Operational parameters for EC assisted start-up in ITER

D. Ricci[1], D.Farina[1], L. Figini[1], G. Granucci[1], M. Cavinato[2]

[1] *Istituto di Fisica del Plasma – CNR, Milano, Italy*

[2] *Fusion for Energy, Barcelona, Spain*

Introduction and model validation

The low toroidal electric field foreseen in devices with superconductive coils (0.3 V/m), like ITER, limits the operations in terms of prefill gas pressure range, impurity content and error field. The addition of Electron Cyclotron (EC) heating is required to sustain the initial stage of the discharge and widen the operational space.

Many authors [1-3] developed 0D models in order to study the start-up phase, using different approaches to describe the behavior of the impurities, which increase the radiation barrier, as well as the EC injected power needed to ionize the neutral gas, overcome the burn-through phase and raise the plasma current.

At the beginning of the discharge, the electron density and temperature are low and the EC power absorption is poor. A realistic evaluation of the absorbed power in this initial phase is a crucial issue, particularly in ITER, to prevent damage eventually caused by not absorbed EC power or by runaway electrons.

The 0D plasma transport model BKD0 [4] has been developed based on [1]. It simulates the evolution of the plasma parameters considering the energy and particle balance equation for electrons and ions together with the circuit equation and includes the plasma-wall interaction model presented in [3]. Unlike previous models, the EC power absorption has been estimated self-consistently coupling BKD0 with the quasi-optical beam tracing code GRAY [5].

Successful validation of BKD0 simulations has been performed against the JET experimental data with ITER-like wall and without additional heating [3], and the Frascati Tokamak Upgrade (FTU) start-up data, using oxygen as the main source of impurity and ECRH absorption computed by GRAY. An example is shown in Fig.1a, where a FTU plasma at 5.3 T is simulated by BKD0 and GRAY for EC injection (350kW, 140 GHz) [4]. The FTU operational space determined with BKD0 for pure deuterium plasma in case of ohmic and EC assisted initiation is in good agreement with the experimental results (Fig.1b). The minimum required electric field for P_{EC}=0 has been computed in the pressure range 0.5mPa - 10mPa. The start-up is successful when the input powers (P_{oh} + P_{EC}) overcome the radiation and ionization power losses (P_{rad} + P_{iz}) during the burn through phase, that means $E_{min} \geq |P_{rad} + P_{iz}$ -

$P_{EC}|^{0.5}\ \eta/V_p$, η being the Spitzer resistivity and V_p the plasma volume. The Townsend criterion is shown for comparison for a connection length of 371 m, with a=0.28m, and B_{stray} = 1mT.

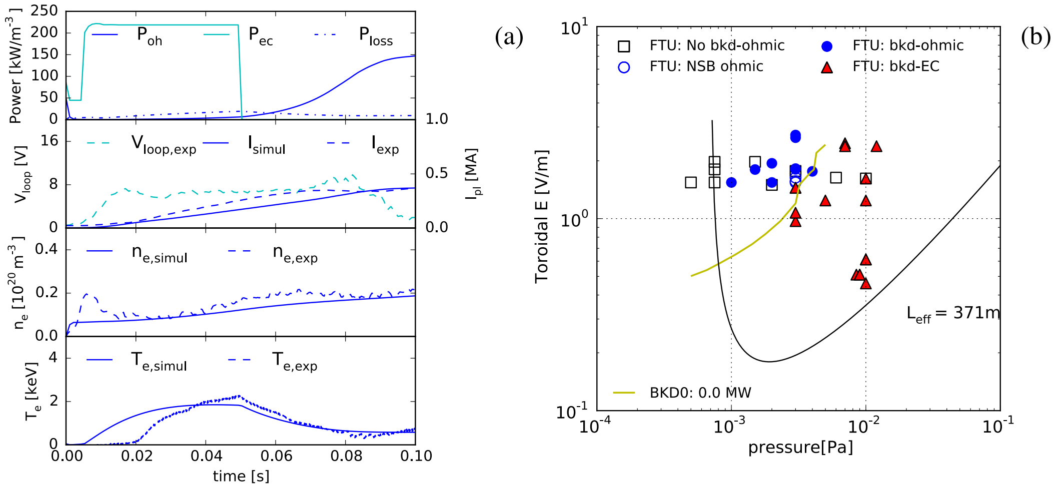

Fig.1. *(a) Simulation of FTU shot # 38376. V_{loop} is the input of the simulation, all the other quantities are outputs. Results and experimental data are in good agreement. (b) Operational space for successful start-up on FTU: experimental data with (red) and without (blue) additional heating in good agreement with minimum electric field calculated by BKD0, orange and green line respectively.*

