First experiments in H-mode plasmas with the Passive-Active Multijunction (PAM) LHCD launcher in HL-2A and impact on pedestal instabilities

A. Ekedahl[1], X.Y. Bai[2], B. Lu[2], R. Magne[1], G.L. Xiao[2,3], W.L. Zhong[2], E. Bertrand[1], Y.L. Chen[2], J. Cheng[2], Z.Y. Cui[2], L. Delpech[1], X.T. Ding[2], J.Q. Dong[2,4], X.R. Duan[2], B.B. Feng[2], K. Feng[2], J.M. Gao[2], G. Giruzzi[1], M. Goniche[1], J. Hillairet[1], G.T. Hoang[1], X.Q. Ji[2], M. Jiang[2], J. Liang[2], R. Mao[2], D. Mazon[1], Y. Peysson[1], J. Rao[2], Z.B. Shi[2], S.D. Song[2], X.M. Song[2], C.Wang[2], J.Q. Wang[2], H. Wang[2], M. Xu[2], L.W. Yan[2], Z.C. Yang[2], D.L. Yu[2], H. Zeng[2], B.Y. Zhang[2], Y.P. Zhang[2], Y. Zhou[2], X.L. Zou[1] and the HL-2A team[2]

1) CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France.
2) Southwestern Institute of Physics, P.O. Box 432, Chengdu 610041, China.
3) Department of Engineering Physics, Tsinghua University, Beijing, China.
4) Institute for Fusion Theory and Simulation, Zhejiang University, Hangzhou, China.

Email: annika.ekedahl@cea.fr

Abstract. The passive-active multijunction (PAM) [1], an ITER-relevant lower hybrid current drive (LHCD) launcher design, was developed in view of a LHCD system for the second phase of ITER. PAM launchers have so far been successfully tested in L-mode plasmas on FTU [2, 3] and Tore Supra [4, 5]. This paper now reports on the first and unique experiments with a PAM on H-mode plasmas. The experiments were carried out on HL-2A tokamak, for which a new PAM launcher had been designed and constructed. In the first experiments, the LH power (in the range 200 – 500 kW) was coupled during type I ELMs in H-mode plasmas triggered and sustained by Neutral Beam Injection (NBI) combined with LH waves. The LH power was coupled at large plasma-launcher gap, more than 10 cm. Local gas injection was found primordial to allow good coupling at large plasma-launcher gap. These first experiments also show that the LH power can have a mitigating effect on the ELMs in HL-2A H-mode plasmas. Increase in ELM frequency and decrease in ELM amplitude was observed in shots with coupled LH power above 300 kW. Following modifications on the LH system and on the plasma control system, the coupled LH power in H-mode plasmas has now reached 900 kW in the second experimental campaign.

1. Introduction

Current drive with waves in the lower hybrid (LH) frequency range is a well-proven method of non-inductive current drive in tokamaks, used in numerous tokamaks around the world since the early 1980s. By injecting lower hybrid waves into one toroidal direction in the tokamak, a fraction of the plasma current is replaced by the non-inductively driven LH current, allowing to increasing the duration of the plasma discharge. A comprehensive review of the recent advances in LH theory, experiments and modelling can be found in [6].

In view of foreseeing a LH system for the second phase of ITER [7], a relevant LH launcher design, the passive-active multijunction (PAM), has been developed [1]. This concept fulfils the requirements of withstanding the heat load in the ITER environment under long pulses. It also offers very low reflected power fraction at low electron density, which is highly advantageous when operating at large plasma-launcher gaps and during H-mode edge with steep density gradient. The first experimental test of a PAM module was carried out in the FTU tokamak [2, 3]. Those experiments clearly demonstrated the possibility to operate at high power density, albeit in short pulses (< 1s). Following this, a PAM launcher was designed and constructed for Tore Supra [4], demonstrating long pulse operation at high coupled power (2.7 MW, 80 s) and ITER-relevant power density [5]. So far, the PAM experiments in FTU and Tore Supra have shown excellent results of power handling and coupling at large plasma-launcher distances, making it an attractive launcher design for operation in high performance scenarios and in long pulses. However, this has up to now only been demonstrated in L-mode plasmas. This paper now reports on the first and unique LH coupling experiments with a PAM launcher on H-mode plasmas that were carried out on the HL-2A tokamak [8, 9].

