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On the use of Lower Hybrid Current Drive in ASDEX Upgrade

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1. Introduction

The ASDEX Upgrade tokamak program focuses on preparing the physics basis for ITER operation. Different options for 'advanced' tokamak scenarios allowing more attractive ITER operations [1,2] exist, such as higher performance, longer pulses or reduced plasma current operation. The most prominent candidates are reversed shear scenarios with internal transport barriers (ITB) [3], aiming at a bootstrap fraction of more than 80%, or 'hybrid' scenarios [4], with a somewhat lower bootstrap fraction, but less demanding control issues regarding current and pressure profiles. A common feature of these scenarios is the need for external current drive (CD) in order to control stability and confinement properties as well as extend the pulse length. At present, ASDEX Upgrade uses Electron Cyclotron Current Drive (ECCD) and Neutral Beam Current Drive (NBCD). However, both methods have specific drawbacks: ECCD has a relatively low CD efficiency whereas the profile of the NBCD current is relatively broad, not well controllable and in addition not found to be consistent with theoretical predictions under certain circumstances [5]. Thus, another CD method with good CD efficiency, reasonable localisation and a capability to externally control the profile of the driven current is highly desirable. Such a method is the current drive with lower hybrid waves, LHCD. In this paper, we present conceptual studies of such a system for ASDEX Upgrade and an assessment of its capabilities. A preliminary design assumes a frequency of 3.7 GHz and a parallel index of refraction of $n_{\|} = 2.2, 2.5$, according to a plasma density of 4-6 x 10^{19} m^{-3} and a magnetic field of 2.5 –3 T. An additional launch of waves with a higher $n_{\|}$ of 4-5 could be used to create a suprathermal electron population at larger minor radii providing a 'seed' for absorption there, thus offering a possibility to control the profile of the driven current.

Calculations are carried out by the transport ASTRA code [6]. The LHCD model combined to ASTRA is the ray tracing Fokker Planck package FRTC [2,7]. This code, based on a 1-D ($v_{\|}$) Fokker Planck model, has ad hoc corrections to the collision operator accounting for 2-D effects, such as pitch angle scattering [8] and has been largely benchmarked on LHCD experimental data of FTU [9].

Since this first approach is aimed at establishing the power requirements, CD efficiency and current and power deposition profiles, the LHCD modeling is carried out on ASDEX Upgrade experimental data relevant to the scenarios of interest, that is hybrid and ITB scenarios. Plasma parameter profiles are set to the experimental values, while the magnetic flux diffusion equation is solved in the presence of all the external current components, updating the q-profile calculation to the presence of LHCD. The approximation of using the same T_e profile as in the absence of LHCD power, holds as long as $P_{LH} << P_e$, where $P_e = P_{eNBI} + P_{OH} - P_{RAD} - P_{CLei}$ is the net power to the electrons in the reference discharge. In the cases considered here this approximation is only marginal ($P_{LH} \leq P_e$). That means that also a temperature increase is expected which in turn can affect (but only slightly) deposition and CDE in the desired direction (more LHCD localization, larger CDE). A deeper, fully self-consistent analysis is outside of the scope of this paper and is postponed to the future. It would include also the solution of the energy transport equations and could predict possible ASDEX Upgrade scenarios where LHCD provides the current control from the very beginning of the discharge. In sec.2 the results are presented and discussed. In sec 3 conclusions are drawn.

2. The results

LHCD simulation is carried out on two ASDEX Upgrade shots, one reference for the Hybrid scenario and one for ITB scenario.

Hybrid scenario. In the reference shot for the hybrid scenario (steady state improved H-mode, #13679, I_P= 1MA, B_T=2.5, $<n_e>$ = 0.4 10^{20} m^{-3}) 5.3MW of NB injection (NBI) provide heating and CD (T_{i0}= 13KeV, T_{e0}=5 KeV, and I_{NBI}= 0.26 MA, 26% of I_P) while the bootstrap effect drives 0.29MA. This is illustrated in Fig. 1a) and b). On this plasma target, 1.5 MW of LH power are supposed to be coupled to the plasma. Figure 1a) shows the LH absorbed power, 1.35MW corresponding to 90% of the launched power. As a term of comparison the net power to the electrons in the reference discharge is also shown, $P_{e.}$ The figure 1b) shows the LH driven current, I_{LH}=0.4 MA. According to this simulation, almost all the residual current is driven by 1.35MW of LHCD. That corresponds to a CD efficiency η_{LHCD}= I R $<n_e>$ /P_{ABS}, of 1.9 10^{20} m^{-2} AW^{-1}. At this value of η_{LHCD}, the further power requirement to drive the rest of the current (50KA) is 170KW. Figure 1c) shows the loop voltage of the discharge almost vanishing in the presence of LHCD, compared to the loop voltage in the absence of LHCD. Finally figure 1d) shows q_0 rising in time in the presence of LH, while the internal inductance is almost constant.

