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MAST Upgrade Divertor Facility: A test bed for novel divertor solutions

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***Abstract*— The challenge of integrated exhaust consistent with the other requirements in DEMO and power plant class tokamaks (ITER-like and alternative DEMOs, FNSF approaches) is well-known and the exhaust solution is likely to be fundamental to the design and operating scenarios chosen. Strategies have been proposed such as high main plasma radiation (e.g. [1]), but improved solutions are sought and will require revised research methodologies. While no facility can address all the challenges, the new MAST Upgrade tokamak enables exploration of a wide range of divertor plasma aspects in a single device and their relation with the core plasma (e.g. access to H-mode), in particular the development of fundamental understanding and new ideas. It has a unique combination of closed divertor, capability of a wide range of configurations from conventional to long-leg (including Super-X), and fully symmetric double null (plasma and divertor structures). To extrapolate to DEMO and power plant scale devices where full integrated tests in advance are not feasible yet different physics mechanisms may dominate, theory-based models are likely to be essential, for confident performance prediction, optimisation, and a "qualification" of the concept. Development and validation of such models is at the heart of the programme around MAST Upgrade. Amongst the many areas to be explored, there will be a strong focus on the closely coupled topics of plasma detachment and cross-field transport mechanisms (e.g. plasma filaments), key ingredients of effective and reliable protection of the plasma facing components at DEMO-scale.**

***Index Terms*— Fusion reactor design, divertor, plasma exhaust, plasma filaments, super-X, tokamak devices.**

I. INTRODUCTION– ALTERNATIVE EXHAUST APPROACHES

Tokamaks at reactor scale need effective and practical exhaust systems. An integrated exhaust solution accommodates both a high performance plasma and the engineering and materials requirements of reliably protected long-lifetime plasma-facing components (PFCs). Its many challenges are well documented - it involves far more than the divertor configuration. The fastest path would be to use the single-null divertor configuration (e.g. as implemented on ITER) accompanied by a highly radiating main plasma and a fully detached divertor [1]. However, while there is some basis for optimism, it is not yet clear whether such a constraint on the main plasma is optimal (confinement and cleanliness) and stable. It is also questionable whether the divertor solution can fulfill its role in power and ash removal with adequate margin given the many plasma, materials and engineering constraints in a high fusion power density DEMO or power plant. Therefore, alternate power exhaust strategies are explored to find solutions with higher confidence levels, usually at some additional cost or technical complexity. Even if they are not used for the first DEMOs, they could be part of a portfolio of design options for power plants. Arguments to industrial partners for or against an alternative exhaust will depend upon, inter alia, whether the conventional exhaust solution has adequate margin for core and exhaust, i.e. whether an alternative is a necessity or an option.

There is a range of alternative exhaust approaches using different magnetic configurations, advanced plasma facing materials and components (e.g. liquid metals of vapour targets). MAST Upgrade is designed to look at alternative magnetic configurations, with a particular emphasis on the Super-X, with and without a poloidal field minimum, and also snowflake and X-point target configurations. All of these can be studied in symmetric double null. These configurations have the potential to increase substantially the detached divertor operating window in such areas as upstream density (lower densities would be more compatible with current drive), power leaving the main plasma (more compatible with transients) and required impurity concentration in the divertor (lower concentration). The detached divertor plasma should be more controllable, and there is expected to be additional flexibility for the core plasma scenario. First studies of the magnetic design have been done for a DEMO with an aspect ratio ~3, for snowflake [2], an indicative Super-X for the outer leg [3], and a "double decker" which brings the inner leg out to large major radius [4]. The extra magnetic forces appear to be manageable after a first design optimisation. There is a cost involved, for example due to extra poloidal field coils (even internal [4]) and larger toroidal fields coils relative to the plasma size [2] [3]. Horizontally extended divertor legs are especially attractive for spherical tokamak concepts, which often assume demountable toroidal field coils (see [5], [6] and references therein) and where benefits may accrue with reduced impact on the outboard part of the toroidal field coil.

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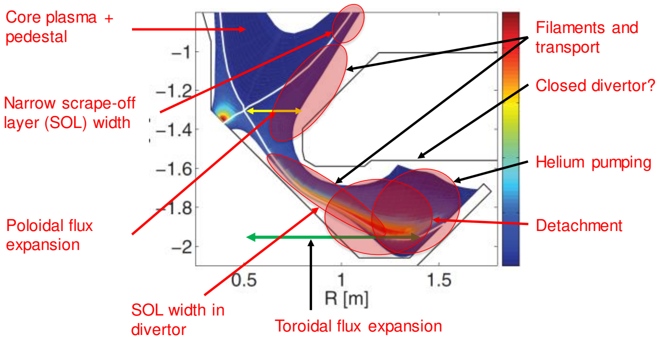

Figure 1 Illustration of the many plasma elements that need to be integrated for a consistent exhaust scenario. The background plasma shows carbon radiation for a simulated detached Super-X plasma in MAST Upgrade [29]

Since MAST Upgrade is a new machine, it is appropriate to look at its role in an overall strategy towards a solution for DEMO-class devices and beyond, linking to a first strategic framework for exhaust developed in Europe by EUROfusion. This paper outlines how MAST Upgrade can be used to develop effective novel concepts in a framework that always looks towards the goal of a practical implementation at DEMO and power plant scale, with a recognition of what is needed to support the final “qualification” required to allow major decisions. For simplicity “DEMO” is used here to cover any device in the stage after ITER, i.e. with fusion power and power density approaching that needed for a commercial power plant.

