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THE PHYSICS BASIS FOR IMPLEMENTING ALTERNATIVE DIVERTOR CONFIGURATIONS ON REACTORS

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Abstract

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.

1. INTRODUCTION

Fusion energy is accelerating through designs based on established technologies (DEMO, CFETR) and alternative compact reactor designs that are potentially faster and cheaper to build (e.g., STEP [1], ARC), pursued via public-private partnerships. **Power exhaust** remains **one of the biggest challenges across all these efforts.**

Heat and particles are expelled from the core into the edge region (Scrape-Off-Layer – SOL). Using coils to change the magnetic topology, these fluxes are 'diverted' into a dedicated area called the 'divertor'. The very narrow width of the SOL results in **extreme** divertor target **heat fluxes** (150 MW/m^2 for the DEMO reactor design [2]), which ***become even larger for alternative compact reactor designs*** as the power is distributed over an even smaller surface [3,4]. These heat loads far exceed tolerable engineering limits (5-10 MW/m^2): **order-of-magnitude heat flux reductions are required.**

To achieve this, the power must be spread over a larger area. First, radiating impurity gasses are injected to cool the divertor plasma and convert the heat carried by charged particles into heat carried by photons (radiation) that do not follow the magnetic field lines, dissipating the power volumetrically. However, there is a limit to how much power dissipation can be achieved this way. Cooling the plasma increases the ion fluxes towards the target, increasing heat load due to the recombination of ions at the target's surface, limiting the total heat flux reduction to ~4 [5]. Larger heat flux reductions require 'divertor detachment' to reduce the ion target fluxes. At electron temperatures of 3-5 eV, the ionising plasma 'detaches' from the target, forming a neutral buffer downstream of it [6,7]. Plasma-atom and molecular interactions in that buffer cause simultaneous power and momentum losses, reducing target temperatures, ultimately leading to volumetric recombination of the ions – preventing surface recombination target heat loads [6,7].

Obtaining a quasi-steady-state detached solution in reactor-scale devices using conventional divertor strategies require massive amounts of impurity injection, damaging core performance [8]. Once detachment is triggered, it can be highly sensitive to changes in core power, impurity seeding and fuelling [9,10]. A high sensitivity could more easily result in a loss of detachment, damaging the reactor walls, or in the detached region reaching the hot fusing core, resulting in a radiative collapse of the plasma that can catastrophically damage a reactor. Maintaining detachment thus requires very precise, active control; whereas traditional actuators (i.e. valves) for power exhaust control are relatively slow. Fast transient effects will occur in reactors (e.g. sawteeth, LH HL transitions, potentially ELMs, …), causing perturbations that are too fast for actuators to respond. Thus, some level of passive stabilisation by the divertor itself is required to buffer fast transients and reduce requirements on actuator response, aiding power exhaust control. It is currently **uncertain** whether an **acceptable core-edge compatible quasi-steady state solution** can be found for **conventional divertor** approaches [2,11]. It is even **more uncertain** whether such a state and whether **detachment** can be **reliably maintained and controlled**. These challenges require **novel power exhaust solutions** as risk mitigation strategy. Alternative compact designs, where the power exhaust challenge is even more daunting, requires such solutions as a baseline strategy [3,4].

One of such novel solutions are Alternative Divertor Configurations (ADCs), where the magnetic divertor topology is modified to enhance power exhaust performance [12]. 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 MAST Upgrade [13] and TCV [14] 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.

2. POWER EXHAUST BENEFITS ON MAST-U AND TCV

The magnetic topology can be modified in various ways to enhance power exhaust performance, spanning a range of small modifications (strike point angle, divertor leg length, neutral baffling), to moderate modifications (long-legged divertors, increased target radius (total flux expansion), increased poloidal flux expansion) to more extreme modifications (inclusion of secondary null), which aim to increase the dissipative volume of the divertor. The X-Point Target on TCV (Figure 1) can give rise to an 'X-Point Radiator (XPR)'-like structure in the secondary X-point [15], providing localised power dissipation without the operational risks typically associated with an XPR [15]. If the secondary null is relatively close to the primary null, interactions between these two can occur – leading to the snowflake configuration, which can result in significant power exhaust benefits [16] and an ELM-free X-Point Radiator [17].

