Improved Confinement with Counter Neutral Injection into ASDEX

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Counter injection into ASDEX leads to good particle, momentum, and also energy confinement with $\tau_E = 80$ ms at 1 MW (43 ms for co-injection). The improved confinement develops gradually during the heating phase and correlates with a simultaneous peaking of the density profile. The ion heat transport has to be reduced for a consistent transport analysis, in agreement with theoretical expectations. The sawtooth instability flattens the density profile and transiently reduces the energy content.

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An important goal of tokamak research is the development of plasma regimes with good confinement under auxiliary heating conditions to provide well established scenarios for the upcoming deuterium-tritium experiments. An important and challenging task is the understanding of the energy and particle transport in a tokamak plasma. In particular, it is the electron transport which is much higher than neoclassical theory predicts and which shows an unexplained variation with plasma parameters. But there is also accumulating experimental evidence that the ion heat transport is enhanced as well above the neoclassical expectation.[1] The effort to increase the plasma temperatures by auxiliary heating generally causes the electron transport to increase even further, resulting in the degraded confinement properties of the *L* mode. An alternative to the *L*-mode confinement is the *H* mode which shows good confinement properties even at high heating power[2] (*L* denotes low and *H* high confinement properties).

In this paper we report on another operational regime characterized by good confinement properties. It develops when neutral injection as an auxiliary heating method is applied in the counter direction (against the direction of the plasma current). The injection of energetic neutral atoms into the plasma is presently the most successful and reliable auxiliary heating method. The orbits of the energetic ions after ionization depend strongly on the injection geometry. In case of counter injection (ctr-NI) the power and particle deposition profiles are broader and the fraction of ions which is lost during the slowing down phase is somewhat larger. There have been many attempts in the past to study ctr-NI heated plasmas and to compare their characteristics with those under co-injection (co-NI).[3,4] The main results were that particle confinement improves and remarkable differences in impurity transport have been noted. While co-NI reduces the impurity concentration, ctr-NI causes the impurities to accumulate in the plasma center. The different transport behavior was explained on the basis of neoclassical impurity transport in a situation with momentum input and plasma rotation.[5] The energy confinement time τ_E, however, was found to degrade like that of *L*-mode plasmas heated with co-NI.

On ASDEX we observe improved particle confinement with ctr-NI both affecting the bulk plasma (leading to a density increase without any external gas puffing only fueled by the beam) and giving rise to low-*Z* and high-*Z* impurity accumulation. The average ion charge Z_{eff} increases during the counter-injection phase from $Z_{\text{eff}} = 2.0$ to 2.7. In contrast with other experiments, however, τ_E is also found to improve substantially in comparison to a co-injection case of the same power. Technically the crucial difference of ASDEX seems to be the capability for long-pulse heating which allows the ctr-NI regime to develop fully. Rapid impurity accumulation with ctr-NI was prevented by wall carbonization.

Figure 1(a) shows the equilibrium and the diamagnetic β_{pol} during the ctr-NI phase (β_{pol} is the ratio of plasma pressure to that of the poloidal magnetic field); Fig. 1(b) compares β_{pol} equilibrium with β_{pol} of the electrons as measured by the repetitive Thomson scattering system. β_{pol} increases gradually during the beam phase; at the maximum, the increase in β_{pol} with NI is about twice that of a comparable co-NI discharge (the ctr-NI cases of Fig. 1 are obtained at 0.42 MA; the co-injection results for comparison are at 0.38 MA; the level of co-injection cases at 0.42 MA which have previously been investigated but with short NI pulses are indicated as dashed lines). The energy confinement time τ_E of the ctr-NI cases shown in Figs. 1(a) and 1(b) is up to 80 ms at the maximum of β_{pol} ($P_{\text{NI}} = 0.9$–1.0 MW).

