H-mode operation scenarios in JT-60SA initial research phase predicted by integrated core-pedestal-SOL/divertor simulation

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An integrated simulation encompassing core-pedestal-SOL/divertor regions was performed for the first time in the world to establish H-mode operation scenarios in the JT-60SA initial research phase. The simulation demonstrated that the baseline H-mode scenario will achieve its target performance parameters for normalized beta $\beta_N \geq 1.8$ and energy confinement factor $H_{98y2} \geq 1$, while maintaining divertor heat flux well below maximum allowable limit $q_{\parallel} < 10\mathrm{MW/m^2}$ through controlled extrinsic impurity gas injection. This accomplishment addresses both ITER/DEMO-relevant operational objectives and scientific research priorities. The predictions were enabled by implementing advanced models and codes that analyze the complete plasma volume, with specific focus on achieving compatible density predictions between the SOL/divertor and pedestal regions to optimize both plasma performance and divertor heat load reduction. This integrated simulation framework significantly enhances predictive capabilities for future tokamak operations, providing essential insights for advancing research at JT-60SA, ITER, and next-generation fusion reactors.

The JT-60SA Experiment Team has established operation plans for its initial research phase focusing on ITER/DEMO contributions and scientific significance. All the plans require H-mode operation to achieve target performance, therefore, accurate prediction of H-mode pedestal profiles is essential. While the EPED model and its proxies effectively predict pressure pedestal profiles in existing tokamaks[1], they cannot separately predict density and temperature profiles. Pedestal confinement performance strongly depends on pedestal density, therefore, to achieve a fully predictive capability, a model for predicting the pedestal density profile was developed [2]. The model has been validated across several tokamaks, and it was confirmed that its predictions require the electron density at the separatrix $n_{e,sep}$ as an input parameter, which significantly impacts the predicted values. Additionally, the density in the SOL/divertor region including $n_{e,sep}$ must be controlled to maintain divertor heat flux below maximum allowable limit through various methods, including impurity seeding. Consequently, SOL/divertor simulation is crucial for the self-consistent determination of plasma density and temperature profiles.

In this paper, we performed a fully predictive integrated simulation among core-pedestal-SOL/divertor models to predict the baseline H-mode operation scenario in JT-60SA initial research phase. Operation parameters of this scenario are designed as toroidal magnetic field on axis $B_t = 2.28\mathrm{T}$, plasma current $I_p = 4.6\mathrm{MA}$, plasma ellipticity and triangularity $\kappa = 1.85$, $\delta = 0.5$, safety factor at the 95% poloidal flux surface $q_{95} \sim 3.0$. Target performance parameters are determined as $\beta_N \geq 1.8$ and $H_{98y2} \geq 1$ with $f_{GW} \equiv \overline{n_e}/n_{GW} \geq 0.5$, where $\overline{n_e}$ is the line averaged value of electron density n_e, and n_{GW} is the Greenwald density limit. In this case, P_{LH} predicted by ITPA08 scaling is 8.5MW for deuterium when $f_{GW} = 0.5$. The integrated modeling consists of a core transport simulation code GOTRESS+[3] involving EPED, the Saarelma's density pedestal model[2], and a SOL/divertor simulation code SONIC[4]. The coefficient C_{ped} used in EPED as $\Delta_{ped} \propto C_{ped}\sqrt{\beta_{p,ped}}$ is set as $C_{ped} = 0.089$, where Δ_{ped} is the pressure pedestal width, and $\beta_{p,ped}$ is the pedestal poloidal beta value.

First, we performed the predictive simulation without extrinsic impurity for divertor heat load control; in this case, only intrinsic Carbon (C) is considered. It should be noted that the plasma profiles in core-pedestal-SOL/divertor regions were determined in an iterative manner between SONIC and GOTRESS+, because the power across the separatrix P_{sep} is affected by the amount of impurity species due to radiation, which has impact on both confinement performance and divertor heat flux. With total heating power $P_H = 19\mathrm{MW}$ and D_2 gas puff at a rate of $\Gamma_{puff,D2} = 1.0 \times 10^{21}$/s, the simulation result, shown with blue lines in Fig. 1, indicates that the plasma parameters (β_N, H_{98y2}) are (2.19, 1.17) satisfying the target values, where SONIC determined $n_{e,sep} =$

$2.89 \times 10^{19}/m^3$ and the effective charge at the middle of pedestal Z_{eff}~1.4, and the Saarelma's model evaluated $n_{e,ped} = 5.26 \times 10^{19}/m^3$. In this intrinsic C-only case, the radiation power inside the separatrix is $P_{rad,core} = 0.3$ MW, that in SOL/divertor region is $P_{rad,DSOL} = 3.1$ MW, and the resultant peak heat flux to divertor becomes $q_{\parallel}$~10MW/m^2. The peak $q_{\parallel}$ is at the maximum allowable limit for discharge duration up to 5 seconds, therefore, to operate the baseline scenario more safely, we need to find an alternative scenario which has lower $q_{\parallel}$ while maintaining the target plasma parameters.

