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Impact of the Plasma Boundary on Machine Operation, and the Risk Mitigation Strategy on JET

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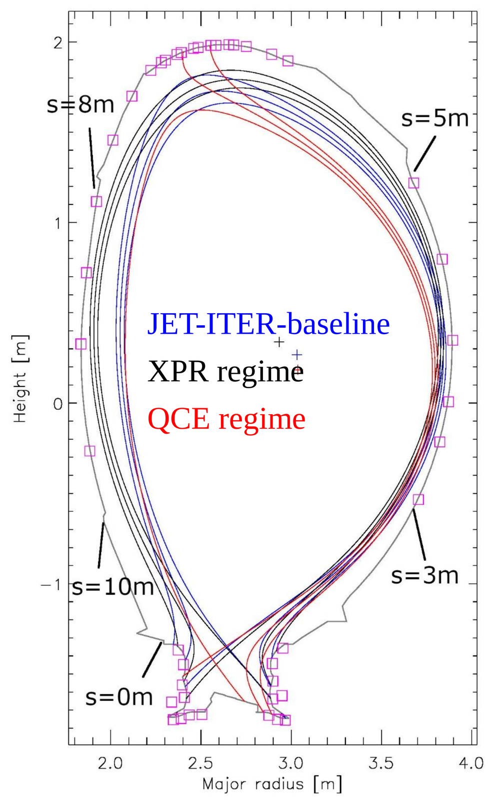
ABSTRACT

We investigated separatrix and Scrape-off-Layer (SOL) behaviour in three JET regimes: the Quasi-Continuous Exhaust (QCE), ITER Baseline, and X-point Radiator (XPR). QCE, characterised by higher collisionality and a broader SOL in near-double-null configurations, introduces several operational challenges. With careful operational planning and real-time protection, these challenges were managed, demonstrating integrated effort needs to implement new scenario for future devices.

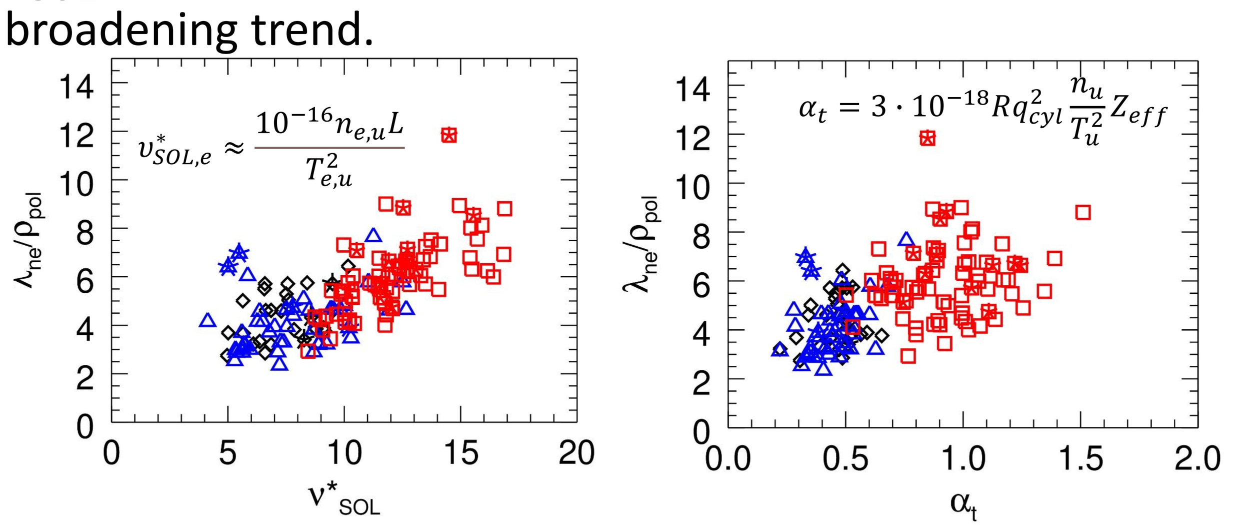
1. BACKGROUND

- Fusion scenarios must deliver high performance while protecting plasma-facing components.
- ITER will face much higher steady and transient heat loads than current devices.
- JET develops and tests integrated solutions: ITER Baseline – reference scenario for 15MA; XPR – impurity radiation to spread power; QCE – intrinsic small ELM regime with broad SOL transport.

