# Assessment of neutron emission for ITER operation with deuterium plasmas in the new baseline ITER Research Plan

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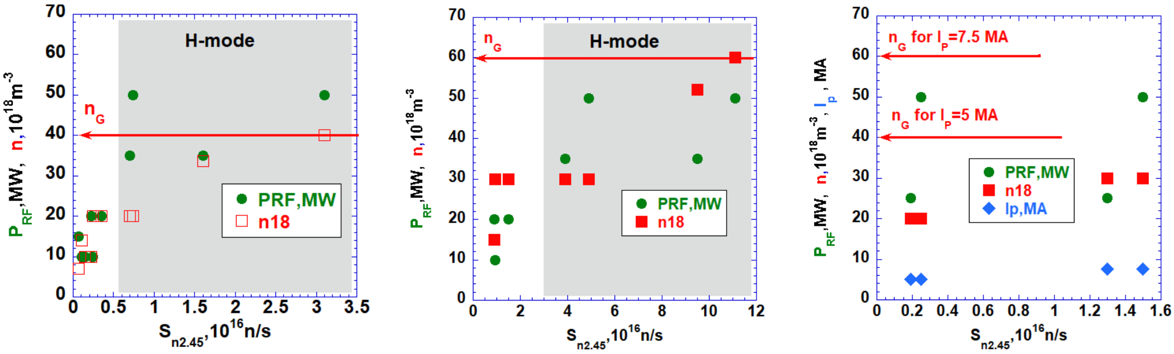
**Introduction.** In present tokamaks the minimal power threshold required for transition from the L- to H-mode reduces with increase of the fuel mass and reduction of the magnetic field, $P_{LH} \sim A_i^{-1} B^{0.8}$ in the range of densities $n_e \geq n_{e,min}^{scal} \sim 0.35 n_G (q_{95}/3)^{2/3}$, predicted for ITER [1]. Thus, deuterium plasmas are going to be used at Start of Research Operation (SRO) for early H-mode demonstration and in the first Deuterium-Tritium (DT-1) phase of the ITER Research Plan (IRP) [2]. The main goal of deuterium operation in these phases is to allow the development of H-mode scenarios with high plasma performance and low neutron production required for commissioning of the ELM mitigation system, plasma fuelling and control, studies of D pumping and retainment. DD operation also enables using of the hydrogen minority Ion Cyclotron Heating (ICH) at B=2.65T to maximize the operational space of H-modes. H-mode operation in DD is possible thanks to the increased auxiliary heating power in the new baseline to 50 MW of the Radio Frequency (RF) heating at the SRO, 70 MW of RF + 33 MW of Neutral Beam Injection (NBI) at DT-1 phase. This allows D H-mode operation in half-field at SRO and full field at DT-1 in deuterium plasmas (c.f. 20 MW ECH for PFPO-1 and 20 MW ECH + 20 MW ICH + 33 MW NBI at DT in the 2016 baseline IRP [3]). Here we assess neutron production for a range of plasma currents, densities, and mix of RF and NBI heating and Current Drive (CD). The emission of 2.45 MeV neutrons from DD reactions as well as 14 MeV neutrons from DT reactions, including slowing down of 1 MeV T ions born in DD reactions, is assessed in the IRP for different plasma currents and densities for full- and half-field operation. The simulations are carried out by self-consistent 1.5D transport simulations of the core plasma parameters in the frame of ASTRA [4] with the pedestal and boundary conditions predicted by EPED1 and SOLPS codes, with H&CD and fueling parameters designed for ITER. The simulations were carried out with the scaling-based transport model [5] assuming fitting of the transport coefficients to provide the energy confinement predicted by the H-mode and L-mode scalings. The neutron emission from interaction of fast ions with Boron is assessed.

**Neutron yield during SRO phase.** At the SRO phase of ITER it is planned to install 20 MW of the ECH injected at the Equatorial Launcher (EL), 20 MW of the ECH injected from the Upper Launchers (ULs) with Upper and Lower Steering Mirrors (USM), (LSM). Besides this, it is planned to use 10 MW of the ICH (with 42 MHz at B=2.65T for hydrogen minority and 53 MHz at B=5.3 T for $^3$He minority heating schemes).

