Recent progress on lower hybrid current drive and implications for ITER

J. Hillairet[1], **A. Ekedahl**[1,7], **M. Goniche**[1], **Y.S. Bae**[2], **J. Achard**[1],
A. Armitano[1], **B. Beckett**[6], **J. Belo**[3], **G. Berger-By**[1],
J.M. Bernard[1], **E. Corbel**[1], **L. Delpech**[1], **J. Decker**[1], **R. Dumont**[1],
D. Guilhem[1], **G.T. Hoang**[1], **F. Kazarian**[6], **H.J. Kim**[2], **X. Litaudon**[1],
R. Magne[1], **L. Marfisi**[1], **P. Mollard**[1], **W. Namkung**[4], **E. Nilsson**[1,7],
S. Park[2], **Y. Peysson**[1], **M. Preynas**[8], **P.K. Sharma**[5], **M. Prou**[1] and
the Tore Supra Team[1]

[1] CEA, IRFM, F-13108 St-Paul-Lez-Durance, France
[2] National Fusion Research Institute, Daejeon, Korea
[3] Associação Euratom-IST, Universidade Técnica de Lisboa, 1049-001 Lisboa, Portugal
[4] Department of Physics, Pohang University of Science and Technology, Pohang, Korea
[5] Institute for Plasma Research, Bhat, Gandhinagar, Gujarat, India
[6] ITER Organization, Saint-Paul-lez-Durance, France
[7] Department of Applied Physics, Nuclear Engineering, Chalmers University of Technology, SE-41296 Göteborg, Sweden
[8] Max-Planck-Institut für Plasmaphysik, D-17491 Greifswald, Germany

E-mail: julien.hillairet@cea.fr

Abstract

The sustainment of steady-state plasmas in tokamaks requires efficient current drive systems. Lower hybrid current drive is currently the most efficient method to generate a continuous additional off-axis toroidal plasma current and to reduce the poloidal flux consumption during the plasma current ramp-up phase. The operation of the Tore Supra ITER-like lower hybrid (LH) launcher has demonstrated the capability to couple LH power at ITER-like power densities with very low reflected power during long pulses. In addition, the installation of eight 700 kW/CW klystrons at the LH transmitter has allowed increasing the total LH power in long-pulse scenarios. However, in order to achieve pure stationary LH-sustained plasmas, some R&D is needed to increase the reliability of all the systems and codes, from radio-frequency (RF) sources to plasma scenario prediction. The CEA/IRFM is addressing some of these issues by leading a R&D programme towards an ITER LH system and by the validation of an integrated LH modelling suite of codes. In 2011, the RF design of a mode converter was validated at a low power. A 500 kW/5 s RF window is currently under manufacture and will be tested at a high power in 2012 in collaboration with the National Fusion Research Institute. All of this work aims to reduce the operational risks associated with the ITER steady-state operations.

(Some figures may appear in colour only in the online journal)

1. Introduction

The demonstration that a sustainable production of energy is achievable from nuclear fusion under steady-state conditions in a tokamak requires sustaining the plasma current by non-inductive current drive and by the self-generated bootstrap current. The high current drive efficiency of lower hybrid (LH) waves makes a lower hybrid current drive (LHCD) system a crucial actuator to save inductive flux and to generate additional plasma current in present-day tokamak experiments. Several superconducting tokamaks (EAST [1], HT-7 [2], Tore Supra [3], TRIAM-1M [4]) have demonstrated the feasibility

of long-pulse operation using LHCD. Continuous wave (CW) LHCD capabilities are planned in the KSTAR [5, 6] and SST1 [7] tokamaks. Following the ITER Science and Technology Advisory Committee recommendation, LHCD is considered for a future upgrade of its heating and current drive (H&CD) capability [8].

