Advances in Lower Hybrid Current Drive for Tokamak Long Pulse Operation: Technology and Physics*)

Gia Tuong HOANG, Léna DELPECH, Annika EKEDAHL, Young-soon BAE[1)], Joelle ACHARD, Gilles BERGER-BY, Moo-hyun CHO[2)], Joan DECKER, Remi DUMONT, Heejin DO[2)], Cedric GOLETTO, Marc GONICHE, Dominique GUILHEM, Julien HILLAIRET, Haejin KIM[1)], Patrick MOLLARD, Won NAMKUNG[2)], Seungil PARK[1)], Hyeon PARK[2)], Yves PEYSSON, Serge POLI, Marc PROU, Melanie PREYNAS, Promod Kumar SHARMA[3)], Hyung-Lyeol YANG[1)] and Tore Supra Team

CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
[1)]*National Fusion Research Institute, Daejeon, Korea*
[2)]*Department of Physics, Pohang University of Science and Technology, Pohang, Korea*
[3)]*Institute for Plasma Research, Bhat, Gandhinagar, Gujarat, India*

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The paper gives a picture of the present status and understanding of technology and physics of Lower Hybrid Current Drive for long pulse operation in tokamaks, including the development of continuous wave (CW) high power klystrons, and its evolutions towards ITER. 3.7 GH / 700 kW CW klystrons produced in series by Thales Electron Devices are now in operation on Tore Supra. First series of eight klystrons delivered more than 4 MW to sustain non-inductive plasmas during 50 s. Moreover, a prototype of 500 kW CW klystron operating at 5 GHz developed for KSTAR by Toshiba Electron Tubes and Devices, and foreseen for ITER, is able to produce RF output powers of 300 kW / 800 s and 450 kW / 20 s on matched load. The situation on wave coupling and antennas is reported, with the latest Tore Supra results of the new CW Passive-Active Multi-junction (PAM) launcher: the antenna concept foreseen for ITER. First experiments with the PAM antenna in Tore Supra have provided extremely encouraging results in terms of power handling and coupling. Relevant ITER power density of ~25 MW/m^2 (2.7 MW of power injected into the plasma) has been maintained over ~80 s. In addition, LH power of 2.7 MW has been coupled at a plasma-antenna distance of 10 cm.

Keywords: lower hybrid current drive, CW klystron, ITER, tokamak, long pulse operation

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1. Introduction

Long pulse operation (LPO) of magnetically confined fusion plasmas is considered as one of the “grand challenges” of the future decades. Reaching such a goal requires the high-level integration of both science and technology aspects of magnetic fusion into self-consistent plasma regimes in the reactor-grade devices. On the physics side, the first constraint addresses the magnetic confinement itself which must be made persistent. This means either rely on intrinsically steady-state configurations, like the stellarator one, or turn the inductively driven tokamak configuration into a fully non inductive one [1]. In superconducting tokamak devices, several examples (EAST, HT-7, Tore Supra and TRIAM-1 M) have demonstrated the feasibility of LPO using Lower Hybrid Current Drive (LHCD). In LPO-class devices, discharge of over one hour has been successful sustained by ICRH and ECRH in the stellerator Large Helical Device (LHD) [2]. In spite of a number of open questions still under investigation, LHCD is the fundamental element for inductive flux saving needs in tokamaks. During the past five decades, impressive progress in terms of plasma discharge duration is recorded (Fig. 1). The initial couple of milliseconds achieved in the first tokamaks (e.g., JFT-2 [3], JIPPT-II [4], WT-2 [5]) now lead to minutes of multi-megawatt mega-ampere class of plasma operation, e.g. EAST [6], HT-7 [7], JET [8] and Tore Supra [9], or on smaller devices like TRIAM-1 M for hours [10].

