Suppression of Sawtooth Oscillations by Lower-Hybrid Current Drive in the ASDEX Tokamak

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The sawtooth oscillations in tokamak discharges with Ohmic and neutral-beam heating could be suppressed when a large part of the plasma current was driven by lower hybrid waves ($I_{HF}/I_p \approx 0.5$). The stabilization is due to a flattening of the current profile $j(r)$ and an increase of $q(0)$ above 1. Higher central electron temperatures are obtained with neutral-beam heating if the sawteeth are stabilized. The increase in total energy content in this case was 30% higher than in the presence of sawteeth.

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The sawtoothlike oscillations usually observed in tokamaks have been considered for a long time as beneficial for stable and clean discharges. The time-averaged power loss due to the sawtooth instability is small during Ohmic heating (OH) and is still not serious with additional neutral-beam heating. The situation has changed drastically with high-power ion-cyclotron heating where giant sawteeth, with modulation of the central electron temperature by up to 50%, have been observed.[1] The resulting clamping of the central energy content could strongly impair core ignition in large fusion experiments. Methods for stabilization of the sawteeth are therefore of greatest interest.

Application of lower hybrid (LH) waves may lead to the suppression of sawteeth in OH discharges.[2,3] On the ASDEX tokamak we have studied the influence of LH waves on the sawtooth period. Appropriate wave spectra and power requirements for suppression of sawteeth are discussed. Local current-profile measurements allowed clarification of the mechanism of sawtooth stabilization. Application to neutral-beam heating finally demonstrates the possible gain in total energy content in sawtooth-free discharges.

The experiments reported here were performed in the divertor tokamak ASDEX ($R = 165$ cm, $a = 40$ M). LH waves were injected with powers of up to $P_{LH} = 1$ MW and pulse lengths of up to 1.5 s. Details of the LH system and of the plasma behavior with LH heating and current drive are presented elsewhere.[4-6]

The influence of LH waves on sawtooth oscillations is seen in Fig. 1. The soft-x-ray emission along a central chord is shown there for three modes of LH operation: normal LH current drive (LHCD) with antenna phasing $\Delta\phi = +90°$, LH current drive opposite to the

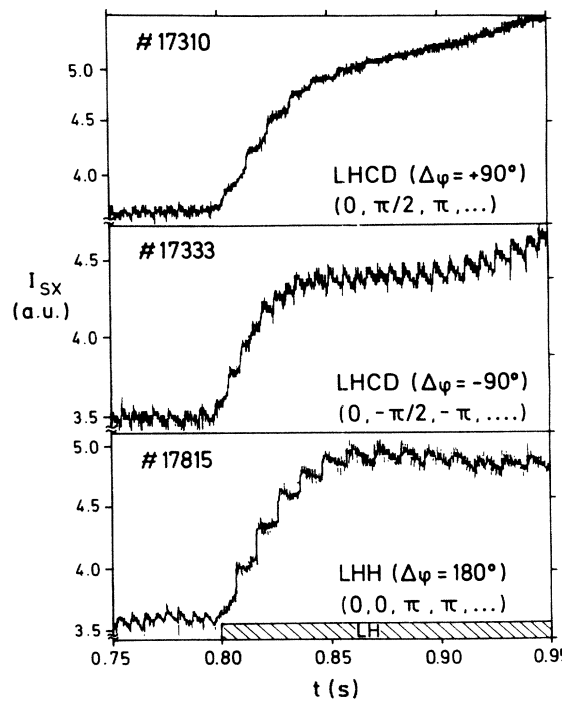

FIG. 1. Soft-x-ray emission for different LH wave spectra. $\bar{n}_e = 1.2\times10^{13}$ cm^{-3} (D_2), $I_p = 300$ kA, $B_t = 2.2$ T, $P_{LH} \approx 520$ kW.

dc electric field ($\Delta\phi = -90°$), and LH heating (LHH) without net momentum transfer to the electrons. The mean phase velocity in all three cases is the same: $\bar{v}_{\text{ph},\parallel} = c/2$. Inverted sawteeth are seen on all curves for instrumental reasons: Low-energy cutoff filters were fixed at 0.5 keV while the electron temperatures were considerably higher ($T_{e0} = 1.5\text{–}2$ keV). Therefore the line-integrated signals are dominated by noncentral radiation from regions outside $q = 1$ even on a central line of sight. The total x-ray intensity increases as a result of the radiation from suprathermal electrons generated by the LH waves. The sawtooth period rises immediately after the start of the rf power for normal LH current drive and for LH heating. No change is seen with opposite current drive. With normal LH current drive the sawteeth disappear with a time delay $\tau_d \approx 75$ ms after the start of the rf power. They do not reappear until the end of the LH pulse (maximum pulse length $= 1.5$ s).