2. Description of the LH system in HL-2A

The new 3.7 GHz LHCD system in HL-2A consists of a Passive-Active Multijunction (PAM) launcher, fed by four 3.7 GHz klystrons [10]. The PAM was designed by SWIP, Chengdu, in cooperation with IRFM (*Institut de Recherche sur la Fusion par confinement Magnétique*) at CEA. The ALOHA coupling code [11] was used for defining the design parameters for the PAM launcher. The peak parallel refractive index was chosen to $n_{//0}$ = 2.75, in order to allow accessibility of the LH wave in HL-2A plasmas at toroidal field B_T = 1.4 T. The PAM launcher consists of 16 modules, with four active and four passive waveguides each, mounted in four rows and four columns. One passive waveguide is added at the end of each toroidal row, resulting in four rows with 16 active and 17 passive waveguides (see photo in Figure 1). The total width and height of the launcher are 365 mm and 325 mm, respectively. As seen in Figure 2, the ALOHA calculations show that the power reflection coefficient, averaged over the 16 modules, is less than 3% when the electron density at the launcher mouth is larger than 2×10^{17} m^{-3}, the cut-off density for the LH wave being $n_{co} = 1.7\times10^{17}$ m^{-3} at f = 3.7 GHz.

A dedicated gas puffing system with three poloidal injection points is installed next to the launcher mouth, on the left of the launcher, as seen in Figure 1. Local gas puffing near LH launchers has been used routinely, for example in JET [12] and EAST [13], as a method to increase the local density and improve the LH coupling, in particular during H-mode operation. A set of Langmuir probes, consisting of a total of eight probes mounted at two radial locations, is installed on the right hand side of the launcher mouth. The probes allow measuring the electron density and temperature at two radial locations and will thus also allow deducing the density and temperature decay lengths at the launcher location.

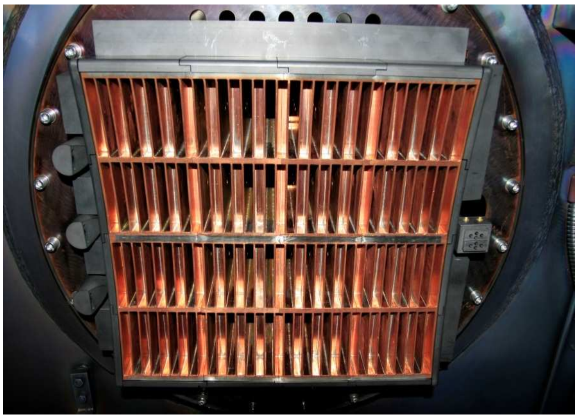

FIG. 1: Photo of the PAM launcher in HL-2A (w = 365 mm; h = 325 mm). A gas puffing system with tree poloidal injections are located at the left of the launcher (viewed from the plasma). A set of Langmuir probes is located to the right.

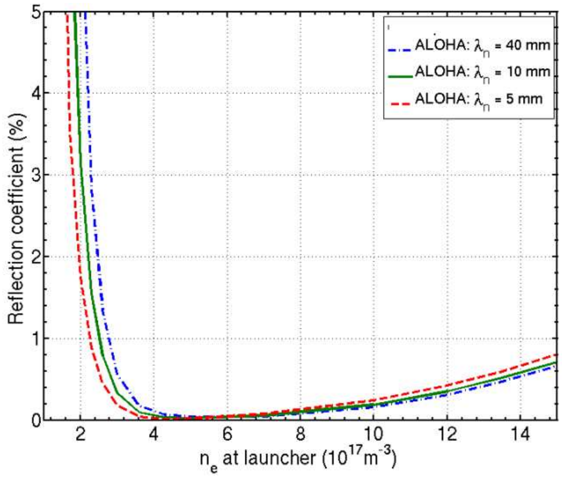

FIG. 2: Reflection coefficient on the PAM launcher versus electron density at the launcher mouth, as calculated by ALOHA [11] for three different density decay lengths.