LHCD CW capability is planned in superconducting tokamaks KSTAR [11] and SST1 [12]. In ITER, a 20 MW LHCD system operating at 5 GHz is mandatory to sustain steady state [13]. Following the ITER Science and Technology Advisory Committee recommendation, LHCD is now considered for future upgrade of heating and current drive (H&CD) capability. Both physics and technology conceptual designs of the previous 2001 Detailed Design Document have been reviewed in 2009-2010 [14], includ-

author's e-mail: tuong.hoang@cea.fr
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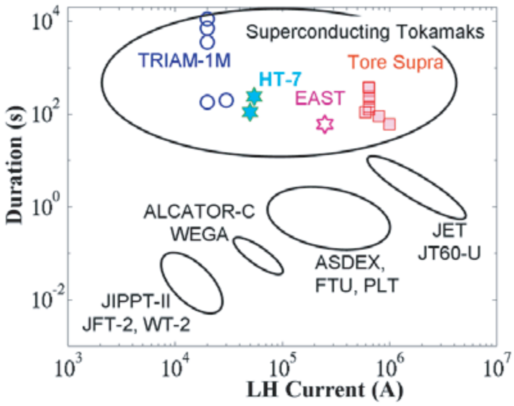

Fig. 1 Progress on LHCD experiments in tokamaks: plasma duration versus LH driven current (ALCATOR-C [22], ASDEX [23], FTU [24], JET [25], JT60 [26], JT60-U [27], PLT [28], WEGA [29]).

Table 1 Performance of existing CW klystrons. Output RF powers of the 5 GHz tubes were obtained at the NFRI test bed facility.

Frequency (GHz)	Design target	Achieved performance
5 (TETD-E3762RD0)	500kW/CW	**300kW/800s (VSWR=1.12)** (Factory test: 300kW/12min.) 450kW/20s (VSWR=1.2) 500kW/2s (VSWR=1.2)
4.6 (CPI)	250kW/CW	**259kW/CW** (*)
3.7 (TED-TH2103C)	700kW/CW	**767kW/CW (VSWR=1)** **670kW/CW (VSWR=1.4)**

(*) Lenci, Vacc. Electronics Conf. IVEC 2009, IEEE International

ing the integration aspect, under EFDA in close collaboration with the world-wide LHCD community and the ITER Organization. Most of critical issues such as the frequency choice, the power coupling as well as the risk assessment aspects have been carefully analyzed, with the goal to launch as soon as possible the required R&D on the construction critical path. Based on experimental results, simulations of ITER scenarios using LHCD have been revisited including advanced modes of operation in tokamaks and the LHCD-assisted start-up. The physics review report figures out the crucial and unique role played by far off-axis LHCD capability ($r/a = 0.6 - 0.8$) in ITER [15]. LHCD in combination with other H&CD methods will be a key tool for these two tasks:

i) to save Volt-seconds, from early plasma phases, extending the burn duration (up to 500 s) [16, 17]

ii) to help accessing and sustaining steady-state (Advanced Tokamak Physics), complementarily to Bootstrap current, Neutral Beam Current Drive and Electron Cyclotron Current Drive.

The paper presents the recent achievements of LHCD Physics and Technology. After an overview of high power CW klystron development and its evolutions towards ITER relevance, the latest results of Tore Supra long pulse experiments with its new LHCD CW system are presented. This includes the wave coupling aspect of new CW Passive-Active Multi-junction (PAM) antenna - the concept proposed in Ref [18] foreseen for ITER [19–21] - and performance of new CW klystrons at 3.7 GHz, recently commissioned on Tore Supra.