The dependence of the change in sawtooth period on the phase velocity of the LH waves was studied for the whole range available with various antenna phasings: $1.7 \leqslant \bar{N}_\parallel \leqslant 4$ ($75° \leqslant \Delta\phi \leqslant 180°$). It is found that the sawtooth period during LH-wave application $\tau_{\text{ST}}^{\text{LH}}$ closely correlates with the observed drop in loop voltage $-\Delta U_l^{\text{LH}}$. A similar correlation between $\tau_{\text{ST}}^{\text{LH}}$ and $-\Delta U_l^{\text{LH}}$ is found with variation of the rf power in the LH-heating mode. The drop in loop voltage in this case may be explained by an increase only of the electrical conductivity due to the generation of suprathermal electrons.[6] The increase in sawtooth period $\tau_{\text{ST}}^{\text{LH}}$ therefore seems to be mainly determined by the increase in electrical conductivity. This occurs rapidly after switching on of the rf power within the time scale of generation of a suprathermal electron population. The increment of the sawtooth period during the LH phase decreases with increasing density, as shown in Fig. 2 for the current-drive mode. Below a density threshold of $\bar{n}_e = 1.2 \times 10^{13}$ cm^{-2} the sawteeth are suppressed by the LH waves. They are only stabilized with some delay after the start of the rf power. This delay τ_d is reduced by an increase of the rf power: $\tau_d \approx 80$ ms at $P_{\text{LH}} = 400$ kW, $\tau_d \approx 40$ ms at $P_{\text{LH}} = 1$ MW.

Suppression of sawteeth could be attained only with current-drive spectra. It is not related to the generation of suprathermal electrons, as revealed by rf power scans with LH heating or LH current drive. With the same amount of rf power the drop in loop voltage $-\Delta U_l^{\text{LH}}$ is slightly larger in the current-drive mode, but a much larger population of high-energy electrons is produced in the heating mode. Sawteeth, however, persist during LH heating up to the maximum applied power of $P_{\text{LH}} = 1$ MW, while they are suppressed in LH current drive with $P_{\text{LH}} = 400$ kW ($\bar{n}_e = 1.1 \times 10^{13}$ cm^{-3}, $I_p = 300$ kA, $B_t = 2.2$ T). The increase of the

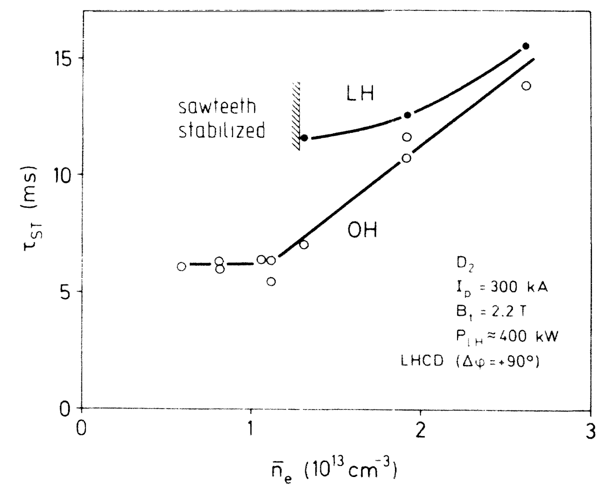

FIG. 2. Sawtooth period τ_{ST} during Ohmic and LH current drive.

electrical conductivity during the LH phase is not decisive for stabilization either. With LH heating, sawteeth were still present at a drop of the loop voltage $-\Delta U_l^{\text{LH}}/U_l^{\text{OH}} = 0.8$, while stabilization could be achieved with LH current drive at $-\Delta U_l^{\text{LH}}/U_l^{\text{OH}} \approx 0.5$. A correlation between the disappearance of sawteeth and the increase of the electrical conductivity or the generation of suprathermal electrons also seems to be ruled out by the different time scales. The drop in loop voltage and the buildup of the fast-electron population occur within typically 25 ms, while the time delay between the start of rf power and stabilization of sawteeth is of the order of 50–500 ms, depending on $\bar{n}_e$ and P_{rf}.