Simulations of ITER scenarios using LHCD have been updated in [9, 10] and show that there is a demand for an efficient off-axis current drive. Since this is the main feature of LHCD, LH will reduce the risks associated with the achievement of such steady-state scenarios. Moreover, adding LH power during the current ramp-up phase would

efficiently reduce the poloidal flux consumption, resulting in a significant longer flat top for the burn phase [11]. Therefore, preparing the ITER steady-state operations not only requires the development of ITER operating scenarios or burning plasma physics, but also to master the LHCD auxiliaries. The achievement of stationary plasmas sustained by LHCD[9] requires addressing a number of technological and physical issues. From the technological point of view, these include the development of high-power CW radio-frequency (RF) sources, actively cooled low-loss transmission lines and CW antennas with high coupling efficiency. Real-time control systems and reliable predictive coupling and current deposition codes are also required in order to minimize the operational risks associated with the ITER missions. All of these items—from RF sources to current deposition scenarios—must have a high reliability and efficiency.

 This paper summarizes the recent progress in the LHCD field with respect to the steady-state operation issues listed above and focuses on their potential implications for the ITER project. The paper is organized as follows. The recent achievements in LHCD technologies and operations in the Tore Supra tokamak and LH simulations are reported in section 2. Section 3 emphasizes the potential role of an LHCD system in ITER and reports the current research and development activities conducted by the CEA/IRFM in collaboration with the ITER Organization (IO) towards an ITER-relevant LHCD system. The LHCD capabilities of the Tore Supra tokamak to address these steady-state issues and the implications to the operational risk reduction in ITER from the know-how and the experiences gained are summarized in the conclusions.

2. Recent advances in LHCD

In order to address steady-state operational issues, eighteen 700 kW/CW 3.7 GHz klystrons (Thales Electron Device) manufactured for Tore Supra [12] were validated on 700 kW/CW matched loads at the in-house test bed facility, before their installation on the LH transmitter [13]. Each klystron produced routinely ∼620 kW/CW in the Thales Electron Devices test bed, under conditions simulating plasma operation (voltage standing wave ratio (VSWR) = 1.4). Eight of them were installed in the LH plant and operated during the 2010–2011 experimental campaign, generating a coupled power up to 3.8 MW to an actively water-cooled fully active multijunction (FAM) LH launcher [14]. High coupled power, greater than 3 MW for long durations, was routinely obtained in Tore Supra during the 2011 campaign. A total of 16.65 GJ of accumulated energy was coupled to the plasma in 2011 by the new klystrons with the FAM launcher.

 The second LH antenna of the Tore Supra tokamak is a passive–active multijunction (PAM), an ITER-relevant concept whose design consists in inserting a passive waveguide (short-circuited waveguide) between two active (directly power fed) waveguides [15]. Such an arrangement allows placing water-cooling pipes behind the passive waveguide, thus leading to an efficient exhaust of thermal fluxes coming from the plasma radiation, RF losses or neutron damping

---
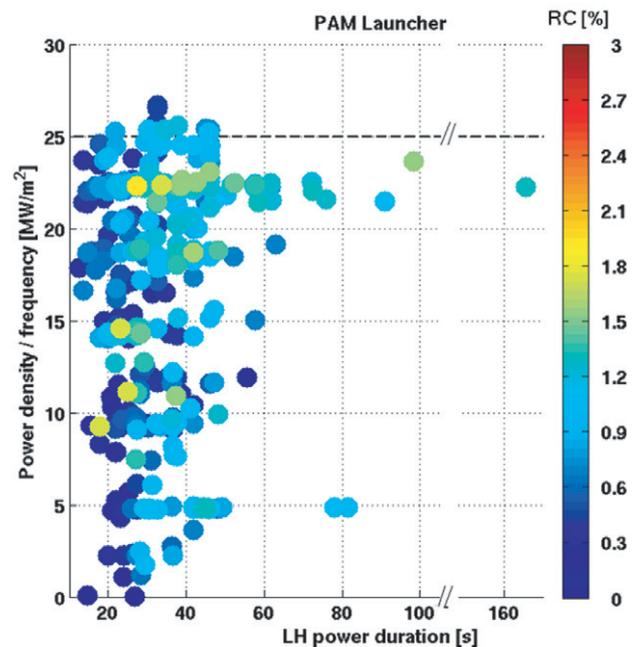
Figure 1. LH power density injected into the plasma versus the power duration during the 2011 Tore Supra campaign for the ITER-like PAM launcher. In total, 494 points are plotted, corresponding to the set of the Tore Supra pulses in 2011 having a net power larger than 50 kW. The colour scale illustrates the reflected power (in percentage of the input power) at the rear of the launcher. The dotted line is the power density design value of 25 MW m^{-2}, which is also the ITER design objective (at 3.7 GHz).

