IMPACT OF PLASMA BOUNDARY ON MACHINE OPERATION AND THE RISK MITIGATION STRATEGY ON JET

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This work examines the separatrix and Scrape-Off Layer (SOL) characteristics in three scenarios on JET: the Quasi-Continuous Exhaust (QCE) regime [1], the core-edge-SOL integrated ITER Baseline scenario [2], and the X-point Radiator (XPR) regime [3]. The QCE regime in particular serves as a case study to illustrate the critical need for integrating physics insights, risk identification, operational strategies, and real-time protection to successfully implement new scenarios for fusion devices. The QCE regime is distinguished by its generally higher separatrix and SOL collisionality, associating with broader SOL width. These features, combined with the near-double-null (DNX) configuration, introduce several operational challenges. The enhanced cross-field particle transport and resulting broader SOL width interact with fast Beam neutrals, contributing to an unfavourable power load on local limiter. Additionally, the heat load on the Upper Dump Plate Tiles (UDPT) and outer limiter in the QCE regime can be up to 5–6 times higher compared to the other scenarios. However, through careful operational planning and robust real-time protection system, the power loads were effectively managed within acceptable limits during QCE pulses, enabling successful scientific outcomes.

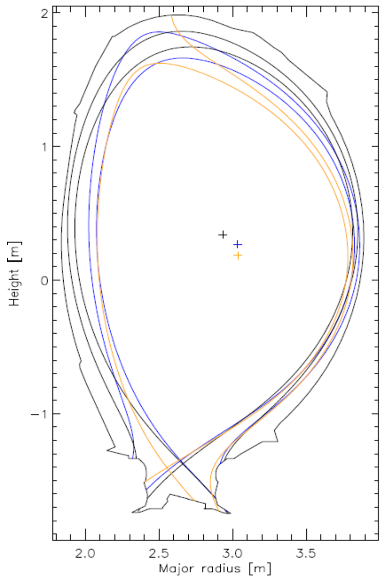

Figure 1. Poloidal cross-sections of plasma configurations for the ITER-baseline (blue), XPR (black), and QCE (yellow).

All three scenarios aim to provide power exhaust solutions through different approaches. The ITER-baseline employs intermediate level of impurity to create a partially detached divertor; the XPR regime leverages an X-point radiator created by heavy impurity seeding to dissipate a significant portion of power; the QCE regime relies on strong shaping and high $n_{e,sep}$ to suppress ELMs by producing low-amplitude filaments instead. Figure 1 shows the typical plasma configurations for the three scenarios. The normalized SOL density decay length $\lambda_{n_{e,u}}$ increases with the normalized collisionality, ν^*_{SOL}, in figure 2, consistent with previous observation on AUG [4] and JET [6]. QCE pulses, exhibiting generally higher υ^*_{SOL}, show significant SOL width broadening, up to 3-4 times at high υ^*_{SOL} compared to pulses from the other two scenarios. Enhanced cross-field particle transport and the resulting broader SOL width led to increased ionization of fast beam neutrals, which caused re-ionization power load on the Be limiter, as previously reported in Tritium campaign [7]. The broadening SOL width in QCE pulses can also lead to excessive power loads on the plasma-facing components (PFCs) in the main chamber. The energy density on both UDPT and the outer limiter can be up to 5–6 times greater in QCE pulses. For both ITER-baseline and XPR pulses, the ratio of the energy load on the UDPT to the total radiated energy remains nearly constant across a large range of ν^*_{Sep}, suggesting that the energy load on UDPT is primarily due to radiation, figure 3. In contrast, for QCE pulses, the energy load on the UDPT is not only higher overall but also increases with ν^*_{Sep}, this is consistent observation in AUG [8].

