Investigation of operational space for long pulse ITER scenarios

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Long pulse or hybrid operation mode, in which a substantial fraction of the plasma current will be driven by non-inductive CD, is considered now as one of the ITER basic operation scenarios. This mode of operation with longer pulse duration than in the basic scenario will make possible scenarios with high neutron fluence to test ITER construction elements. In this presentation, the Operational Space (OS) for long pulse scenarios is investigated using predictive modeling by the ASTRA transport code [1]. The other task is the sensitivity study of these scenarios to high-Z impurity contamination.

In simulations, we used fixed boundary equilibrium and empirical scaling-based plasma transport model where plasma transport coefficients were normalized to make the calculated energy confinement time equal to ITER H- or L-mode scaling predictions [2]. Impurity ionization state, transport and radiation were simulated using the ZIMPUR code [3]. Anomalous transport coefficients were selected as:

$$\chi_e = D_e = D_{imp} = \chi_A \cdot F_{H\text{-mode}}, \quad \chi_i = 2\,\chi_e,$$

where $\chi_A = \chi_o(1 + 3\cdot\rho_N^2)$, χ_o is the normalizing coefficient, $\rho_N = \rho/\rho_{max}$ is the radial coordinate and the reduction coefficient $F_{H\text{-mode}}$ decreased anomalous transport coefficients in the region of external transport barrier ($\rho_N > 0.94$) to the level of the neoclassical ion thermal conductivity [4]. Anomalous pinch velocity for plasma and impurity particles was assumed to be $V = 0.2\,D_A(\rho_N/a)$. Neoclassical impurity transport coefficients have been calculated using the NCLASS code [5]. As the boundary conditions on the separatrix for the bulk plasma parameters, we have used $T_{es} = 0.2$ keV and $n_{es} = 0.3 \langle n_e \rangle$. Thermalized Helium pumping speed was selected to keep $\tau_{He} / \tau_E = 3$. Argon contamination was changed by the boundary flux of Ar atoms to keep power to the divertor layer below 100 MW what is acceptable for conditions in divertor. Beryllium contamination $n_{Be} / n_e \approx 2\%$ has been supported by changing of Be atoms boundary flux. Possible plasma current flat-top length was calculated by the formula $\Delta t_{flar\text{-}top} = \Delta\Psi[Vs] / U_{res}[V] = (240\text{-}14{*}I_p) / U_{res}$ where the resistive voltage is $U_{res} = P_{OH} / I_P$. Neutron fluence was equal to $Fl = 0.8{*}P_{fus}{*}\Delta t_{flat\text{-}top}$.

Simulations start from the basic 15 MA inductive scenario with the fusion power $P_{fus} = 530$ MW and fusion gain $Q = 10$. Then the plasma current and density scans have been performed keeping the same assumptions as those for the basic inductive scenario and keeping the basic set of heating and current drive powers (16.5 MW on- and 16.5 MW off-axis NBCD and 20 MW ECCD in the region of $q(\rho) \approx 2$).

The main results of this scan are presented in Fig.1. Simulations show a wide operational domain for the hybrid mode scenarios. At small plasma density, OS is limited by value of $n_e \sim 5 \cdot 10^{19} m^{-3}$ due to high Neutral Beam shine-through losses at smaller densities. At high density, it is limited by the values close to the Greenwald density limit. At plasma current I < 10MA, the fusion power is too small. At plasma current higher than 14MA, discharge duration and neutron fluence decrease. In this scan, power flux to the divertor layer always exceeds the L-H-mode threshold power.