A crucial parameter for suppression of sawteeth seems to be the total amount of rf-driven current. About half of the power necessary for full LH current drive had to be applied in the density range 0.5×10^{13} cm$^{-3} \leqslant \bar{n}_e \leqslant 1.6 \times 10^{13}$ cm^{-3}, where sawteeth could be stabilized with the rf power available. The current distribution during the LH phase seems to differ from the OH current profile, as indicated by a change in the internal inductance l_i. This may be derived from measurements of the quantities $\beta_p^{\text{equ}} + l_i/2$ and $\beta_p^\perp$ [$\beta_p^{\text{equ}} = \frac{1}{2}(\beta_p^\perp + \beta_p^\parallel)$ is the poloidal beta value determined from the equilibrium fields, $\beta_p^\perp$ the perpendicular β_p determined from measurements of the diamagnetism of the plasma, and $\beta_p^\parallel$ the parallel β_p]. Magnetic measurements allow one to determine only the sum of the pressure anisotropy and internal inductance: $(\beta_p^\parallel - \beta_p^\perp) + l_i$. In LH-current-drive experiments this quantity typically first rapidly increases and then slowly decreases. The initial rise occurs within the same time as the drop in U_l and the increase in suprathermal electron-cyclotron emission, and it may

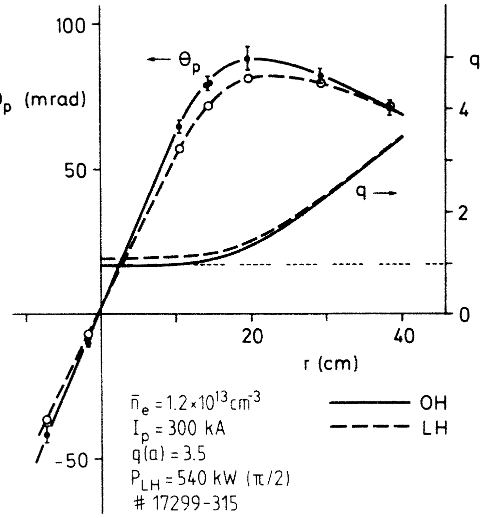

FIG. 3. Radial profiles of the magnetic field pitch angle θ_p from Li-beam $q(r)$ profiles during Ohmic and stationary LH current drive.

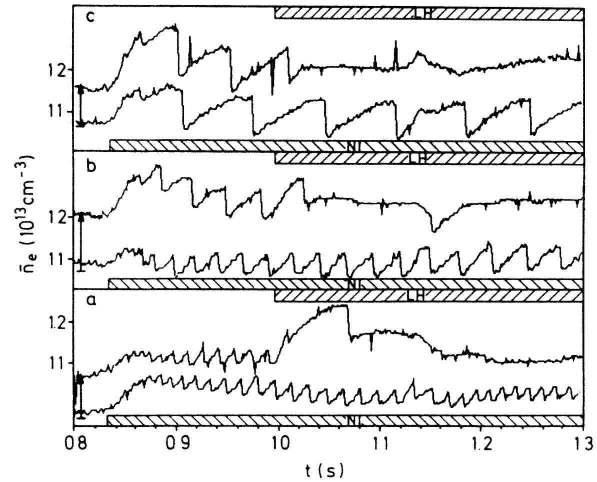

FIG. 4. Sawteeth on the density $\bar{n}_e$ for NBI with different powers: (a) 0.45 MW, (b) 0.9 MW, (c) 1.35 MW. Lower traces, for NBI alone; upper traces (offset as indicated by the arrows), for NBI plus LH current drive ($P_{\rm LH} \approx 720$ kW). $\bar{n}_e = 1.1\times 10^{13}$ cm^{-3} (D_2), $I_p = 300$ kA, $B_t = 2.2$ T.

be explained by a pressure anisotropy due to the acceleration of electrons parallel to the magnetic field. The subsequent slow decrease indicates a drop of l_i and therefore a flattening of the current profile $j(r)$.

