Long pulse RF heating and current drive scenarios for WEST

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Introduction. The longstanding expertise of the Tore Supra team in long pulse radiofrequency (RF) heating and current drive systems will now be exploited in the WEST device (tungsten-W Environment in Steady-state Tokamak) [1]. WEST will allow an integrated long pulse tokamak programme for testing W-divertor components at ITER-relevant heat flux (10-20 MW/m^2). At the same time, crucial aspects relevant for ITER-operation will be treated, such as avoidance of W-accumulation in long discharges, monitoring and control of heat fluxes on metallic plasma facing components (PFCs) and coupling of RF waves in H-mode plasmas. To fulfil its programmatic goals, the WEST research plan has been structured in two main headlines, namely: “ITER grade PFC tests” and “Towards long pulse H mode and steady-state operation” [2]. The WEST device and research plan is open to all ITER partners.

The transformation of Tore Supra to WEST involves replacing the carbon PFCs by a combination of bulk and coated tungsten (W) elements and inserting upper and lower divertor coils in order to produce a divertor plasma configuration. The plasma volume in WEST is therefore reduced to 15 m^3, compared to 25 m^3 in Tore Supra. With major radius R ≈ 2.5 m and minor radius a ≈ 0.5 m, the aspect ratio of WEST is fairly large (A ≈ 5), as compared to other tokamaks. The expected L-H power threshold in WEST has been assessed with different scaling laws [2], yielding an expected power threshold below 5 MW at $n_e = 8\times10^{19}$ m^{-3} and B_T = 3.6 T. Considering the installed additional heating power capability in WEST, access to H-mode appears feasible with good margin.

Heating and current drive in WEST. The additional heating and current drive power in WEST is provided by RF heating systems, namely Ion Cyclotron Resonance Heating (ICRH) and Lower Hybrid Current Drive (LHCD), delivering up to 9 MW of ICRH power and 7 MW of LHCD power. Successful long pulse operation with LHCD + ICRH, leading to 1 GJ injected energy, has been achieved in Tore Supra L-mode plasmas [3, 4], but the WEST programme now brings new challenges. The main plasma heating is provided by ICRH and scenarios compatible with high ICRH power, without causing W-accumulation, must be developed. The LHCD system needs to provide sufficient non-inductive current in high density H-mode plasmas in order to sustain long pulse scenarios required for testing the W-divertor under ITER-relevant particle fluence (~10^{27} D/m^2) and time scale (>100 s).

To allow coupling to H-mode plasmas, three new ELM-resilient ICRH antennas have been designed for WEST [5, 6]. They are provided by ASIPP (Hefei, China) as in kind contribution. The antennas are based on a load resilient antenna concept already tested on Tore Supra. Starting from this design, a number modifications have been made, e.g. improving the coupling by optimising the antenna front face design and adding cooling throughout the antenna for long pulse operation (3 MW / 1000 s). The ICRH generator has been upgraded to allow high power operation (9 MW / 30 s) at high reflected voltage. The WEST ICRH system is thus the first ever ICRH system combining continuous wave (CW) operation and load tolerance capability for coupling on H-mode. The nominal operating frequencies are 53 ± 2 MHz and 55.5 ± 2 MHz, in order to allow flexibility in the resonance layer location around the magnetic axis.

A high power (9 MW at the generator), CW LHCD system is already available for WEST, consisting of 16 high power CW klystrons (f = 3.7 GHz), feeding two actively cooled multijunction launchers [7]. The main modification of the system involves a reshaping of the toroidal profile of the launcher mouth on the Full-Active-Multijunction launcher, in order to guarantee the LH wave coupling on WEST plasmas [7]. The Passive-Active-Multijunction (PAM) launcher will not be modified in the first instance, since this ITER-relevant concept already offers good coupling properties at low edge density [8].

Local gas injection will be added to all five antennas [9]. The gas injections are poloidally distributed along the antennas, the radial location being ~15 cm behind the protection limiters and the toroidal location being ~15 cm outside the protection limiters. According to recent 3D SOL-modelling [10], these choices for the gas injection locations should allow poloidally homogeneous SOL density at the antennas. In addition, 2D modelling of the WEST SOL has been carried out with SolEdge2D-EIRENE [11], showing that gas injection from the outer mid-plane indeed increases the SOL density at the radial location of the antennas.

H-mode scenario (B_T = 3.6 T)	High power	Standard	High fluence
Plasma current	0.8 MA	0.6 MA	0.6 MA
Line averaged density	8 10^{19}m^{-3}	7 10^{19}m^{-3}	7 10^{19}m^{-3}
Greenwald fraction	64%	75%	75%
Total RF power	**15 MW**	**12 MW**	**9.3 MW**
Lower Hybrid Current Drive	6 MW	6 MW	6.3 MW
Ion Cyclotron Resonance Heating	9 MW	6 MW	3 MW
Pulse length	**30 s**	**60 s**	**1000 s**

Table 1: Reference scenarios for WEST operation (from METIS).

Modelling of WEST scenarios. Based on the RF heating and current drive capability, three reference plasma scenarios are targeted (Table 1). These scenarios have been constructed from integrated modelling with the 0D version of the CRONOS code, called METIS [12], by imposing several constraints, such as maximum tolerable electron temperature on the divertor target and energy confinement factor (H = 1). Well established scaling laws are used for the density profile peaking and radiated power, etc. The “Standard scenario” (12 MW / 60 s) is targeted for testing ITER-like divertor components at relevant heat flux (10-20 MW/m^2) and demonstrating integrated long pulse H-mode operation (~60 s). The “High fluence” scenario is envisaged for plasma-wall interaction studies (up to 1000 s at 10 MW). Finally, a “High power” scenario (15 MW / 30 s) is developed for high performance discharges.