2. Broader SOL width in QCE regime



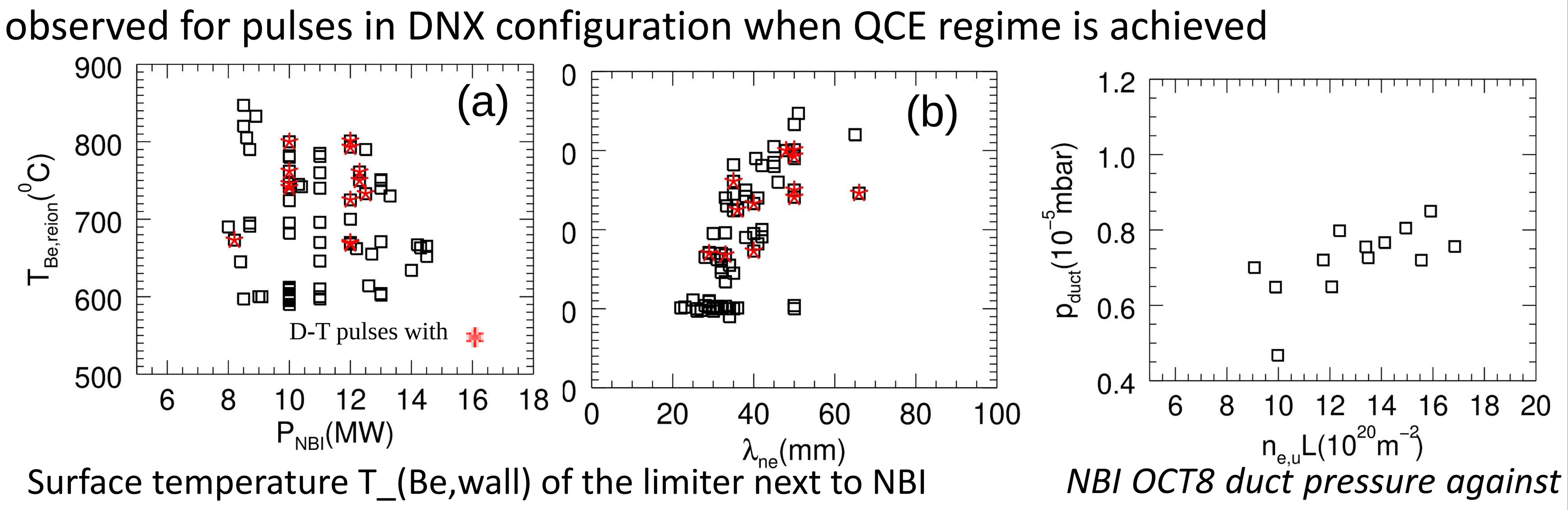
The near-double-null (DNX) shape is used for QCE on JET and the regime is distinguished by its generally higher separatrix and SOL collisionality, associating with broader SOL width. ν^*_{SOL} appears to be a good ordering parameter for the SOL broadening trend.



3. Impact of QCE plasma boundary on JET operation

3.1 Interaction with NBI: duct pressure and re-ionisation issue

The resulting broader SOL interacts with fast Beam neutrals, contributing to an unfavourable power load on local limiter. Elevated pressures in the Beam Duct were observed for pulses in DNX configuration when QCE regime is achieved

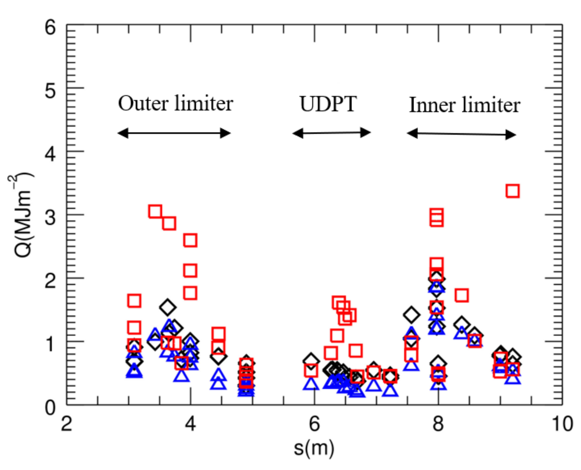


Surface temperature T_(Be,wall) of the limiter next to NBI Octant(a) Octant 4 NB total input power; and (b) near SOL density decay length $\lambda_{n_{e,u}}$ for QCE pulses

