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An Assessment of Alternative Divertors for the European DEMO

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The uncertainties surrounding the physics of plasma exhaust and its centrality in reactor design require a thorough evaluation of promising alternatives as a precautionary measure to avoid delays in DEMO, if the ITER solution for the divertor could not extrapolate to reactor relevant machines. In this contribution, we review the physics and engineering work carried out within EUROfusion's work package DTT1/ADC on the subject (see Fig.1), showing with a quantitative assessment that alternative configurations provide a larger operating space than the single null according to multifluid simulations (in particular, lower Argon seeding levels and core concentration; lower separatrix density for comparable divertor protection; greater resilience to high power operations), but also highlighting the many engineering challenges that these configurations entail. The 3D engineering analysis of the alternative designs shows that the balance between port space for remote maintenance and the reinforcement of the supporting intercoil structures, stiffening the structure with respect to out of plane forces, is crucial to achieve acceptable solutions. In addition, active and passive magnetic control, pumping, neutronics and turbulence in alternative configurations will be discussed with quantitative analyses.

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With alternative configuration we define here any divertor solution that cannot be qualified by ITER and it includes, but is not limited to, Double Null, Snowflake, Super-X and X divertors. As a risk mitigation strategy, EUROfusion has worked on understanding the physics and engineering of new exhaust configurations for reactor relevant devices and DEMO in particular. The objective is to provide a physics and engineering assessment of the usefulness and feasibility of alternative divertor configurations for DEMO by December 2023.

The primary activity of this project is to deliver integrated results through a "loop"where physics and the engineering concepts for sufficiently well-developed alternative designs are synergistically iterated and optimized, see Fig.1. In parallel, it develops more refined techniques and novel concepts that will become part of the "loop"when (or if) they reach maturity. The first iteration between physics and engineering is completed and its results will be presented. All alternative configurations investigated could be generated with external coils only and respecting the engineering force constraints on the poloidal field coils and the central solenoid.

As far as physics is concerned, detachment behaviour in the alternative configurations was assessed at an unprecedented level by comparing each design for an identical and large range of fuelling and Argon seeding influxes. The analysis is performed with state-of-the-art tools (SOLPS) so that future simulations will enable the correct understanding of complex effects such as the fluxes from neutral recycling and kinetic neutral effects. Also, the resilience of the operating point with respect to variations is systematically examined with this procedure for the first time, leading to a full map of the plasma response to changes in fuelling and seeding. Hence, detachment onset, depth and stability are obtained for these configurations, rather than just the operating point. The simulations show, for example, that the super-X and X-divertor configurations are effective in broadening the operating range by allowing acceptable heat fluxes and temperatures at the divertor at a significantly smaller Argon seeding level than the single null, a result reported in Fig.2. In the double null configuration, a lower fraction of the radiated power is localised in the core with respect to the single null, thus providing more margin.

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The multifluid studies were complemented by 3D turbulent simulations, assessing for the very first time the behaviour of the anomalous perpendicular transport in alternative configurations. Four state of the art codes (GBS, GRILLIX, STORM and TOKAM3X) were used to simulate all the alternative configurations albeit on a reduce scale to make the computational cost manageable. The simulations show that turbulence is enhanced in the long leg of the Super-X divertor and that the Snowflake generates at the X-point a convective cell induced by drifts that helps redistributing the particles and heat to the four legs (this is similar to the churning mode,

but the perturbation is electrostatic). This insight not only sheds light on the fundamental mechanisms behind alternative designs, but it will also help optimize the configurations in the next iteration by refining the SOLPS modelling.

In addition, a new detailed engineering analysis of the structural loads in the toroidal field coils of each configuration will be presented, including an assessment of the importance of the out of plane forces versus the hoop forces, which contribute to ˜30% of the total. Our results show that former play an important role in taking the configurations beyond the acceptable stress threshold, thus suggesting that more rigid configurations could be beneficial. Full 3D builds (see Fig. 3), including port access for remote maintenance and intercoil structures have been produced and the technical complexities associated with them will be discussed, including the difficulties associated with the extraction of the divertor cassette in Super-X and Snowflake designs. Controllability of all the solutions has been investigated for variations of beta poloidal and Li of order of 10%. Large excursions of the strike point and significant changes of shape in the Snowflake configuration were observed, while the X-divertor configuration produces a visible but acceptable sweeping on the divertor plates and separatrix of the Super-X tends to get closer to the unprotected upper wall (24cm of vertical excursion). In addition, the paper will give a review of a number of issues associated with alternative configurations, such as helium pumping, which preliminary results predict to be acceptable in all configurations; force constraints on the structures during the whole discharge from ramp up to ramp down, which might be problematic; and detailed neutronic calculations of relative tritium breeding ratios, irradiation of the coils and nuclear heating performed with the Monte Carlo particle transport code MCNP based on geometry from the CAD design of the different configurations, with particular attention to the potential shielding that alternative configurations could provide.

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The work carried out suggests that a milder version of the alternative configurations, combining some concepts together (for example a version of the Super-X with shorter leg and significant poloidal flux expansion) could be more suitable for reactor conditions.

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