2. Klystron Power Source Development

Fusion research has triggered the development of several klystrons in the high frequency range, most notably at 3.7, 4.6, and 5 GHz (Table 1). The present situation with industry is satisfactory on the CW klystron production. No significant R&D of CW klystron is necessary but the competence of the LHCD community and the industries must be maintained in view of the use of LHCD in ITER or for DEMO. At present, only *Toshiba Electron Tubes and Devices (TETD)* has initiated a development program of the 5 GHz klystron, the first option foreseen for ITER. The *Thales Electron Devices* (TED) 3.7 GHz / 500 kW / 210 s klystrons (TED TH2103A) have demonstrated good reliability in JET and Tore Supra for more than 20 years. These tubes are used on Tore Supra to sustain plasmas lasting up to 6 minutes [6]. Existing CW/4.6 GHz tube manufactured by CPI, being used in Alcator C-Mod and installed in EAST, is able to provide 250 kW/CW which is not high enough with respect to the ITER LHCD system specification. Other CW power sources at 3.7 GHz and 5 GHz are either in the final stage of development (5 GHz) or already produced in series (3.7 GHz [30]) and operated on Tore Supra plasmas. It is worth noting that CW tubes at higher frequency have been also developed by Communications and Power Industries Inc (CPI) [31]: 8 GHz / 100 kW and 8.5 GHz / 250 kW klystrons which are being used in QUEST [32].

CW test bed facilities, which are necessary for prior klystron commissioning and the validation of high power CW transmission line components to minimize risks for the LHCD operation, now exist for these tubes 5 GHz and 3.7 GHz at respectively NFRI in Daejeon, South of Korea and CEA-IRFM in Cadarache, France.

At present, A prototype (TETD E3762RD0) of 500 kW CW klystron operating at 5 GHz has been developed by Toshiba Electron Tubes and Devices (TETD) for the steady-state RF source. This prototype CW 5 GHz klystron is not yet validated for ITER specification (500 kW/CW at Voltage Standing Wave Ratio VSWR = 1.4). However, it has been already validated for KSTAR condition, i.e. ~300 kW/CW (Fig. 2). In this prototype, a multi-cell cavity is introduced to reduce the applied cavity voltage and Ohmic power loss, and the gun is designed with a triode system for optimization of the gain efficiency and beam control. The prototype klystron was demonstrated with the RF output power of 300 kW at the

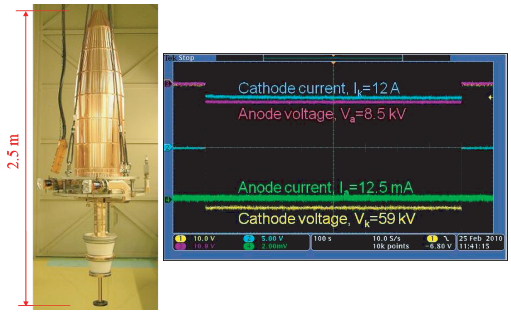

Fig. 2 Photo of 5 GHz prototype klystron and the test results on matched load obtained at the NFRI test bed facility, illustrated by (oscilloscope screen) shot of the cathode (beam) and the anode voltages and current for 304 kW / 800 s pulse.

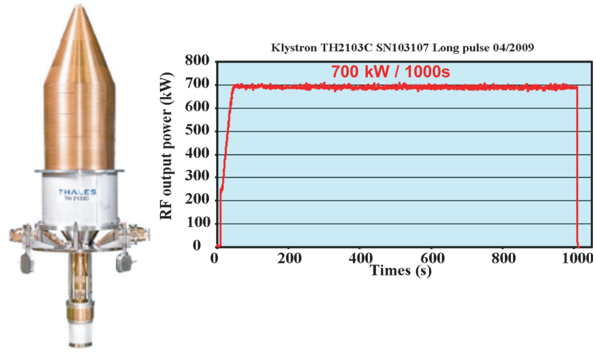

Fig. 3 Photo of the 3.7 GHz klystron and output RF power of 700 kW of a klystron over 1000 s, obtained at the CEA-IRFM test bed facility.

Table 2 Main specification of the prototype TETD 5 GHz/CW klystron.

