EC assisted start-up experiments reproduction in FTU and AUG for simulations of the ITER case

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Abstract. The breakdown and plasma start-up in ITER are well known issues studied in the last few years in many tokamaks with the aid of calculation based on simplified modeling. The thickness of ITER metallic wall and the voltage limits of the Central Solenoid Power Supply strongly limit the maximum toroidal electric field achievable (0.3 V/m), well below the level used in the present generation of tokamaks. In order to have a safe and robust breakdown, the use of Electron Cyclotron Power to assist plasma formation and current rump up has been foreseen. This has raised attention on plasma formation phase in presence of EC wave, especially in order to predict the required power for a robust breakdown in ITER. Few detailed theory studies have been performed up to nowadays, due to the complexity of the problems. A simplified approach, extended from that proposed in ref[1] has been developed including a impurity multispecies distribution and an EC wave propagation and absorption based on GRAY code. This integrated model (BK0D) has been benchmarked on ohmic and EC assisted experiments on FTU and AUG, finding the key aspects for a good reproduction of data. On the basis of this, the simulation has been devoted to understand the best configuration for ITER case. The dependency of impurity distribution content and neutral gas pressure limits has been considered. As results of the analysis a reasonable amount of power (1 - 2 MW) seems to be enough to extend in a significant way the breakdown and current start up capability of ITER. The work reports the FTU data reproduction and the ITER case simulations.

Keywords: Plasma Break-down, ECRH.
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INTRODUCTION

In the framework to determine the condition for a reliable and robust breakdown in ITER several experiments have been performed in tokamaks equipped with an ECRH systems [2]. The results of such an effort is positive indication on the fact that, with the assistance of EC power in the initial phase of plasma formation, a sustained breakdown can be achieved also at the low electric field of ITER (0.3 V/m). A second step, presented in this work, is the attempt to modeling the EC assisted break-down process in ITER in a most realistic way, this to extrapolate the conditions required (EC power, launching angles and error field) to overcome the *burn-trough* phase in different impurity content concentration and mix.

The model in the 0-d approximation (BKD0), that has been used initially to reproduce to reproduce the FTU [3] and AUG experimental data, follows the description of breakdown given in [1], consisting of five differential equations describing the evolution of the plasma parameters. The equations are energy and particle balance, for ion and electron, plus the circuit equation for plasma current evolution. In BK0D model a particular attention has been devoted to the inclusion of impurity behavior that is relevant in the initial stage of plasma current formation. A non–coronal model has been used to treat impurities. The emitted radiation has contributions from line radiation, recombination and bremsstrahlung (P_{rad}). Impurities considered are mainly carbon and oxygen in simulations of FTU and AUG start up phase, while in case of ITER also beryllium and nitrogen have been included. Concentration typically ranges from 1% to 3%. A further improvement to the original proposed set of equations regards the term corresponding to the EC absorbed power, included in the energy balance equation. Data used by BKD0 have been calculated by means of the GRAY code [4] in case of FTU simulations and ITER prediction, while TORBEAM [5] is used to reproduce AUG data. The computation is coherent with the measured quantities when used to reproduce experimental data, while density and electron temperature extrapolated from BKD0 are used as input for power absorption evaluation in case of ITER. In the work presented here we used an upgraded version of GRAY code that takes into account two important features of EC propagation in the breakdown phase:

a- Reflection at the inner wall (important in case of low first pass absorption in the typical initial plasma)

b- Mode conversion at the reflection in case of oblique injection (as it is in one of the considered FTU case and for all cases in ITER).

To properly take into account the propagation of the reflected power, the inner wall shape should be included in the GRAY, especially when the EC power is oblique injected, as for FTU and in future for ITER. This has been done for FTU case, while in ITER we have considered a flat smooth cylinder as reflection surface.

SIMULATION OF FTU ASSISTED BREAKDOWN

The simulated data of FTU are part of an experiment on assisted breakdown performed in 2009 [3]. We choose to apply BKD0 at three different cases, a pure ohmic startup with the lowest possible loop voltage (#32295), an EC assisted with perpendicular injection (#32602) and one with oblique (20°) injection (#32611) at a lower level of loop voltage. Plasma configuration was identical for the 3 shots and the machine conditions were similar. For all the cases the prefill pressure was not measured but calculated from the opening time of the calibrated gas puffing. This gives only a relative indication about the real pressure inside the vessel and the agreement with BKD0 simulations can be only qualitative.

Simulation outcomes are classified as successful or failure according to the following criteria: 100 ms after the current starts to rise, if the current reaches 150 kA with the same rate as that measured, and the power balance for electrons is positive (Poh+Pecrh-Ploss) then the simulation is classified as a success, otherwise it is classified as failure.

Evolution of plasma volume/section is important in start-up outcome for its relevance in determining the plasma resistance and consequently the I_p sustained by toroidal electric field. In the simulation of FTU data we have considered the initial plasma section coincide with the field null defined by B_z < 30 G (~10 cm in radius) and evolving it following the not-inverted density profile and finally equilibrium reconstruction.