The ICRH power deposition profile is obtained from the full wave solver EVE, with the Fokker-Planck module AQL [13]. Figure 1a illustrates an EVE/AQL simulation for 6 MW ICRH at 55.5 MHz and hydrogen minority concentration $n_H/n_e = 6\%$. The power is deposited within a normalised radius of 0.4, essentially on minority hydrogen ions (~4.8 MW). It is then redistributed through collisional relaxation of the fast minority ions between electrons (~2.6 MW) and bulk ions (~1.1 MW). The missing power (~ 1.1 MW) is partly due to the losses of fast ions due to the magnetic ripple (2% at the outer mid-plane in WEST). Some flexibility in terms of electron/ion heating can be obtained by varying the ICRH power level, as seen in Figure 1b, or the hydrogen minority concentration.

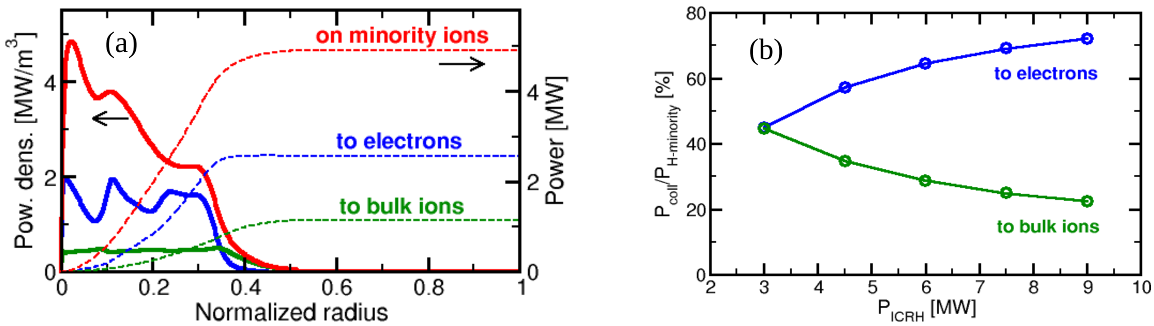

Figure 1: EVE/AQL modelling of a WEST scenario for 6 MW ICRH at 55.5 MHz and $n_H/n_e = 6\%$. Power density absorbed by species (a), power split between electrons and bulk ions as a function of ICRH power (b).

The LHCD modelling is carried out with ray-tracing + Fokker-Planck codes C3PO/LUKE [14]. The three reference scenarios listed in Table 1 have been modelled using $N_{//}$-spectrum peaked at $N_{//0} = 2.0$, to improve the accessibility of the LH waves to the plasma. Figure 2a shows the electron density and temperature profiles from METIS for the “High fluence” scenario ($I_P = 0.6$MA, $n_e = 7\times10^{19} m^{-3}$, $P_{Add} = 9$ MW), while Figure 2b shows the ray trajectory for a ray with $N_{//0} = 2.0$. The LH power deposition and current profiles have been modelled with the recent "Tail LH" model in LUKE [15], which has proven to reproduce well the experimental results on Tore Supra and EAST [14]. The LH power deposition and current profiles are rather central (Figure 2c) and yield a current drive efficiency of $\eta = 0.12\times10^{20}$ $Am^{-2}W^{-1}$. It should be notes that the current drive efficiency predicted in WEST is higher than that obtained in the Tore Supra configuration. This is attributed to the X-point configuration that introduces an $N_{//}$-upshift that facilitates the propagation of the waves to the plasma core.

Based on the ICRH and LHCD simulations presented above, together with the METIS simulations, it is expected that the LHCD power available to the plasma (7 MW) should be sufficient to sustain long pulse operation in WEST. Indeed, the simulations show that the loop voltage (V_{Loop}) is only ~6 mV in the "High fluence" scenario, when using 6.3 MW of LHCD power + 3 MW ICRH, which should allow reaching 1000 s pulse length.

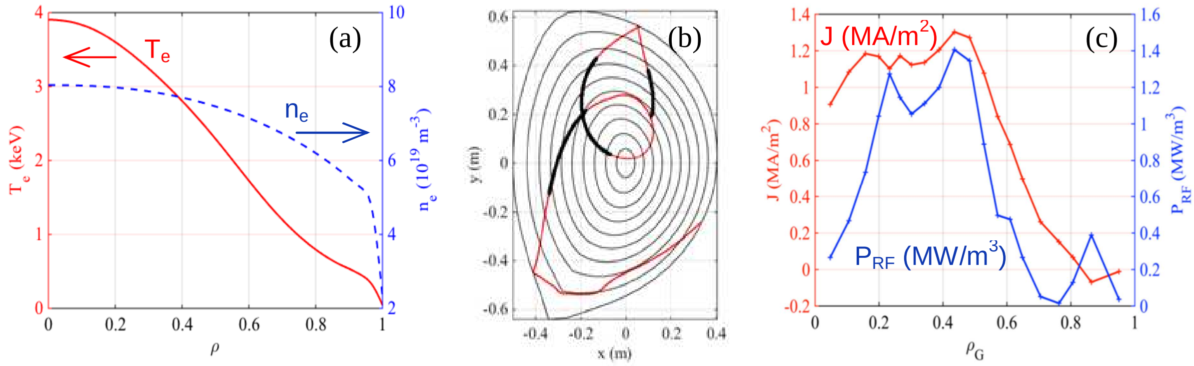

Figure 2: LHCD modelling for the "High fluence" scenario: electron density and temperature profiles (a), poloidal ray trajectory for a ray with $N_{//0}$ = 2.0 (b), current density and absorbed power profile (c).

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