PUMPING REQUIREMENTS FOR CORE PLASMA PERFORMANCE IN STEP USING JINTRAC

[1]E. THOLERUS, S.S. HENDERSON, D. MOULTON, R. FUTTERSACK, F.J. CASSON, A. HUDOBA, S.P. MARSDEN, O. MYATRA, R.T. OSAWA, J. SIMPSON, L. XIANG, [2]A. TARAZONA, [3]F. KOECHL

[1]UKAEA (United Kingdom Atomic Energy Authority), Culham Campus, Abingdon, OX14 3DB, UK
[2]UK Industrial Fusion Solutions Ltd, Culham Campus, Abingdon, OX14 3DB, UK
[3]ITER Organization, Route de Vinon-sur-Verdon, CS 90046, 13067 St. Paul Lez Durance Cedex, France

Email: emmi.tholerus@ukaea.uk

The interplay between pump and core plasma in tokamaks is a highly integrated problem, requiring consistent plasma solutions from the magnetic axis all the way to the pump via the scrape-off layer (SOL). This is a crucial problem for any DEMO-class reactor, such as the Spherical Tokamak for Energy Production (STEP), which requires efficient pumping of helium ash to avoid degradation of fusion power performance due to impurity dilution. STEP is intended to demonstrate net electric output power of the order 100 MW during steady-state flat-top operation, which means that the total fusion power will need to significantly exceed the power required for heating, fuelling and coil systems to account for various loss mechanisms [1]. JINTRAC [2], which is a unique tool for integrated core, edge, SOL, pump and divertor modelling at runtime, has been used in this work to model α-particle generation, thermalisation and transport to the pump surfaces. The benefits of running a core/SOL/pump integrated model as opposed to a core-only plasma model are that self-consistent boundary conditions can be applied at the last closed flux surface, and quantitative pump parameters, such as the pumping speed, can be directly correlated with core plasma performance. If the study reveals that the required pumping speed cannot be achieved due to technical limitations, the design of the exhaust systems, and possibly the whole tokamak, might need to be reassessed. Another option would be to develop scenarios with higher helium compression (ratio of helium density in the divertor and the main chamber) to increase the helium throughput. Preliminary results have indicated that helium pumping speeds around $S_{\mathrm{He}} \sim 50\ \mathrm{m}^3/\mathrm{s}$ or larger might be required to sustain adequate fusion power performance. Although this value is higher than what has been achieved experimentally for similar types of pump systems (e.g. $S_{\mathrm{He}} = 7\ \mathrm{m}^3/\mathrm{s}$ for ASDEX Upgrade [3]), advancement in pump technology until ~2040, when STEP is expected to operate, could potentially push the achievable pumping speeds. ITER works with the assumption of pump systems that support $S_{\mathrm{He}} > 52\ \mathrm{m}^3/\mathrm{s}$ [4].

A comprehensive overview of the STEP exhaust scenario, including divertor and pump designs, is presented in [5]. Fig. 1 below illustrates the full geometry of the first wall, divertors and pump surfaces that have been assumed in the presented JINTRAC simulations, which matches the latest iteration of the designs in [5]. It includes a highly elongated plasma (κ ≈ 3), with up-down symmetric geometry, double-null divertors and extended outer legs. Active pumping is limited to the outer divertor regions, and dome structures are included to direct the neutral flow between the inner and outer divertor regions. D, T and non-helium impurities are pumped via a cryopump system, whereas helium is carried via separate turbomolecular pumps to the rest of the fuel cycle, meaning that the pump system designs can be optimised separately for helium ash and for other species.

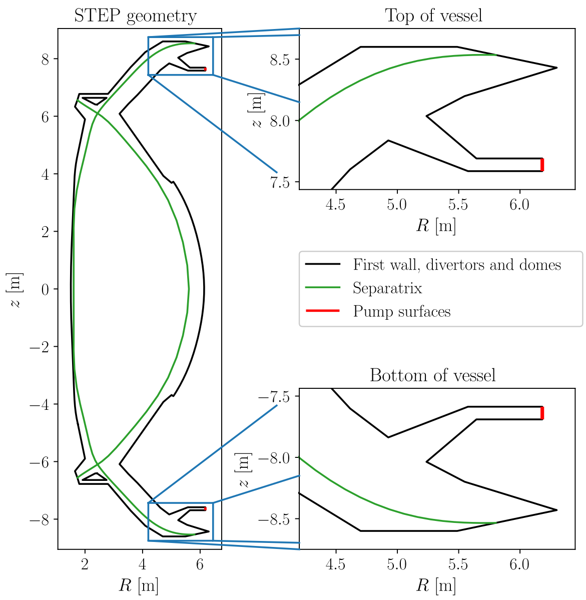

Figure 1. Cross-sectional view of the wall, divertor and pump geometries that have been assumed in the presented JINTRAC simulations.