The PAM launcher is fed by four 3.7 GHz TH2103A klystrons. These are equipped with circulators that protect the klystrons from excessive reflected power. The microwave power is transmitted to the launcher in TE_{10} propagation mode through the rectangular waveguide (WR284) transmission lines. The transmission line is pressurised with two bars of nitrogen in order to prevent arcing. Prior to the experiments in H-mode plasmas in HL-2A, the klystrons and the PAM launcher were commissioned in L-mode plasmas up to 500 kW coupled power in 400 ms long pulses [10].

3. LH coupling in H-mode plasmas

The first LH coupling experiments with the PAM in H-mode were carried out in a lower single null (LSN) configuration with plasma current I_P = 160 kA, toroidal magnetic field B_T = 1.4 T and edge safety factor q_{95} = 4. In most of the discharges, the distance from the last closed flux surface (LCFS) to the poloidal limiter was ~10 cm at the mid-plane, and slightly further away from the top part of the launcher and closer at the bottom part of the launcher. The PAM launcher was retracted 1.0 cm behind the poloidal limiter, resulting in a plasma-launcher gap of ~11 cm at the mid-plane. This poloidal variation was noticeable on the reflection coefficients (RC), i.e. RC was consistently higher on the modules in the uppermost row than on the modules in the lowest row. The time evolution of the same discharge (#26862) is shown in Figure 3. The plasma was heated by 700 kW of Neutral Beam Injection (NBI) between t = 500 ms and t = 1000 ms. The plasma remained in L-mode with NBI alone, since 700 kW was not enough to trigger H-mode in this scenario, for which the central line average density was less than 2×10^{19} m^{-3}. The LH power, which was 200 kW in this discharge, was applied at t = 800 ms. As seen on the Dα-emission, denoted I_{Div} in Figure 3, H-mode was triggered 20 ms after the application of the LH power. The H-mode transition is a consequence of the additional LH power.

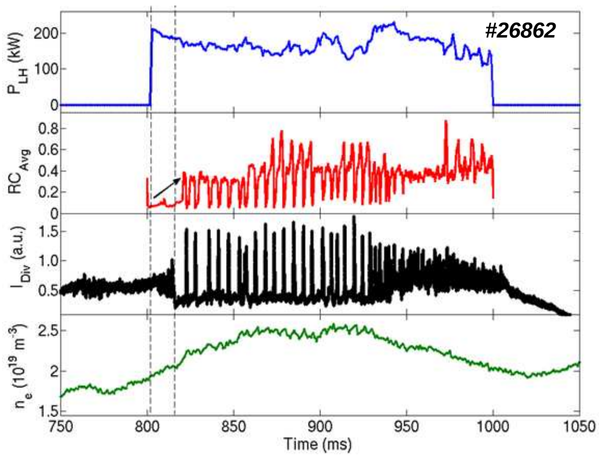

FIG. 3: Time evolution of shot #26862, showing the coupled LH power, the average reflection coefficient (RC), the Dα-signal and the line integrated density.

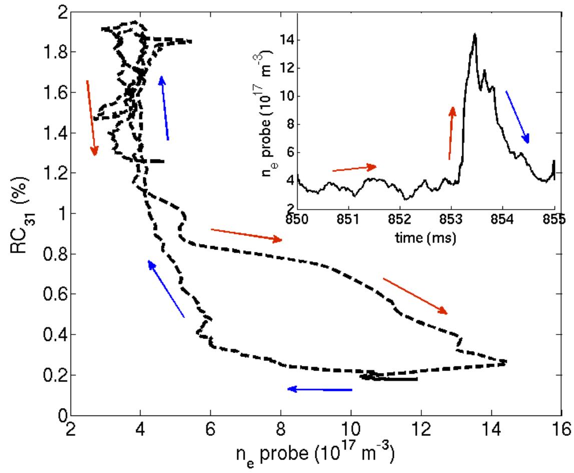

FIG. 4: Reflection coefficient (RC) on one module (row 3, column 1) versus the electron density measured by a Langmuir probe on the launcher.