[16]. Moreover, the passive–active alternation increases the coupling efficiency under conditions with low density in front of the launcher mouth, e.g. at a large plasma–launcher gap. Both of these properties solve the general key issues of common LH launchers and are relevant for ITER steady-state operations. The PAM launcher has been frequently operated at an ITER-relevant power density (25 MW m^{-2}) as illustrated in figure 1, in which the power density coupled to the plasma is plotted versus the LH power duration. The capability of the PAM to address long-pulse operation issues has been demonstrated in Tore Supra, through the sustainment of a fully non-inductive discharge for more than 50 s, as illustrated in figure 2. This launcher is characterized by very low reflected power from the plasma (2–6% of the input power) [17], even at a distance from the last closed flux surface (LCFS) of 10 cm in or during fast supersonic molecular beam injections mimicking edge-localized modes in L-mode plasmas [18]. A total of 11.4 GJ of accumulated energy was coupled to the plasma in 2011 with the PAM launcher, which was powered by old-generation klystrons (400 kW/klystron). Eight 700 kW/CW klystrons have now been installed in 2012 to power the PAM launcher, but have not yet been used on plasma operation.

 Alongside experiments, a general framework is used to interpret Tore Supra LH experiments. This framework includes the LH wave coupling modelling with realistic antenna geometries either in the linear regime with the ALOHA code [19] or with the PICCOLO code in the non-linear regime [20]. The current deposition properties are calculated by ray-tracing calculations from C3PO associated with the Fokker–Planck solver LUKE [21]. The ray-tracing code

---

[9] We define here a stationary state of the plasma as a zero loop voltage discharge over duration much longer than the resistive time scale and the total thermalization time scale of the tokamak components.
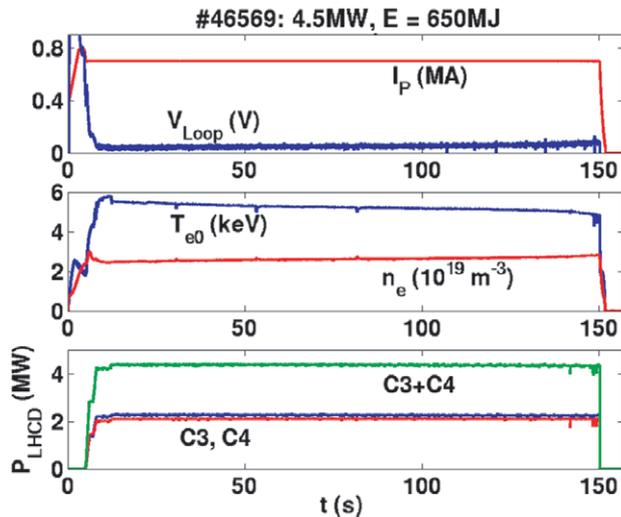
Figure 2. Tore Supra pulse #46569 with both FAM launcher (C3) and the LH ITER-relevant PAM launcher (C4); reproduced with permission from [14]. © 2011 American Institute of Physics.