Frequency	5 GHz
Output RF power (Factory test)	510 kW, 0.5 s
	460 kW, 10 s
	300 kW, 12 min
Gain	48 dB
VSWR	<1.4 any phase
Cathode voltage (for 500 kW)	68 kV
Anode voltage (for 500 kW)	58 kV
Beam current	15 A
Collector power	800 kW

pulse duration of 800 s and 450 kW at the pulse duration 20 s using the two water dummy loads during the commissioning [33]. The highest temperature at collector top surface was saturated at 83°C and power loss at the tube body did not exceed 10 kW which is an interlock level for the protection of the klystron. The RF output characteristics of the klystron are validated during the commissioning at KSTAR. Table 2 shows the main specifications of the 5 GHz, 500 kW/CW klystron prototype.

The prototype of the 5 GHz klystron will be used for the initial 500 kW LHCD system on KSTAR from the 2012 campaign for the physics studies of 5 GHz LH wave. A fully active waveguide grill launcher will be developed made of sixteen four-way waveguide splitters, half of them being connected to the first 500 kW klystron. To improve the performance of the initial KSTAR LHCD system, the source power will be upgraded to 1 MW by adding a second 500 kW CW klystron from 2013.

The TH2103C klystron jointly developed by TED and French atomic energy commission CEA (CEA-IRFM) can deliver output RF power of 700 kW/CW [16, 34]. Compared to the old generation klystron 500 kW / 210 s (TH2103A), major modifications and improvements have been done (e.g., geometrical dimensions (collector size 1740 mm), water cooling system (1500 l/minute in collector), electronic system controlling the high voltage, etc.) [18]. Eighteen klystrons manufactured for Tore Supra have been validated on matched load at the in-house test bed facility before their installation on the LH transmitter. Each klystron produced routinely ~620 kW/CW in relevant plasma conditions (VSWR = 1.4), and ~700 kW/CW with a VSWR = 1 (Fig. 3). The validation of a first series of eight klystrons with a Full Active Multi-junction (FAM) launcher on plasma have been performed during the 2010-2011 experimental campaign showing a good reliability of the LHCD transmitter.

3. Long Pulse Operation with the ITER-Relevant LHCD System in Tore Supra

One of main missions of the Tore Supra tokamak is preparing the long pulse operation in ITER, addressing physics and technology issues of long duration discharges. For this purpose, the 3.7 GHz LHCD system is upgraded to capability of ~10 MW/CW on the generator, using sixteen klystrons TED TH2103C. Together with increasing the power source, a new concept ITER-relevant antenna Passive Active Multi-junction (PAM) launcher is recently installed (~1/4 ITER antenna; weight of 7 tons), complementarily to an existing Full Active Multi-junction (FAM) launcher. Both the launchers are actively cooled, able to operate for 1000 s. The PAM design allows mechanical strength to withstand disruptions and enables to put water cooling pipes close to the antenna front face (Fig. 4). Detailed design and manufacturing are reported in Ref [35]. Note that an uncooled PAM launcher has been tested successfully at 8 GHz on FTU [36]. Since 2011, eight new generation CW klystrons are connected to the FAM antenna and eight 500 kW / 210 s klystrons (TED TH2103A) are connected to the PAM. Here, we present the results obtained in the first commissioning period of the PAM antenna and the CW klystrons on Tore Supra plasmas, as well as the ongoing long pulse experiments.

First experiments with the PAM launcher in Tore Supra have provided extremely encouraging results, which confirm the design specification relevant for ITER: i) effi-

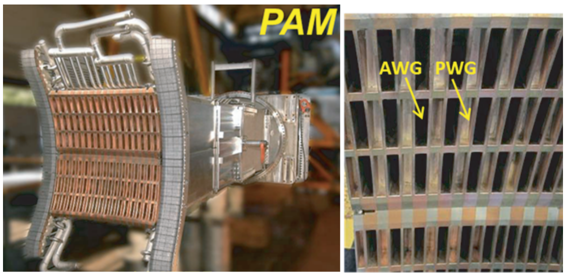

Fig. 4 Left: the Tore Supra LHCD Passive Active Multi-junction launcher. Right: zoom of the front face, showing active waveguides (AWG) alternately with passive waveguides (PWG).