MAST Upgrade is a spherical tokamak (ST); while this is different from many present DEMO-class designs (not all, an ST FNSF is actively pursued [5]), low aspect ratio allows some effects to be more visible and more easily studied. For example, flux tube expansion due to reduction in mod(B) along the divertor leg leading to reduced parallel heat flux, detachment with higher power into the SOL and/or fewer impurities [7]. STs amplify the in-out power ratio in double null and increase visibility of Larmor-radius scale effects (for similar $k\rho_i$). STs generally operate further from the Greenwald density, providing more experimental flexibility for detachment studies.

While the focus here is on alternative exhaust approaches, much of the physics is common and synergistic with conventional approaches; it is expected that MAST Upgrade will make significant contributions to the understanding and optimisation of conventional approaches – exploring common physics in different environments can be a powerful aid for understanding, and for confronting and improving models.

Alongside a description of the challenges of integrated exhaust, there is a discussion of a general strategic framework to give confidence in an alternative exhaust approach on a DEMO-class device and thus to guide the MAST Upgrade programme. Then the capabilities of MAST Upgrade are outlined, followed by a short discussion of its role in two related areas – detachment optimisation and cross-field transport.

II. INTEGRATED EXHAUST AND THE ROLE OF MAST UPGRADE

An integrated exhaust solution needs to cover a wide range of aspects, from control of the core plasma (the source of time-dependent heat and helium ash) to design of the plasma facing components, pumping structures and magnets. A controlled exhaust plasma, the focus of MAST Upgrade, is the intermediary, and figure 1 shows some of the features. The solution must cover the whole discharge from initiation to termination, and be consistent with tritium breeding as well as sufficient lifetime of the components.

The step from ITER to DEMO-class devices such as [8] is large, e.g. a factor 3-5 in the power to exhaust, and larger if an exhaust approach different from ITER's is to be used. The integration is also complex and quite dependent on the detailed design, parameters and environment. This makes the traditional approach, embodied in Technology Readiness Levels [9], of empirical demonstration of the full integrated solution very challenging, from scientific, technical, cost and timescale aspects. However, it is already recognised that the TRL system anyway needs supplementing in other fields [10]. New methodologies are therefore needed, almost certainly involving comprehensive theory-based modelling to simulate the final integration and parameter and environment steps. The models should allow the uncertainties (systematic as well as statistical) to be quantified and hopefully minimised, and the solution’s robustness to be quantified and maximised. Failure modes and their impact are also important elements [11].

In the early phase simplified models are powerful guides, quick to use compared to complex models (which are presently incomplete). Flux-tube models such as the two-point model [12] [13] and the recent model of the effect of mod(B) variation along a flux tube [7] show trends. These simplified models are not usually suitable for final design and major design decisions.

A critical aspect is model validation, a subtle concept given the many physics mechanisms at play and the differences between today’s machines and DEMO. It affects the design of experiments and diagnostics (real and synthetic). An example from another area [14] shows today’s edge pedestal transport can be modelled reasonably well without considering ion-scale turbulence which could be dominant on ITER and DEMO.

In particular plasmas on DEMO (and ITER) will have a different mix of physics mechanisms from MAST-U – phenomena critical for DEMO may be minor or not present on MAST-U, and vice versa (figure 2). Furthermore their interactions (often nonlinear) will change. Similarly the theory and models today are different from that needed for designing and optimising DEMO-class devices. There are however “common” aspects, for example the sensitivity of detachment to variations in parallel heat flux due to variation in mod(B) along a flux tube or transport of heat and particles parallel to **B** (non-thermal populations can affect impurity cooling curves [15] [16]); the principle of interchange drive for filament

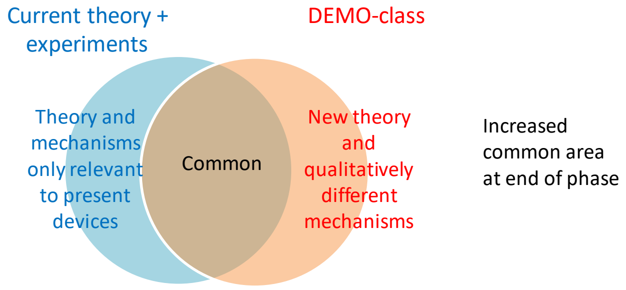

Figure 2 The relation of the physics of today’s and DEMO-class devices. The “common” area is expected to expand during the exploration phase.

