EC assisted start-up experiment and predictions for the next generation fusion experiments

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Introduction In the past, several experimental studies have been performed to define the operation scenario in case of EC assisted start-up, especially in view of ITER[1]. ECRH has been demonstrated to successfully sustain the burn-through of pre-filling gas and impurity coming from the wall. Anyway, a complete database in presence of controlled impurity puffing in the prefill phase that mimics not favourable post-pulse conditions (such as would be expected after disruption event), does not exist yet (for a low applied toroidal electric field as will be used in superconductive machine).

Experiments Experiments on TCV and FTU tokamaks have been performed in reduced loop voltage conditions in order to reach a toroidal electric field of 0.7 and 0.5 V/m, respectively, well below the values used in most of the operating tokamaks in case of ohmic start-up. Main characteristic of the experimental set up are shown in table 1.

Table 1

	TCV	FTU
Wall	C	Metallic
EC power / f / polarization	750 kW / 82.7 GHz / XM2	400 kW / 140 GHz / OM1-XM2
ECRH timing	EC power rt controlled T_on at ~V_{loop}=2 V	EC power constant for 200 ms, T_on at ~V_{loop}=0 V
E toroidal (V/m)	0.7	0.5
Impurity	Ar	Ne

The injection of impurity has been used to mimic not favourable post-disruption conditions and makes EC heating necessary to pass the burn-through phase. Figure1 (left) summarises FTU results in terms of dIp/dt (calculated after the first 100 ms) for the two polarisations used, ordinary (O1) and extraordinary (X2), as function of injected Ne. The current ramp rate is independent on polarization, while, as expected, the presence of Ne influences plasma resistivity reducing the ramp rate. A straight comparison with TCV data is not feasible because, in this case, the EC power has been actively controlled during burn-through to keep dIp/dt constant. Results on TVC have been summarized in figure 2 (right), where the delay between the onset of EC and the maximum of Dα emission has been shown for a sequence of successive pulses performed without the standard cleaning procedure. The EC input power needed to balance the radiative losses increases with impurity. The presence of Ar anticipates the measurable plasma ionization.

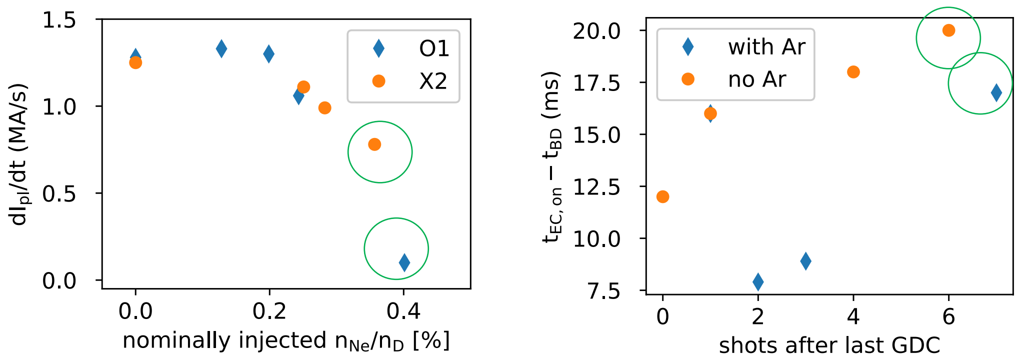

Figure 1 Comparison of experimental results on FTU (left) and TCV (right). Points highlighted with green circles represent pulses where the start-up is not successfully sustained due to an excess of impurity.

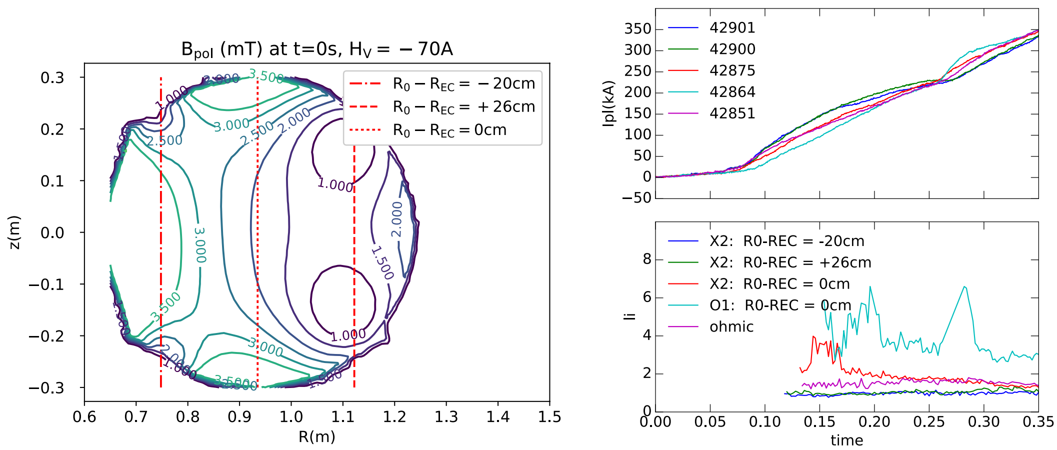

Figure 2: (Left) Poloidal field configuration (<4mT) during a scan of relative position between the field null and EC resonance with X2-scheme. D2 pre-fill pressure (without Ne) and loop voltage (Etor ~0.5V/m) were kept constant. The magnetic structure (null quality and position) is reconstructed from magnetic measurements using MAXFEA code. (Right) Evolution of plasma current and corresponding internal inductance (li), as calculated from the equilibrium code ODIN [2].