The presented simulations only target steady-state flat-top DT-plasma solutions, which corresponds to the part of the scenario where net electric power is intended to be demonstrated, and where helium ash is produced at the highest rate. A study of the STEP flat-top operational space, including a list of candidate operating points, is presented in [6] (the scenario modelled here most closely resembles the operating point labelled EC-HD in [6]). The main components of JINTRAC are EDGE2D/EIRENE for modelling of SOL plasma and neutrals, first wall, divertor, gas puffing and pumping, and JETTO for integrated core plasma modelling, including transport, heating & current drive, pellet fuelling, equilibrium calculation and fusion reactions. JETTO and EDGE2D/EIRENE are coupled via boundary conditions at the last closed flux surface. The pedestal height and width are scaled as described in [6], and a Bohm/gyro-Bohm model is used for core transport, rescaled on feedback against a target value of total (thermal + fast) normalised beta β_N. The confinement assumption is then assessed by comparing the heat confinement time against empirical scalings (see details in [6]).

A pre-study with a set of core-only simulations have been done to find the acceptable level of helium dilution, as seen in Fig. 2.a. Each point corresponds to a steady-state JETTO simulation, where the helium density boundary condition applied at the separatrix has been varied. Assuming a minimum value of P_{fus} = 1.5 GW [6], the helium concentration must be below about 10.5 % on average for sufficient fusion power performance. Four coupled core + SOL/pump/divertor scenarios have then been evolved with different values of the helium pumping speed S_{He}, as shown in Fig. 2.b – 2.f, to estimate the pump parameters required for reaching $\langle n_{\mathrm{He}}\rangle/\langle n_e\rangle$ < 10.5 % at steady-state operation. Although none of the cases have yet reached steady-state, the lowest pumping speed case (S_{He} = 12 m^3/s) already has $\langle n_{\mathrm{He}}\rangle/\langle n_e\rangle$ > 12.1 % and increasing, and a fusion power below 1.47 GW. On the other hand, the three remaining pumping speed cases will most likely saturate at helium concentrations below 10.5 %. In principle, a scenario can collapse towards $P_{\mathrm{fus}} \rightarrow 0$ if the fusion power and the resulting α-heating is too low to maintain the ion temperature, causing a feedback loop with decreasing P_{fus} and T_i. To prevent this from happening in transient stages of the scenarios, the feedback on transport against β_N with a resulting variability of the heat confinement breaks this feedback loop (the oscillations in Fig. 2.c, 2.e and 2.f are a consequence of the variable heat confinement). However, with decreasing α-heating, more optimistic confinement assumptions are required to maintain target kinetic pressures, which will result in an elevated confinement factor. So far, all of the scan points have confinement factors H^*_{98} oscillating around values 1.35 – 1.38, as seen in Fig. 2.f. As the scenarios approach steady-state, high values of the confinement factor ($H^*_{98} \gtrsim$ 1.4) could indicate that overly optimistic heat confinement assumptions are required to sustain the target fusion power performance, which would invalidate the corresponding scenario.

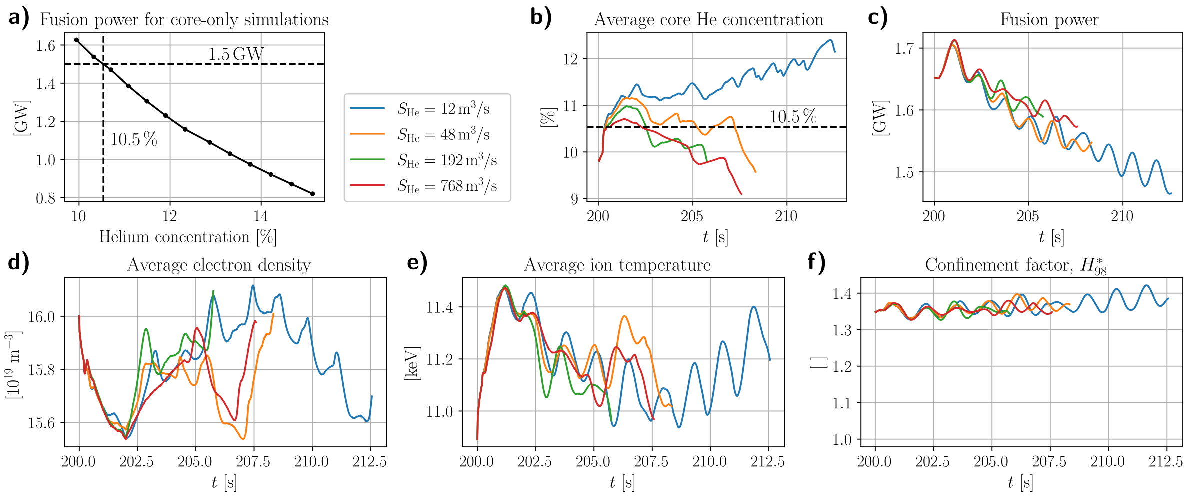

Figure 2. a) Core-only simulations for studying relationship between helium dilution and fusion power performance. b) – f) Main results from the scan in helium pump efficiency with JINTRAC. The scan parameter is the helium pumping speed, S_{He}, which is increased by a factor of 4 in each step. H^*_{98} follows the same definition as given in [6].

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