Only the EC power deposited in the null (radius 10 cm) is considered useful for power balance in BKD0 in the first 50 ms, after that confinement due to plasma current starts to play its role and all the EC absorbed power is included in the balance equation.

The EC power absorption term (P_{ecrh}) calculated by GRAY has been included in the electron energy balance equation. The EC power (400 kW) has been switched on at t=0 s. The EC resonance (at 5 T) is in the field null. The two considered cases are shot #32602 with power perpendicularly injected to the centre in pure OM polarization, and shot #32611, with power injected with an angle of 20°.

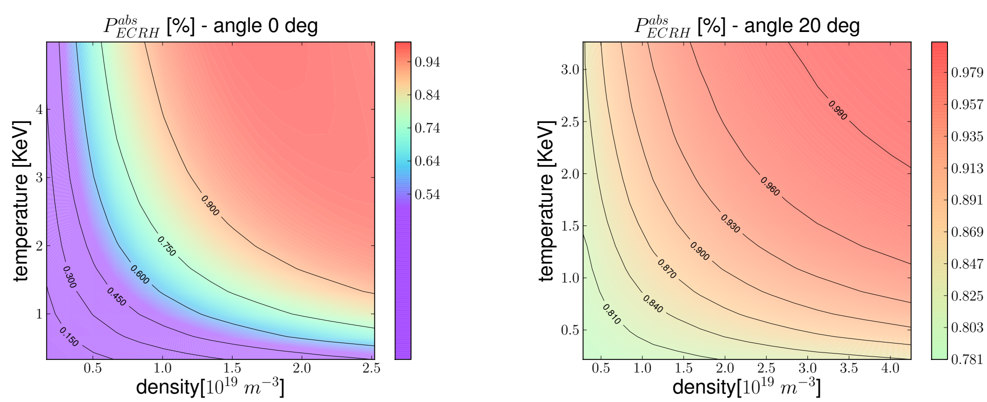

FIGURE 1. EC power absorption as a function of electron density and temperature, as calculated by GRAY code after 2 passes. On the left perpendicular injection case (shot #32602), on the right (shot #32611) the 20° toroidal injection one.

The GRAY output is shown in Fig 1, where the rate of power consumption is reported with respect to the injected one in the different plasma parameters. At each time step of the simulation, given electron density and temperature, BK0D interpolates out the new value for P_{ecrh} and solves the equations. The input powers used in simulations are 400 kW and 800 kW. The total EC power absorbed is calculated as the rate evaluated by GRAY multiply by the input power.

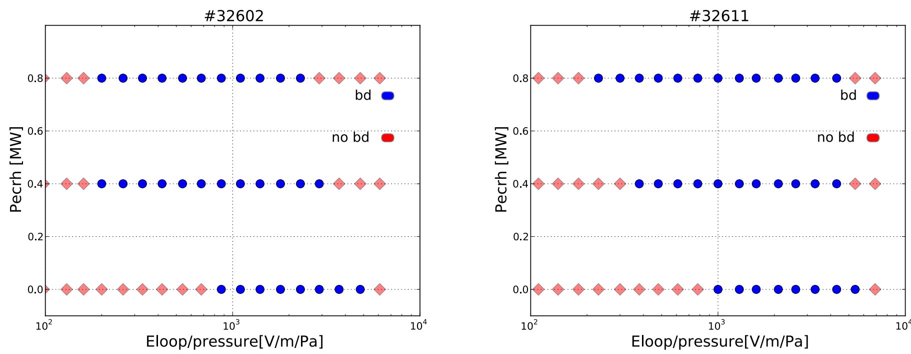

FIGURE 2. Simulations of BKD0 for perpendicular (left) and oblique (right) EC injections in FTU. The plasma equilibrium and V_{loop} behavior are from the experiments, while E/p rate and level of EC power has been varied.

In Fig.2 summary of outcomes obtained with BKD0 in case of EC assisted startup is reported. The simulation achievements have been obtained varying the pressure and selecting two different EC input powers, together with the ohmic case, reported to evaluate the improvement obtained with EC assistance.

The BK0D simulations show how the increased EC power to 800 kW does not bring improvements with respect to the lower one (400 kW) in case of perpendicular injection, while in the oblique case increasing EC power the breakdown is more effective at high E/p values, while at low E/p values give less satisfactorily performing case.

The experimental results of FTU are qualitatively reproduced in term of E/p by BKD0, giving confidence to apply the model to the ITER case.

SIMULATION OF ASEDX UPGRADE CASE

The code BKD0 has been applied also to ASDEX UPGRADE in order to verify its applicability to a D-shaped tokamak. Actually break-down and plasma start-up phases can be considered identical for both cases (circular and D-shaped machine), because the initial plasma is ever (?) limited by limiter. In any case the interest in simulating AUG plasmas is due also to the use of X2 configuration, which has a larger absorption. The available data on AUG refer only to perpendicular injection, and the absorption has been calculated using TORBEAM [5].