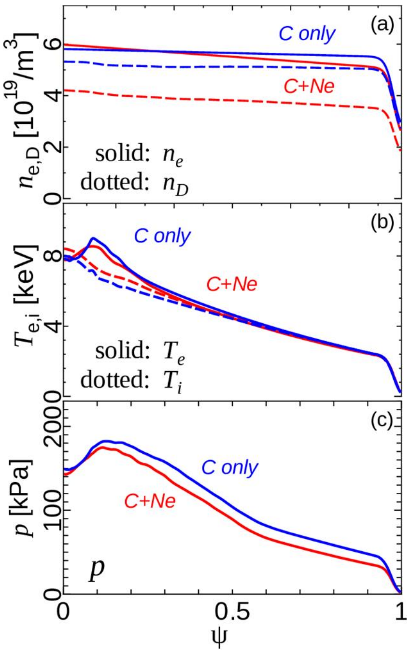

Fig.1: Comparison of profiles of JT-60SA baseline scenario plasma predicted using GOTRESS+ and SONIC in C only (blue) and C+Ne (red) cases; (a) n_e, n_D, (b) T_e, T_i, (c) p. Both plasmas satisfy the target parameters β_N and H_{98y2}.

Hence, we performed the simulation with not only intrinsic C but also Neon (Ne) as the extrinsic impurity seeded at a rate of $\Gamma_{puff,Ne} = 3.1 \times 10^{19}$/s with P_H and $\Gamma_{puff,D2}$ same as the first simulation. In this case, after several iterations between GOTRESS+ and SONIC, the peak heat flux was successfully reduced to 6.2MW/m^2 with $P_{rad,core}$~3.0MW , $P_{rad,DSOL} = 6.6$ MW, $n_{e,sep} = 2.56 \times 10^{19}/m^3$ and Z_{eff}~3.4, where $n_{e,ped}$ was predicted as $5.02 \times 10^{19}/m^3$. The resultant plasma profiles, illustrated with red lines in Fig. 1, demonstrate that the profiles of electron and ion temperature T_e, T_i remain comparable to those in the C-only case. However, the reduction in total pressure can be attributed to the decrease in bulk ion density n_D resulting from larger Z_{eff} and larger $P_{rad,core}$. In addition, the decrease in pressure at pedestal top p_{ped} stems from the destabilization of current-driven MHD modes due to reduced pedestal collisionality. Even in this C+Ne case, the plasma parameters (β_N, H_{98y2}) satisfy the target values as (2.04, 1.05), meaning that we successfully established the H-mode baseline scenario in the JT-60SA initial research phase with the divertor heat flux well below the maximum allowable limit.

Figure 2 shows a two-dimensional plot of total radiation power density in SOL/divertor region in the (a) C-only and (b) C+Ne cases, as calculated using SONIC. In the C-only case, large radiation in the low field side (LFS) of SOL was observed only near the divertor plate, and as the result, an attached condition of divertor plasmas was observed. In contrast, in the C+Ne case, broad Ne radiation throughout the LFS of SOL was observed, resulting in effective cooling of outer divertor plasma. Consequently, T_e at the divertor plate was less than 5eV near the strike point, indicating achievement of a partially detached condition and successful reduction of peak heat flux.

Our predictive integrated simulation across core-pedestal-SOL/divertor regions enables the development of operation scenarios that account for both density pedestal predictions and divertor heat load conditions controlled by extrinsic impurity gas injection. This capability is essential for predicting operation scenarios not only for JT-60SA but also for ITER and future reactors.

References

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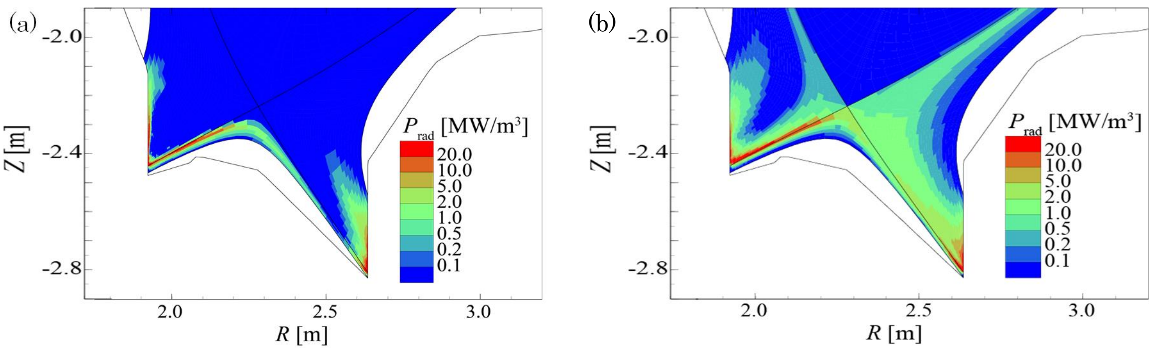

Fig.2: 2D plot of radiation power density in (a) C-only and (b) C+Ne cases. On the outer divertor target, a partially detached condition was achieved in C+Ne case, although an attached one was found in C-only case.