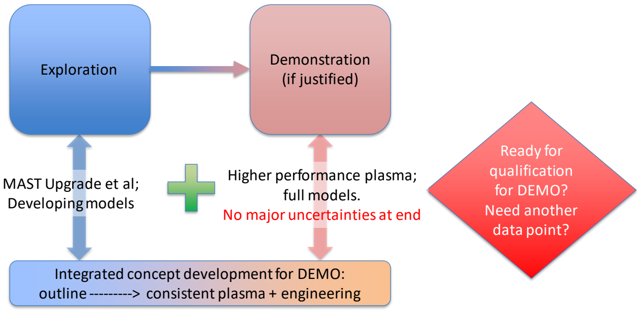

Figure 3 Outline of a general strategy as context for the MAST Upgrade research programme.

motion; and how filament and divertor physics affect the density profile in the scrape-off layer.

The models, diagnostics and experiments need to be tuned to explore this, and indeed this will affect the choice of plasma parameters and regimes for the demonstration stage after MAST-U (figure 3) – that stage should ideally leave acceptably small uncertainty in the behaviour on DEMO. The strategy to achieve the final qualification is beyond the scope of this paper – some ideas were presented in [17]. The situation would be eased if the core plasma could be less affected by the divertor, and this is one of the aims of long-leg divertors (i.e. with substantially longer fieldlines between the main plasma and the divertor target). MAST Upgrade would thus contribute to the design of the demonstration phase, and to concept development for alternative exhaust on DEMO.

A. *A possible research strategy for MAST Upgrade*

The research strategy is derived from the major engineering design choices for DEMO and the scientific elements of the plasma models needed to design and optimise the exhaust on ITER and DEMO. The engineering choices most relevant to MAST Upgrade relate to:

- Single or double null
- Length of the divertor legs, and their angle (e.g. vertical vs horizontal legs)
- Pumping, fuelling and seeding of the divertor (tritium usage and activated impurities)
- Impact on the toroidal field coil size and energy

The scientific elements are numerous, especially as the dominant physics mechanisms on DEMO may be very different from those seen on today's tokamaks (figure 2), with different optimisations needed for the exhaust. They include (figure 1)

- Detachment threshold and operational window (in terms of main plasma parameters), including hysteresis (different conditions for detachment and reattachment)
- Cross-field transport and power and density scrape-off widths (before and after detachment)
- Effect of slow and fast transients
- Detachment behaviour in double null conventional and alternative configurations
- Impact on the main plasma, e.g.
    - L-H threshold
    - pedestal structure (link to upstream SOL density, strong poloidal variations with intense X-point radiation),
    - helium removal
    - impurity levels,
    - range of P_{SOL} transients allowed (e.g. are ELMs of any form allowed)
    - end-to-end scenario (e.g. when to go into H-mode, when to detach, and the reverse)

The difference between DEMO's and today's plasmas may mean that early "proof" (or "disproof") of a concept is unlikely. For example, some exhaust solutions would lead to very high upstream density at DEMO scale which could mean that the pedestal optimisation might differ from present devices. So the programme around MAST Upgrade needs to consider the DEMO context from the outset. The main elements are:

- Identification, by theory and experiment, of mechanisms likely to play a role at DEMO parameters
- Experimental and theoretical exploration and development of those mechanisms
- Understanding how those mechanisms differ at the exploratory and DEMO levels
- Development of outline integrated exhaust concepts applicable at DEMO-scale, identifying the key areas of uncertainty so that R&D can focus on these, in a quantitative way

III. MAST UPGRADE CAPABILITIES

MAST Upgrade [18] [19] [20] [21] [22] has been designed to create a flexible exhaust physics platform, taking advantage of the spherical tokamak configuration to accentuate physics mechanisms, and the large vessel to allow a wide range of configurations and a large divertor region, figures 4, 5. Furthermore it supports development of spherical tokamak

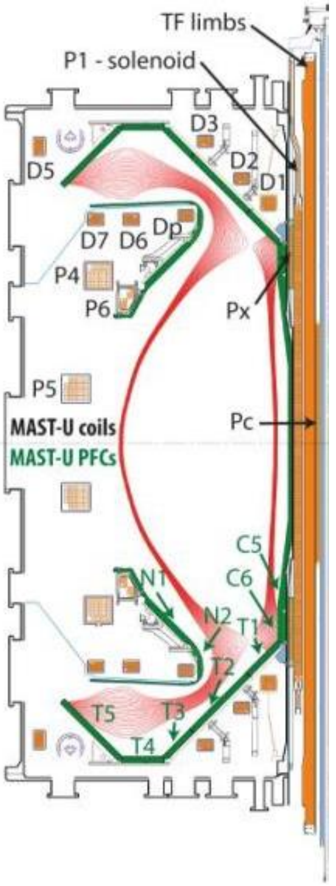

Figure 4 MAST Upgrade cross-section, with the PF coils and PFCs (in green) labelled. A Super-X equilibrium is shown.

fusion devices, such as the ST FNSF [5]. The details and parameters are described in [18] and references therein and [22]; here the focus is on the exhaust plasma capabilities.

