MULTI-MACHINE VALIDATION OF PLASMA INITIATION MODELLING AND PROSPECTS FOR FUTURE DEVICES

Predicting plasma initiation using only hardware design and control room input data

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Multi-machine validation of full electromagnetic plasma initiation modelling with DYON was carried out by the joint modelling activity of the ITPA - Integrating Operating Scenario group. Despite the very different hardware geometry i.e. VEST (spherical torus, Stainless steel wall + outboard C limiter, R/a=0.4m/0.3m, V_v=3.7m^3), MAST-U (spherical torus, full C wall, R/a=0.9m/0.6m, carbon wall, V_v=55m^3), and EAST (conventional tokamak, metallic wall + inboard C limiter, R/a=1.8m/0.45m, V_v=38m^3), using only the individual hardware design and the control room input data in each discharge the required operating spaces of the loop voltage induction and prefill gas pressure for ohmic plasma initiation in the three experiment databases were successfully reproduced in the predictive simulation of DYON (see Figure 1). Further multi-machine validation is ongoing with the experiment data from K-STAR, DIII-D, and JT60-SA, and the results will be included in the contribution paper of 2025 IAEA FEC. The successful reproduction of the operating space in multiple devices demonstrates that the full electromagnetic DYON can capture the essential physics of ohmic plasma initiation. This suggests that DYON should be a useful tool for assessing the feasibility of ohmic plasma initiation with the given hardware design and operating scenario in future devices such as ITER and STEP.

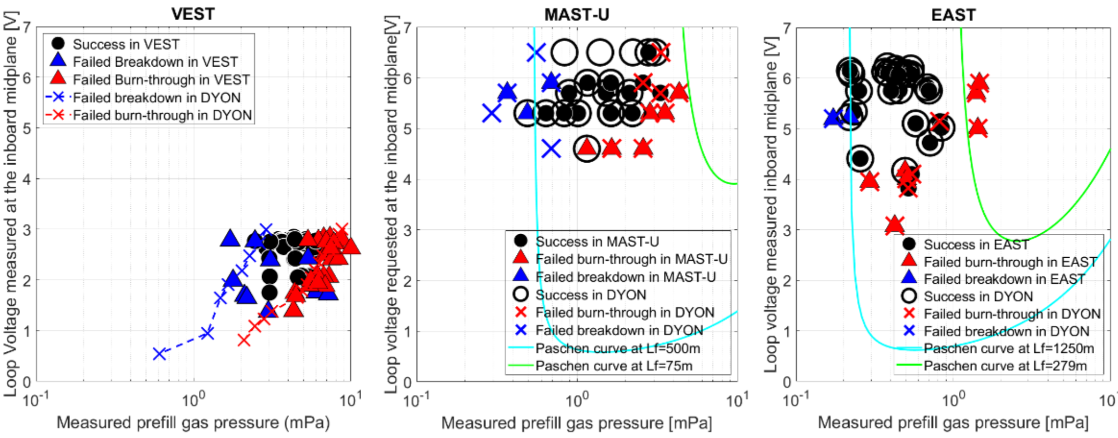

Figure 1 Operating space of loop voltage induction and prefill gas pressure for ohmic plasma initiation in VEST[2], MAST-U[3], and EAST[4]. When no or very weak D_{alpha} signal was detected and I_p does not increase, the discharges are defined as 'failed breakdown'. When clear D_{alpha} signals are detected but I_p does not increase, the discharges are defined as 'failed burn-through'.

The plasma initiation feasibility is one of the important aspects, which should be assessed in the design process of a fusion device. It is because the highest loop voltage induction in the whole plasma pulse is required during the plasma initiation phase. Since the loop voltage is induced by fully charging and rapidly decreasing the currents in the central solenoid and poloidal field coils, the required hardware specification of coils and power supplies depends on the feasibility of plasma initiation. In addition, the high loop voltage in the plasma initiation phase induces strong eddy currents, which may impede the loop voltage induction in the vacuum centre and degrade the magnetic field null configuration. Hence, the toroidal electric conductivity of the vessel and the surrounding supporting structures also impact on the feasibility of plasma initiation.

DYON is a 0D plasma modelling code, dedicated to the plasma initiation phase. It solves the differential equation system of the global energy balances of electrons and ions and the global particle balances of the main fuel species and the impurities in each charge state. DYON calculates both the parallel and perpendicular transport of energy and particles with respect to the magnetic field lines. The recycling of main fuels and sputtering of impurities are calculated by coupling global models for the outward ion particle flux and plasma-wall interaction. The full circuit equations describing all toroidally conducting vessel structures, solenoid, and PF coils were integrated into DYON[1]. The full electromagnetic feature allows not only the modelling of the vessel eddy currents, but also the calculation of the loop voltage in the plasma region with the coil current time traces. Implementation of the full circuit equations enables simulating the time evolution of 2D poloidal magnetic flux map (i.e. ψ map) in the vacuum space. This enables evaluation of the Townsend break-down along each field line, thereby calculation of the plasma volume.

In order for systematic validation of the full electromagnetic DYON on multiple machines, the same strategy was employed for all devices. The first step is to employ calibration for the electromagnetic response of the conducting structures to represent the 3D nature in the 2D model. The next step is to reproduce the plasma initiation phase in a reference discharge. The simulation results of plasma current, line radiation emission such as D_{alpha}, C-II, O-III, average T_e and n_e are then compared with the corresponding measured values. Based on the comparison with the experiment data, the prefill gas pressure value used in the modelling is corrected by multiplying a scaling factor to account for errors, possibly arising from the distance between the plasma and the pressure diagnostic system or/and the calibration of the fast ion gauge. The "calibration" factor of the pressure to account for measurement uncertainties in the existing devices is less of a problem for the prediction as the gas pressure can be easily adjusted during operation. It is important that a feasible wide enough pressure range exists. The fuel recycling coefficient and impurity sputtering yield are also adjusted to reflect plasma-wall interaction characteristics, including device-specific features such as carbon limiter geometry. Finally, if the reproduction of a reference discharge is successful, all the discharges in the database are simulated with the same simulation settings, without any further adjustment for individual discharges. In order to test the capability of DYON to predict individual discharges in experiments and thus the operating space in the device, a dedicated experiment database was established in VEST[2], MAST-U[3], and EAST[4] by scanning the prefill gas pressure and the induced loop voltage. The experiment databases of the three devices show the common features. In the experimental operating space for plasma initiation, the lower and the upper limits of prefill gas pressure are determined by the plasma breakdown failure and the plasma burn-through failure, respectively. The lower limit of loop voltage induction is determined by the plasma burn-through failure. Using only the control room input data of each discharge (i.e. currents in the solenoid, poloidal field coils, and toroidal field coils, prefill gas pressure, and gas puffing rate), the full electromagnetic DYON consistently predicted the failed breakdown, failed burn-through, and successful plasma initiation discharges in the dedicated experiment database of the three devices. This demonstrates the capability of predicting the operating space for ohmic plasma initiation and indicates the readiness of the full electromagnetic DYON to test further physics models such as EC pre-ionization and EC heating assist.

This paper will present a comparative analysis of the various experimental operating spaces for ohmic plasma initiation across different devices. The influences of hardware design parameters on plasma breakdown and plasma burn-through are investigated. The simulation settings commonly employed for all modelling will be reported, along with the necessary modifications to the simulation settings to account for the discrepancies between individual devices. Finally, the results of the multimachine modelling will be discussed, and based on that, the predictive modelling of ITER and STEP will be presented.

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