HIGH POWER RF SYSTEMS FOR LONG PULSE OPERATION ON TORE SUPRA AND PLANNED UPGRADES

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Abstract

The last experimental performances achieved on Tore Supra using the radio frequency heating and current drive systems are presented. In view to increase the injected power and the pulse length new developments are undertaken. Results concerning the 118 GHz ECRH system, a new guard limiter and an advanced LHCD antenna are reported.

1. INTRODUCTION

The main mission of Tore Supra is to achieve controlled long pulse high performances discharges. The superconducting toroidal field system of Tore Supra and the new internal actively cooled components developed in the frame of the CIEL project [1] open the possibility to exhaust until 25 MW of power over 1000 s. In view to heat the plasma and to generate the plasma current necessary for these very long discharges, three radio frequency (RF) systems have been selected.

Some recent performances achieved with the RF systems on Tore Supra are presented and the main developments in view to satisfy the CIEL objectives are described.

2. RF EMITTERS OF TORE SUPRA

Two RF systems are operating presently on Tore Supra (i) the Ion Cyclotron Resonance Heating (ICRH) system (ii) the lower hybrid current drive (LHCD) system. The third system at the Electron Cyclotron Resonance Heating (ECRH) frequency is under development. The characteristics of the RF emitters are summarized on Table I.

The ICRH system [2] is powered by 6 large band generators (40-80 MHz). The end stages are using tetrodes (TH525) which have been developed to allow a maximum anode dissipation power of 2 MW and a maximum output power of 2.2 MW between 40 and 70 MHz for pulse duration up to 30 s. The output power drops at 1.5 MW for CW operation (extensive 45 mn tests). A possible future improvement, in view of CIEL project, is to use a diacrode which can increase by a factor up to two the generated power by tube.

The LHCD system is powered by 16 klystrons operating at 3.7 GHz and delivering 500 KW up to 210 s [3]. On test load, very long pulses (up to 1000 s) with 400 KW of RF power has been performed. A Thomson Tubes Electroniques study has shown possible improvements (cavity design, advanced materials, beam focusing...), in view to build a klystron delivering 700 KW for 1000 s at 3.7 GHz.

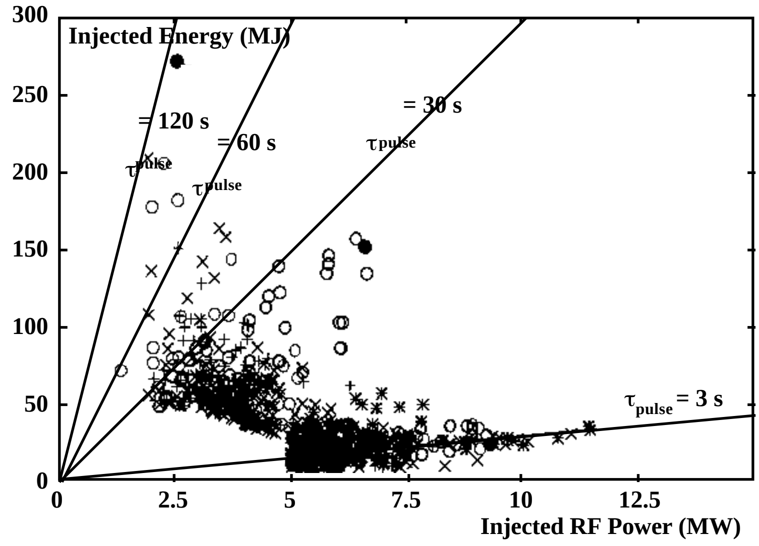

FIG. 1. Injected energy function of the injected power of the RF systems on Tore Supra.