Figure 3 also shows the evolution of the average reflection coefficient during the ELMs. As can be expected, RC is highest during the phase between ELMs, as the density in the scrape-off-layer (SOL) is lowest in this phase. During the ELM-bursts the electron density increases and RC decreases significantly, as expected by ALOHA modelling. In order to show the RC behavior more clearly, the reflection coefficient on one module at the lower part of the launcher (row 3, module 1) is plotted against the electron density given by one of the Langmuir probes. On this module (row 3, column 1) the RC varies between 2% and 0.2% (Figure 4). One can note in Figure 4 that the reflection coefficient behaves differently during the ELM-rise and after the ELM-crash. One plausible hypothesis is enhanced SOL ionization by the LH power during an ELM, as was investigated and modelled in JET [14]. During the ELM-crash, the SOL temperature increases and so the ionization by the LH power is enhanced. The ionization will increase the electron density locally in front of the powered waveguides, leading to a reduction in reflected power. However, this local increase in electron density many not necessarily be measured by the Langmuir probes, since they are located outside the waveguide region.

The local gas injection was found to be crucial in this experiment for increasing the local electron density at the launcher, since the plasma-launcher gap was always very large (usually more than 10 cm). The gas dosing was controlled by opening the valve during short intervals. This timing of the gas puffs is indicated for the discharge shown in Figure 5. The reflection coefficient decreases typically 10 ms after the gas puff is switched on. In this discharge, the average RC decreases to 8% following the gas puffs.

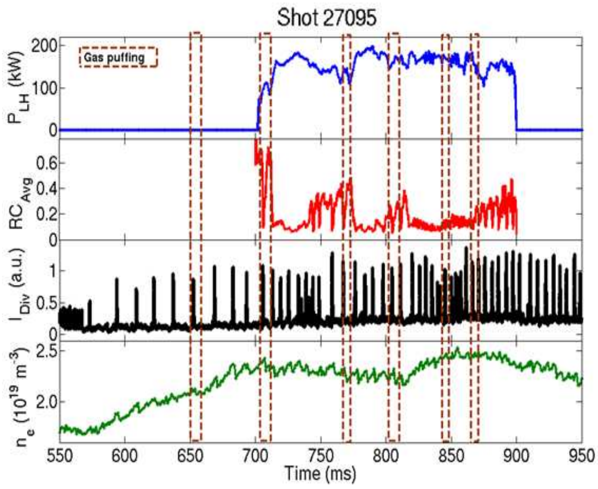

FIG. 5: Time evolution of #27095, showing coupled LH power, average reflection coefficient (RC), Dα-signal and line integrated density. The timing of the gas puffs are indicated by dashed vertical lines.

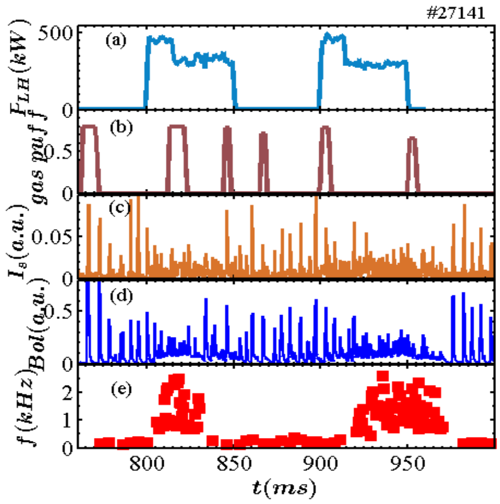

FIG. 6: ELM mitigation with LHCD: Launched LH power (a), local gas puff signal (b), ELM behaviour, as seen on ion saturation current (c) and plasma radiation (d), ELM frequency (e).

4. Effect on ELMs

The effect of LH power on the H-mode pedestal was investigated in these experiments, in particular the ELM frequency and ELM amplitude. The results indicate an effect on the ELM behaviour, i.e. an increase in ELM frequency and decrease in ELM amplitude during LH power modulations with LH power > 300 kW [15]. One example is shown in Figure 6. The mitigation effect with LH waves was found to be sensitive to plasma parameters and there appears to be a minimum density, $n_e \sim 2.5\times10^{19}$ m^{-3}, above which the mitigation effect occurs. An increase of the pedestal turbulence measured by Doppler reflectometry could also be observed, which suggests that an enhancement of the particle transport due to pedestal turbulence could be the cause of the ELM mitigation. Similar effect was previously observed during supersonic molecular beam injection (SMBI) in HL-2A [16] and it appears that the LH power can produce a similar effect, as also observed in EAST [17].