Direct measurements of $j(r)$ are made on ASDEX by use of a neutral-Li-beam probe.[7] In Fig. 3 the measured profiles of the magnetic pitch angle $\theta_p = \tan^{-1}(B_p/B_t)$, and the corresponding profiles of $q(r)$ are shown during the Ohmic phase and during the stationary sawtooth-free phase of LH current drive with $P_{\rm LH} = 540$ kW ($\Delta\phi = 90°$) at $\bar{n}_e = 1.2\times 10^{13}$ cm^{-3}, $I_p = 300$ kA, $B_t = 2.2$ T, and $-\Delta U_l^{\rm LH}/U_l^{\rm OH} \approx 0.7$. The q is slightly below 1 in the central plasma region during inductive current drive and above 1 in the whole plasma region during the LH current drive. The central value rises from $q(0) = 0.98^{+0.03}_{-0.01}$ during the flat-top Ohmic phase to $q(0) = 1.14 \pm 0.07$ during the stationary LH phase. The error bars on the measured points in Fig. 3 are half due to systematic errors on the absolute value. Relative changes of the local current distribution are determined with higher accuracy. A decrease in the internal inductance l_i of $\Delta l_i = -0.12 \pm 0.03$ is determined from the measured $j(r)$ profiles. This agrees well with the magnetic measurements for which $\Delta l_i \approx -0.1$ is derived. The suppression of sawteeth is therefore achieved by a flattening of the current profile $j(r)$ in the central part of the plasma such that $q > 1$ everywhere. This, in fact, was corroborated by current-profile measurements for other discharges with different densities, different $q(a)$, and also with other LH-current-drive wave spectra. In all cases where sawteeth are stabilized, $q(0)$ increases above 1. Consistently, no changes of the current profile are found in the cases of opposite current drive and of LH heating that are shown in Fig. 1 where sawteeth remain. Under these conditions $q(0) = 0.96$–0.99 during the LH phase. A detailed discussion of the influence of the LH wave spectrum on the current distribution is found in the work of McCormick, Söldner, and Leuterer.[8] The electron temperature profile, on the other hand, peaks during both LH heating and LH current drive, with a strong increase of the central temperatures due to LH power deposition in the plasma core.

Large-amplitude sawteeth are observed during neutral-beam-injection heating (NBI) as a result of both the higher local heating rate and the longer sawtooth period. LH current drive was combined with NBI at low density, where the current-drive efficiency is high. Magnetic measurements again indicate a drop of the internal inductance l_i during the LH phase and therefore a flattening of $j(r)$. With the LH power above a critical value, which depends on the beam heating power, the sawteeth could be stabilized in the whole range of beam heating powers where they were observed. In Fig. 4 the sawteeth on the line-averaged density $\bar{n}_e$ are shown for discharges with different injection powers. They disappear after the beginning of the LH phase, the time delay being reduced with increasing beam power.

After stabilization of the sawteeth the central electron temperature increases above the maximum value attained with NBI alone. Also the total energy content W_p is higher than in sawtoothing discharges. In Fig. 5

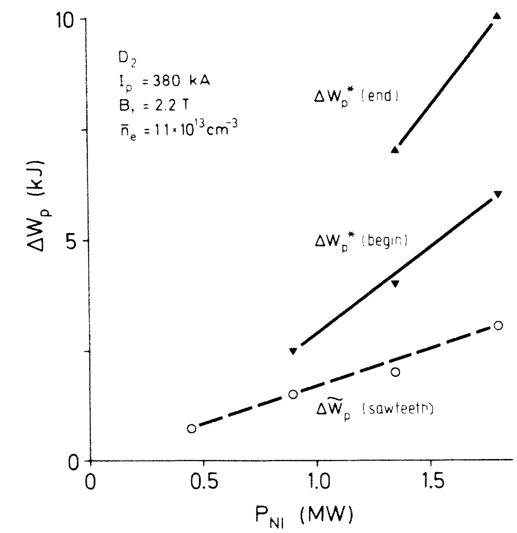

FIG. 5. Sawtooth amplitude of total energy content $\Delta \tilde{W}_p$ and difference in energy content ΔW_p^* between sawtoothing and nonsawtoothing NBI-heated discharges vs beam power. In the latter case LH current drive with $P_{\rm LH} = 550$ kW is applied.

the fluctuation level of the energy content $\Delta \tilde{W}_p$ due to sawteeth is plotted versus the beam power together with the increase in energy content ΔW_p^* at the beginning and at the end of 300-ms-long stationary sawtooth-free phases. ΔW_p^* is the difference in energy content between sawtoothing and nonsawtoothing NBI-heated discharges. The increase in ΔW_p^* at the beginning comes essentially from the additional LH heating, while the higher values of ΔW_p^* at the end indicate a net gain in energy content after the sawtooth-free phase.

Suppression of the sawtooth oscillations in tokamak discharges therefore may lead to a higher plasma energy content. LH current drive has proven its ability to stabilize the sawteeth also under conditions of high-power neutral-beam heating by driving $q(0) > 1$. The decoupling of current and temperature profiles in this case allows for an independent external control of the current profile and heat deposition. This, in fact, may improve the global energy confinement.

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