MAST Upgrade has unique capabilities to produce conventional and novel divertor configurations for detailed studies and comparison in a single device, with full up-down symmetry [23]. The two closed divertor chambers are each surrounded by eight poloidal field coils for detailed control of the magnetic geometry, more demanding for some advanced configurations, including strike point location, field line length within the divertor, poloidal flux expansion and their variation across the scrape-off layer, whilst keeping the shape of the core plasma unchanged. It will be equipped with neutral beam heating, and a wide range of high resolution diagnostics with a strong emphasis on the scrape-off layer and divertor plasma, allowing new levels of detail in testing of models. Cryopumps have been installed in each divertor, and the large radius divertor targets (T5) have been specially designed to compensate power concentrations due to ripple effects, using a CAD-based optimisation tool [20] [24].

The plasma facing components are made of graphite. This is not the material expected to be used at DEMO scale, but it is a very forgiving material for exploratory experiments. Chemical sputtering means that there will always be significant carbon content in the divertor plasma, but if this can be modelled and measured, it is not an a priori restriction. The extensive gas puffing system means that the effect of different seed gases and injection locations (poloidal and toroidal) can be explored in a controlled way.

A historical gap in many tokamaks is good information on the plasma parameters at various locations along the SOL and in the divertor; this will be a focus for MAST Upgrade. While the confrontation of the experimental data with SOLPS and other fluid modelling codes will be central to the understanding of the divertor physics, it is hoped to extract the plasma solution directly from an integrated analysis of most, if not all, of the divertor measurements – each measurement corresponds to a location (or chordal integral), local plasma parameters (e.g. n_e and T_e) and thus, with proper implementation can constrain the plasma solution across the divertor region *without specifying the physics*. The plasma solution derived can then be used to calculate exactly which mechanisms are dominant and where there are additional mechanisms not included (e.g. turbulent-driven cross-field transport). This approach has been used in various fields in the past [25], but not for the divertor plasma. The plasma solution derived directly from the experimental measurements can be compared with the solution derived from SOLPS and synthetic diagnostics which will enable a much stronger interaction between experiment and modelling.

The MAST Upgrade diagnostics have been designed for as high space and time resolution as currently feasible, and compared with current estimates of that required to observe the major exhaust mechanisms (Table I), to confront and develop the models. In addition, these diagnostics should assist in revealing any new mechanisms that emerge (e.g. unexpected filaments in the private flux region seen on MAST [26])

IV. DETACHMENT OPTIMISATION WITH ALTERNATIVE CONFIGURATIONS

Plasma detachment, namely the use of atomic and molecular losses to dramatically reduce the ion and electron temperature, as well as particle, momentum and power flux at the target, appears to be essential for DEMO. If the plasma is detached then the power conducted/convected to the target as well as the target power due to recombination of ions in the surface are greatly reduced. Thus the sputtering and melting erosion of the PFCs can be very low, assuming no ELMs burn through (probably because the scenarios are designed to have no

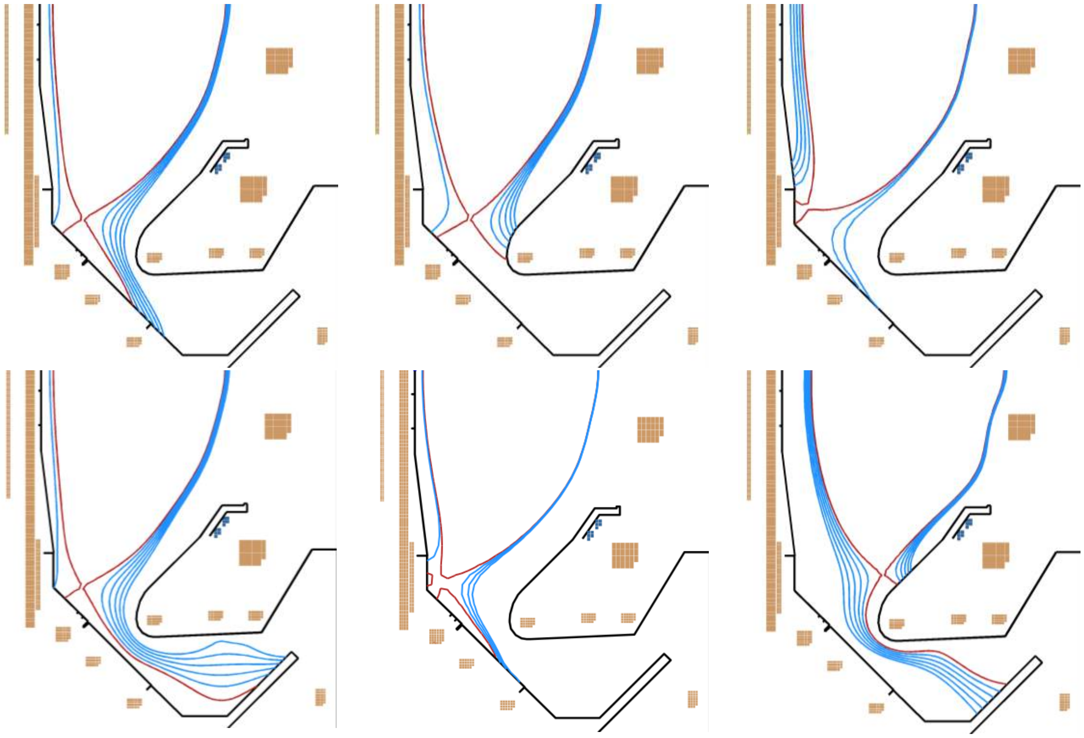

Figure 5: Examples of divertor configurations possible in MAST Upgrade. Top row left to right: Conventional, vertical target, X-divertor. Bottom row left to right: Super-X, snowflake, inner leg Super-X (related to “double decker”)