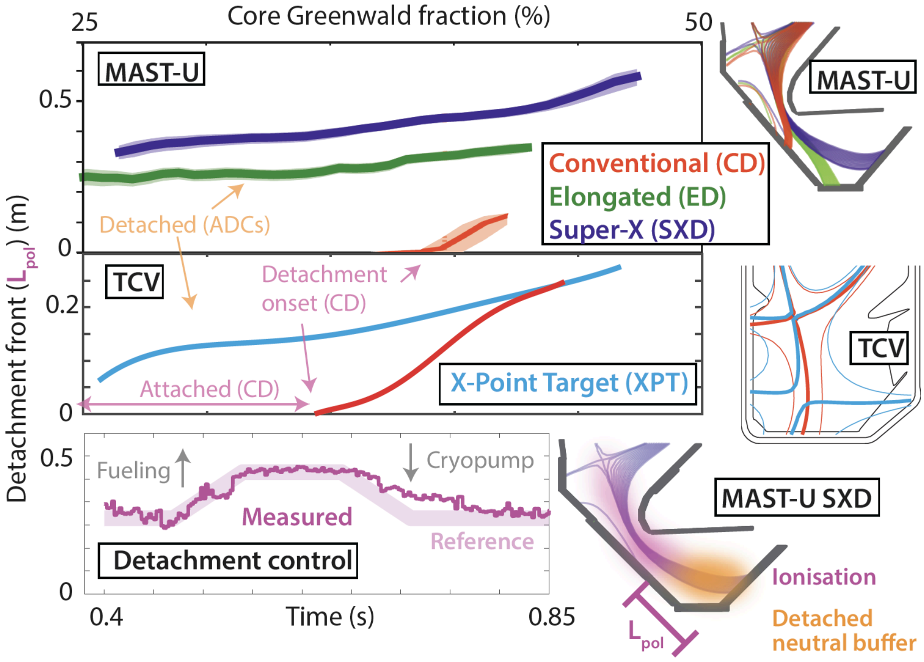

Figure 1: Detachment front evolution showing ADC benefits in terms of detachment access (front detached at lower core density) [15,18, sensitivity (reduced slope front movement) [15,18], operational window (larger window in which the front is between the target and X-point) [15,18] and detachment control [9].

The strongest experimental benefits to date are observed in long-legged ADCs (Figure 1) with either increased total flux expansion (MAST-U's Super-X (SXD) and Elongated Divertor (ED) [9,18]) and/or those featuring a secondary null (TCV's X-Point Target (XPT) [15]). These configurations offer critical advantages over Conventional Divertors (CDs) without **any adverse impact on core performance**. They 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) [15,18,19]. 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. These ADCs enable the passive absorption of disturbances, acting as 'shock absorbers' to **increase the resilience of detachment** compared to CDs [18]. These ADCs reduce the sensitivity of this detachment front location to changes in core density (by >5 x) [15,18] and heating [7] (Figure 1 [15,18]). The reduced sensitivity and increased window of detachment make detachment more resilient and **increases the flexibility to find suitable reactor operating points.**

A critical reactor challenge is not only finding a viable (quasi-steady-state) operating point, but to continuously remain in “safe” operating conditions despite inevitable core disturbances. The reduced sensitivity is observed to extend to faster timescales where the plasma dynamically responds to fuelling (30-130 ms) [9], relevant for power exhaust control. **This provides actuators more time to respond to disturbances,** enabling real-time control of the detachment front in MAST-U’s ED & SXD, which was not possible in MAST-U’s CD due to its high sensitivity (Figure 1 [9]). Additionally, ADCs can protect the target from fast transients (~ ms), including small ELMs, in conditions where a conventional divertor would be attached [20-22]. **Divertor design can thus improve detachment resilience and power exhaust control**, tackling one of the biggest power exhaust concerns.