ITER case

Various EC injection schemes have been investigated for the ITER assisted start-up, at both the nominal field 5.3T and at half field 2.65 T, either launching the 170 GHz EC wave from the Upper (UL) or Equatorial (EL) Launcher, aiming to deposit the EC power in the null region. The analysis has been performed in all the above cases, and here the focus will be on the UL injection only. Beam reflection at the inner wall with the polarization conversion has been taken into account whenever relevant. No further reflections are considered in the EC computation. Two different injection schemes (Fig. 2a) have been analyzed: a direct scheme and a reflection scheme, depending on whether the EC beam crosses the resonance in the equatorial plane at first or second pass after wall reflection. Note that at full field, ordinary mode (OM1) injection in the reflection scheme is the most efficient since conversion at the wall to extraordinary mode (XM1) allows for larger power absorption in second pass even at low plasma densities and temperatures (Fig. 2b). At half field, on the contrary, XM2 injection in the direct scheme is more effective than in the reflection one, although with lower absorption with respect to the full field case.

Startup simulations are performed in deuterium plasma at full field (5.3 T) and half field (2.56 T). The operational space has been calculated running BKD0 for prefill pressure and toroidal electric field in the range 0.3 mPa ≤ p ≤ 10 mPa and 0.1 V/m ≤ E_{tor} ≤ 0.5 V/m. The results shown in figures 3-4 are relative to E_{tor} = 0.3 V/m, which is the ITER toroidal electric field limit. At full field (Fig 3a) the maximum prefill pressure range achievable is narrow in pure ohmic start-up, limited to 0.3-0.7 mPa, i.e. close to the limit of the pumping system capability and practically negligible. In order to extend it, the EC power is therefore necessary. The EC pulse is assumed to start at the beginning of the simulation and last for 1 s (possible damage due to a fraction of not absorbed power is not discussed here). It is found that at 5.3 T the pressure can be extended by 0.8 mPa for every MW of additional EC power, this is valid for both the EL and the UL in the wall-reflection scheme. The same analysis performed at half field shows that XM2 operations at half field look less promising than OM1 at full field (Fig 3b).

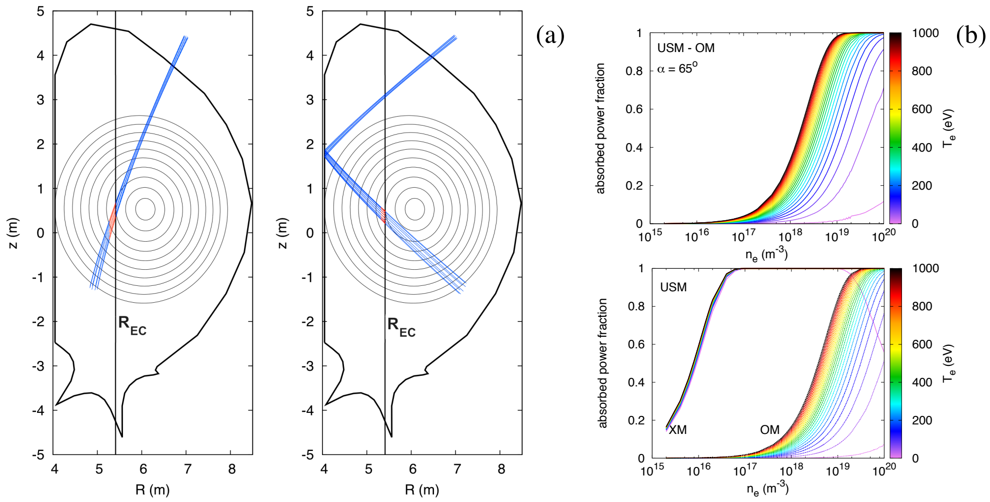

Fig. 2 *(a) ITER UL injection schemes without and with wall reflection at 5.3 T. (b) EC absorbed power fraction versus density for various temperature (color code), for direct (top) and reflection scheme (bottom). In the reflection scheme polarization conversion at the inner wall from OM to XM allows larger absorption also at low density and temperature characteristics of start up phase.*

The results of simulations including impurities are shown in Fig. 4 at full field and for a stray magnetic field of 1 mT. The maximum prefill pressure achievable for successful start-up decreases in the presence of Berillium, although it depends very slightly by the Be fraction in the considered range. Again, the EC power can be used to recover the operational space.