TABLE I

MAST Upgrade Exhaust Diagnostics and their Performance

Observable	Diagnostic	Required spatial resolution	Expected spatial resolution	Required time resolution	Expected time resolution
Filament propagation	Multi-view fast cameras, Reciprocating & target probes	≤ 1cm	0.15 - 1cm (variable)	<10µs	1-10µs
Upstream λ_q	Main plasma, X-point and divertor Thomson scattering	3mm upstream	1-2mm upstream	Inter ELM	✓
Divertor λ_q	Divertor TS, IR cameras	≤ 5mm	2mm	Inter ELM	✓
Peak divertor radiation emissivity location	Divertor bolometers Imaging bolometer	≤ 10cm (SXD), ≤ 3cm (conv)	6cm (SXD) ≤ 1cm (conv)	50ms	1ms
Detachment front shape and position	Filtered cameras, Spectroscopy	2cm	≤ 1cm	50ms	20ms
Divertor static pressure loss	Divertor Thomson scattering	≤ 5cm	1-5cm	50ms	15-30ms

Diagnostics are arranged according the phenomenon to be studied. Type-I ELM frequencies as seen on MAST are used. More information is available in [22].

ELMs). In these conditions the upstream scrape-off layer width (λ_q) does not set the power load on the divertor PFCs via conventional flux-mapping, but may be important for the detachment onset, detachment control, and its value on reattachment (at whatever power level that occurs).

Critical issues for detachment optimisation include:

- Threshold for detachment in terms of exhaust power and upstream density, e.g. at the midplane separatrix: affects scenario flexibility as well as the heat load on the divertor PFCs before detachment, when to detach during the pulse, e.g. before or after pedestal formation
- Hysteresis, i.e. the relation of detachment and reattachment criteria: affects stability and control and the overall scenario planning
- Structure/location of the detachment region: affects pumping efficiency, X-point radiation and core plasma purity, recombination and radiation power at the PFCs
- Stability and controllability: affects feasibility of the scenario, resilience to slow and fast variations and ability to maintain optimal conditions
- Impact of any change in the SOL width on the interaction with the main chamber as the plasma density is raised and as it becomes detached.

The magnetic and hardware configuration is an important optimisation tool for all of these, for example use of double null; variation in mod(B) along the divertor [7], [27]; enhanced dissipation in long well-baffled divertors [28]. Double null configurations introduce new aspects related to simultaneous management of upper and lower detachment regions.

A major question for long leg divertors at conventional aspect ratio is how short the legs can be, i.e. the benefit as a function of length, given the impact on the toroidal field coil envelope. Divertor closure and strong gradients in mod(B) over the divertor region ($B_{\text{X-point}}/B_{\text{target}}$) also have important implications for design and need to be quantitatively studied as to how much is needed.

The above points are now expanded to show some of the areas where MAST Upgrade can contribute, alongside modelling as always.

A. *Detachment threshold*

Long divertor legs can make the detachment window larger and potentially allow the detachment front to be more controllable especially if the leg is extended horizontally to lower mod(B) regions. First calculations of detachment access in MAST Upgrade [29] illustrate the gain in the Super-X configuration, with detachment attained with about 1/7th the level of seeded impurities compared with a reference conventional divertor, partly due to the closed divertor (raising the neutral level), partly due to toroidal flux expansion [7], [27]. This can be translated to lower upstream density for the same exhaust power (or higher exhaust power for the same operating density). If this transferred to DEMO it would provide more flexibility in choosing the main plasma separatrix and core density ($n/n_{\text{Greenwald}}$) and phase in the discharge for detachment onset, and would allow a wider range of pedestal structures, not only pedestals with very high separatrix density. Alternatively, it could reduce the level of impurities needed in the divertor to achieve/maintain detachment and radiate enough. At the high powers of MAST Upgrade or DEMO, seed impurities have to be added, and the Super-X is predicted to lower the required level substantially, proportional to $(B_{\text{xpt}}/B_{\text{target}})^2$ [27], [30].

The detachment threshold and front location depends on the parallel power flux amongst other things, which is set by the upstream λ_q and power into the SOL. It is also modified by the flux tube area and cross-field transport along the divertor leg.