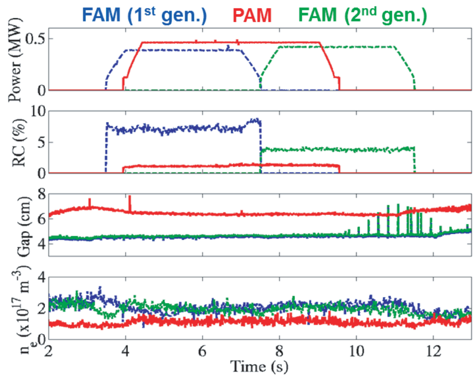

Fig. 5 Comparison of coupling capability between PAM and FAM antennas: time evolution of injected power, reflection coefficient, gap between the plasma and the antenna (red: PAM; blue/green: first and second FAM generations respectively).

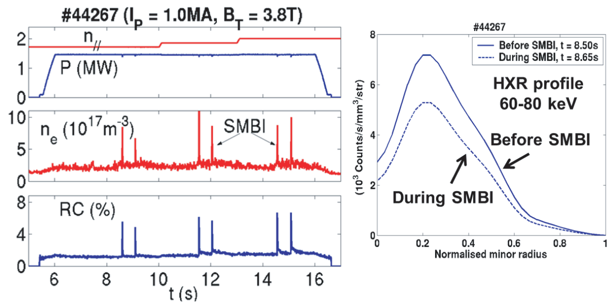

Fig. 6 Left: Time evolution of a discharge with SMBI during LHCD ($n_{//}$: parallel refractive index of the waves; P: coupled LH power (P); n_e: density in front of the antenna; RC: reflection coefficient). Right: Radial profile of Hard X-ray 60 keV - 80 keV.

cient cooling (capability to deal with ITER environment) and ii) low reflected power at large plasma-antenna gap [37].

After two days of operation on plasma, the PAM antenna already coupled 450 kW / 4.5 s into the plasma with low reflected power level, confirming the prediction performed with the LH coupling code ALOHA [38]. Figure 5 shows the comparison of the reflection coefficient between the PAM antenna and the FAM antennas, in similar experimental conditions. This figure clearly shows that the PAM has a lower reflection coefficient (RC) than FAM antennas: RC ~1.5%, i.e. 3-5 times lower than the RC of the FAM launchers even though the plasma-antenna distance is larger and the electron density is lower for the PAM antenna. Coupling experiments at low power level (200 kW, i.e. power density ~2 MW/m^2) yielded very good agreement with linear coupling simulations [39] performed with ALOHA taking into account the realistic 3D antenna geometry, for density at the antenna mouth ranging from 0.5×10^{17} m^{-3} to 8×10^{17} m^{-3} (cut-off density = 1.7×10^{17} m^{-3} at the frequency 3.7 GHz).

The power coupling capability of the PAM in conditions with strong edge perturbations and at large plasma-antenna distance was also demonstrated. To mimic Edge Localized Modes behavior (ELM), Supersonic Molecular Beam Injection (SMBI) was used during LHCD application. As shown in Fig. 6, at least at intermediate power level of 1.5 MW (13 MW/m^2), the LH power coupled to the plasma remains constant when the electron density in front of the antenna increases by a factor of about 5 (from $\sim2\times10^{17}$ m^{-3} to $\sim10\times10^{17}$ m^{-3}) during each SMBI. At the same time, RC increases from 1.5% to 7%, in agreement with ALOHA predictive coupling calculations. Figure 6 also shows that no significant change in RC is obtained when varying the parallel refractive index ($n_{//}$) of the LH waves. During each SMBI, slow decrease in hard X-ray emission (HXR energy < 200 keV) was observed, while its radial profile did not change as a consequence of the SMBI. This indicates that the edge perturbation itself does not cause a redistribution of the fast electron profile and the decrease of HXR emission is rather due to the perturbation of the bulk density.