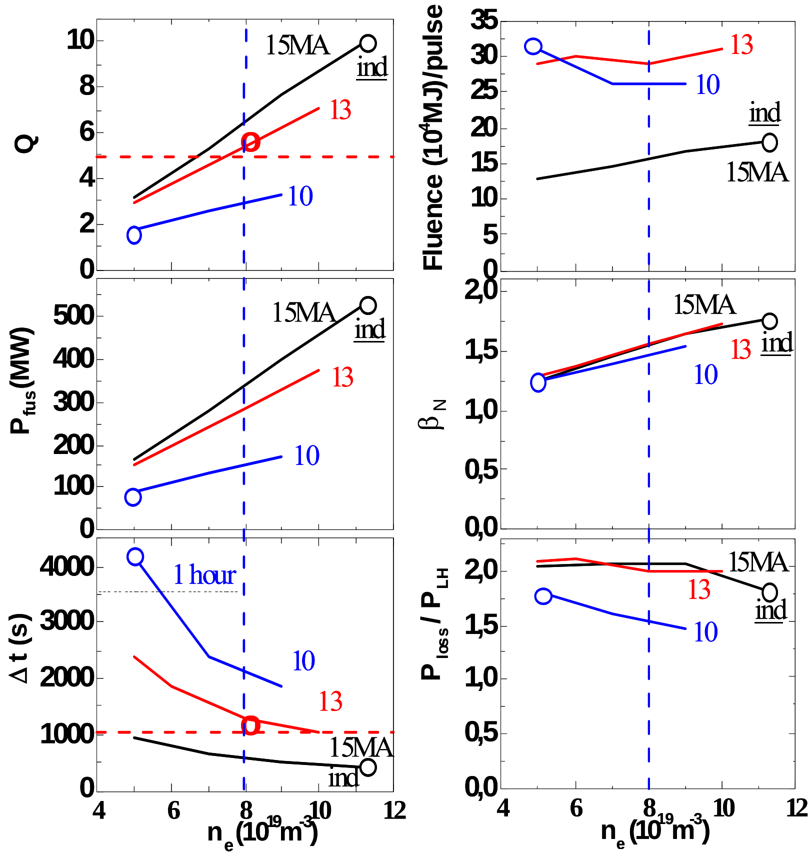


Fig.1 Plasma current-density scan for long pulse operation

As one can see, reduction of the plasma current and plasma density results in decreasing of fusion power and fusion gain Q. However the discharge duration increases and the total neutron fluence (P_{fus}* $\Delta t_{flat\text{-}top}$) has weak dependence on the plasma density and slightly decreases with the plasma current. So, the OS of plasma currents (when the declared ITER parameters Q $\geq$ 5 and Δt $\geq$ 1000s can be realized with confinement enhancement factor HH = 1) is ~ 12 - 14 MA at plasma densities ~ (7 - 10) $10^{19} m^{-3}$.

Reduction of the plasma current below 12 MA and density below $6 \cdot 10^{19} m^{-3}$ leads to discharges with a lower fusion power and longer duration which can exceed 1 hour. In these discharges, approximately the same total fluence as at 13 MA plasma current can be realized. These discharges can be useful for experiments with small wall power loads.

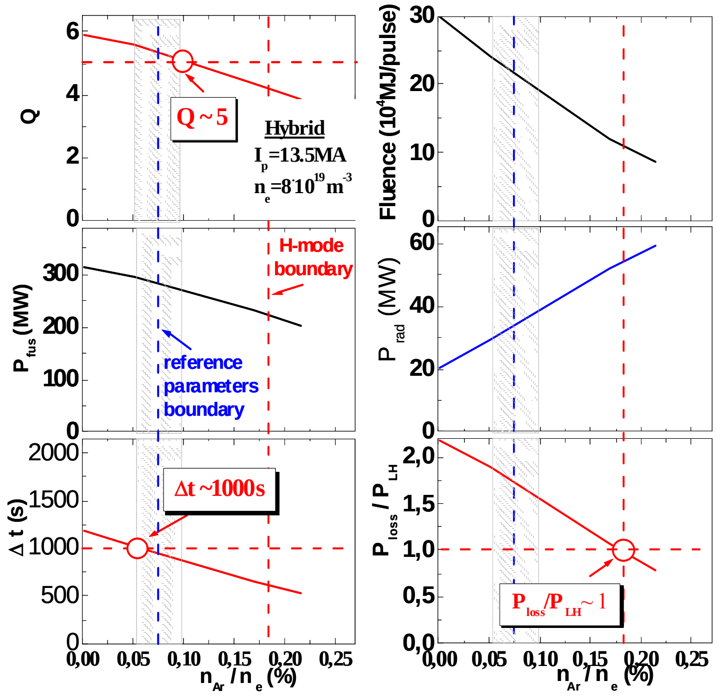
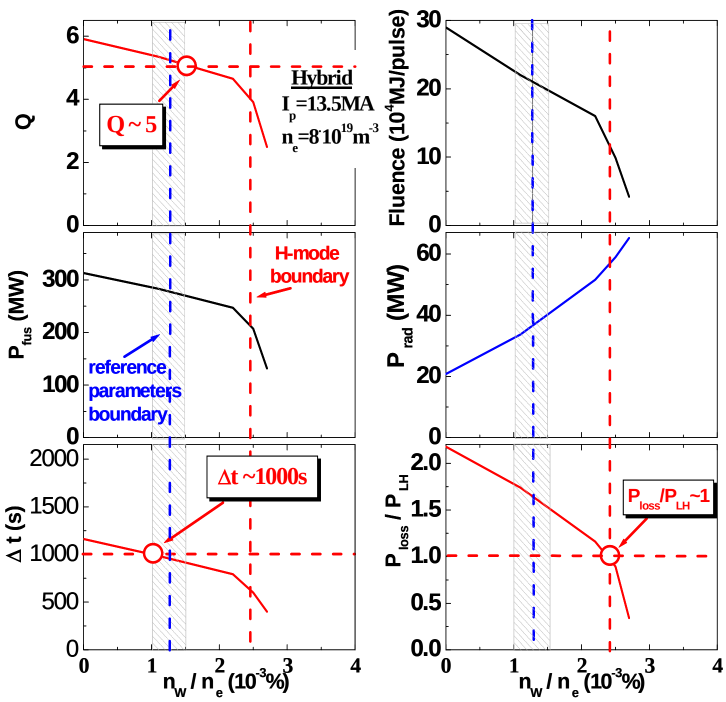