Due to the relatively low electron temperature and to the high plasma density, multiple ray passes (more than 6) are needed to get the LH power fully absorbed. In this condition, it is the toroidicity induced $n_{||}$ variation that determines the LHCD localization, which typically results in quite broad profiles. However, most of the LH current is driven at $\rho/a>0.5$. i.e. more externally than the bootstrap current. This is shown in Figure 2a) where the current density profiles, J_{TOT}, and its different components, J_{NBI}, J_{BS}, and J_{LH} are reported. J_{LH} has a peripheral channel at $\rho \sim 0.35$m, just where J_{BS} is low. In figure 2b) the q profile in the absence and in the presence of LH is shown.

ITB scenario. In the reference ITB scenario (#17902, I_P= 0.8MA, B_T=3T) 10MW of NBI, switched on at t=0.8 sec, provide the heating and CD to this shot [10]. During the early phase of the discharge (0.8< t <1.05 sec) the plasma density increases from $<n_e>$ = 0.14 10^{20} m^{-3} to the value $<n_e>$ = 0.5 10^{20}, so that all the parameters are evolving in this temporal range (T_{i0}= 20-10KeV, T_{e0}=5-6 KeV). At t=0.9 sec the LH power starts to be injected into the reference plasma, according to a power spectrum centered at $n_{||}$=2.5. This higher $n_{||}$ value is requested to avoid power losses due to slow-fast mode conversion of LH waves at high density. At 0.9 < t <1.0, when the density is low, only 1.2MW of LH power are injected, in order to avoid a large current overdrive already present in the real discharge. Later on, at t >1.0 sec, the power is risen to 1.5MW. Figure 3a) shows the waveform of the absorbed LH power P_{LH}, 1.35MW in the range 1.0 < t < 1.1sec ((90% of the launched power), then the absorbed LH power lowers to 1.22MW at t> 1.1 when $<n_e>$ overcomes 5.2 $10^{20}m^{-3}$. This power loss is associated to the loss of accessibility of 10% of the power spectrum. The figure 3b) shows the temporal evolution of all the current components. After the overdrive phase, almost all the current is non-inductively driven in steady state: I_{NBI}=0.225MA, I_{BS}=0.184MA, with a contribution due to LHCD of I_{LH}=0.184MA, corresponding to a CD efficiency, η_{LHCD}, of 1.4 10^{20} m^{-2} AW^{-1}. Finally figure 3c) shows the loop voltage to vanish in the presence of LHCD, while the loop voltage in the absence of LHCD is higher. In figure 4a) and b) all the current density components are shown at t=0.9

sec, before LH, (reference shot ones) and at t=1.2 sec, in the presence of LH. As in the previous case, LHCD is broad and peripheral.

Conclusions

According to the modeling reported so far (f=3.7GHz), LHCD is characterized in ASDEX Upgrade plasmas, by multiple pass absorption and a broad LH current profile but with a substantial part of current driven peripherally ($\rho/a>0.5$). A power spectrum centered at $n_{//}= 2.2\text{-}2.5$ is appropriate, but, at very high density ($<n_e> > 5\ 10^{19}m^{-3}$, BT=3T), the use of $n_{||} = 2.5$ is mandatory. The theoretical CD efficiency, calculated in cases where the power is the effectively absorbed one, resulted to be in the range, $\eta_{LHCD} = 1.4\text{-}1.8\ 10^{20}m^{-2}\ AW^{-1}$, while the absorbed power was about 80-90%. An analysis of LHCD both in the Hybrid scenario and in the ITB scenario showed that 1.5-1.7 MW of LHCD (absorbed at 80-90%) provides all the residual current (~ 40% of the total current in the hybrid and ~ 25% in the ITB) making these shots fully non inductively driven. To estimate the power requested at the source one has to take into account the directivity of the power spectrum (typically ~85%), the power reflected at the plasma antenna interface (~5-10%), and the transmission lines losses (~30%). In this way we get that a system at 3.7 GHz, delivering 3MW at $n_{||}=2.5$, is suitable to make ITB and hybrid scenarios fully non-inductively driven in ASDEX Upgrade plasmas. Thus, LHCD may be a very useful tool for ASDEX Upgrade to develop steady state scenarios for ITER.