Note that in the design of the PAM antenna for ITER, the ELM-resilient aspect has been further optimized. Indeed, the present ITER LHCD design expects smaller variations in RC during an increase in density, compared to that of the Tore Supra PAM antenna [15].

High power commissioning of the PAM was very fast and without any difficulty. Indeed, a coupled power of 2.7 MW during 17 s was obtained after only 240 pulses on plasma. This power level corresponds to a power density of 25 MW/m^2, considering only the active surface of the antenna. So far, the maximum power and energy achieved on the PAM is 2.7 MW during 78 s flat-top, which correspond to an injected energy in a single discharge of 220 MJ (Fig. 7 (left)). It should be noted that the power limit on the PAM has not yet been fully assessed, partly due to lack of power at the generator (as mentioned above, the PAM antenna was fed by the 500 kW / 210 s klystrons). The generator plant equipped with the new klystrons 700 kW/CW will allow assessing the PAM power limit in 2012. During the discharge shown in Fig. 7 (left), the infrared thermography

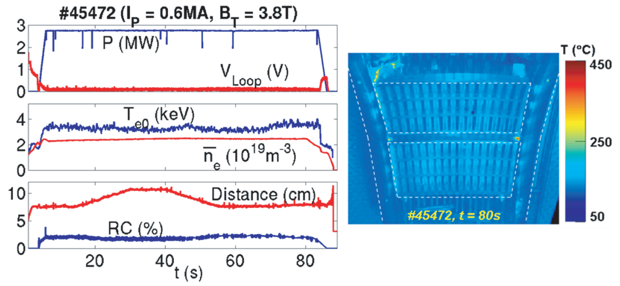

Fig. 7 Demonstration of ITER-relevant capability of the PAM launcher. Left: 25 MW/m^2 over 78 s and good coupling at long plasma-antenna distance (RC < 2%); right: efficient cooling temperature of the antenna front face < 250°C (hot spots correspond to a thermocouple wire and Langmuir probes).

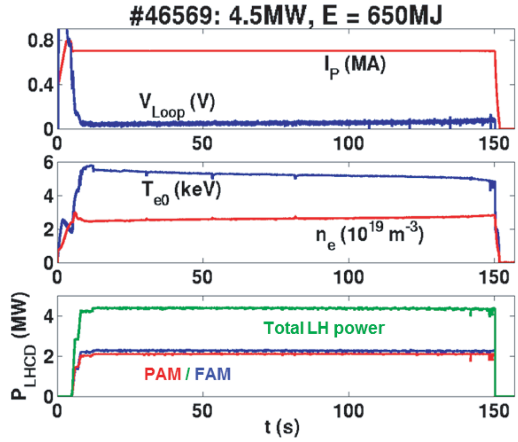

Fig. 8 Tore Supra discharge lasting 150 s, using both the PAM and FAM antennas (I_P = 0.7 MA and line averaged density 2.5×10^{19} m^{-3}).

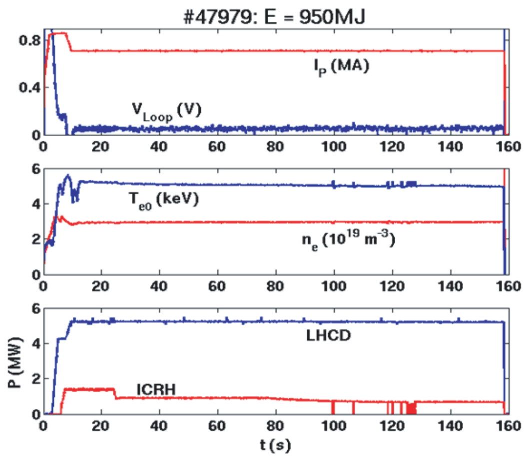

Fig. 9 Combined LHCD&ICRH Giga-Joule discharge with a non-inductive current fraction of 80% (plasma current 0.7 MA, line averaged density ~3×10^{19} m^{-3}). At t ~80 s, the ICRH power is decreased by real time protection control because an overheating of Langmuir probes was detected.

indicates that the PAM is efficiently cooled. The apparent temperature measured on the waveguides and the antenna protection limiters remains below 250°C throughout pulse lasting 78 s (Fig. 7 (right)).