5. LHCD modelling

The LH power deposition and driven current profile has been modelled with the ray-tracing + Fokker-Planck codes, C3PO/LUKE [18]. The rays were launched from four poloidal locations, corresponding to the poloidal positions of the waveguide rows. The initial value of $n_{//}$ for each ray was chosen so as to correspond to the LH wave spectrum calculated by ALOHA. When using the standard version of C3PO/LUKE, the simulations predict that the LH power is absorbed off-axis, at normalized radius (r/a) in the range 0.2 < r/a < 0.6. Simulations have also been carried out the with the recent “Tail LH” model [19], in which approximately 50% of the LH power is transferred to higher $n_{//}$-values, in order to mimic the effect of edge density fluctuations on the launched wave spectrum. When the “Tail LH” model is used, the driven current profile becomes more central and the current drive efficiency increases. The same tendency is obtained for EAST discharges that were modelled with the same codes [20]. It should be noted however that hard X-ray measurements were not yet available for the LHCD experiments in HL-2A, meaning that information about the experimental LH power deposition is not available. This will be the subject of future experiments in HL-2A.

6. Recent results

Following the first experimental campaign (in 2015) with the PAM in H-mode, a number of modifications on the LH system and on the plasma control system were carried out in order to increase the coupled LH power. A part of the transmission line was changed in order to reduce transmission line losses and the RF measurements at the directional couplers were improved to get better reliability of forward and reflected power measurements in each module. On the plasma control system part, the divertor coil currents could be better controlled so as to maintain a smaller plasma-launcher gap during the H-mode phase. These modifications all had a significant effect on the LH power injection capability. In the experiments carried out in June 2016, the plasma-launcher gap could be controlled at a smaller value during the H-mode phase, allowing lower fraction of reflected power to the LH launcher. The coupled LH power has thus reached 900 kW in H-mode plasmas and 1 MW in L-mode plasmas (Figure 7). One H-mode discharge with NBI + LH is shown in the right panel in Figure 7. One can note that the ELM amplitude is significantly smaller in the recent discharges. This could possibly be due to different plasma shape compared to the earlier campaign. Local gas injection was not systematically used in these discharges, since the reflected power level was sufficiently low event without local gas puffing.

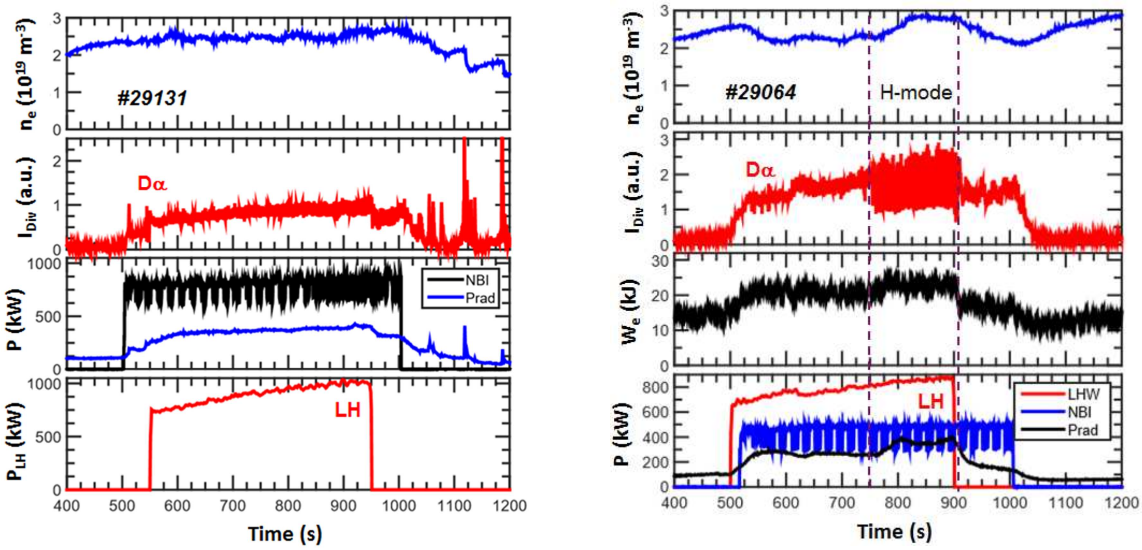

FIG. 7: Time evolution of two shots from the second experimental campaign, with coupled LH power reaching 1 MW in L-mode (#29131, left) and 900 kW in H-mode (#29064, right).

