THE PHYSICS BASIS FOR IMPLEMENTING ALTERNATIVE DIVERTOR CONFIGURATIONS ON REACTORS

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Executive summary: *Alternative Divertor Configurations (ADCs) offer promising solutions to one of the biggest challenges for fusion energy: power exhaust. Recent EUROfusion collaborative research on TCV and MAST Upgrade demonstrated key ADC benefits, increasing their readiness for reactor implementation. These benefits include reduced target heat loads, an expanded detached operational regime, improved power exhaust control, and enhanced core-edge compatibility. These findings agree with predictions from reduced models and simulations, reinforcing confidence in extrapolating current results to reactor conditions. Our analysis highlights the synergy between different divertor optimisation strategies, showing that modest yet strategic divertor shaping can significantly enhance power exhaust performance, supporting ADC integration in future reactor designs.*

Fusion energy is accelerating through designs based on established technologies (DEMO) and alternative compact reactor designs that are potentially faster and cheaper to build (e.g., STEP, ARC), pursued via public-private partnerships. Power exhaust remains one of the biggest challenges across all these efforts. Alternative Divertor Configurations (ADCs) modify the magnetic divertor topology to enhance power exhaust performance, serving as risk mitigation for DEMO and enabling power exhaust in compact reactors. ADC research is a top priority within the EUROfusion tokamak experimental programme. This work presents its key findings that provide the strongest evidence to date of ADC benefits, from TCV [1] and MAST-U [2] experiments, consistent with reduced models and simulations. These results establish a physics basis for ADC reactor implementation, revealing a continuum of divertor optimisation strategies, balancing engineering complexity with power exhaust performance.

1. POWER EXHAUST BENEFITS

Our studies demonstrate that long-legged ADCs (Figure 1) with either increased total flux expansion (MAST-U's Super-X (SXD) and Elongated Divertor (ED)) and/or featuring a secondary null (TCV's X-Point Target (XPT)) offer critical advantages over Conventional Divertors (CDs) without adversely impacting core performance. These ADCs exhibit **more than an order of magnitude heat flux reductions** (q_t), exceeding expectations based on geometric spreading alone due to additional volumetric power dissipation (>x3) [3-5]. Beyond reducing q_t, these ADCs aid detachment access, enlarging the operational parameter ranges (core density (by >3.5 x), P_{SOL}, impurity content) in which the divertor is detached, **increasing the flexibility to find suitable reactor operating points**.

These ADCs enable the passive absorption of disturbances, acting as 'shock absorbers' to **increase the resilience of detachment** compared to CDs [3]. First, they enable a sizeable dense neutral buffer downstream the detachment front (Figure 1) that can protect the target from fast transients (~ ms), including small ELMs, in conditions where a CD would be attached [6]. Secondly, these ADCs reduce the sensitivity of this detachment front location to changes in core density (by >5 x) [3,5] and heating [7] (Figure 1 [3]), a behaviour extending to faster timescales where the plasma dynamically responds to fuelling (30-130 ms) [8]. This reduced sensitivity provides actuators more time to respond to disturbances. This enabled real-time control of the detachment front in MAST-U's ED & SXD, which was not possible in MAST-U's CD (Figure 1 [8]). **Divertor design can thus improve detachment resilience and power exhaust control**, tackling one of the biggest concerns in the power exhaust challenge.

2. PHYSICS BASIS OF ADCS AND REDUCED MODELS

The enhanced performance of ADCs is rooted in well-understood physical mechanisms, confirmed by multi-device experiments and reduced models. Key factors include **divertor poloidal leg length**, which enlarges the neutral buffer downstream the detachment front, helping to mitigate transient fluctuations and deepening detachment via plasma-neutral interactions [3,8]. **Neutral baffling** raises the divertor neutral pressure, augmenting those plasma-neutral interactions while limiting neutral leakage. This minimises ion flows from the main SOL into the divertor on MAST-U/TCV and decouples divertors from each other (and the core) - improving power exhaust control. This enables **total flux expansion** [9] to improve detachment access and reduce its sensitivity to core changes, consistent with reduced models and simulations [3,4]. The magnetic topology induced by a secondary null can give rise to an **'X-Point Radiator (XPR)'**-like structure **in the secondary X-point** [5], providing localised power dissipation without the operational risks typically associated with an XPR [5]. Combining the XPT with total flux expansion yields additional power exhaust benefits, **demonstrating that different divertor shaping strategies can work synergistically.**

