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Power exhaust in tokamaks and scenario integration issues

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ABSTRACT

A review of the main concepts, proposed solutions and results of R&D as well as outstanding issues on power exhaust in tokamaks is presented with specific emphasis on the expected issues that need to be resolved for ITER and future fusion reactors such as DEMO for both conventional and advanced divertor concepts.

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1. Introduction

The achievement of fusion production in tokamak reactors can only be realized through the integration of DT plasmas with thermonuclear characteristic (achievement of $T > 10$ keV and $nT\tau_E \sim 10^{22}$ m^{-3} keVs) with power and particle fluxes to the reactor vessel which are compatible with the power handling capabilities and erosion lifetime of the components that protect it (plasma-facing components or PFCs). In turn, the erosion of the plasma-facing components generates impurities that can enter the confined plasma and decrease fusion power production by DT fuel dilution and increased electromagnetic radiative losses. In addition the helium ash from DT reactions must be removed by the plasma to avoid DT fuel dilution and this must be achieved within a given total fuel throughput to limit the amount of tritium that is required for the operation of the fusion reactor. These integration issues already have to be addressed to maintain plasma performance in the present generation of experiments, particularly those operating with high Z PFCs [1–3] and with DT plasmas [4,5]. Moreover, the successful resolution of such integration issues is essential for the success of ITER, presently under construction, DEMO and future fusion power plants given the significantly larger edge power and particle fluxes and duration of plasma discharges (from several minutes to continuous operation). These large particle and power fluxes and the long duration of the plasma discharges requires that the PFCs are actively cooled; this limits the power fluxes that can be deposited by the plasma (≤ 10 MW m^{-2}) on the PFCs [6] and the thickness of the PFCs themselves (≤ 1 cm) [7] and thus their erosion lifetime.

Extensive R&D carried out in present tokamaks to resolve the challenges of particle and power exhaust has already provided the basic concepts on which the designs of ITER [8] and DEMO (a demonstration fusion reactor e.g. [9]) are based:

- the modification of the magnetic field at the edge plasma by coils external to the plasma which creates a magnetic separatrix in which the poloidal magnetic field is zero at one or more points (so called poloidal divertor configuration and X-points respectively see Fig. 1). This separates the region of interaction between the confined thermonuclear plasma, through a region of open field lines or scrape-off layer (SOL), and the PFCs and allows the reduction of the power flux on the PFCs (so-called divertor targets) and the increase of particle exhaust by the establishment of high density and low temperature conditions in the divertor plasma itself.
- the use of metallic PFCs, in particular made of tungsten (W), for the divertor targets which are subject to high fluxes, which do not form strongly bound chemical compounds with hydrogenic isotopes and thus prevent T to be trapped in the reactor vessel [14]. While this PFC choice is not directly linked with the general problem of power and particle exhaust it leads to specific issues due to the erosion of the materials resulting from the interaction