The SRO research plan considers up to 27 months of operation to commission ITER with the initial SRO configuration and to demonstrate the deuterium H-mode operation within a neutron fluence of 1.5 $10^{20}$ neutrons to be mostly produced about 1 year before post-SRO in vessel entry. Simulations of DD SRO scenarios are carried out for B=2.65 T and B= 5.3 T in the wide range of densities, $n_e/n_G = 0.25 - 1$, safety factor $q_{95} = 3 - 9$, and different mix of the RF heating, $P_{RF} = 10 - 50\ MW$ covering L-mode and H-mode conditions. Some results presented in figure 1 help to clarify how to choose the scenarios with the minimal neutron yield. Note that at low densities increase of the RF heating to the level sufficient for transition to the H-mode affects mainly the electron temperature, rather than the ion one and therefore does not increase much neutron yield (figure 1 (a), (b)). The duration of the high-power phase is limited by the capabilities of the inertially cooled first wall, typically limited to ~ 30 s. Longer pulses at lower power levels are considered for commissioning purposes.



(a) B/$I_p$=2.65/5 T/MA (b) B/$I_p$=2.65/7.5 T/MA (c) B/$I_p$=5.3/5-7.5 T/MA

Figure 1. Operational space for DD L- and H-modes with 10-50 MW of RF heating.

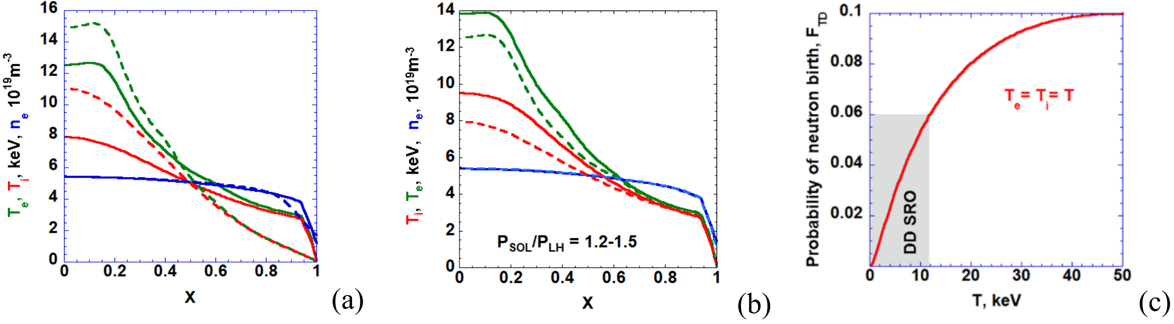


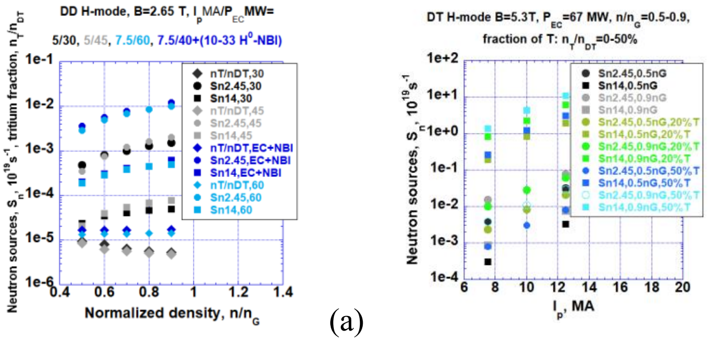
Figure 2. Profiles predicted for DD phase of SRO: (a) (---) L-mode (B/$I_p$=5.3/15 T/MA), (—) H-mode, (B/$I_p$=2.65/7.5 T/MA)$P_{EC}$=40 MW; (b) H-mode (B/$I_p$=2.65/7.5 T/MA), (---) $P_{EC}$=40MW, (—) $P_{RF}$= 50 MW); (c) $F_{TD}$=$S_{n14}/S_{n2,45}$(for neutron sources $S_n$: 14 MeV from $T_{1MeV}D_{th}$/ 2.45MeV from $D_{th}D_{th}$)

The maximal ion temperature predicted for DD SRO phase is rather moderate (Figure 2). Therefore, the ratio of 14 MeV neutron source due to interaction of 1 MeV Tritons born in DD reaction to DD neutron source is small, $S_{n14,T1MeV+Dth}/S_{n2.45,Dth+Dth} < 6\%$ [6].