7. Summary and conclusions

A new passive-active multijunction (PAM) launcher, operating at 3.7 GHz, was successfully brought into operation on HL-2A and used in H-mode experiments. In the first experiments, LH power in the range 200 to 500 kW was coupled to H-mode plasmas with type I ELMs at large plasma launcher gap, often larger than 10 cm. Although large variations in reflection coefficient over the poloidal rows were observed, the reflection coefficient on the lowest row is in agreement with the ALOHA-code predictions, i.e. RC less than 2% if the density above the LH wave cut-off density. In the scenario chosen (I_P = 160 kA, B_T = 1.4 T, $n_e \sim 2\times10^{19}$ m^{-3}), H-mode was triggered when additional LH power (200 – 500 kW) was applied in combination with 700 – 800 kW NBI power. Local gas injection near the launcher was mandatory for obtaining good coupling of the LH wave at large plasma-launcher gaps. In H-mode plasmas at high density and LH power > 300 kW, a reduction of the ELM amplitude and an increase in ELM frequency was observed, suggesting that ELM mitigation could take place, as already observed in EAST. The second experimental campaign with the PAM launcher on HL-2A has now allowed obtaining further results in H-mode plasmas, with coupled LH power reaching 900 kW in H-mode and 1 MW in L-mode.

LHCD experiments on HL-2A have shown that the PAM launcher is a viable concept for high performance scenarios. LHCD power can be coupled at large plasma-launcher gap, and assist in triggering and sustaining H-modes.

Acknowledgments

The authors gratefully acknowledge the support of the HL-2A Team at SWIP, in particular the Control & Operation group, the Vacuum & Gas puffing group, the Diagnostic group and also the ECRH group. The IRFM members acknowledge the warm hospitality of the HL-2A Team during the commissioning of the LH system and during the experimental campaigns thereafter. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European research and training programme under grant agreement N° 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] BIBET, Ph., et al, Nucl. Fusion **35** (1995) 1213.
[2] MIRIZZI, F., et al, Fusion Eng. Des. **74** (2005) 237.
[3] PERICOLI RIDOLFINI, V., et al, Nucl. Fusion **45** (2005) 1085.
[4] GUILHEM, D., et al, Fusion Eng. Des. **86** (2011) 279.
[5] EKEDAHL, A., et al., Nucl. Fusion **50** (2010) 112002.
[6] BONOLI, P., Physics of Plasmas **21** (2014) 061508.
[7] HOANG, G.T., et al, Nucl. Fusion **49** (2009) 075001.

[8] DUAN, X.R., et al., IEEE Transactions on Plasma Science **40** (2012) 673.
[9] XU, M., DUAN, X.R., et al., Nucl. Fusion **55** (2015) 104022.
[10] BAI, X.Y., et al., Proc. 42nd EPS Conference on Plasma Physics, Lisbon (2015), paper P5.137.
[11] HILLAIRET, J., et al, Nucl. Fusion **50** (2010) 125010.
[12] EKEDAHL, A., et al., Plasma Phys. Control. Fusion **51** (2009) 044001.
[13] LIU, F.K., et al., Nucl. Fusion **55** (2015) 123022.
[14] PETRZILKA, V., et al., Plasma Phys. Control. Fusion **54** (2012) 074005.
[15] XIAO, G.L., et al., this conference.
[16] XIAO, W.W., et al., Nucl. Fusion **52** (2012) 114027.
[17] LIANG, Y., et al., Phys. Rev. Lett. **110** (2013) 235002.
[18] PEYSSON, Y., and DECKER, J., Fusion Sci. Technol. **65** (2014) 22.
[19] DECKER, J., et al., Phys. Plasmas **21** (2014) 092504.
[20] PEYSSON, Y., et al., Plasma Phys. Control. Fusion **58** (2016) 044008.