C3PO takes into account the effect of density fluctuations, and current drive calculations are applicable when power absorption lies far from the fluctuating region. The framework can integrate equilibrium and kinetic profiles from METIS [22] or CRONOS simulations [23], as well as realistic antenna spectra calculated by ALOHA. A fast electron bremsstrahlung synthetic diagnostic R5X2 efficiently reproduces the hard x-ray (HXR) signal in Tore Supra steady-state discharges at low densities, i.e. absolute count rate, HXR profile and photon temperature [24–26]. All these tools, which have been validated on low-density plasmas ($n_e < 2 \times 10^{19}\,\text{m}^{-3}$), are mature enough to be used with confidence for the design of next-generation LH systems.

Alongside the modelling of the LH power deposition at the plasma centre, the unwanted effect of fast electron generation in front of the LH launchers, known to cause hot spots on the lateral protection, has been modelled. From the electric field at the mouth of the launcher, calculated by LH coupling codes, the electron power flow has been evaluated from test electron modelling [27, 28] and the associated heat flux on walls has been compared with infra-red measurements [29].

3. LHCD to sustain steady-state operations in ITER

In the frame of an international collaborative task, coordinated by CEA/IRFM under the European Fusion Development Agreement Organization [8], the design of the 5 GHz 20 MW/CW LH system for ITER has been updated from the initial 2001 Detailed Description Document with regard to the new results obtained by the LH community. This task, which also involved the training of future RF and mechanical engineers, has now led to the initiation of R&D projects of critical components of a 5 GHz LH system.

The LH system proposed for ITER is made of 48 identical modules, each one independently fed by one 5 GHz/500 kW/CW klystron (12 in the toroidal direction and 4 in the poloidal direction) [30]. The RF power is carried through a transmission line from each klystron up to a double 500 kW
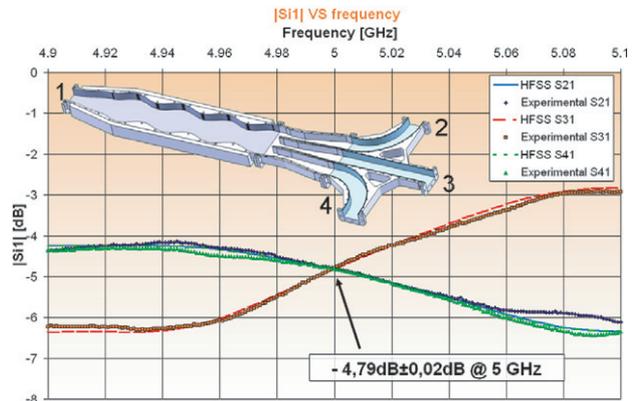

Figure 3. Power transmission of the 5 GHz mode converter and power splitter mock-up [31]. The symbols correspond to the three measured transmission coefficients of the mode converter. The lines correspond to the transmission coefficients calculated by the RF software HFSS.

RF window located outside the plug frame and connected to a 3 dB splitter, which feeds two TE_{10}–TE_{30} mode converters. After the mode converter, the power is divided into three vertical rows, corresponding to the inputs of a four-active waveguide PAM launcher. Thus, a launcher module consists of four active waveguides in the toroidal direction and six (2×3) lines of waveguides in the poloidal direction. The whole antenna contains 1152 active waveguides whose dimensions are $9.25 \times 58\,\text{mm}^{-2}$.

In 2011, a 5 GHz TE_{10}–TE_{30} mode converter was successfully tested at a low power at CEA/IRFM, and the measurements are in very good agreement with the computations made by the RF modelling [31]. Figure 3 illustrates the transmission coefficients from the input of the mode converter to its three outputs (S21, S31 and S41) and shows a balanced power division (-4.79 dB at 5 GHz, i.e. one-third of the input power). The mode conversion efficiency was measured by direct electric probing and found to be more than 99% and with low reflection (-40 dB).

In parallel, the space allocation of the LH transmission lines, RF plant and high-voltage (HV) supply was performed in association with IO, as illustrated in figure 4. Concerning the launcher design, further RF optimizations were conducted in order to decrease the maximum electric field inside the 5 GHz multijunction and increase the safety margins against possible arc events.