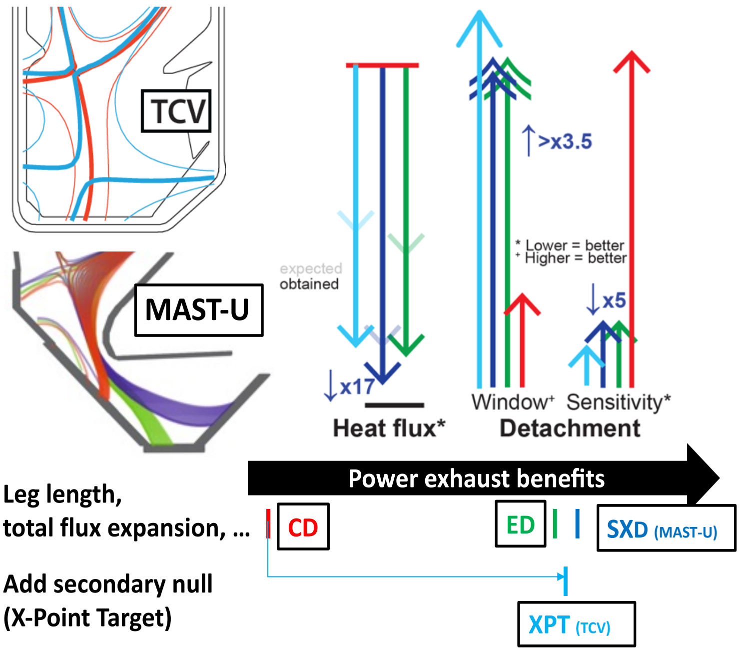

Figure 2: Schematic overview of power exhaust benefits different Alternative Divertor Configurations on MAST Upgrade and TCV, showing similar power exhaust benefits between the Super-X Divertor on MAST-U [18] and the X-Point Target divertor on TCV [15].

It should be underscored that both the quasi-steady-state and control benefits are obtained for a range of different core conditions, including both L- and H-mode scenarios [23-25], heating levels as well as impurity seeded and divertor fuelled avenues to detachment.

ADCs carry key power exhaust benefits, but their integration in reactors is limited by engineering constraints [11,12], requiring a balance between power exhaust benefits and engineering feasibility. A key outcome of this research is that **ADC benefits** are already obtained in **modestly,** yet strategically, **shaped geometries**. Remarkably, the SXD benefits observed on MAST-U were largely maintained in the Elongated Divertor (ED, Figure 1, [18]; Figure 2) – a configuration with lower total flux expansion, consistent with reduced models (section 3) [18, 26]. The ED features similar total flux expansion as the ARC X-Point Target [3] and DEMO SXD designs [8], making its results highly relevant for next-gen devices. 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.

Not only are ADC benefits already obtained in moderately shaped geometries – different approaches to ADCs can provide similar benefits: a **continuum of ADC characteristics and benefits** exist. Strikingly, we find that two very different magnetic topologies (MAST Upgrade’s Super-X and TCV’s X-Point Target) yield very similar power exhaust benefits (Figure 2) – not only in terms of reduced heat loads, but also detachment access and control benefits. **Different divertor optimisation strategies can be “mixed and matched”** to tailor further power exhaust benefits – for example, combining the MAST-U Super-X with an X-Point Target geometry resulted in further target cooling [27] – a concept being considered for ARC. This philosophy enables tailoring ADC solutions for a particular reactor design by utilising an improved ADC physics basis to synergise multiple power exhaust optimisation strategies, requiring reduced models as a rapid design tool and validated edge modelling for ADCs.

3. PHYSICS BASIS OF ADCS AND REDUCED MODELS

The performance benefits obtained for both the X-Point Target as well as the totally flux expanded divertors are driven by a synergy of multiple divertor optimisation strategies.

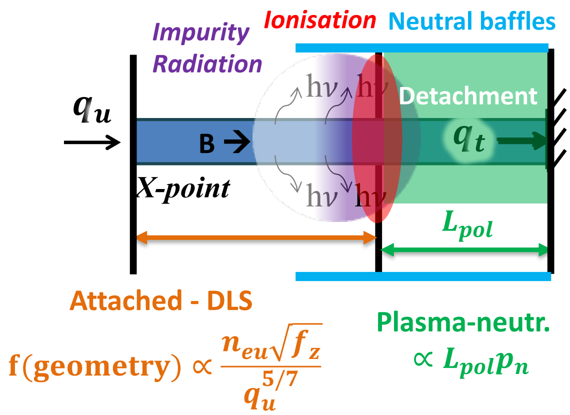

Figure 3: Schematic illustration of divertor processes, highlighting the importance of magnetic geometry, divertor poloidal leg length and neutral pressure and neutral baffling.