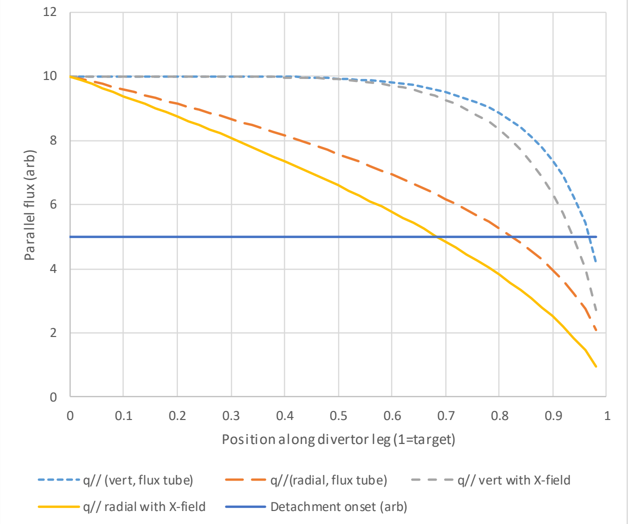

Figure 6. Cartoon showing how the orientation of a long-leg divertor and cross-field transport can ease detachment and allow shorter legs. The curves indicate the peak parallel power flux dropping along the leg – when it crosses the horizontal line detachment occurs. The shapes of the curves are purely indicative. The curves differ in the orientation of the leg (vertical, radial) and whether cross-field transport is included (X-field) or not (flux tube). For specific examples see [7], [27]

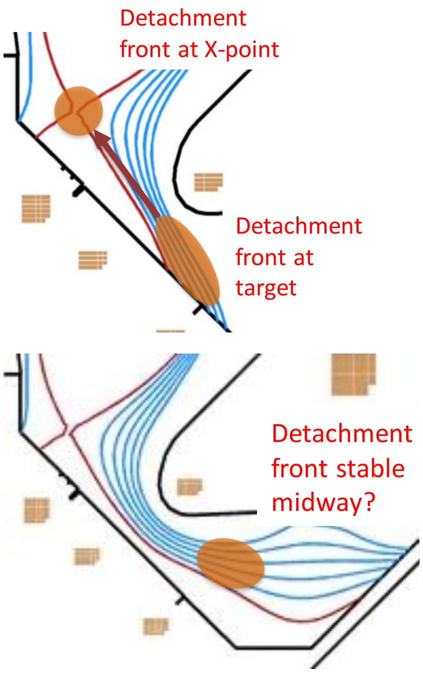

Figure 7 Detachment front. For conventional divertors (top) the front tends to be stable only at the target or the X-point. For a long radial leg there is potential for it to be stable at intermediate positions [7]

Figure 6 shows a cartoon of the generic effects of orientation of the leg and cross-field transport on detachment – detachment occurs with progressively shorter field-line length as cross-field transport and total flux expansion are increased and combined. Finally, the upstream conditions can be affected by the operating scenario, e.g. regimes with small or mitigated ELMs.

B. *Reattachment at higher exhaust power and hysteresis*

Hysteresis in detached plasmas (i.e. higher exhaust power is needed to reattach) is a research theme as it could be important for discharge design (when to detach and re-attach for example), and for control of detachment in double null configurations where the upper and lower detachment fronts can also "communicate" via parallel transport: detachment in double null is a relatively unexplored field. Whether detachment is retained at higher exhaust power depends on how much more power can be dissipated in long leg configurations compared to the conventional divertor, a complicated question related to the tolerable impurity density of seed impurities [30], impurity distribution, and details of the radiation cooling curve, $L(T_e)$ [15]. If the reattachment power can be raised there are several advantages: it reduces the control problem (measuring and controlling the core plasma radiation fraction at high levels is very challenging), it reduces the radiative power load on the first wall. Finally, it could lead to a main plasma scenario closer to the reference Q=10 scenarios on ITER which presently have relatively low core radiation fractions.

C. *Position and stability of detachment front*

In conventional configurations there is a tendency for the detachment front to move towards the X-point (figure 7), and snowflake configurations generally assume the high radiation zone and detachment front are in the X-point region (but mainly outside the last closed flux surface). There is now evidence that such X-point radiation can be sustained stably, e.g. [31], which is a very positive development (previously disruptions had often resulted), even if not yet in ITER/DEMO relevant conditions. Such scenarios are likely to create additional poloidal variations in the pedestal, which could complicate the pedestal extrapolation – it is not yet known if this is beneficial overall or not. If it is important to maintain the detachment front between the target and the X-point (figure 7) thus obviating the risk of keeping a very cold region (e.g. ~1 eV) next to, or inside the X-point, then features of long leg divertors such as the toroidal flux expansion may help.

D. *Other aspects of detachment*

Since a primary function of the divertor, other than heat handling, is to pump helium ash, then there must be sufficient pressure in front of the pumping orifice, and good transport of helium into the divertor (compression), i.e. past the detached region. This will need further investigation.

Partially detached divertors [32] are seen to be more stable experimentally than fully detached, and are considered as the reference option for ITER [33], and some simulations that show cross-field interactions with the attached flux tubes help prevent movement of the front in the detached flux tubes [34]. However, in regions where the plasma is attached the total power flux includes the surface recombination energy [35] [32] [36]. This is at least 13.6eV/(electron-ion pair) which is comparable to the conducted heat flux γT_e/(e-i pair), with γ typically 5-7 (at $T_{e,t}$~2.5 eV). This suggests that at least the near-SOL needs to be fully detached to reduce the power flux sufficiently, and the detachment front has to be far enough away from the surface that the recombination radiation power to the surface is not too high.