TABLE I. MAIN CHARACTERISTICS OF RF EMITTERS OF TORE SUPRA

System	Sources	Frequency	Total installed power on load (MW)	Pulse length (s) (duty cycle)
ICRH	6 tetrodes (TH525)	40 to 80 MHz	6 × 2.2 = 13.2	30 (0.125)
LHCD	16 klystrons (TH2103)	3.7 GHz	16 × 0.5 = 8	60 (0.25)
ECRH	8 gyrotrons (TH1506)	118 GHz	6 × 0.5 = 3	210 (0.35)

The building of Tore Supra's ECRH system (3 MW at 118 GHz) is now in an advanced stage [4]. The prototype gyrotron is being developed by a consortium including the Commissariat à l'Énergie Atomique (France), the Ecole Polytechnique Fédérale de Lausanne (Switzerland), the Forschungzentrum Karlsruhe (Germany) and Thomson Tubes Electroniques (France). The achieved performances of the gyrotron prototype are summarized on Table II.

The main features of this tube, which works on the $TE_{22.6}$ mode, are an improved quasi-optical mode converter with three mirrors and a cryogenic liquid nitrogen cooled window. The tube is now being tested in CEA' site of Cadarache : long pulse tests are planned for duration up to 210 s.

TABLE II. MAIN CHARACTERISTICS OF THE 118 GHz gyrotron

	Specified	Achieved
Output power	500 KW	10 ms pulse : 800 KW 5 s pulse : 500 KW
Efficiency	> 30 %	30 %
Beam voltage (current)	85 KV (22 A)	85 KV (25 A)
Pulse length	210 s	5 s
Output mode HE_{11}	mode purity > 95 %	mode purity > 98 %

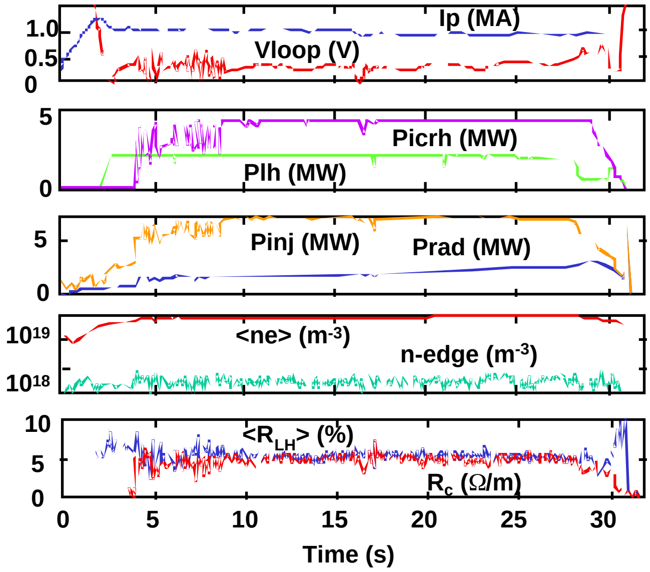

FIG. 2. Tore Supra discharge with 6.5 MW of RF power injected for 25 s.

The performances achieved by the RF systems on Tore Supra are summarized on Figure 1. Almost 12 MW are injected in short pulses and a 2 minutes discharge was obtained with 2.5 MW of LH waves. Using two ICRH antennas and one LH antenna, 6.5 MW were coupled for 25 s (Fig. 2) to a I_p = 1 MA plasma. As seen on figure 2 in this combined high power heating scenario, a good stationary coupling is maintained with R_c = 5 Ω/m for ICRH and a mean reflection coefficient $\langle R_{LH} \rangle$ = 5 % for LH.

3. RF ANTENNAS

On Tore Supra the RF antennas are in-port components as designed for ITER.

The 3 ICRH antennas use the resonant double loop concept proposed by ORNL [2]. This set up allows to reduce to the current strap and matching capacitors the volume where high voltages and currents can be found. High RF power densities have been reached (15 MW/m^2) and routinely used (10 MW/m^2) for pulse length between a few seconds and 30 s. The remote vacuum feed through is located in a matched transmission line working with a VSWR < 1.2. A feedback control of the matching capacitors keeps the VSWR below 1.2 during any plasma conditions.