1. The **magnetic topology** plays a critical role in the *attached part* of the divertor plasma (from the X-point until the ionisation/detachment front). The Detachment Location Sensitivity (DLS) model [24] predicts the relative position of the detachment front as function of only the magnetic geometry for a given detachment driver parameter (which depends on upstream density, impurity fraction and upstream heat flux). This correctly predicts the **reduced detachment onset**, **increased detached operational space** and **reduced detachment sensitivity** for MAST-U's Super-X and Elongated divertor (primarily driven by **total flux expansion**, [18]**)** as well as TCV's X-Point Target divertor (driven by an increase of the **connection length** near the **secondary null**). Furthermore, this model predicts that modifying the divertor topology downstream the detachment front does not impact the detachment front – consistent with MAST-U experiments [15]. In this region, the upstream heat flux is spread volumetrically through photons, dissipating ~75% of the power (~x4 heat flux reduction [5]).
2. **Divertor poloidal leg length** plays a critical role in the *detached part* of the divertor plasma (from the ionisation/detachment front to the target, Figure 3). This enlarges the neutral buffer downstream the detachment front, driving the power, momentum and particle (i.e. volumetric recombination of ions into neutrals) losses required for detachment through plasma-neutral collisions. This enables additional heat flux reductions by spreading the power volumetrically through neutral particles and photons, enabling order-of-magnitude heat flux reductions. Interactions in this region are primarily driven by the **neutral pressure** and the **size of the neutral buffer** [6,18] (detachment front and, potentially, poloidal flux expansion): increasing the divertor leg length further (when detached) results in additional power, momentum and particle losses [18].
3. **Neutral closure** plays a crucial role in decoupling the divertor state from the core and decoupling interactions between different divertors, improving simultaneous control of multiple divertors [9]. Preventing the flow of neutrals from the divertor to the core does not only enable deep detached conditions without compromising the hot fusion core, but it also enables the full benefit of magnetic topology in detachment access and reduced sensitivity [28]. Reduced models [28] and simulations explain that the escape of neutrals from the divertor to the core is the reason why the benefits of total flux expansion on TCV were reduced compared to MAST-U (which is more strongly baffled). Although neutrals are more self-baffled on reactor class devices that operate at higher powers, neutral mean-free-path will inevitably be large in detached conditions: neutral baffling is of key importance for detached reactor divertors – motivating the STEP [4], SPARC [3] and ARC divertor designs. The importance of baffling is being investigated further on TCV by implementing a Tightly Baffled Long-Legged Divertor (TBLLD – TCV) [14]

4. IMPLICATIONS FOR ITER AND BEYOND

The implications of ADC research are not limited to only next-gen reactors but are also relevant to ITER. Validating the edge models used to extrapolate current knowledge to reactor design requires detailed validation efforts on current devices, in which ADC research can play a critical role.

1. **Long-legged ADCs enable improved diagnosis of the divertor state** enabling the highest fidelity power exhaust control studies and most rigorous model validation exercises to date [29]. Power exhaust is a volumetric phenomenom, requiring 2D diagnostic techniques. The advent of multi-wavelength imaging techniques (i.e. TCV's MANTIS diagnostic [30]), paired with advanced diagnostic analysis and imaging techniques [31,32], revolutionised the degree to which the 2D state of the divertor can be monitored for model validation [33] and power exhaust control [9,34]. These techniques are enabled by the long-legged ADC configurations studied on MAST-U and TCV.
2. ADCs **enlarge the parameter space** that can be explored, enabling **model and control validation at extreme conditions** and unravelling the complexities of detachment physics.
    1. **Detachment physics**. ADC research showed plasma-molecular interactions drive dominant parts of detachment physics. Aided by the improved diagnosis capability, the importance of plasma-molecule collisions in driving dominant *detached* momentum and power losses was discovered [6], consistent with SOLPS-ITER simulations. Plasma-molecular chemistry, driven by molecular ions, drive dominant

dissociation and strong ion sinks in detached conditions [5,7,18]. Comparison with SOLPS-ITER results highlighted that such interactions are underestimated in modelling [35], prompting the derivation of corrected rates [7] which improve agreements with experiments [18]. Investigating reactor-scale simulations show such interactions have key impacts in reactor-relevant conditions [7].