A second set of experiments have been performed on FTU by varying the EC resonance position and keeping fixed the field null in deuterium plasma. When the resonance for X2 polarisation has been moved off-axis as shown in figure 2 (left), a reduction of the internal inductance (li) is found, with respect to the case with resonance on-axis (figure 2 (right)). This is due to a broadening of the current density profile, confirmed by Te profiles. Similar behaviour, typical of ohmic discharges, is found also when O1-scheme and resonance on-axis is used in presence of Ne impurity.

Simulation A correct and consistent evaluation of the EC absorbed power together with the role of the magnetic configuration in the early stage of the discharge has been successfully used to reproduce experimental data with BKD0 code [3]. The modelling of the burn-through is clearly dependent on the level of the initial % of impurity in the prefill mixture. BKD0 is a predictive 0D model for the burn-though phase, consistently coupled to the GRAY code [4] to model EC heating starting from the available specifications of the ECRF system, including EC power localisation, polarisation effect and wall bouncing effect. A benchmark activity between BKD0 and DYON [5] codes was successfully carried out for the simplified ITER case (ohmic). BKD0 validation on experiments have been based on data from FTU in OM1 and XM2, and on TCV in XM2 (figure 3).

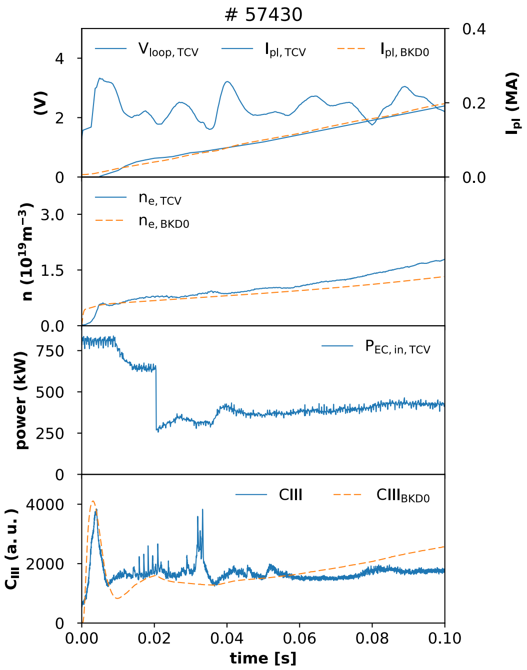

Figure 3 TCV pulse 57430. Vloop and EC power have been used as input of the simulation. The plasma current, density and the CIII experimental data (blue) have been compared with the simulation results (orange)

Prediction BKD0 can be used as a tool to extrapolate the operational parameters for the next generation fusion experiments like ITER and JT-60SA, providing values of, e.g. the required EC power for a given neutral gas composition and pressure, or the optimization of the EC launcher in different experimental conditions. In ITER it was found that, compared to the ohmic case characterised by an maximum operational pressure <1mPa, the EC heating is able to extend it by 0.8 mPa/MW. In case of JT-60SA, an accurate magnetic model has been studied by means of the CREATE-BD code [6], which integrates and optimizes the active circuit currents and considers eddy currents in the passive structures for developing plasma breakdown scenario. BKD0 coupled to CREATE-BD show as electron temperature and plasma current depend on ECRH power and present a threshold for successful start-up. Figure (4) shows this threshold as a function of the initial neutral H2 pressure for two cases: one with injection scheme that allows single pass absorption (blue) and the other characterised by second pass after wall reflection (green), at different initial C content and nO/ne=0.1%. As the initial pressure increases, more power is required to overcome the radiation barrier. Optimized injection angles allow to improve the absorption and increase the operational space even in presence of impurity.

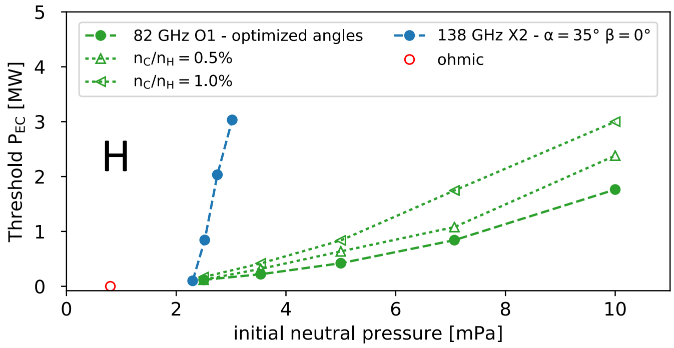

Figure 4 EC power threshold as a function of the initial neutral H2 pressure for two cases: (i) 138 GHz (X2), injection perpendicular to the magnetic field and at fixed poloidal angle 35.5° with respect to the horizontal direction (blue curve) and (ii) 82 GHz (O1), optimised injection angles (green), i.e., poloidal angle 21° and toroidal angle (with respect to the perpendicular) of 20° , where mode conversion from O to X strongly enhances the EC wave effect. For this second case, two different values of the initial nC/nH have been considered, with oxygen fraction nO/nH=0.1%. Point at 1 mPa (red) is the condition for ohmic discharges.

Conclusions. Experimental activity has been performed on FTU and TCV where the injection of impurity mimics not favourable post-pulse conditions (such as would be expected after disruption event), and EC power is used as a tool to assist the burn-through phase in both O1 and X2 schemes. BKD0+GRAY simulations have reproduced plasma parameters, calculating the EC absorbed power needed at burn-through as well as the impurity content.

Based on these results, BKD0 is used to extrapolate the operational parameters for the next generation fusion experiments like ITER, JT-60SA, providing values of, e.g. the required EC power for a given neutral gas composition and pressure.

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