One of the main critical components of a LH system is the RF windows, which separate the tokamak vacuum from the pressurized transmission lines. In ITER, RF windows form part of the vacuum containment boundary and must fit demanding specifications and qualifications. They should be bakeable to 250 °C and be of a double-window design, unless permanently installed behind an ultra-high vacuum isolating valve [32]. In contrast to certain LH antenna designs, the RF windows cannot be located close to the plasma, because of the high heat loads and neutron fluxes expected in ITER. Thus, they should be located at the rear of the antenna, which imposes to work at a higher RF power density. As a high RF power device, the interspace pressure between two consecutive windows needs to be monitored continuously and interlocked
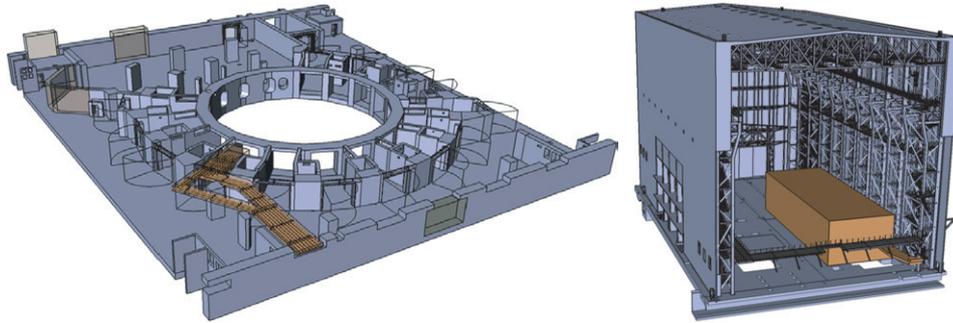
Figure 4. Space allocation for the LH system. Left: LH transmission lines in the tokamak building to equatorial port plug t#11. Right: location of RF sources and HV supplies in the assembly hall.

with the power system. Moreover, the window assembly must comply with the ITER Remote Handling Code of Practice.

In order to address these challenges without delay, a 5 GHz 500 kW/5 s beryllium oxide (BeO) window prototype is under manufacture. This model is a pill-box window, i.e. a sudden transition from a rectangular waveguide to a circular waveguide in which the ceramic is located. The RF dielectric constant and losses of the BeO ceramic were measured to be $\varepsilon_r = 6.36$ and $\tan(\delta) = 4.5 \times 10^{-4}$ at 5 GHz. From these results the ceramic width and the cylindrical guide dimensions were calculated to minimize both the reflected power and the integrated power losses in the ceramic volume. The rectangular waveguides are kept cut-off to higher modes than the fundamental one in order to avoid spurious modes in the transmission line, excited by the rectangular to circular transition. An appropriate TiN coating on the vacuum side of the ceramic is applied to reduce the secondary electron emission. This prototype will be tested at a high power in collaboration with the National Fusion Research Institute (NFRI) in Korea. These tests will allow validating both the RF and the mechanical design for short pulses at a high power, before pursuing a CW high-power prototype, compatible with the full ITER water cooling, structural and remote handling requirements.

4. Conclusion

The results obtained with the ITER-relevant 3.7 GHz LH system in Tore Supra represent a significant milestone on the way towards future integration of a LH launcher on ITER. The experience gained during the LH PAM launcher manufacturing allows us to be confident concerning the realization of an ITER LH launcher. The Tore Supra 700 kW/CW 3.7 GHz klystrons were validated in the test bed at 620 kW/CW on VSWR = 1.4, at a power level required for ITER. The 16-klystron RF plant, the water-cooled pressurized transmission lines and LH launchers are unique tools to develop and test reliable interlock systems, closely integrated to the main CODAC system. The know-how acquired through the use of the whole Tore Supra CW LH system, through the last experimental campaigns, is of the order of the future technical challenges that ITER RF systems will encounter. These technical advances are now complemented by more and more realistic LH simulation tools. The current drive performance can be predicted in identified ranges of plasmas with good accuracy through the use of integrated LH tools, from the

RF antenna to the current deposition in the plasma and the associated synthetic diagnostics.

