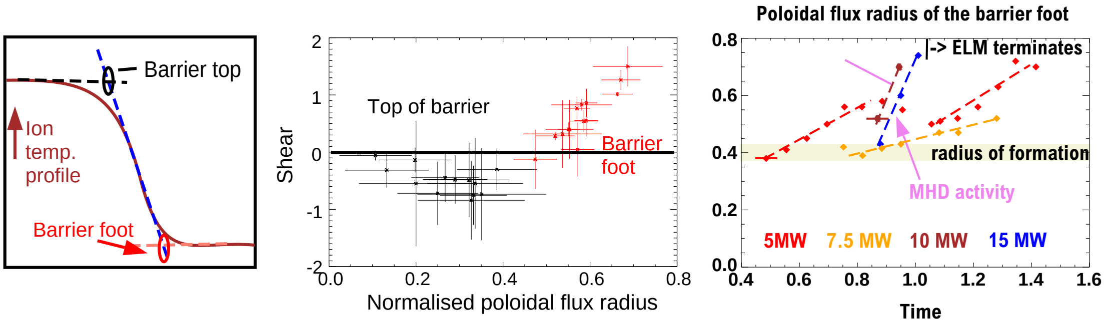

Figure 3: *left Definition of barrier top and foot, middle Shear at the top and foot of an strong ion transport barrier, right propagation of the barrier in the old and new scenario*

The barrier position when it is formed lies further inward as also shown in figure 3. As a function of time it propagates outward, with a timescale that is relatively long in the old scenario (5 and 7.5 MW), i.e. a timescale that is not inconsistent with a resistive time.

4. Performance of the new scenario

The finding that the density plays a role in the formation (not necessarily in sustainment), was one of the reasons to delay the neutral beam heating in the current ramp. The beams provide a density source and, therefore, it might be more advantageous to have a current ramp without beams until a favourable q-profile has established, and then switch on all the NBI power at once. It can be seen in Fig. 2 (blue) that indeed the density is kept at a lower value, and that the sudden switch on of the beams leads to a more ready formation of the ion transport barrier, i.e. much steeper increase in the central ion temperature with time.

The new scenario, in contrast to the old, generates reproducible barriers, and has more freedom in applied heating power. Also, in this scenario it was possible to generate barriers in lower single null configurations, with high triangularity. The timing of the beams can be varied between 0.6 and 0.9s, however, yielding somewhat less strong barriers at both ends. The new scenario is not limited to 7.5 MW, and powers up to 17.5 MW have been applied. At 17.5 MW, however, the beta rise in the plasma is so fast that the control coils can not keep the plasma at its position leading to a vertical instability. This limitation at present sets the limit to the applied power.

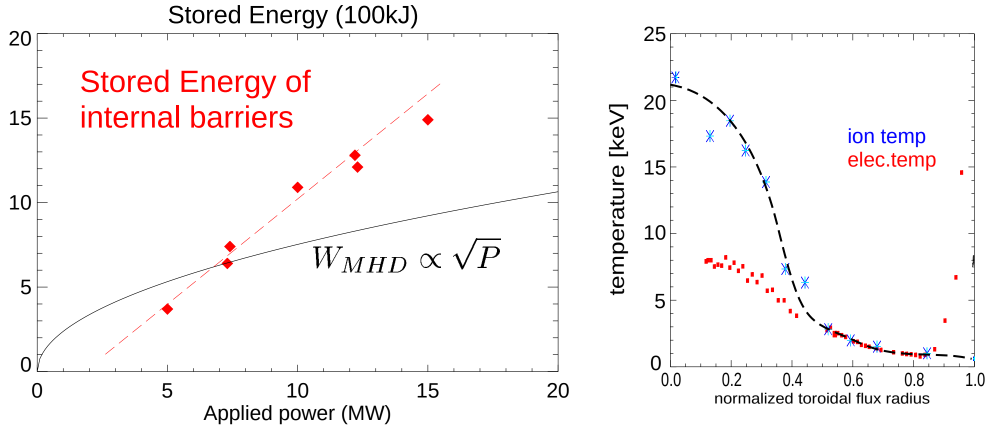

Figure 4: *left: Stored energy of barrier discharges as a function of applied heating power, right: Temperature profile of a discharge with 10 MW NBI heating and 1.6 MW counter ECCD*

Figure 4 shows that for the internal transport barriers the stored energy increases almost linearly with the applied power. Therefore, in terms of normalised parameters, the performance (confinement as well as normalised pressure) goes up with heating power. At a toroidal field of 2.9 T, plasma current of 1 MA, and an NBI heating power of 15 MW, a record stored energy (on AUG) of 1.5 MJ has been reached with an ion temperature in excess of 20 keV. This plasma has a normalised pressure $\beta_N = 3.2$. At this toroidal field the plasma position control does not allow more heating power. Record values in normalised plasma parameters are, therefore, obtained at lower magnetic field (2 T) and lower plasma current (800 kA) and is shown in Fig. 5. At these values a normalised pressure $\beta_N = 4.$ and $H_{89} = 3.3$ are reached. The barrier in these discharges, however, is weaker with a maximum temperature of 16 keV.