The 2 LHCD antennas use the multijunction concept [3]. On Tore Supra, 6 MW were coupled for 8 s (37 MW/m^2, E_{RF} = 5.5 KV/cm). A power density of 25 MW/m^2 (E_{RF} 4.5 KV/cm) can be routinely achieved. Such a power density was injected for 70 s in the limiter configuration and 20 s in the ergodic divertor configuration. In both cases we have respectively $\langle R_{LH} \rangle$ = 5 % and 7 % and a stationary temperature, below 800°C, of the most heat loaded component, the antenna guard limiter, were obtained.

The ICRH and LH antenna guard limiter have to sustain high heat fluxes and is presently the most demanding component. A new guard limiter made from carbon fibre composite tiles attached on Cu-Cr-Zr water cooled plates using the AMC (Active Metal Casting) technology is now under tests on Tore Supra [5]. On the figure 3 are indicated the time evolution of the maximum surface temperature of the old and new generation of guard limiter measured with an infrared camera for a 10 MW total of ICRH power. It appears that the cooling time constant of the new guard limiter (2.5 s) is significantly reduced compared to the old one (8 s) and this explain the important reduction on the surface temperature.

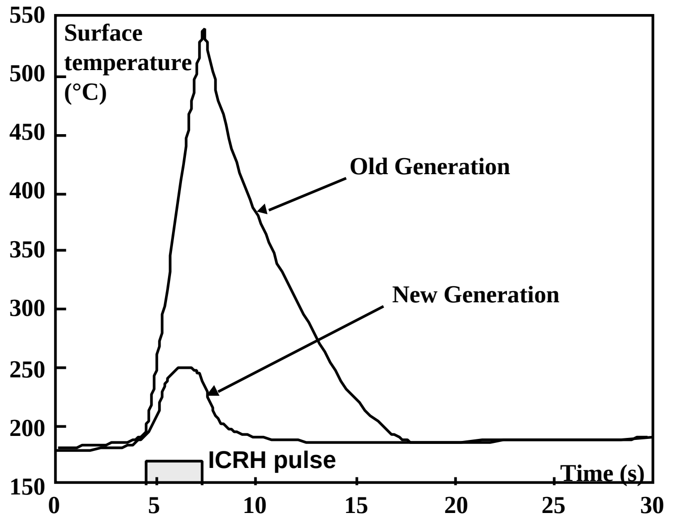

FIG. 3. Time evolution of the surface temperature of the old and new guard limiters with 10 MW of ICRH power.

The ECRH antenna already installed on Tore Supra will launch from the low field side six microwave beams grouped in pairs in three sets of independently steerable beams. Each set can be directed, using a water cooled movable mirror, from top to center of the plasma in the poloidal plane and at an angle of + 30° to - 30° in the toroidal direction. The polarization direction and ellipticity can be changed for all beams, making possible experiments of heating and current drive both at the first harmonic in ordinary mode or at the second harmonic in the extraordinary mode.

In order to increase the power available by antenna, a new LH launcher is under construction with a radiating surface enhanced by close to a factor 2 [6]. This new LH antenna will allow to couple 4 MW at 25 MW/m^2 level. This antenna includes a new type of poloidal splitter, a $TE_{01\text{-}03}$ mode converter and a 6 waveguide multijunction as a toroidal divider. The water-cooled prototype module has been successfully tested on test bed at high power (E_{RF} = 6.8 KV/cm) for 1000 s with stationary temperature.

4. CONCLUSIONS

High power (and power density) heating and current drive facilities are required in Next Step tokamaks such as ITER. High reliability and continuous operation are very important for the further development of these systems. On Tore Supra, the superconducting toroidal field system provide an unique opportunity to perform long pulse operation systems. The results already obtained :

(i) 15 MW/m^2 to 10 MW/m^2 for pulse of few seconds to 30 s with the ICRH system,

(ii) 37 MW/m^2 to 25 MW/m^2 for 8 s to 70 s with the LHCD system,

are very encouraging. Various developments are undertaken in order to improve these performances in the frame of the CIEL project.

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[6] Bibet Ph. et al., Proc. of the 20th Symp. on Fusion Technology, Marseille 1998, Vol. 1, p. 339.