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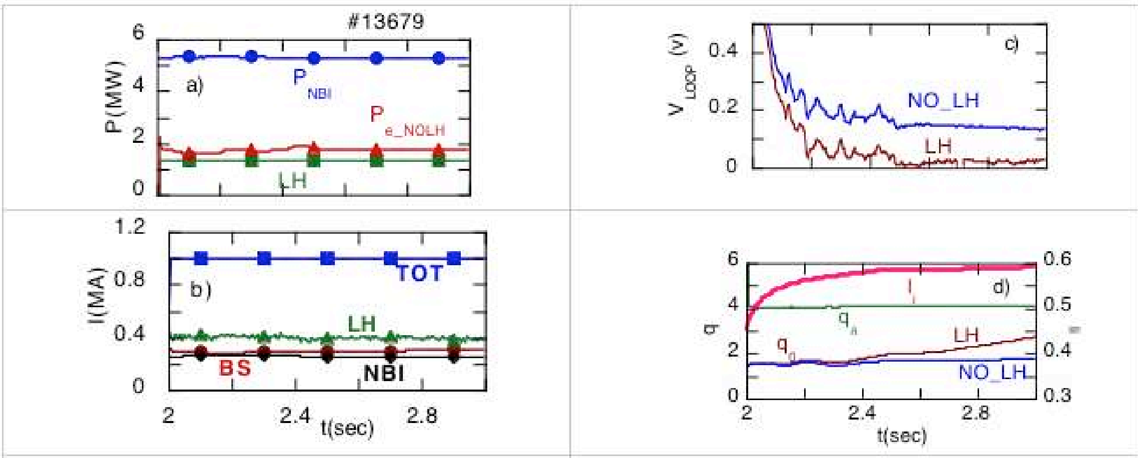

Fig. 1::Hybrid scenario: a) Power vs. time , b) current components and total current vs. time

c) Loop voltage vs. time with and w.o. LHCD, d) safety factor value q_0 *(at r=0) with and w.o. LHCD and internal plasma inductance li (scale on the left)*

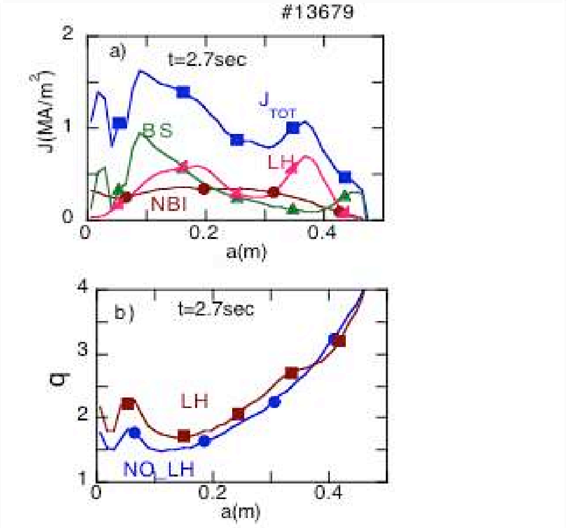

Fig. 2. Hybrid scenario a) total current density profile and its components. b) q profile with and w.o. LHCD

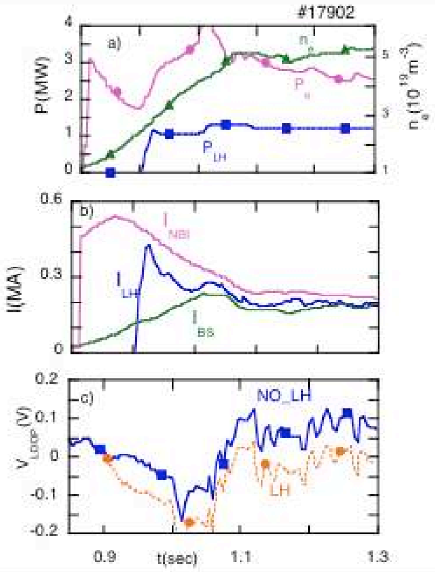

Fig. 3. ITB scenario: a) Power vs. time, b) current components and total current vs. time. c) Loop voltage vs. time with and w.o. LHCD.

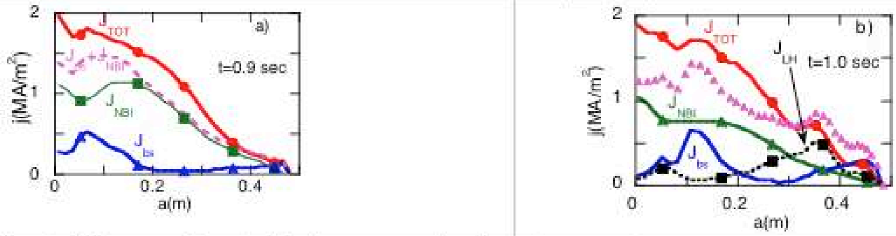

Fig. 4 ITB scenario. a) Total current density profile and its components at t=0.9sec, before LHCD.

b) Total current density profile and its components at t=1.0 s, during LHCD. Triangles are $J_{LH}+J_{BS}+J_{NBI}$ *to be compared to* J_{TOT}.