E. *MAST Upgrade contributions on detachment*

MAST Upgrade can enable research into many important divertor characteristics and physics, the effects of mod(B) variations to control the front position, the role of divertor closure, partial detachment options, the effect of cross-field transport changes, explore helium compression and pumping. All of these contribute to determining how short a long-leg divertor can be, whether the detachment front is required to be close to the target and the role of mod(B) variations in detachment front control as well as detachment operating windows. The full symmetry of MAST Upgrade should be a powerful tool for exploring detachment in double null, and both divertors are diagnosed. Furthermore, the vertical position control system of MAST Upgrade will be enhanced assisted by FPGA control of the switching of the multi-level radial field power supply for very precise control (small fraction of a millimetre) of the gap (δr_{sep}) between the separatrices linked to the upper and lower X-points. Impurities play a critical role in detachment, so their distribution and transport is critical, and can also influence where seed impurities should be injected in the divertor. MAST Upgrade will have extensive impurity diagnostics, e.g. coherence imaging [37]

MAST Upgrade is also equipped to investigate the effect of 3-D magnetic perturbations on detachment, due to error fields (perhaps due to uncompensated ferritic blankets or inserts e.g. for development plasmas at lower toroidal field), and applied fields for ELM mitigation/suppression. Different configurations also have different levels of toroidal field ripple close to the targets.

V. UNDERSTANDING AND EXPLOITING CROSS-FIELD TRANSPORT

Cross-field transport is probably the biggest uncertainty in modelling the plasma exhaust, and it is critical to the design and choice of integrated exhaust scenarios. There are four main reasons for wanting to understand and increase cross-field transport in the SOL and divertor:

- Reducing the peak steady-state and fluctuating power density at the target when the plasma is attached
- Allowing detachment at higher exhaust power and increasing the detachment window by reducing $q_{//}$ and increasing the volume available for radiation losses if possible
- Easing detachment control by slowing the movement of the detachment front
- Controlling the width of the SOL which determines interactions with the first wall and divertor throat, and affects coupling of RF waves

Alternative divertor concepts offer the chance to study and perhaps change cross-field transport, as well as using the longer connection length of most alternative configurations (certainly for the near SOL) to allow the cross-field transport to have a bigger influence, as described theoretically for a particular type of transport in [38] and observed in experiments [39], [40].

Following the theme developed above, theory-based models of the underlying mechanisms are needed, developed in cooperation with experiments (which may identify phenomena not yet investigated theoretically). In the end these need to have well-quantified and sufficiently small uncertainty when used for DEMO-like parameters.

The wide variation of plasma parameters across and along the SOL means that even if there were suitable dimensionless parameters like ρ^*,ν^*,β, as in the core plasma, single values will not be enough to characterise usefully the whole SOL and exhaust, be they the upstream values or some kind of average across the SOL and divertor. Since there are major factors which cannot be treated non-dimensionally (such as electron temperature and atomic and molecular physics, neutral free path, normalized to SOL thickness, all critical for the detachment behaviours), simple scalings will be far from adequate. However, to design the demonstration stage (see figure 3) it will be important to have some guiding parameters to ensure that the relevant mechanisms are all present and interact in a relevant way.

The near-SOL (close to the separatrix) is the region of highest power flux and thus the most important, but probably the least well understood region. A heuristic model combining classical ion drifts and anomalous electron transport describes present experiments quite well [41], but projections will depend on the behaviour of the anomalous part. Theoretical models of the near SOL transport are being developed – e.g. [42], which suggest that the transport is mediated by filaments, blobs or streamers on a hybrid length scale ~$(a\rho_i)^{1/2}$. MAST Upgrade, with its low B field on the outside, but moderate average B is in principle well-placed to observe these small structures, especially if T_i is reasonably high (assisted by high neutral beam heating) the scale length might be ~1cm, in the range measurable (see table I). However it is not yet clear what the parameter thresholds are for the full spectrum of structures to appear – they may not all be visible on MAST Upgrade, and thus fall into the category of mechanisms that only appear beyond today's devices.

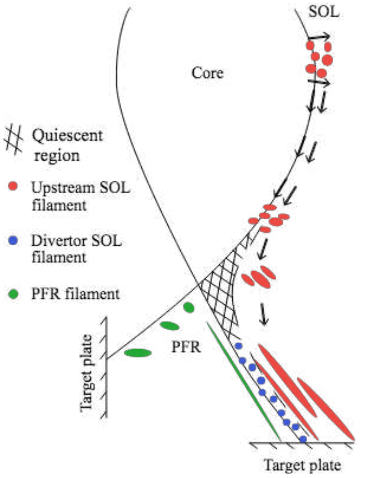

Figure 8. Schematic diagram showing where filaments are seen and not-seen on MAST. Some are generated in the main plasma or the near SOL, propagate into the SOL and extend towards the divertor (changing shape according to the changing magnetic shear), other appear to be generated in the divertor leg and in the private flux region (PFR). Finally there is a quiescent region where filaments are not seen even though they might be expected to propagate into this region from upstream.