Fig. 2 Dependence of hybrid scenario performance on Ar contamination

However, at higher impurity concentrations than in this scan, enhanced plasma radiation and D/T fuel dilution can deteriorate discharge characteristics. Sensitivity study of long pulse scenarios performance to high-Z impurity contamination has been produced. Argon and Tungsten (W) were considered as the main possible impurities. Ar injection is proposed as one of the ways for creation of the re-radiating layer near the plasma boundary, and W can penetrate plasma from the divertor region. Scenario with plasma current $\approx$13.5 MA and plasma density $\approx$ $8{\cdot}10^{-19}m^{-3}$ was considered. In these simulations we assumed Be contamination n_{Be}/n_e $\approx$2% (keeping it by the boundary flux) and confinement enhancement factor equal to HH$\approx$1. Dependence of hybrid scenario performance on the Ar contamination at n_W = 0 is shown in Fig.2. One can see that rise of Ar contamination results in increase of the plasma radiation and reduction of the fusion power, discharge duration, fluence and loss power. There is no limit at small Ar contamination because power to the divertor layer is less than 100 MW. There are two boundaries of this regime at high Ar



Fig, 3 Dependence of hybrid scenario performance on W contamination

contamination. First of them (blue left dashed line) is the boundary of reference parameters (Q ~ 5; Δt ~ 1000 s) which corresponds to n_{Ar} / n_e ~ 0.08%. The second stronger limit (red dashed line) is the boundary of the H-mode operation (when $P_{loss}/P_{LH} \leq 1$ and there is a danger of transition to the L-mode and plasma cooling). It gives $n_{Ar} / n_e > 0.18\%$.

Similar results for W contamination are shown in Fig.3 at $n_{Ar} = 0$. First boundary corresponds to W relative concentration ~0.0012% and second boundary to n_W/n_e~ 0.0024%.

Summary

Results of the plasma current-density scan for long pulse scenarios (starting from the basic inductive scenario) are presented.

Simulations show that the fusion power and Q value decrease with the reduction of plasma current and density, but the discharge duration increases. That is why the change of neutron fluence with plasma density is small and weakly increases with the reduction of plasma current. As a result, the working region of plasma currents (12 – 14 MA) and densities (7 - 10)$\cdot 10^{19}$m^{-3}) where declared parameters Q ~ 5 and Δt ~ 1000 s are realized can be selected.

At a reduction of the plasma current and density, the discharges with a lower fusion power and longer duration (which can exceed 1 hour) at approximately the same total fluence as at 13 MA can be realized.

Results of sensitivity study of long pulse scenarios performance to high-Z impurity contamination are presented. Operational space at high impurity contamination is limited by two constraints. The first one is attributed to the rise of radiated power when the main scenario thermal characteristics degrade compared to the reference characteristics. The stronger second limitation is caused by the drop of the heat flux through the separatrix below the reversed H-L-mode transition threshold power resulting in deterioration of the confinement and plasma cooling. For argon, it gives maximum relative concentration n_{Ar} / n_e ~ 0.08-0.18% and for tungsten $n_W / n_e \sim (1.2 – 2.4)\cdot 10^{-3}$ %.

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