The most obvious feature of ctr-NI, which may also be the actual reason for the improvement in confinement, is the gradual peaking of the density profile during the beam heating phase. In the initial beam phase the density n_e rises slowly repetitively reduced by sawteeth (the safety factor $q_a = 2.3$). Between sawteeth there is a steep density rise. The increase of the sawtooth period later in the beam phase gives rise to a dramatic change in density profile as shown in Fig. 2. The data on the right-hand

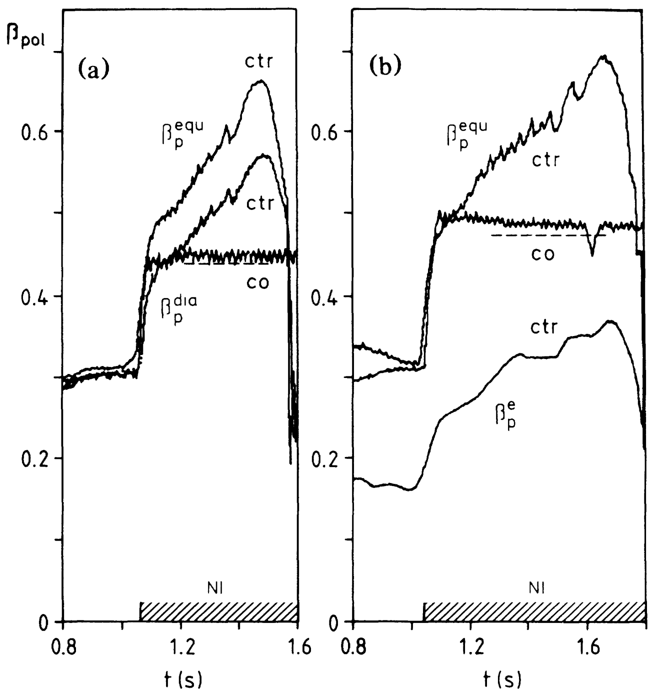

FIG. 1. β_{pol} during the counter neutral injection phase; comparison of (a) β_{pol} from plasma equilibrium and diamagnetism (shot No. 20943) and (b) of β_{pol} from equilibrium with β_{pol} of the electrons deduced from Thomson scattering (shot No. 21621). The traces are modulated by sawteeth. The co-injection β_{pol} levels are indicated by dotted lines for the diamagnetic (left) and the equilibrium (right) β_{pol}. $I_p=0.42$ MA; $B_t=2.0$ T; $q_a=2.3$; $P_{\mathrm{NI}}=0.9$ MW.

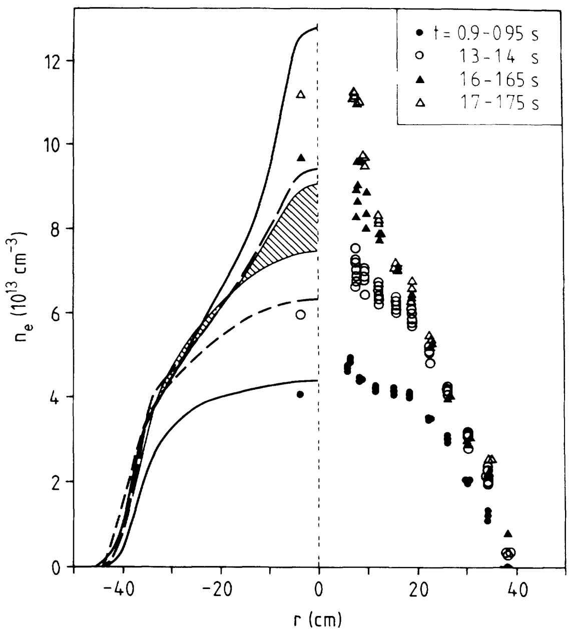

FIG. 2. Development of the electron density profile during ctr-NI starting from the OH target plasma. The profiles on the right are obtained from Thomson scattering; the ones on the left from fitting to the line integrals (the labels indicate the time points). The hatched area indicates the effect of the last sawtooth on n_e. (Shot No. 21621.)

side are obtained from Thomson scattering; those on the left-hand side from HCN interferometry. With ctr-NI the n_e profile continuously peaks from $n_e(0)/\langle n_e\rangle=1.4$ [the Ohmically heated (OH) target plasma] to 2.4. In a comparable co-NI discharge the n_e profile remains broad and similar in shape to the one in the OH phase (see Fig. 2).