The progress in normalised parameters is large since the old scenario reached $H_{89} = 2.$ and $\beta_N = 1.7$. Especially the increase in normalised pressure is striking since the beta values in the old scenario are limited by the external kink. The reason for the strong difference remains unclear, but it is possible that the q-profiles in the new scenario is less inverted and provides better stability. At 2.7 T with 10 MW heating power a (3,1) resistive mode has been observed as far in as $\rho = 0.25$, indicating that the q-profile is reversed, but the record discharges with there lower current and magnetic field, might have a more flat q-profile. Current profile measurements are necessary to clarify this point.

In the new scenario the ELMs terminate the internal barrier. The high triangularity, high power low density discharges have a very large first ELM that perturbed the plasma over a large radius

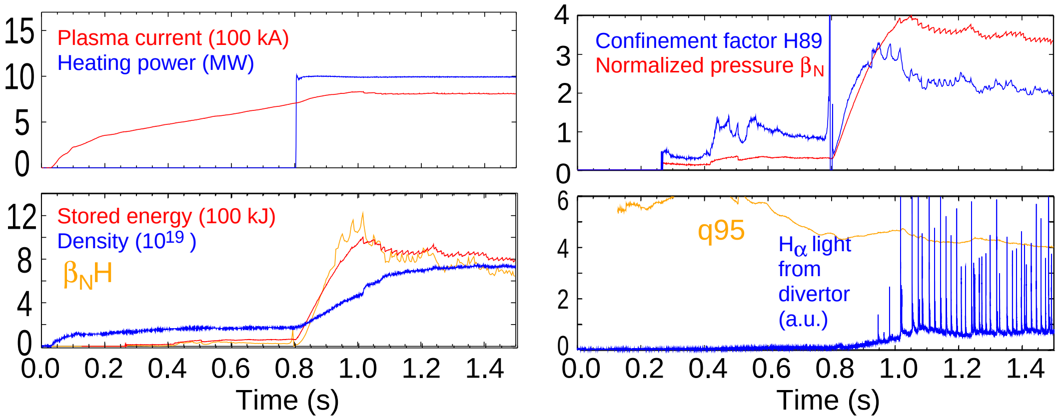

Figure 5: *Time traces of the record beta normalised shot*

reaching into the barrier region. This leads to a collapse of the barrier.

Experiments with variation in the power deposition of the neutral beams have been undertaken. At 7.5 MW, which is close to the threshold, no strong barrier forms if one uses 2 on-axis sources and one off-axis neutral beam source [5], in contrast to the case with 3 on axis sources. At 10 MW (4 sources) the switch of one source makes a negligible difference. In discharges with reversed current and magnetic field, in which the power deposition is largely off-axis, no barrier could be obtained even at heating powers of 15 MW. It is concluded that a minimum amount of central heating is necessary to generate an ion transport barrier.

5. electron heating in ion barriers

Various experiments with ECRH pre-heating and ECCD counter current drive have been undertaken. The electron temperature can be raised by counter current drive without destroying the ion barrier as is clear from the temperature profiles in figure 4. Although the electron temperature is significantly raised (from 5 keV to 8.5), no clear barrier structures can be observed in the electron temperature profile. Of course, the EC wave power is only 1.6 MW against 10 MW beam power.

Off-axis ECRH pre-heating is expected to slow down the current diffusion and, therefore, generate more reversed shear discharges. This could influence position and strength of the barrier. It is found experimentally, that the pre-heating did not have a favourable influence as can be seen in figure 6. In this case the barrier did not form at the switch on of the beams, but formed at a later time point at roughly the same radial position and was somewhat less strong. The implication of this result is unclear, it is possible that the current profile is changed and is only favourable at a later time point in the discharge. Also, these experiments were performed with 7.5 MW which is close to the threshold, and more neutral beam heating power might change the picture.

References

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