Recharging of the Ohmic-Heating Transformer by Means of Lower-Hybrid Current Drive in the ASDEX Tokamak

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Recharging of the Ohmic-heating transformer of a tokamak by means of lower-hybrid waves is demonstrated experimentally in ASDEX. The results are analyzed on the basis of a simple transformer circuit. A recharging efficiency is defined and found to depend on rf power, plasma density, and plasma resistivity modified by the applied rf power. Up to now, we achieved in our recharging experiments in ASDEX a flux swing of $\int \dot{I}_{\mathrm{OH}} M\,dt = 0.24$ V sec, at rf power of $P_{\mathrm{rf}} = 690$ kW, with a pulse duration of 1 sec, while maintaining a plasma with $\bar{n}_e = 4\times 10^{12}$ cm^{-3} and $I_p = 290$ kA.

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A variety of lower-hybrid (LH) current drive applications have been investigated during the last years. One goal was to achieve a steady-state tokamak operation by clamping the Ohmic-heating (OH) transformer and maintaining a stationary plasma current.[1,2] But only in high-field tokamaks with a high frequency of the LH transmitter[3] could current drive be observed up to reactorlike densities of 10^{14} cm^{-3}. Rampup of the plasma current[4,5] has shown its potential for high-current operation in tokamaks with moderate size OH transformer. Finally, startup of a tokamak discharge by LH waves alone[6–8] offers the possibility of the complete omission of the OH transformer in future tokamaks. Severe restrictions on all three of these applications are imposed by the so-called high-density limit. Whether this can be overcome in a given machine by an increase in the frequency remains to be shown yet. Another mode of operation which takes into account the actual restriction of LH current drive to low densities has been proposed for the quasi-stationary operation of tokamaks.[9–11] In this scenario each OH-driven burn phase at high density is followed by an LH-driven phase at low density, with recharging of the OH transformer by the rf-driven current. As shown in this note, such a recharging of the OH transformer has been demonstrated for the first time in the ASDEX tokamak.

Lower-hybrid current drive was investigated in a wide parameter range in the ASDEX tokamak.[12] ASDEX has an air-core transformer and a double null poloidal divertor.[13] The major radius is $R = 1.65$ m and the plasma radius is $a = 0.4$ m. The experiments described here have been performed with a toroidal magnetic field of $B_0 = 2.2$ T, a plasma current $I_p \approx 300$ kA, and in a density range $\bar{n}_e = (0.2\text{–}3)\times 10^{13}$ cm^{-3}. The LH waves were launched with an eight–wave-guide grill antenna whose spectrum peaks at $\langle N_\parallel \rangle = 1.8$ for $\Delta\phi = \pi/2$. The frequency is 1.3 GHz.[14] Total net rf powers of up to 800 kW for up to 1.5 sec were used.

Usual current-drive experiments were performed in such a way that the primary current I_{OH} in the Ohmic-heating transformer was kept constant as soon as a suitable plasma was created so that no more power was transferred from the transformer into the plasma. The plasma current I_p then decays with its characteristic time $\tau_p = L_p/R_p$. If an LH-driven current is excited in such a plasma, the rate of plasma current decay, $-\dot{I}_p$, is decreased.[12] At sufficiently high rf powers, or at low enough plasma densities, the decay rate can even be reversed and the plasma current can be ramped up. Thereby the energy stored in the poloidal magnetic field of the plasma current is increased.[4]

In ASDEX we found an analogous behavior for the primary current I_{OH}, if the plasma current I_p is kept constant during the rf pulse by means of a feedback control acting on the OH-power supply. In particular, again with high rf powers and low plasma densities, the primary current rate of change, $\dot{I}_{\mathrm{OH}}$, can be reversed. This leads to a recharging of the Ohmic-heating transformer.

In Fig. 1 we compare two LH-current-drive experiments in the same Ohmic target plasma, one with a rampup of the plasma current I_p (dashed lines), the other one with a rampup of the primary current I_{OH} (solid lines). In the first case the primary current I_{OH} was held constant for $t > 1.05$ sec. A high-power LH wave launched into this plasma resulted in rampup of the plasma current at a rate of $\dot{I}_p = +50$ kA/sec. During the rf pulse, the loop-voltage signal U_L dropped