The central electron temperature $T_e(0)$ rises during ctr-NI heating from 800 eV in the OH phase to maximally 1300 eV at 1.4 s ($P_{\mathrm{NI}}=0.9$ MW). Thereafter, $T_e(0)$ decreases because of the increasing density and the simultaneous rise of central impurity radiation. At 1.75 s, a hollow T_e profile is developed with the maximum of 1000 eV at $r=15$ cm.

In the phase of continuously peaking density, β_{pol} increases along with it. This gradual improvement of confinement over several hundred milliseconds (the beam power is fully developed after 35 ms) seems to be characteristic of the mechanisms responsible for the reduction of the heat transport. It cannot yet be decided unambiguously whether the peaking of the n_e profile is the cause or the effect. But it is interesting to note that a ctr-NI case does not develop the good confinement properties when the sawteeth do not disappear. In this case the peaking of the n_e profile is marginal [$n_e(0)/\langle n_e\rangle=1.6$] and $\Delta\beta_{\mathrm{pol}}$ is 20% above the comparable co-injection value. Therefore we have to conclude tentatively that it is indeed the peaking of the density profile which leads to improved confinement. As a consequence, sawteeth in the ctr-NI case seem to have a bigger effect on β_{pol} than those with co-NI though the amplitude of the sawtooth crash in the electron temperature is not significantly different in the two cases ($\Delta T_e=205\pm15$ eV). In particular the deleterious effect of sawteeth on the energy content seems to be aggravated during the counter-injection beam pulse when the density profile increasingly peaks. The last sawtooth in the counter-injection phase has the biggest effect on the density profile (as shown by the hatched area in Fig. 2) and on β_{pol} (see Fig. 1). The sensitivity of the confinement to sawteeth in the ctr-NI case correlated with the peaking of the density profile may indicate the causality. After a sawtooth collapse the overall confinement is reduced because the broader n_e profile may lead to enhanced transport. Between sawteeth the n_e profile peaks again and we indeed observe the energy content to rise at a high rate (≈1 MW) comparable to the heating power.

The ctr-NI phases in which ultimately sawteeth disappear and which reach good confinement are terminated by a disruption. The final phase is determined by a sudden high-Z impurity accumulation in the plasma center which causes the impurity radiation to increase to 70% of the total power input and the central impurity radiation to increase to 1.5 W/cm^3 at a central input power of only 0.4 W/cm^3. In this phase the T_e profile becomes hollow. As the stainless-steel vessel wall has been carbonized, the high-Z impurity species which accumulates is copper from the target plates inside the divertor chamber. The increase in impurity concentration is due to the changed plasma transport since the impurity influx does not increase. In particular, the charge-exchange wall erosion (as measured by probes) is reduced with ctr-NI by a factor of 4 in comparison to a co-injection case.

The ctr-NI confinement is improved by other mechanisms than those which cause the good properties of the H mode.[2] While the H mode develops in a sudden and distinct transition out of an L phase, the confinement with ctr-NI develops gradually from the beginning of the counter-injection beam pulse. The difference between the two good confinement regimes is most clearly indicated by the fact that H transitions can additionally occur with ctr-NI. In these phases the density rises even faster. At the presently available heating power on ASDEX of 1.3 MW the H phases are transient and do not last longer than 20–30 ms.

There is accumulating evidence that peaked density profiles may lead to improved confinement. Other examples are Ohmic discharges refueled with pellets[6,7] which also display the tendency towards reduced sawtooth activity and the supermode of balanced injection into TFTR.[4]

Theoretically it is expected that peaked density profiles reduce anomalous transport if the threshold condition $\eta_{e,i} = d\ln(T_{e,i})/d\ln(n_e) \leq 1\text{–}1.5$ is fulfilled.[8] Otherwise, so-called η_e and η_i modes are expected to be destabilized and to contribute to the heat transport of electrons and ions. η_e is experimentally accessible via Thomson scattering and coincides with η_i because of the strong electron-ion coupling at the high density with ctr-NI. The range where η_e is below 1–1.5 expands during the ctr-NI phase up to $r \leq 25$ cm at the end of the ctr-NI phase. In the co-injection case or the ctr-NI case with sawteeth, η_e remains above 1.5 for $r > 10$ cm throughout the beam pulse. η_i modes enhance the ion transport and their presence is made responsible for the saturation of Ohmic confinement at high density.[9] Indeed the transport analysis for pellet-refueled discharges indicates that the ion transport is reduced to the neoclassical value and it is speculated that this reduction is caused by the peaked density profile which stabilizes η_i modes.[6]