**Neutron yield due to Boron.** Fast ions can appear at the SRO phase of the new baseline ITER Research Plan operation due to application of ICH and also as products of fusion reactions. These fast ions can interact with B ions producing neutrons and gamma radiation. For the new ITER baseline IRP only 2 values of magnetic field are planned, full-field B=5.3 T and half-field B=2.65 T operation. The 3-ion heating scheme will be explored in SRO but is not foreseen anymore to be of routine use. In hydrogen plasmas for half-field operation ICH absorption (second harmonic) is not efficient and will not be used. Thus, our consideration for interactions of the fast ions accelerated by ICH with B will be limited by full-field operation with $^3$He minority heating scheme for both H and DD and for half-field operation with H minority scheme in DD plasmas. There are two stable Boron isotopes (20% of $^{10}$B and 80% of $^{11}$B) which have several reactions with fast $^3$He and hydrogen ions producing neutrons. Using the results of simulations [7],[8] it is possible to express the upper limits for neutron sources with fast ions as $S_{n,3HeB,max}[n/s] \sim 2.4\ 10^{12} c_{3He,\%} c_{B,\%} n_{20}^2$ , $S_{n,pB,max}[n/s] \sim 9\ 10^{12} c_{H,\%} c_{B,\%} n_{20}^2$ , where $c_{H,\%}$ , $c_{3He,\%}$ , $c_{B,\%}$ are the fractions of the hydrogen, $^3$He minorities and Boron ions, $n_{20}$ is the plasma density in $10^{20}$m$^{-3}$. For half-field/half-current operation the plasma density limit is 2 times smaller than for full field operation. It should be noted that this limit $S_{n,pB,max}$ (typically lower than 3 $10^{14}$ n/s for 10% boron and hydrogen concentrations) is much smaller than the neutron yields due to DD reactions (> $10^{16}$ n/s). Similarly, for $^3$He operation at 5.3 T in DD plasmas at 7.5 MA the neutrons produced by B reactions are negligible compared to DD.

Therefore, the only relevant process for neutron production by fast particles and B is that associated with $^3$He-B reactions in H plasmas. Assuming all L-mode plasmas in H at 5.3 T operating in L-mode at $n_e = 0.5 n_G$ with 10% B and 10% $^3$He with 13 effective shots per day and 50 s heated flat-top duration, the cumulated $^3$He/p-B neutron production during the SRO for L-mode at full field with $^3$He minority heating is assessed as 6 $10^{18}$ n in 8.5 month of operation.

**Neutron yield during DT-1 phase.** In DT-1 it is planned to extend the auxiliary heating to 60 MW ECH + 10 MW ICH + 33 MW NBI for DT-1. The duration of the shots can be essentially increased beyond 30 s due to actively cooled wall. The DD operation at DT-1 phase is planned to develop control in the scenarios at low activation starting from low currents, increase tritium content to 50%, extrapolate and validate DD scenario to higher currents and repeat such steps until the plasma reaches full Q=10 DT performance within a total neutron fluence of 3.5 $10^{25}$ neutrons. In the new baseline it is planned to use DD operation in 50 s shots in the initial campaigns (FPO-1 to FPO-3) as follows: 4 months of H-mode at $I_p/B$ = 3.5-5/2.65 MA/T; 1 months at $I_p/B$ = 5-7.5/5.3 MA/T; 2.5 months at $I_p/B$ = 10/5.3 MA/T; 5 months at $I_p/B$ = 12.5-15/5.3 MA/T. . This is followed by long pulse operation 300 s: 3x3 months at $I_p/B$ = 12.5-15/5.3 MA/T, 2 months at $I_p/B$ = 15/5.3 MA/T in FPO-4 and FPO-5 respectively.



(a) (b)

Figure 3. Neutron sources and tritium fraction for $n/n_G$=0.5-0.9: (a) $I_p/B$=5-7.5/2.65 MA/T DD, $P_{aux}$=30-73 MW, (b) $I_p/B$=7.5-12.5/5.3 MA/T DD-50:50 DT, $P_{aux}$=67 MW.

Examples of the scans of current, density, heating mix and tritium fraction are presented in Figure 3. For the DT-1 phase contribution of DD operation to the fluence limit of 3.5x$10^{25}$ neutrons is negligible compared to DT.

**Discussion and conclusions.** The results of this assessment are used to provide the background for the choice of plasma scenarios for the ITER Research Plan, within the limits of the neutron budget imposed for such operational phases (1.5x$10^{20}$ for SRO and 3.5x$10^{25}$ for DT-1), and for associated assessments. In this assessment we neglected presence of thermal deuterium due to limited purity of hydrogen ($n_D \sim 1.5\ 10^{-4}\ n_H$). For SRO the predicted level of 14 MeV neutron yield does not exceed 6% of total fluence. and the cumulated contribution of neutrons originated from interaction of fast ions (p, $^3$He) accelerated by ICH minority heating with Boron is below 4% of total fluence during the SRO.

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