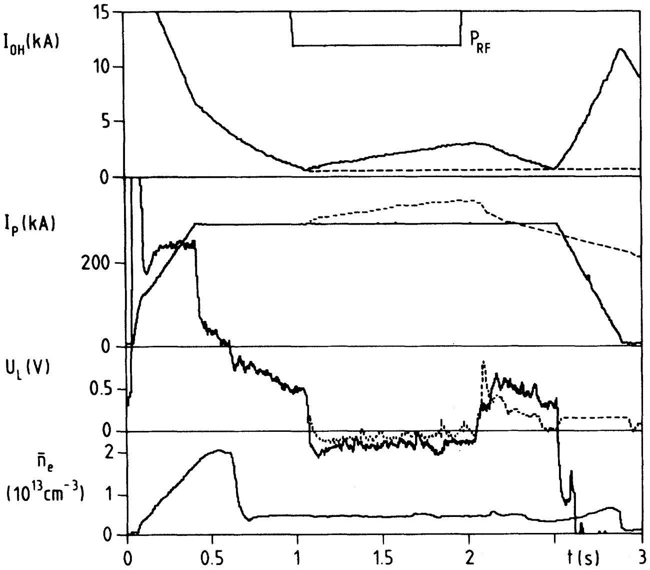

FIG. 1. Plasma current rampup with LH-current drive. $P_{\rm rf}=675$ kW, $\Delta\phi=\pi/2$, $\bar{n}_e=3.7\times10^{12}$ cm^{-3}, $I_{p0}=290$ kA, $B_0=22$ kG; gas, D_2. Solid lines, $I_p=$const; dashed lines, $I_{\rm OH}=$const.

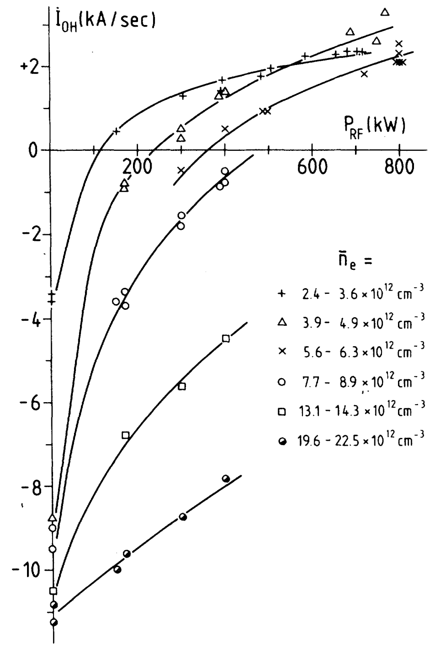

FIG. 2. Primary current rate of change, $\dot{I}_{\rm OH}$, as a function of net rf power for different densities.

below zero as a consequence of an induced reverse electric field. In the second case the plasma current I_p was maintained constant at 290 kA. In order to prevent an increase of the plasma current due to the high rf power, an opposite dc electric field had to be induced in the plasma by the feedback-controlled increase of the primary current $I_{\rm OH}$ at a rate of $\dot{I}_{\rm OH}=+2.3$ kA/sec. Such a current increase leads to a recharging of the OH transformer. Consequently, the loop-voltage signal U_L during the rf application became negative also in this case.

The dependence of the rate of change $\dot{I}_{\rm OH}$ on the rf power is shown in Fig. 2 for different mean electron densities. These curves show the same nonlinear relationship between $\dot{I}_{\rm OH}$ and $P_{\rm rf}$ as was already observed in the corresponding scans for $\dot{I}_p$ vs $P_{\rm rf}$ when $I_{\rm OH}$ was kept constant.[12] Figure 3 shows density scans of $\dot{I}_{\rm OH}$ which again exhibit the same dependence as $\dot{I}_p$ vs $\bar{n}_e$ in the mode of operation with constant $I_{\rm OH}$.[12]

For LH-current drive with $I_p=$const, we can determine the primary current rate of change