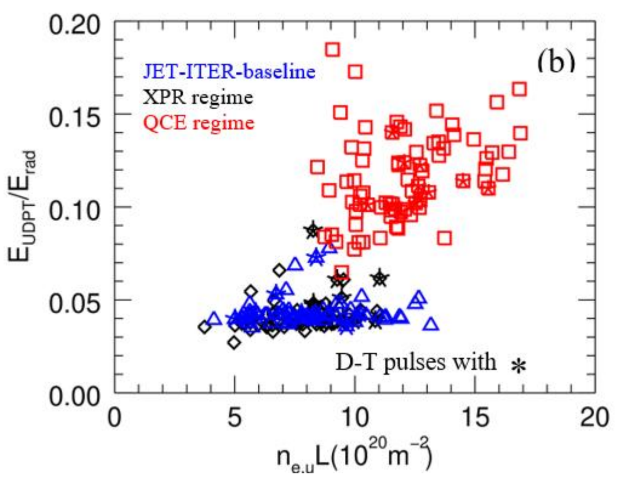
NBI OCT8 duct pressure against $n_{e,u}L$ for QCE non-neon seeding pulse.

3.2 Impact on energy distribution to PFCs

The heat load on the Upper Dump Plate Tiles in the QCE regime can be up to 5–6 times higher compared to the other scenarios. Additionally, the energy distribution shows a pronounced inner-outer asymmetry in QCE pulses, with the energy deposited on the outer limiter being up to four times higher than on the inner limiter



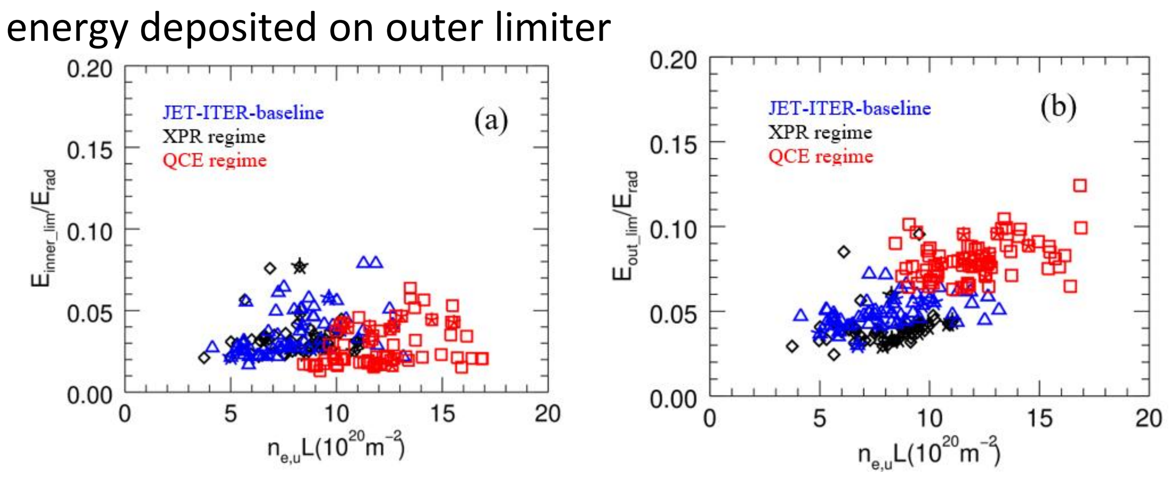
LHS: Energy density along the first wall poloidally for three regimes with comparable input energy. RHS: The normalized energy found on UDPT by total radiated energy.



3.3 Inner-outer asymmetry of power load

QCE pulses have 3-4 times higher energy deposited on outer limiter

a) The normalized energy to inner limiters by total radiated energy against $n_{e,u}L$. (b) The normalized energy to outer limiters by total radiated energy against $n_{e,u}L$