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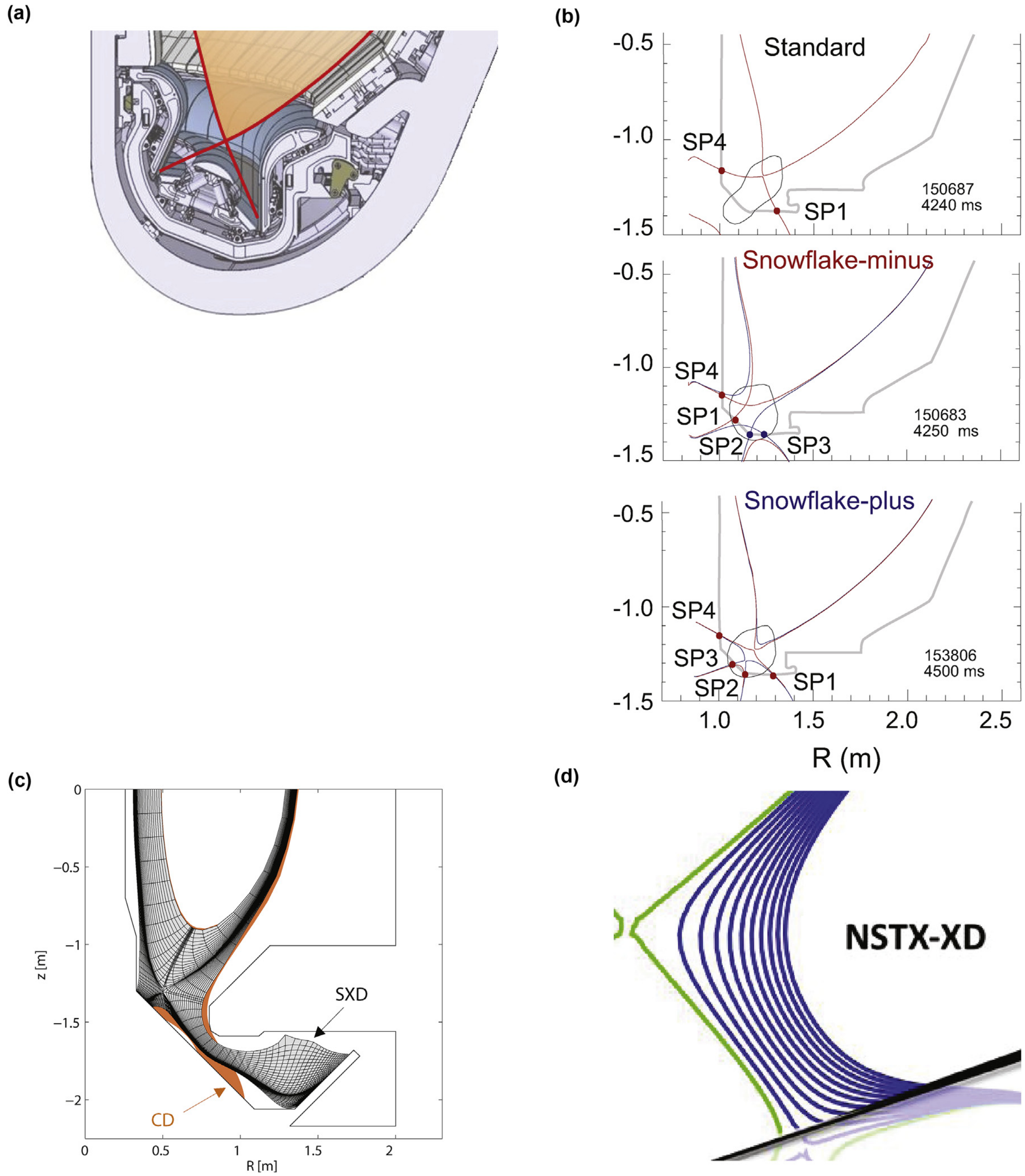

Fig. 1. Magnetic configuration of a conventional vertical divertor and various advanced divertor configurations: a) ITER vertical divertor (conventional), b) Snowflake divertor configurations in DIII-D [11], c) Super-X divertor in MAST-U [12] and d) X divertor in NSTX [13].

with the plasma and to the very small amounts of W which can be tolerated in thermonuclear plasmas due to its large electromagnetic radiation efficiency [15]. It should be pointed out that another potential solution to the power exhaust problem is based on the use of liquid metals which has potential advantages with respect to erosion lifetime and, potentially allows the achievement of power handling capabilities in excess of 10 MW m^{-2}. This approach presents specific issues regarding plasma-wall interactions and the interaction of liquid metals with magnetic fields that will be not be discussed here; the reader is referred to Mazzitelli et al. [16] for details on this topic.

In this paper we review the basic concepts for power and particle exhaust in tokamaks and progress in R&D to address the integration issues mentioned above. We also highlight the remaining challenges that need to be resolved for DEMO both in ITER and other smaller scale devices where the conventional divertor and advanced divertor approaches to this challenge will be investigated. The paper is structured as follows: Section 2 addresses first the basic issues related to power exhaust in tokamaks and the consequences of divertor geometry on this, Section 3 describes the dissipative processes that are utilized to decrease the divertor power flux level, Section 4 describes the use of dissipative processes in the confined plasma to ease the divertor power exhaust problem and the outstanding integration issues, Section 5 discusses issues related to the integration of power exhaust and particle exhaust and finally Section 6 summarises the conclusions.

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