2. **Validation of drift effects**. The importance of including drifts in power exhaust modelling is debated extensively in literature. Power exhaust modelling shows drift effects have a major impact on the X-Point Target, resulting in a complex flow profile, which is reproduced in experiments [36]. Contrary to expectations, poloidal flux expansion scans on TCV showed little impact on the target temperature, inconsistent with no-drift SOLPS-ITER simulations. The inclusion of drifts reproduced the experimental measurements. These results increase confidence in the validity of simulated drift results and showcase how modifying the magnetic geometry can be a powerful variable in experiments for model validation.
3. **Demonstration of control strategies**. The same power exhaust controller was used to control detachment in MAST-U's Elongated and Super-X divertor configurations and the same strategy was successfully applied to TCV [34]. By showcasing power exhaust control works in multiple geometric configurations, confidence in the power exhaust control strategy is increased.

ADC studies, by making use of the unique features of EUROfusion devices, have thus proven themselves to be a valuable tool for improving general power exhaust understanding, modelling predictions for reactors and control; capable of tackling physics gaps of conventional divertor strategies for ITER and beyond.

The finding that ADC benefits extend to moderately shaped geometries, and that we can harness the ADC physics basis to target modest, strategic, divertor optimisation, implies that ADC techniques can be applied for general divertor optimisation. These findings increase the relevance of strategic, modest, divertor modifications that can be more easily integrated in DEMO designs without violating engineering limitations.

The demonstration of key ADC benefits in the last years through EUROfusion research is timely and strategic in the wider fusion landscape. With the advent of private-public partnerships pushing for more compact, alternative, reactor designs, finding robust solutions to power exhaust is of utmost importance. The key topologies discussed in this work: the Super-X and X-Point Target divertor are the proposed baseline solutions for two key compact reactor designs – as such, these results are highly relevant for STEP, SPARC and ARC. ADC research thus enables reactor design innovation.

5. NEXT STEPS IN ADC RESEARCH

The promising results at the highest power and lowest density possible (to increase the power exhaust challenge) on MAST-U and TCV require validation at reactor-relevant power levels, for which power upgrades are underway at MAST-U (4.4 MW -> 10+ MW) [13]. Building on the TCV and MAST-U ADC results, EUROfusion is expanding ADC research to high-power, metallic-wall devices, such as WEST (single and double-null comparisons) and ASDEX Upgrade.

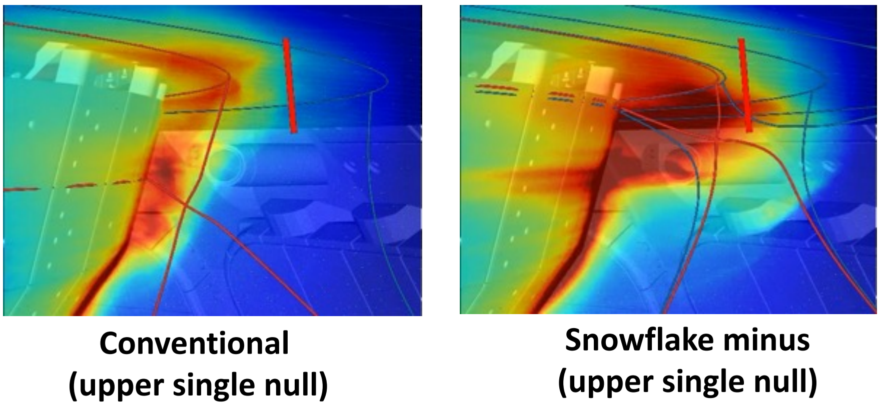

Figure 4: Evidence of successful formation of the snowflake minus configuration on ASDEX Upgrade, using magnetic equilibrium reconstruction as well as divertor imaging.

ASDEX Upgrade [37] underwent an extensive shutdown to install new upper divertor coils to enable ADC studies. First results of ADCs on ASDEX Upgrade showed the successful establishment of a snowflake geometry (Figure 4), based on magnetic reconstructions as well as visible light imaging (Da). An extensive database of ADC configurations on ASDEX at high power conditions (20+ MW) has been obtained, which is currently being analysed.

These new tools pave the way for practical ADC implementations in future fusion power plants and prepare for the next steps in validating ADC concepts at DEMO-relevant target heat loads in the Divertor Test Tokamak [38].

6. CONCLUSION

Collaborative, multi-device research on Alternative Divertor Configurations (ADCs) in Europe in the last years on TCV and MAST Upgrade 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.

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