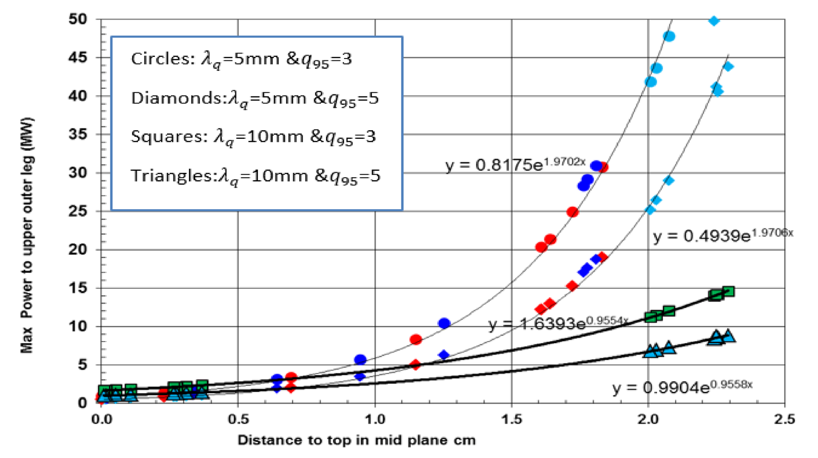


4. The risk mitigation strategy on JET

4.1 Scenario Development strategy

A progressive approach performed:

- Verifying the DNX config with low Ip Ohmic pulse
- Assessing the UDPT power handling by comparing with previous high delta pulse
- Applied DNX progressively with auxiliary heating; reducing top clearance step by step;
- Progress to next step only after confirming no overheating at UDP

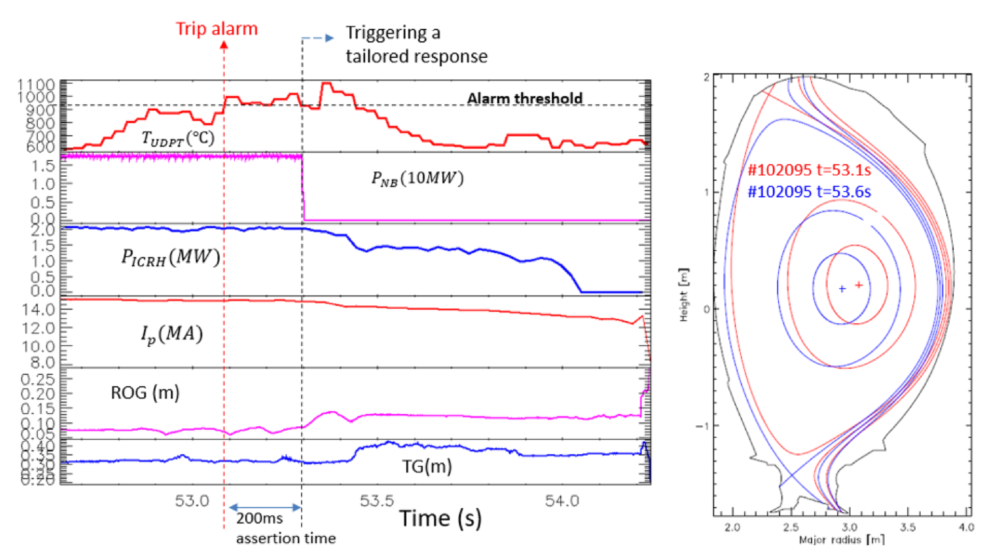


Proteus Code used for:

- designing double null configuration;
- determining the maximum allowable power to the upper divertor leg by performing top gap scan.

4.2 Robust real time protection

- JET's real-time protection system uses IR cameras to monitor PFC loads, with overheating triggering reduced heating or plasma shape adjustments.
- The WALLS system complements this by applying thermal models and boundary checks to prevent unsafe plasma–wall contact during scenario development



An example showing overheating of UDP tiles in QCE regime triggers a tailored response from 53.3 s as in RHS figure

5. Discussion and summary

•**Scenarios analysed**: QCE, JET-ITER Baseline and XPR,. All address power exhaust with different strategies; QCE highlighted for broad SOL profiles and strong shaping.

•**Challenges in QCE**: Broad SOL → enhanced NBI re-ionisation, localized loads on Be limiter, higher flux to main chamber limiters, extra power on UDPT.

•**Risk mitigation strategies**

✓ Operational risks anticipated and precautious experimental strategies set up prior to the execution.

✓ Desired double null configuration and maximum allowable power were simulated by equilibrium Code-Proteus.

✓ Robust Real-time protection system prevented the power load damage and assisted the configuration implementation.

The QCE experiments at JET exemplify how advanced physics understanding, thorough preparation, and innovative risk mitigation strategies enable the successful implementation of new scenario

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