$$\dot{I}_{\rm OH}=(-1/\tau_p)(I_p-I_{\rm rf})(L_p/M),$$

where we have assumed that the rf-driven current $I_{\rm rf}$ can be switched on in a time short compared to τ_p. This equation has a linear relationship between $\dot{I}_{\rm OH}$ and $I_{\rm rf}$, if the other quantities are considered constant. Taking $I_{\rm rf}\propto P_{\rm rf}$ as predicted by steady-state current-drive theory[15] and found for steady-state experiments with $\dot{I}_{\rm OH}=0$ and $\dot{I}_p=0$,[1-3,12] one would also expect a linear dependence of $\dot{I}_{\rm OH}$ on $P_{\rm rf}$. The curves of Fig. 2, however, clearly show a nonlinear dependence which may be explained either by a change of τ_p with rf power (if $I_{\rm rf}\propto P_{\rm rf}$ remains valid also in the presence of a nonzero dc electric field), or by a nonlinear relation between $I_{\rm rf}$ and $P_{\rm rf}$ if there is a dc electric field. Electron-cyclotron emission and hard x-ray measurements show that the electron velocity distribution is highly suprathermal in current-drive experiments,[16] and that the plasma behavior is quite similar to that of suprathermal Ohmic discharges in ASDEX.[17] From these observations we conclude that the plasma resistivity R_p decreases strongly with increasing $P_{\rm rf}$ and decreasing $\bar{n}_e$, as was theoretically predicted.[18,19] In fact our experiments are in good agreement with the theoretical results of Ref. 18 as will be shown in a forthcoming paper.[20] The curves in Fig. 2 also suggest that this effect is less important at higher densities.

An important feature of transformer recharging with LH-current drive may be recognized in Figs. 2 and 3. At high rf powers, in ASDEX for $P_{\rm rf}\gtrsim600$ kW, there exists a maximum of the rampup rate $\dot{I}_{\rm OH}$ as a function of density. This is also a consequence of the decreasing plasma resistivity which diminishes the achievable rampup rates.[18]

To discuss the power flow from the rf source through the plasma into the transformer, we use the circuit shown in Fig. 4. For simplicity, we neglect any interaction with the equilibrium fields and set $I_{\rm OH}>0$ according to the experimental conditions in Fig. 1.

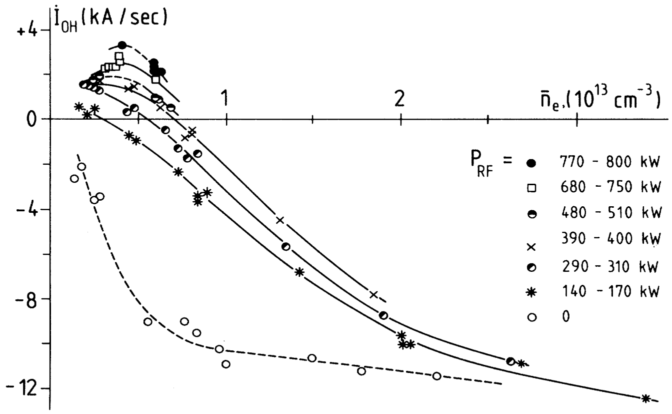

FIG. 3. Primary current rate of change, $\dot{I}_{\mathrm{OH}}$, as a function of density for different rf powers.

Both terminals are fed by programmable power supplies which represent OH power and rf power. For the purpose of this discussion, we assume that all the rf power leaving the antenna is absorbed by the plasma.

Let us consider a situation as in our recharging experiments, i.e., $I_p = \mathrm{const}$ and $\dot{I}_{\mathrm{OH}} > 0$. Ramping up the primary current I_{OH} requires that a power

$$P_{\mathrm{rf},I_p=\mathrm{const}} = I_p^2 R_p + I_p \dot{I}_{\mathrm{OH}} M$$

be fed into terminal 2. The first term represents power dissipated in R_p to maintain the plasma, while the second part is power stored in the mutual inductance M. Simultaneously, the OH-power supply also feeds a power

$$P_{\mathrm{OH},I_p=\mathrm{const}} = I_{\mathrm{OH}}^2 R_{\mathrm{OH}} + \dot{I}_{\mathrm{OH}} I_{\mathrm{OH}} L_{\mathrm{OH}}$$

into terminal 1, which is partly dissipated in R_{OH} and partly stored in L_{OH}. After the transformer is recharged and the rf is switched off ($P_{\mathrm{rf}} = 0$), we must discharge it again ($\dot{I}_{\mathrm{OH}} > 0$) in order to maintain a constant plasma current. Looking at the above equations, we recognize that only the fraction of stored magnetic energy originating from the rf source and stored in M can be used for further heating of the plasma. The magnetic energy which came from the primary side and was stored in L_{OH}, however, flows back, being partly dissipated in R_{OH} and partly reabsorbed by the OH-power supply.

A similar analysis can be performed for the case of ramping up the plasma current, i.e., $I_{\mathrm{OH}} = \mathrm{const}$ and $\dot{I}_p > 0$, in which case energy is stored in L_p and in M. It leads to the same result that, after the rf pulse, only the fraction originating from the rf source, namely $I_p \dot{I}_p L_p$, can be dissipated in the plasma.

