Contribution ID: **1149** Type: **Regular Oral**

Multi-machine SOLPS-ITER comparison of impurity seeded H-mode radiative divertor regimes with metal walls

Wednesday 12 May 2021 11:48 (17 minutes)

During burning plasma operation on ITER, extrinsic impurity seeding will be mandatory for heat flux control at the tungsten (W) divertor vertical targets [1]. A very extensive database of SOLPS plasma boundary code simulations has been compiled for ITER [1], including the most recent advances, obtained with the SOLPS-ITER version, in which for the first time, fluid drifts have been included [2]. These simulations predict that partially detached divertor solutions at high divertor neutral pressure will be possible on ITER for baseline burning plasmas ($Q_{DT} = 10$, power into the scrape-off layer $P_{SOL} = 100MW$), with both neon (Ne) and nitrogen (N) low Z seeded impurity, and with impurity compression sufficient in both cases to maintain the majority of the radiated power in the target vicinity. Drifts are found to be relatively unimportant under such conditions. This is in contrast to observations on smaller devices with W divertors, such as ASDEX-Upgrade (AUG), in which Ne compression is reduced in comparison with N, core plasma performance is compromised and drift effects are stronger. However, Ne is preferred on ITER in DT plasmas to avoid impact on machine duty cycle due to the formation of tritiated ammonia [1]. It is thus critical that the fundamental controlling physics responsible for this behavior be understood, in particular the impact of scale size. This contribution identifies the key factors at play through a unique SOLPS-ITER simulation study in which Ne-seeded H-mode conditions in vertical target W divertor geometries are compared in the three devices, ASDEX-Upgrade (R=1.65 m), JET (R = 3.0 m) and ITER (R = 6.2 m), spanning a factor of more than 3 in linear dimension in almost equal size intervals.
For AUG and JET, the modelling parameters are inspired by existing experimental results, but do not attempt to match a particular discharge. High power, H-modes with $P_{SOL} = 12MW$, $q_{95} = 5.5$ (AUG) and $P_{SOL} = 20MW$, $q_{95} = 3.3$ (JET), and cross-field heat transport chosen to match the typical SOL widths, λ_q observed on these devices under such conditions, give comparable power flows at the divertor entrance to those for the modelled ITER burning plasma with $\lambda_q = 3 - 4mm$, $P_{SOL} = 100MW$, $q_{95} = 3$. All simulations include fluid drifts and currents, with neutrals traced by the EIRENE code. Semi-detached divertor conditions are established in all cases using moderate Ne seeding and high deuterium throughput.
An important finding is that the impact of the poloidal and radial ExB drifts (redistributing plasma between the outer and inner divertors through the private flux region [3]) steadily decreases with increasing machine size. The divertor asymmetry associated with these drifts also thus decreases with size. As shown in Fig. 1, the high field side, high density front observed experimentally in AUG [4] and JET [4] is reproduced by the modelling, but is absent in the ITER simulation. On AUG this front reaches the X-point vicinity and can influence the pedestal plasma [5]. The same divertor asymmetry driven by the ExB drift drives a significant redistribution of Ne impurity, which tends to accumulate in the more detached inner divertor (Fig. 2). The resulting increased impurity radiation further exacerbates the divertor asymmetry, making it harder to achieve partially detached conditions in the outer divertor without impurity concentrations exceeding acceptable limits for core performance. This effect also decreases with increasing machine size. The relative importance of $\nabla B \times B$ and Pfirsch-Schlueter (P-S) driven flows in the SOL region also differs between ITER and smaller devices. Whilst in AUG, P-S flow provides the main contribution to flow reversal in near SOL, in ITER excess ionization in the strike point region will be the principal driver.
A second key size dependent effect concerns the electron temperature (T_e) distribution in the divertor, which depends on the X-point to target connection length. Due to the T_e dependence of the parallel heat conductivity, the region of temperature change near the target or, in the case of detachment, the ionization front, is narrow and does not depend on the X-point position or machine size. The position of this layer thus determines the X-point T_e. For larger devices, with higher confinement, this temperature is higher for the same energy flow at the divertor entrance. Since low Z impurity radiation will be strongest in the region of comparatively low T_e, where many partially ionized states exist, impurity radiation in larger machines is more localized in the divertor. On ITER, this means that even though the strongly radiating region with Ne impurity is more extended than for N seeding at comparable radiated power, both are equally effective at divertor power dissipation. In addition, any Ne ions reaching the ITER pedestal region are fully stripped due to the high T_e there under high performance conditions and cannot radiate, reducing the impact on pedestal power balance.

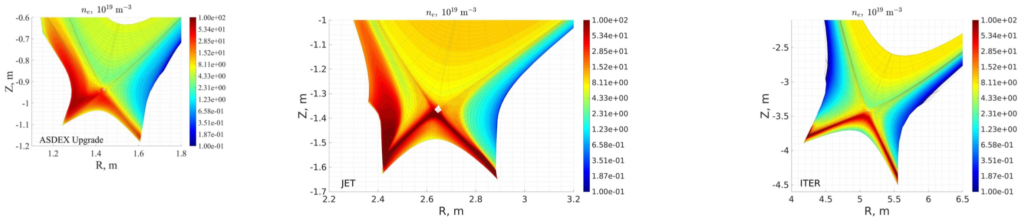

Figure 1: SOLPS-ITER electron density distributions for all 3 machines.

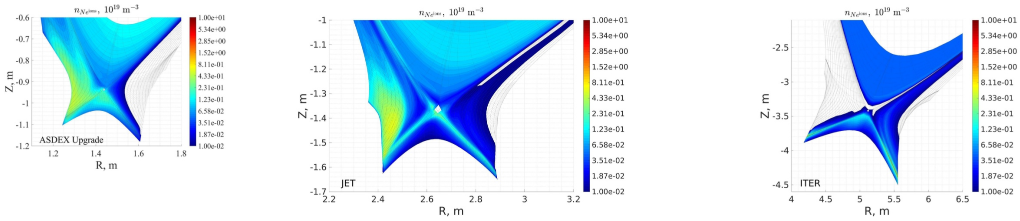

Figure 2: SOLPS-ITER neon ions density(all charge states) distributions for all 3 machines.

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[2] E. Kaveeva et al Nucl. Fusion in press: DOI 10.1088/1741-4326/ab73c1
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Session Classification: TH/3 Pedestal / edge / SOL

Track Classification: Magnetic Fusion Theory and Modelling