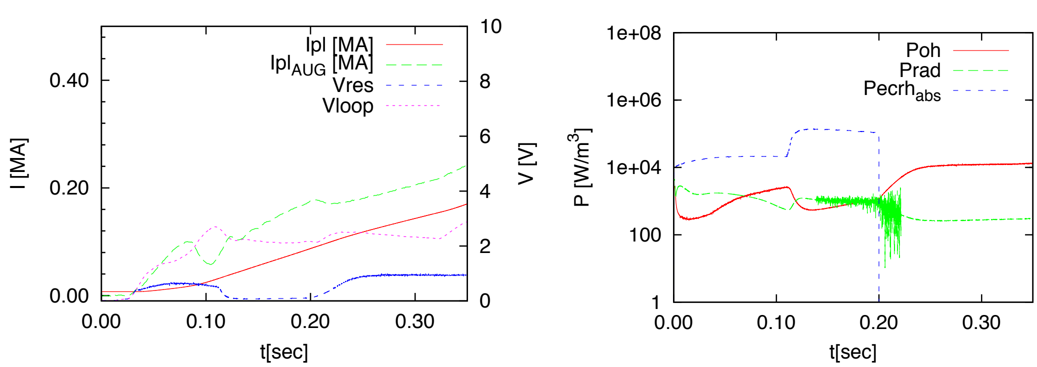

FIGURE 3. Time evolution of AUG plasma current I and loop voltage V_{loop} (left) and power balance (right). EC power is injected in X2 mode by four gyrotrons (~330 kW each) and directed towards the centre. The pulse has a duration of 200 ms.

As counter check the same scenario has been simulated in pure ohmic condition (P_{ecrh}=0) and, as expected, the break down failed.

EXTRAPOLATION TO ITER BREAKDOWN CONFIGURATION

To simulate ITER breakdown the pure ohmic case has been considered (see Fig.4 left), varying pressure and concentration of impurity content (O, N and Be from 0% to 3%). The used magnetic configuration and loop voltage evolution is derived from [6]. The criteria to have a sustained breakdown (SB) is defined by the condition $I_p > 150$ kA in 1 s from the start of the simulation. The ohmic SB is possible but in a small portion of the region E/p between the limit to have the avalanche (white region in the graph) and the maximum electric field available (E=0.3 V/m).

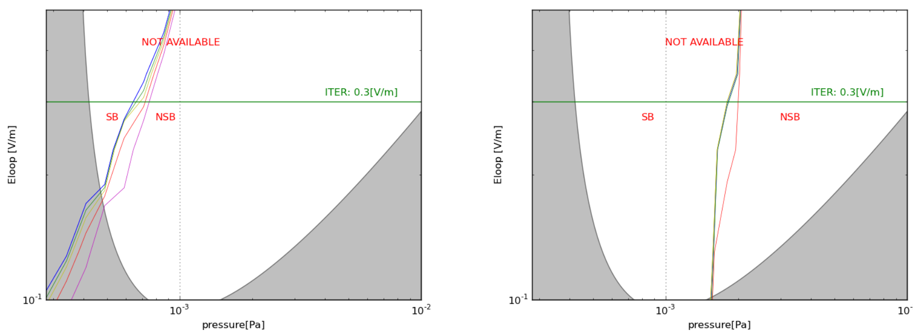

FIGURE 4. Summary of BKD0 results evidencing the advantage of injecting 1MW of EC power (right) compared to the pure ohmic case (left). The gray region is defined by Townsen avalanche criteria, while the limit in toroidal electric field is reported. The region of SB is delimited by vertical line (blue: no impurities, red: 3% of O, C and Be). The case refers to 5.3 T in the centre and an error field of 3mT.

In Fig.4 right the results are reported for 1MW in OM injected at 20° of toroidal angle from the equatorial launcher. In this configuration the wave is poorly absorbed in the first pass (max 10% in the initial plasma) but after the polarization conversion due to the oblique reflection, the propagating XM exhibits absorption up to 85%. A proper reflection at the inner wall of the vessel plays the decisive role to sustain the breakdown even if with a reduced level of power. The effectiveness of EC power injection is not affected by introduction of a mix of light impurities.

CONCLUSION

A 0D model of plasma breakdown has been integrated with beam tracing code in order to determine the better condition (EC configuration, pressure and error field) for a sustained breakdown in ITER. The BKD0 code is benchmarked with data of FTU and AUG, finding a good agreement between simulations and experimental results. A main and first outcome of the simulation is that a sustained breakdown can be obtained with 1 MW of EC power injected at 20° from equatorial launcher, at a field of 5.3 T. This result is mainly due to the polarization conversion occurring at inner wall, that assures high enough absorption in the second pass of EC wave on the resonance.

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