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Demonstration of ITER relevant LHCD operation: Large distance coupling in JET and long pulse operation in Tore Supra

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Introduction. Lower Hybrid Current Drive (LHCD) is one of the most efficient methods for off-axis non-inductive current drive in tokamaks and is therefore used for shaping the plasma current profile in advanced tokamak scenarios. Its usefulness has been demonstrated in the advanced scenario experiments in JET [1], but the question has remained about the possibility of coupling Lower Hybrid (LH) waves in ITER. This paper reports on recent results obtained in JET and Tore Supra, that both demonstrate operation of LHCD systems in ITER relevant regimes: i) LH coupling on ELMy plasmas up to 11cm distance between the launcher and the separatrix in JET and ii) steady state, full non-inductive LHCD operation during 6 minutes in Tore Supra.

ITER relevant LH coupling in JET. High performance internal transport barrier (ITB) plasmas are characterised by an ELMy edge. In order to couple the LHCD power efficiently during ELMy plasmas in JET, gas injection in the scrape-off layer in the region magnetically connected to the LHCD launcher is used. This increases the electron density at the launcher mouth to values above the slow wave cut-off density, with the result that the amplitude as well as the variation in reflected powers during ELMs are reduced, leading to fewer interrupts of the klystron powers. Following a recent modification of the gas injection pipe that has improved the localisation of the gas puffing, D_2 injection can now be used for controlling the LH coupling as an alternative to the earlier used CD_4. This is an important result, as CD_4 may not be possible to use in ITER due to tritium retention. An experiment aimed at demonstrating the feasibility of LH coupling during ELMs, at large distance between the last closed flux surface (LCFS) and the launcher, has been carried out in JET [2]. When puffing CD_4 near the launcher at a flow of 12×10^{21}el/s, 2.5MW could be coupled reliably at 9.5cm distance, even during large type I ELMs. Without any gas injection, the high reflected power levels cause repetitive tripping, limiting the coupled power to ~1MW.

When puffing D_2 at 8×10^{21}el/s, 3MW could be coupled at 11cm distance during small amplitude type I ELMs (Fig. 1). In this experiment, i.e. reversed magnetic shear scenario at I_P=1.5MA and B_T=3.0T, D_2 injection was found to reduce the ELM amplitude. This is due to a slight increase in electron density and decrease in electron temperature at the pedestal. In addition, more reliable LH coupling was found with D_2 injection. This is not only due to lower ELM amplitude, but also to higher electron density at the launcher. Reciprocating Langmuir probe measurements show that the electron density is approximately two times higher when puffing D_2 compared to CD_4 at similar electrons/s rates (Fig. 2). This is probably due to the recycling of D_2. An indication of higher recycling is seen on the D_α signal, which has a higher base line level in the discharges with D_2.

Following this experiment, D_2 injection for LH coupling control has been used in a few ITB experiment in JET. An overview of the LH coupling behaviour in plasmas with an ITB or H-mode as a function of the LCFS-launcher distance is shown in Fig. 3. The gas flows used were 6-8×10^{21}el/s for D_2 and 7-12×10^{21}el/s for CD_4. The power reflection coefficient, averaged over the whole launcher, is similar for the two gases, but the achieved power is higher with D_2 injection. In the experiments made so far, ITBs are always obtained with D_2 injection, but a clear comparison of the ITB evolution compared to cases with CD_4 is not straightforward,

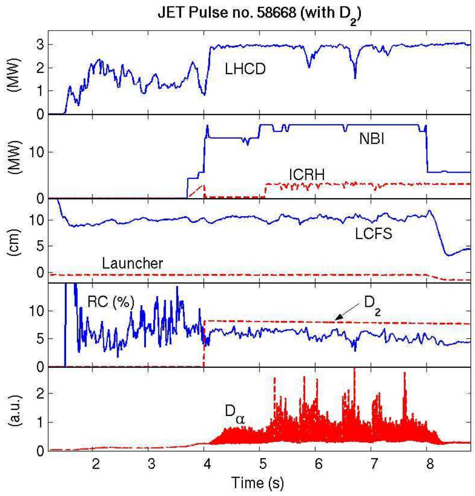

Fig. 1: LH coupling during ELMs using D_2 injection (8×10^{21}el/s).

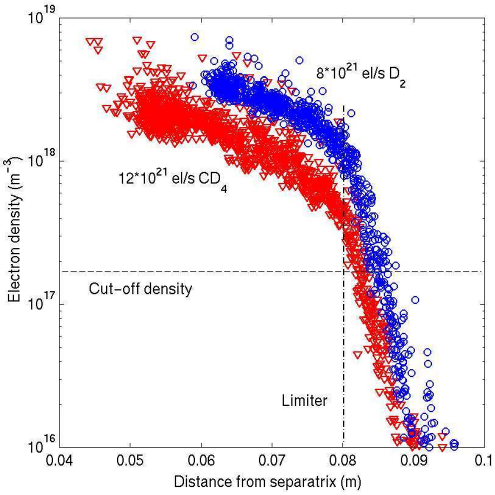

Fig. 2: Effect of CD_4 and D_2 on the scrape-off layer density.

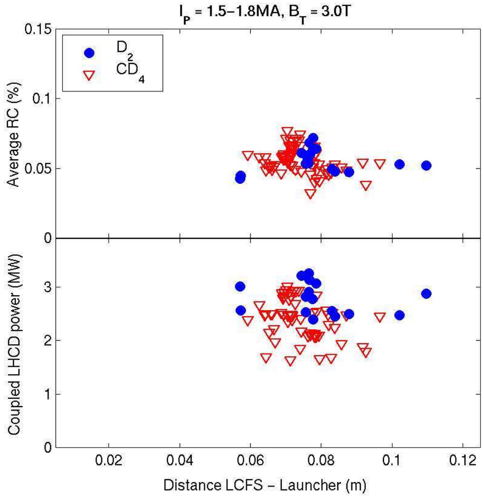

Fig. 3: Overview of LH coupling behaviour with CD_4 and D_2.

due to differences in ELM size, additional heating power and machine conditions in the experiments.

