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Taming the plasma-material interface with the snowflake divertor.

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The present vision for controlling the plasma–material interface of a tokamak is an axisymmetric poloidal magnetic X-point divertor. The divertor must enable access to high core and pedestal plasma performance metrics while keeping target plate heat loads and erosion within the operating limits of plasma-facing component cooling technology and target plate materials. The ITER divertor design is based on standard X-point geometry designs tested in large tokamak experiments and optimized via modeling. It uses tilted vertical targets to generate partial radiative detachment of the strike points [1, 2]. However, the standard poloidal divertor approach is likely to be insufficient for next step advanced tokamak and spherical tokamak devices such as the proposed fusion nuclear science facilities and for the DEMO reactor.

The history of the poloidal divertor development shows many examples of the concept optimization based on tokamak magnetic topology, magnetic geometry, and plasma-facing component geometry [3]. A recently proposed snowflake divertor [4-6] is based on the magnetic configuration where a second-order poloidal field null is created by bringing two first-order null-points together or close to each other, thereby producing a larger region of lower poloidal field in the divertor (cf. standard divertor). Poloidal magnetic flux surfaces in the region of the second-order null have hexagonal separatrix branches with an appearance of a snowflake. Initial experiments in several tokamaks (TCV [7], NSTX [8], DIII-D [9], and EAST [10]) provide increasing support for the snowflake configuration as a viable tokamak heat exhaust concept. This white paper summarizes the snowflake properties predicted theoretically and studied experimentally, and identifies outstanding issues to be resolved in existing and future facilities before the snowflake divertor can qualify for the reactor interface.

1. *Magnetic configuration and equilibria development*. The snowflake configuration has been created on several tokamaks with existing poloidal field coil sets. Equilibria designs are performed using free boundary Grad-Shafranov equilibria codes. The optimization of the poloidal field coil number and layout that involves coil placement outside of the toroidal field coil and at a distance has been demonstrated [11, 12]. Further work is necessary for specific plasma shaping parameters and existing and future tokamak designs.
2. *Real-time feedback control*. Initial experiments used off-line equilibria designs and pre-programmed poloidal field coil currents, with the exception of recent DIII-D control studies [13]. Additional developments of real-time magnetic diagnostics, null-tracking algorithms, and multi-input multi-output control schemes is required to address long-pulse discharge control.
3. *Impact on core and pedestal*. Initial experiments generally show no detrimental snowflake divertor effects on core confinement [7, 8, 9]. The pedestal structure and ELM properties (energy and frequency) are apparently affected, suggesting that MHD stability is modified due to higher edge magnetic shear and modified plasma pressure

gradient [7, 9, 14-17]. Additional experiments and analysis on existing facilities should obtain a systematic assessment of these effects, including clarification of the plasma shaping variations. Increased prompt ion loss through the second-order null region is predicted theoretically [18] and may affect the edge electric field and velocity shear.

4. *Heat and particle flux sharing among all divertor legs*. This unique snowflake divertor property was observed experimentally [16, 19-22] and is highly beneficial for inter-ELM and ELM peak heat flux mitigation. The associated transport mechanism is not well understood and can include particle drifts [23], flute-like and ballooning instabilities [24, 25], fast convection [26-28], and magnetic field stochastization. Additional measurements (e.g., divertor density fluctuations, divertor plasma pressure profiles, and divertor plasma flow) are needed for divertor transport and turbulence studies. Identification and development of a multi-device scaling of the heat flux sharing effect is desirable.
5. *Improved divertor geometry properties*. The increased magnetic flux expansion and connection length have been demonstrated experimentally [9, 20, 29]. Anticipated effects on the divertor plasma include increased radial transport and temperature drop in each divertor leg, a longer divertor particle residence time, disconnection of turbulence along the flux tube due to stronger shearing in the snowflake region, and increased flux tube volume and radiation. Some of these effects have been observed and characterized through modelling [22, 30]. Additional experiments and modleing are needed to systematically investigate divertor heat and impurity transport as functions of geometry properties and plasma collisionality (e.g. in a transition from low-recycling to high recycling and detached).
6. *Radiative snowflake divertor and detachment*. Initial snowflake experiments used D_2 with intrinsic carbon impurities, or additional impurity seeding, and demonstrated significant additional peak heat flux reduction, including peak ELM heat fluxes, nearly full power detachment, and increased divertor radiation [29, 31-34]. Experiments in existing facilities with upgraded diagnostics should clarify impurity radiation distribution in the snowflake divertor, its effect on radiative condensation instability formation and threshold, impurity screening, and compatibility with particle control techniques.
7. Combining the snowflake divertor with applied three dimensional magnetic fields for MHD and ELM control can be studied in existing facilities and could provide interesting potentially synergistic effects for the reactor [35].

Existing facilities in the US (Alcator C-Mod, DIII-D and NSTX-U) can support many of the snowflake development efforts with existing and upgraded diagnostic and facility capabilities. Snowflake divertor studies would also greatly benefit from international collaborations with the HL-2M [36] and EAST tokamaks in China, and TCV and MAST [37, 38] tokamaks in Europe, where snowflake divertor studies are planned in the near future. The ultimate goal of this research is the physics basis for the snowflake divertor in a tokamak fusion reactor.

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