Figure 3 shows the results of the transport analysis (with use of TRANSP). The overall electron heat diffusivity is reduced over the whole plasma cross section even in comparison to the Ohmic phase (the OH phase has $n_e = 4\times10^{13}$ cm^{-3}). χ_e improves in particular in the plasma periphery. It is important to note that for the electron transport analysis a neoclassical ion transport coefficient χ_i^{ncl} (in the form of Chang and Hinton[10]) has been assumed. Under both Ohmic and L-mode conditions the neoclassical value of χ_i has to be increased typically by a factor of 3 to describe the measured ion temperature.[11] With $\chi_i \approx 3^*\chi_i^{ncl}$, the energy content of the plasma is underestimated even in the extreme of no additional electron transport. The later it is in the ctr-NI phase the larger is the discrepancy. The neutron rate Q_n (thermal production; $H^0 \rightarrow D^+$) is found to increase continuously during ctr-NI. In a comparable co-injection case with gas-puff-enforced density rise the decrease in ion temperature and D^+/H^+ ratio causes Q_n to drop.

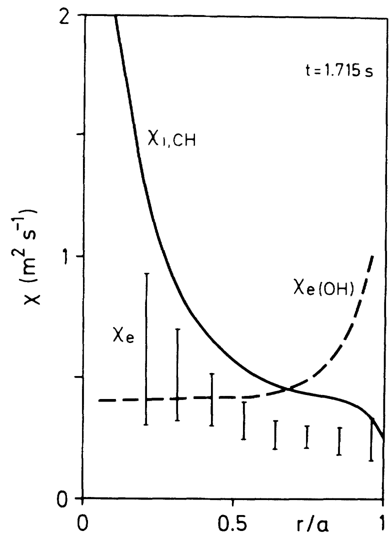

FIG. 3. Radial profile of the electron thermal heat diffusivity χ_e during ctr-NI; χ_e is obtained with the assumption that the ion heat diffusivity χ_i is neoclassical. χ_e of the Ohmic target plasma is given as reference. (Shot No. 21621.)

Along with the improvement of the energy and particle confinement, momentum confinement is also observed to increase with ctr-NI. The plasma rotation velocity is measured for $r \geq a/2$; it increases throughout the counter-injection beam phase up to $v_\phi \approx 1.4\times10^5$ m/s. In a co-injection case with increasing density (by gas puffing from the outside), v_ϕ decreases with rising density. At the end of the counter-injection phase the momentum confinement time is $\tau_\phi \approx 90$ ms (about twice the co-injection value). The momentum diffusivity is comparable to the electron heat diffusivity.

The actual reason for the different developments of the density profile shapes with co-NI and ctr-NI is not known. It could be speculated that the differences are due to the development of a strong negative plasma potential because some of the counter-injection beam ions are deposited onto loss orbits. Though the dominant confinement characteristics (L- or H-mode confinement) of auxiliary heated plasmas seem to be independent of the heating method, it has been shown in this paper that peculiarities of the heating method (like co-NI or ctr-NI) can nevertheless affect the confinement properties.

There are three regimes with peaked density profiles: pellet-refueled discharges,[6,7] the supermode with balanced injection,[4] and counter neutral injection into ASDEX. These operational scenarios are widely different but, nevertheless, have substantially improved confinement as a common element. In two cases (pellet injection and ctr-NI) transport analysis reveals that the ion transport has to be reduced in comparison to the broad-density-profile cases (OH saturation and co-NI). These experimental results may help to reveal some aspects of anomalous tokamak transport, particularly as the beneficial effect of peaked density profiles on ion transport is theoretically expected.[8]

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