The compatibility between the D_2 injection needed for LH coupling and that used for the plasma scenario has been demonstrated in the ITER relevant, high triangularity ITB configuration (δ~0.45). This experiment uses strong D_2 and Neon injection in order to maintain type III ELMs, as they are generally compatible with an ITB. 4×10^{21}el/s D_2 is injected near the launcher for LH coupling control, while three times that amount of D_2 is injected from the divertor region for ELM control. This experiment also demonstrates good LH coupling in a plasma configuration not matched to the poloidal shape of the launcher.

Gigajoule discharges in Tore Supra. After the upgrade of the Tore Supra vacuum vessel in 2001, long pulses in steady state L-mode conditions have now been performed. Full non-inductive current drive with LHCD has been achieved during 6 minutes at P_{LHCD}=2.9MW, leading to an injected energy in the tokamak exceeding 1GJ [3]. The discharges are feedback controlled to maintain strictly zero loop voltage, while the plasma current is maintained at I_P=0.5MA by acting on the LHCD power. Tore Supra has two LHCD launchers: the old design (Mark I), which is the design also used at JET, and a new advanced launcher (Mark II). Due to its higher power handling capability, the Mark II launcher is powered by three times as much power as Mark I (Fig. 4). The average reflection coefficient increases slightly on Mark II, while it remains constant on Mark I. The reason for this is not entirely understood, but could be linked to a continuous phase change in some multijunctions on Mark II due to thermal expansion of the wave-guide transmission lines. An influx of metallic impurity, in this case originating from Mark I, is observed at

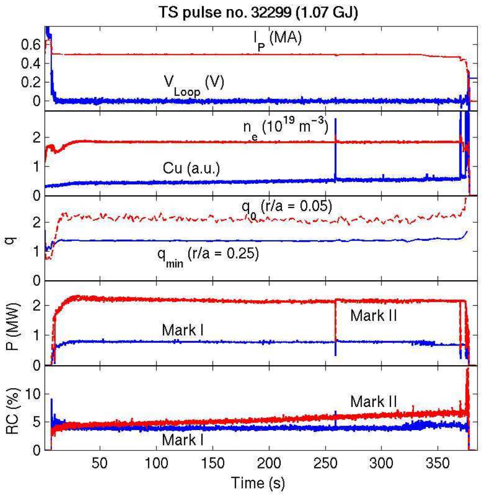

Fig. 4: Tore Supra discharge with 1GJ injected energy.

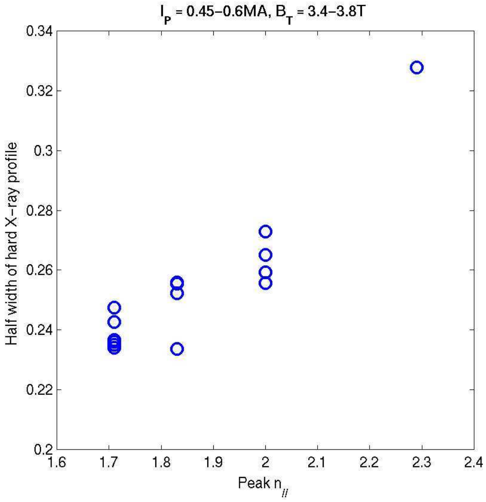

Fig. 5: Half width of hard X-ray profile versus peak $n_{//}$ value.

~260s in the discharge. However, the performance is recovered after this event and the pulse continues another ~110s.

In preparation for the long pulse experiments, the current drive efficiency and current profile versus the launched $n_{//}$-spectrum was studied. Maximum current drive efficiency is obtained for $n_{//}$ peaked at 1.7, and decreasing at higher $n_{//}$, as expected from the subsequent reduction of the high velocity limit of the quasi-linear plateau. The current profile, deduced from the hard X-ray diagnostic, broadens with increasing $n_{//}$ (Fig. 5), as also found in earlier experiments. A study of the MHD activity [4] indicated that the most favourable regime corresponds to B_T=3.4T. In such a way, the dominant MHD mode is a saturated mode at q=3/2, less harmful for the confinement than the q=2 mode, dominant at 3.8T. The parameters for the gigajoule discharges were thus $n_{//}$=1.7 and B_T=3.4T. The CRONOS code simulation of discharge #32299 shows a weakly reversed q-profile with q_{min}=1.3 located at r/a=0.25 and maintained in steady state (Fig. 4). However, confinement improvement is not observed in this discharge, due to the existence of the q=3/2 mode.

Summary and future plans. Experiments in JET have shown that efficient coupling of LH waves can be obtained during ELMs and at ITER relevant distances, with the use of local gas injection. In Tore Supra, reliable LHCD operation in a steady state, full non-inductive current drive regime has been obtained for durations up to 6 minutes. The foreseen upgrade of the Tore Supra LHCD system [5] will allow to extend the operating domain to higher power and higher performance, and to demonstrate the long pulse and coupling capability of a passive active multijunction (PAM) launcher, as foreseen for ITER. Following the recent experimental progress in LHCD, as exemplified here and in [1, 6], it has now been recommended that the development of LHCD be supported by the European Fusion Programme [7], in order to prepare LHCD as an additional heating system in ITER.

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