On the other hand, the *particle* transport across the SOL can probably be described by a combination of classical drifts [41] and dynamics of filament or blobs. A framework has been created which yields profiles similar to experiments by combining theory-based motion and draining of a distribution of filaments (e.g. [43], [44], [45]), the main issues being the source of filaments and some details of their dynamics.

While the focus here is on cross-field transport, parallel transport and non-local effects are also important, and will be folded into the theoretical and experimental approach.

A. Filaments – origin, nature and role

There have been extensive studies of filaments for several years using MAST [46] [47], and recently this has extended into filament behaviour in the divertor [26] [48]. Figure 8 summarises the filament observations to date in various regions in MAST, showing that there is far more than propagation of filaments produced around the midplane. Some of these filament types could be tools for spreading power flux as well as factors in cross-field transport for detachment formation and evolution, and in the flux to PFCs along the divertor. The quiescent region around the X-point [49] could be very significant for assessing the potential of configurations such as the snowflake (the high shearing of the magnetic field around the X-point could lead to filament break-up), and studies would be conducted in collaboration with facilities focused more on snowflake studies, such as TCV, DIII-D and NSTX-U – for example the relative position of the snowflake X-points influences the local shearing. This will allow an assessment of the robustness of the mechanisms leading to the quiescent X-point region, which cannot be done fully on a single machine.

MAST Upgrade will be equipped with improved cameras for imaging filaments and their motion (including the potential for stereoscopic imaging), as well as Langmuir probes at the midplane, in the divertor plasma and at the divertor target. The increased number of views will enable correlation studies to see the relation between filaments in the divertor and main chamber, and the camera resolution allows filaments as small as 2 mm to be imaged (see Table 1). For example, this may help identify any structures that contribute to the expected and observed cross-field spreading down the divertor leg, including into the private flux region [38], [39], [40]

Measuring the size and motion of the filaments is not enough, data are needed on their origin, internal parameters, and the environment, e.g. neutral density. The high resolution midplane, divertor and X-point Thomson scattering systems will be key for this, and burst mode operation (with a short time between successive laser pulses) will provide information on time evolution of individual filaments to complement the visible imaging. Spectroscopic imaging will provide information on the neutrals. To support this, neutral effects are being introduced into SOL and divertor codes running on the BOUT++ platform code [50]. Resolving the filaments' internal structure (which affects their motion) and their break-up will also require further attention.

The novel configurational flexibility will allow exploration of the effect of magnetic geometry (e.g. curvature) on turbulence in the SOL and divertor, building on MAST results. For example, filament generation by interchange-like instabilities in the divertor as well as in the main plasma. The filaments observed in the high field side part of the private flux region may indicate a role of fieldline curvature (like the origin of the in-out asymmetry in turbulent heat flux around the surface of the main plasma) [51] [52]. Since the drive for this will depend on the plasma gradients perpendicular to the flux surfaces, it will be important to have good measurements, not just at the targets – this relates to the interpretive modelling of the measurements, see above.

A further new area will be to explore in detail the behaviour of filaments as the plasma detaches – when the plasma is detached, the current paths at the ends of the filaments changes and this affects their dynamics. This will contribute to the behaviour of the upstream SOL for detached plasmas which is critical to detachment control, the change in upstream conditions, and the way in which the divertor reattaches. If the SOL structure changes during detachment, then significant asymmetry between detachment and reattachment is expected (hysteresis). If the SOL broadens, then the detachment front will move upstream (see above).

VI. SUMMARY

The increasingly detailed studies of DEMO concepts have shown the challenges in integrated plasma exhaust (core plasma to main-chamber and divertor PFC components, over the whole discharge duration). This suggests a research strategy that combines a focus on the end-point with open exploration. Since MAST Upgrade is a new facility, it is appropriate to take this combined approach from the outset. The general strategy for MAST Upgrade is to identify the underlying mechanisms at play in exhaust, especially those revealed or accentuated in novel configurations, notably long leg divertors such as Super-X, to understand and exploit them.

MAST Upgrade has a unique combination of closed divertor, capability of a wide range of configurations from conventional to long-leg (including Super-X), and fully symmetric double null (plasma and divertor structures). It is equipped with extensive high-resolution diagnostics, consistent with its aim of studying mechanisms. At this early stage in developing alternative exhaust, the experimental and theory studies will be exploratory and developmental – MAST Upgrade is not a prototype, as the engineering implementation, parameters, physics mechanisms and optimisation will be different at DEMO parameters.

Early emphases and outputs of the coupled experimental and theory programme are expected to be wide-ranging, including use of the configurational flexibility of MAST Upgrade to explore:

- Detachment physics and control, especially the impact of a large ratio of $B_{\text{X-point}}/B_{\text{target}}$
- Detachment in double null, and the interaction between the upper and lower detached regions via the SOL
- Cross-field transport (heat and particle), especially filaments
- Impact of the divertor on pedestal structure and H-mode access

There is a published MAST Upgrade research plan [22] which indicates the capabilities and research themes. A substantial part of the research will be conducted in the frame of EUROfusion, which will also part-fund some major enhancements that are starting.

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