The example shown in Fig. 7 (left) also demonstrates that high power can be coupled at large plasma-antenna distance. During the LH power application, the gap between the last closed flux surface and the antenna was increased to 10 cm during the pulse. The reflection coefficient decreases slightly (from 2% to 1.5%) as the distance is increased. It has to be noted, however, that the density at the antenna is still above the cut-off density, since the plasma scenario used was characterized by long SOL density decay length (λ_n ~4 cm). This particular scenario may therefore not be considered as representative of the edge conditions that would be obtained during H-mode operation in ITER.

In the autumn 2010 experimental campaign, the first set of eight CW klystrons (TH2013C) was brought into plasma operation, feeding the FAM antenna [17], [40]. These klystrons feed the FAM powers ranging from 520 kW - 620 kW each (i.e., 80% - 100% of their maximum capability). They have been operated routinely up to 500 kW / 10 s and 440 kW / 43 s per klystron (corresponding to coupled power of 3.5 MW / 10 s and 3.0 MW / 43 s, respectively). An example of the increase in the Tore Supra LHCD capability is illustrated in Fig. 8, which shows a long pulse discharge sustained for 150 s with 4.5 MW of LHCD power, using both FAM and PAM antennas [41]. Quasi-fully non-inductive current drive was obtained. The loop voltage was ~40 mV in the beginning of the pulse, and increasing to 80 mV, due to an increase in electron density. In this discharge, the density increase is due to a non-optimized density feedback control.

Long pulse scenario development, combining LHCD and Ion Cyclotron Resonance Heating (ICRH), has also been carried out in 2011. At present, successful Giga-Joule discharge lasting 150 s (total injected power of 6.3 MW) was obtained with 5.2 MW LHCD and an ICRH power ranging from 1 MW - 1.5 MW, as shown in Fig. 9. The non-inductive current fraction in this pulse was ~80%. It is worth noting that the real time feed-back control of RF power using infra-red imaging is integrated in these long pulse scenarios. The pulse length was limited by a lack of LH power. Discharges shown in Figs. 7-9 terminated by the real time control of machine protection, especially by detection of overheating of elements non-essential for long pulse operation (thermocouple wire, Langmuir probes).

From 2012, the completion of the LHCD system upgrade to full CW capability will allow exploring fully non-inductive regime at higher plasma current and density, and also to assess the power density limit of the PAM launcher, which is a key issue for the design of the ITER PAM.

4. Conclusion

LHCD is a mature and reliable H&CD system in a large number of tokamak devices. As the main flux saving system, it is present on all the long pulse tokamak operation. In ITER, LHCD is very efficient CD tool for saving Volt-second to extend the burn duration and helps accessing Advanced Tokamak scenarios in driving current far off-axis (normalized radius between 0.6-0.8), complementarily with the others H&CD methods. A LHCD system at 5 GHz is being considered for future upgrade of the ITER H&CD systems, with a power capability of 20 MW into plasmas using a PAM antenna. The present situation of CW klystron production with industry is satisfactory, as well as the antenna manufacturing. However, only Toshiba has initiated a development program of the 5 GHz CW klystron. A 5 GHz prototype is already available, able to deliver 300 kW/CW, and it will be into plasma operation in KSTAR in 2012. A series of eight 3.7 GHz klystrons - the fall-back solution for ITER - was validated on Tore Supra long plasma discharges up to 150 s so far. Also, a large size CW 3.7 GHz/PAM launcher is in routine operation on Tore Supra (1/4 of the ITER launcher), having demonstrated a power capability of 2.7 MW / 78 s (25 MW/m^2). Its power density limit will be assessed in 2012.

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