Conclusions

BKD0 simulations confirm that the use of additional heating is necessary to widen the narrow and limited ITER operational space (0.3-0.7 mPa) of the ohmic start-up. The most promising configuration is at 5.3 T for both the EL and the UL in the wall-reflection scheme, with an increase of 0.8mPa for every MW of input power. A detailed analysis concerning the runaway electrons formation is ongoing [6].

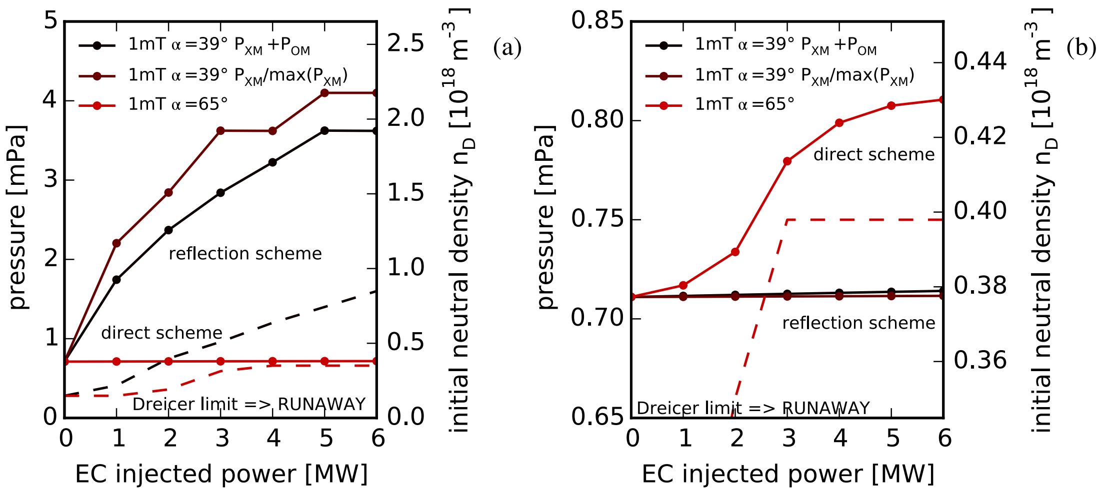

Fig.3 *Maximum prefill pressure for which startup is successful in pure deuterium plasma versus the EC injected power for UL injection, stray field 1 mT, 0.3V/m and* B_0*=5.3 T (a) and* B_0*= 2.56 T (b) at different launching conditions. The dashed line represents the Dreicer limit for runaway production.*

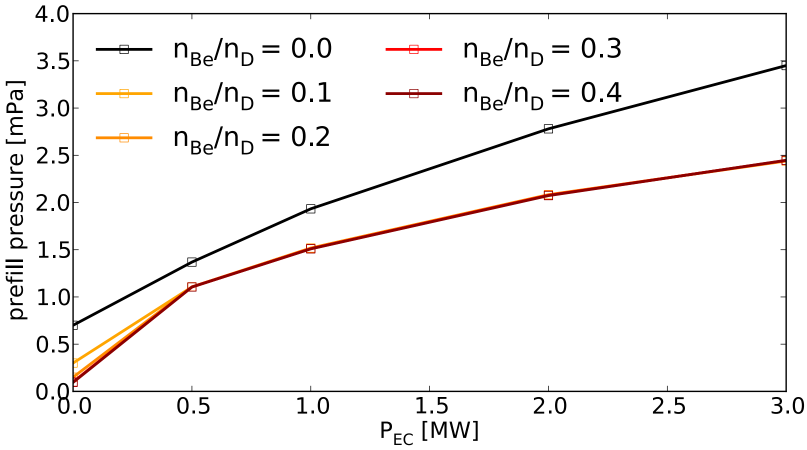

Fig. 4. *Maximum prefill pressure for successful start-up versus EC injected power for various Be concentrations (*n_{O2} *= 0.01* n_D*,* n_{C2} *= 0.005* n_D*,* B_T *=5.3T, Stray: 1 mT).*

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