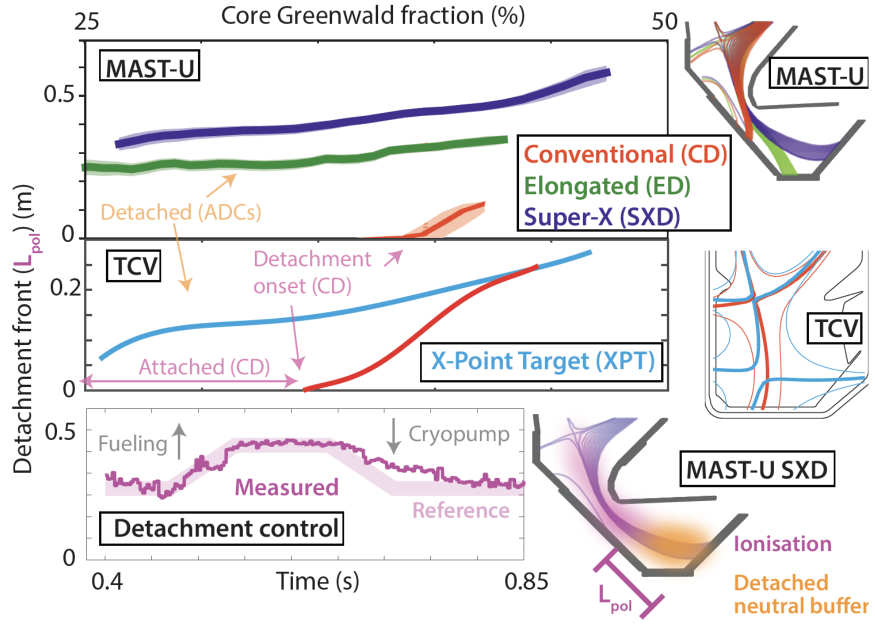

Figure 1: Detachment front evolution showing ADC benefits in terms of detachment access (front detached at lower core density) [3,5], sensitivity (reduced slope front movement) [3,5], operational window (larger window in which the front is between the target and X-point) [3,5] and detachment control [8].

This refined physics understanding highlights a **continuum of ADC characteristics and benefits**, allowing configurations to be tailored to balance power exhaust performance and engineering feasibility. Remarkably, the SXD benefits observed on MAST-U were largely maintained in the Elongated Divertor (ED, Figure 1, [3]) – a configuration with lower total flux expansion, consistent with reduced models. The ED features similar total flux expansion as the ARC X-Point Target [10] and DEMO SXD designs [11]. This underscores the ability to trade-off between engineering constraints and power exhaust advantages, while reinforcing that current ADC experiments provide a strong basis for reactor implementation.

3. IMPLICATIONS FOR REACTOR DESIGNS

These results demonstrate that **ADCs offer a spectrum of solutions**, from modest divertor shaping to advanced configurations, all of which can significantly enhance power exhaust performance. This enables a strategic **balance** between **engineering complexity** and **attractive operating regimes**. The agreement between experimental findings, reduced models and plasma-edge simulations increases confidence in using these strategies for reactor optimisation, raising the maturity of ADCs as a viable reactor solution. Building on these insights, EUROfusion is expanding ADC research to high-power, metallic-wall devices such as ASDEX Upgrade – with its new upper divertor supporting ADCs – and WEST for double null studies, paving the way for practical ADC implementations in future fusion power plants.

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