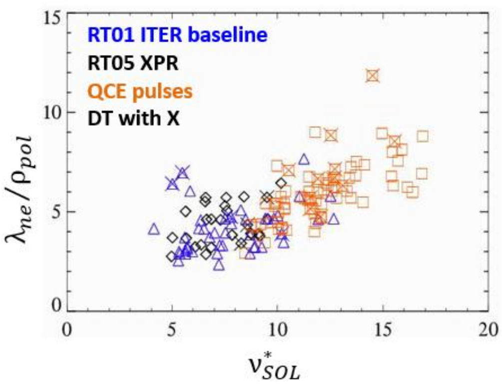

Figure 2. The normalized near SOL $\lambda_{n_{e,u}}$ against $\nu^*_{SOL} = 10^{-16} n_{e,sep}\, L/T^2_{e,sep}$ for the three scenarios studied. Poloidal gyro-radius, $\rho_{pol} \propto \frac{\sqrt{m_i T_{e,sep}}}{eB_{pol}}$

The energy distribution shows a pronounced inner-outer asymmetry, with the energy deposited on the outer limiter being up to four times higher than on the inner limiter. The underlying physics requires further investigation.

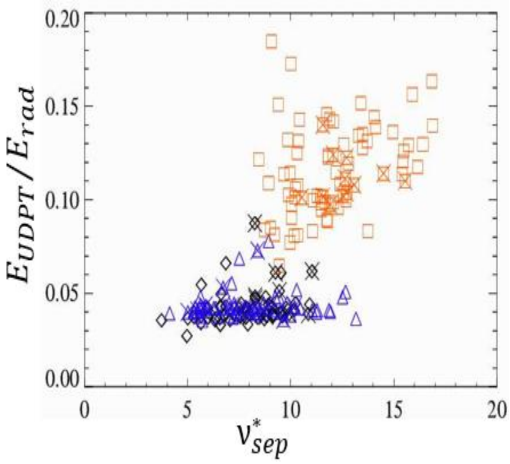

Figure 3. The normalized energy found on UDPT against v^*_{SOL}.

The JET-ILW UDPT are not built to handle excessive power loads, so significant efforts were devoted to operational planning to ensure machine safe execution. The desired configurations were developed with the scenario design code Proteus. During design phase, scans of the plasma separatrix's proximity to the UDPT and the SOL width λ_q were made in Proteus to determine the maximum allowable power to the upper divertor leg, figure 4. This analysis provided a safety guideline for setting the top distance throughout the operation for given heating powers. During execution, a progressive approach was employed. The experiment began with low plasma current configurations in Ohmic pulses to confirm the expected top clearance, with adjustments made as necessary. Heating power was then gradually introduced, starting with a large top clearance. The distance to the top was gradually reduced, and the heating power and duration were increased in cautious, incremental steps.

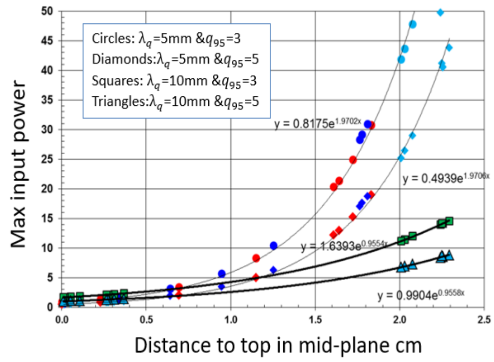

Figure 4. Maximum allowable input power for QCE. The target wetted area calculated by Proteus and 8.5 MWm^{-2} assumed for max allowed power density to Be wall.

JET has developed a robust and sophisticated real-time protection system, including elements to protect against high PFC power loads. A real-time protection [9] of PFCs based on CCD cameras covers the majority of PFCs and connects to all the main tokamak controls and heating systems. During QCE experiment, detection of high temperatures in either the re-ionisation region or UDPT triggers a tailored response: decrease of additional heating power, change of configuration, and movement of the plasma away from the PFCs. A complementary real-time monitoring system, known as WALLS, uses thermal models to evaluate the wall temperature and monitors the plasma boundary geometry, ensuring the plasma does not enter prohibited configurations that could directly expose the wall to the plasma—a critical feature for the development of new scenarios like QCE.

With strategic operational preparations and a robust real-time protection system in place, the risks associated with the QCE plasma boundary were effectively managed, enabling excellent scientific outcomes. The successful implementation of the QCE regime, alongside other record-breaking experiments on JET, highlights the critical role of detailed physics understanding, thorough operational planning, and robust real-time protection in scenario development. These findings on JET not only enhance the understanding of plasma boundary behaviour but also serve as a foundation for developing scenarios in next-generation fusion reactors.

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