Applying the same power P_{rf} in both modes of operation to the same target plasma (with respect to I_p and $\bar{n}_e$) results in the same fraction of P_{rf} stored as magnetic energy; hence,

$$(\dot{I}_{\mathrm{OH}} M)_{I_p=\mathrm{const}} = (\dot{I}_p L_p)_{I_{\mathrm{OH}}=\mathrm{const}}.$$

In ASDEX the ratio M/L_p is about 22, and, in fact, from Fig. 1 we get the same value for the ratio

$$(\dot{I}_p)_{I_{\mathrm{OH}}=\mathrm{const}} / (\dot{I}_{\mathrm{OH}})_{I_p=\mathrm{const}},$$

confirming the validity of the above model. This relation is found to hold approximately in the whole parameter range of the power and density scans, Figs. 2 and 3.

On the basis of these considerations, we define a recharging efficiency μ for the mode of operation with $I_p = \mathrm{const}$ as the ratio between the power which is stored reusably in M and the power input to the plasma, P_{rf}:

$$\mu = (I_p \dot{I}_{\mathrm{OH}} M / P_{\mathrm{rf}})_{I_p=\mathrm{const}}.$$

For the same target plasma, this recharging efficiency is equal to the conversion efficiency $I_p \dot{I}_p L_p / P_{\mathrm{rf}}$ as introduced in Ref. 4 for the mode of operation with $I_{\mathrm{OH}} = \mathrm{const}$. In order to maximize this efficiency we need to obtain a maximum rate of change $\dot{I}_{\mathrm{OH}}$ and $\dot{I}_p$, respectively. For this we not only need to achieve an rf-driven current I_{rf} much larger than I_p, but also to maintain a plasma resistance as high as possible.

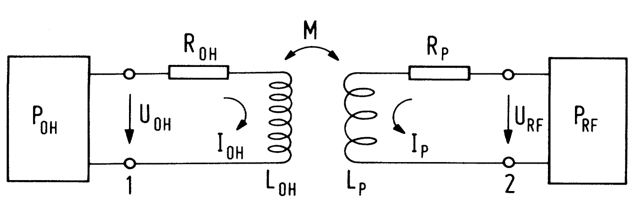

FIG. 4. Transformer circuit with two programmable power supplies (in ASDEX: $R_{\mathrm{OH}} = 16\ \mathrm{m}\Omega$, $L_{\mathrm{OH}} = 8.4$ mH, $M = 83\ \mu$H, $R_p = 0.5\text{–}4\ \mu\Omega$, $L_p = 3.7\ \mu$H).

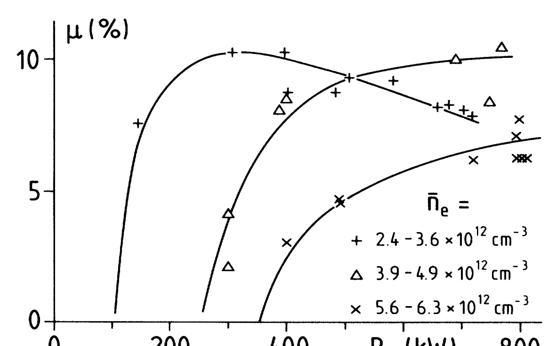

FIG. 5. Recharging efficiency μ vs rf power.

It should be noted that during rampup of the plasma current ($\dot{I}_p > 0$), the conversion efficiency changes and finally becomes zero when the plasma current reaches a higher stationary value ($\dot{I}_p = 0$). In the case of transformer recharging with $I_p = \text{const}$, however, the recharging efficiency remains constant throughout the rf pulse.

The recharging efficiencies obtained in ASDEX so far are plotted in Fig. 5 taken from the data shown in Fig. 2. Only a small part of the applied rf power is stored as magnetic energy. The larger fraction is dissipated in the plasma thereby maintaining or even increasing its energy content.[16] The recharging efficiency saturates or even decreases with increasing rf power. Whether the efficiency can be increased in going to higher densities cannot be answered from our present data.

Recharging of the OH transformer by lower-hybrid current drive has been demonstrated experimentally. With rf energies up to 1 MJ, a fraction of about 10% of the rf energy could be stored as magnetic energy in the OH transformer. The OH-current rampup rate, $\dot{I}_{OH}$, seems to be limited by the decrease in plasma resistivity caused by the rf produced suprathermal electron distribution. The resistivity becomes smaller with increasing rf power and decreasing density. Higher recharging rates might be obtained at higher densities. They are desirable because they would increase the ratio between burn phase and recharging phase (and thereby the mean power output) in a quasistationary tokamak operation as envisaged in the INTOR scenario.

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