The CEA/IRFM is currently conducting an R&D programme towards the validation of such RF devices. In 2011, a 5 GHz mode converter was successfully tested at a low power, thus validating the RF design. In 2012, a 500 kW BeO ceramic window was developed and tested at a low power. High-power tests will be conducted in association with the NFRI/KSTAR LH team.

References

[1] Baonian W. *et al* 2009 *Nucl. Fusion* **49** 104011
[2] Gao X. *et al* 2009 *Plasma Sci. Technol.* **11** 381
[3] Houtte D.V. *et al* 2004 *Nucl. Fusion* **44** L11
[4] Itoh S. *et al* 1999 *Nucl. Fusion* **39** 1257
[5] Park S. *et al* 2010 *Fusion Eng. Des.* **85** 197–204
[6] Kwon M. *et al* 2011 *Nucl. Fusion* **51** 094006
[7] Sharma P.K. *et al* 2010 *J. Phys.: Conf. Ser.* **208** 012027
[8] Hoang G.T. *et al* 2009 *Nucl. Fusion* **49** 075001
[9] Garcia J. *et al* 2008 *Phys. Rev. Lett.* **100** 255004
[10] Wagner F. *et al* 2010 *Plasma Phys. Control. Fusion* **52** 124044
[11] Bécoulet A. *et al* 2011 *Fusion Eng. Des.* **86** 490–6
[12] Beunas A. *et al* 2009 *IEEE Trans. Electron Devices* **56** 864–9
[13] Delpech L. *et al* 2011 *AIP Conf. Proc.* **1406** 145
[14] Ekedahl A. *et al* 2011 *AIP Conf. Proc.* **1406** 399
[15] Bibet P., Litaudon X. and Moreau D. 1995 *Nucl. Fusion* **35** 1213
[16] Guilhem D. *et al* 2011 *Fusion Eng. Des.* **86** 279–87
[17] Preynas M. *et al* 2011 *Nucl. Fusion* **51** 023001
[18] Ekedahl A. *et al* 2010 *Nucl. Fusion* **50** 112002
[19] Hillairet J. *et al* 2010 *Nucl. Fusion* **50** 125010
[20] Preynas M. *et al* 2013 *Nucl. Fusion* **53** 013012
[21] Peysson Y. *et al* 2011 *Plasma Phys. Control. Fusion* **53** 124028
[22] Artaud J.F. *et al* 2005 *32nd EPS Conf. on Controlled Fusion and Plasma Physics (Tarragona, Spain)* vol 29C (ECA) P1.035

[23] Artaud J.F. *et al* 2010 *Nucl. Fusion* **50** 043001

[24] Peysson Y. and Decker J. 2008 Fast electron bremsstrahlung in axisymmetric magnetic configuration *Phys. Plasmas* **15** 9

[25] Decker J. *et al* 2012 *39th EPS Conf. on Plasma Physics (Stockholm, Sweden)* vol 36F (ECA) P2.094

[26] Nilsson E. *et al* 2012 *39th EPS Conf. on Plasma Physics (Stockholm, Sweden)* vol 36F (ECA) P2.081 http://epsicpp2012.spp.ee.kth.se

[27] Fuchs V. *et al* 1996 *Phys. Plasmas* **3** 4023

[28] Petrzilka V. *et al* 2011 *Plasma Phys. Control. Fusion* **53** 054016

[29] Ekedahl A. *et al* 2012 *39th EPS Conf. on Plasma Physics (Stockholm, Sweden)* vol 36F (ECA) P2.088

[30] Hillairet J. *et al* 2011 *Fusion Eng. Des.* **86** 823–6

[31] Hillairet J., Achard J., Brun C., Rasio S. and Soler B. 2012 *Fusion Eng. Des.* **87** 275–80

[32] ITER Organization *ITER Vacuum Handbook* Appendix 6, IDM Ref: ITER_D_2DXZZ3