**“Snowflake” H Mode in a Tokamak Plasma**

F. Piras,1,* S. Coda,1 B. P. Duval,1 B. Labit,1 J. Marki,1 S. Yu. Medvedev,2 J.-M. Moret,1 A. Pitzschke,1 O. Sauter,1 and TCV Team

1École Polytechnique Fédérale de Lausanne, Centre de Recherches en Physique des Plasmas, Association Euratom-Conféderation Suisse, Station 13, CH-1015 Lausanne, Switzerland
2Keldysh Institute of Applied Mathematics, Russian Academy of Sciences, Miusskaya 4, 125047 Moscow, Russia

(Received 15 June 2010; published 5 October 2010)

An edge-localized mode (ELM) H-mode regime, supported by electron cyclotron heating, has been successfully established in a “snowflake” (second-order null) divertor configuration for the first time in the TCV tokamak. This regime exhibits 2 to 3 times lower ELM frequency and 20%–30% increased normalized ELM energy \( \Delta W_{ELM}/W_p \) compared to an identically shaped, conventional single-null diverted H mode. Enhanced stability of mid- to high-toroidal-mode-number ideal modes is consistent with the different snowflake ELM phenomenology. The capability of the snowflake to redistribute the edge power on the additional strike points has been confirmed experimentally.

DOI: 10.1103/PhysRevLett.105.155003 PACS numbers: 52.55.Fa, 28.52.–s, 52.55.Rk

In the dominant tokamak approach to magnetic-confinement nuclear fusion, the divertor configuration has emerged as the preeminent solution to managing power exhaust and core impurity content. In the presence of a magnetic X point, where the poloidal field vanishes, energy and particle losses are channeled primarily into a divertor region that is separated from the confined plasma region. The drawback of this approach is the high power flux impinging on the divertor plates, which may consequently overheat and undergo destructive erosion. This is particularly true during edge localized modes (ELMs) [1–5] occurring in the high-confinement H mode [6], which cause periodic, violent, and potentially highly damaging ejections of energy and particles onto the divertor surfaces [7,8]. Heat flux management in the tokamak divertor and, in particular, the control of ELMs [9–11], remains therefore a primary goal of magnetic fusion research.

A “snowflake” (SF) divertor configuration [12,13] has recently been proposed to reduce the plasma-wall interaction by changing the divertor’s poloidal magnetic field topology. The feasibility of this configuration was demonstrated for the first time in the TCV tokamak [14,15]. The X point of a SF configuration features a second-order null point, i.e., both the poloidal magnetic field and its spatial first derivatives vanish. By perturbing this configuration, a SF+ configuration or SF− configuration is obtained with two contiguous X points that, for the SF− configuration, are both located at the separatrix [12]. The distance between the X points normalized to the plasma minor radius \( \sigma \) parametrizes the proximity to an ideal SF configuration. SF plasmas feature a longer scrape-off layer (SOL) connection length and higher flux expansion in the null-point region compared with conventional single-null (SN) configuration [14]. Additionally, the increased magnetic shear in the edge region is predicted to influence ELM activity [16,17].

This Letter reports the first H-mode discharges obtained with a SF+ divertor. Stationary ELM H modes are obtained and a significant change in the ELM frequency is observed, compared to an equivalent SN divertor plasma, demonstrating the potential of SF plasmas to lead to a new type of high-confinement scenario with better edge properties. In this Letter, we (1) examine the stability and power threshold of the H-mode regime, (2) compare the ELM behavior with an equivalent SN configuration, (3) identify enhanced stability of the kink-ballooning modes consistent with the different SF+ ELM dynamics, and (4) examine the SF+ configuration power distribution to the additional strike zones.

The SF+ configuration studied is shown in Fig. 1(b). The chosen \( \sigma \sim 50\% \) is a compromise between the enhancement of the magnetic properties and the stable sustainment of the configuration by TCV’s poloidal coil array and control system. For this study, the SF+ is compared with the SN configuration [Fig. 1(a)]. The SN shape is tuned to match the shape and wall separations of the SF+ configuration. Differences between the two shapes are significant only in the null-point region where the larger flux expansion of the SF+ configuration results in a small modification of the plasma separatrix geometry. For comparison, the last closed flux surfaces (LCFS) of the two moderately shaped configurations (minor radius \( a = 0.22 \) m, elongation \( \kappa = 1.75 \), upper triangularity \( \delta^{UP} = 0.16 \), and lower triangularity \( \delta^{LW} = 0.21 \) for the SN and \( \delta^{LW} = 0.28 \) for the SF+) are shown in Fig. 5(a).

In these scenarios, the \( \mathbf{B} \times \nabla \mathbf{B} \) ion-drift direction is towards the null point, the plasma current is 300 kA, and the toroidal magnetic field at the TCV major radius \( (R_0 = 0.88 \) m) is 1.43 T. In addition to the Ohmic power, the plasma is heated with 1.5 MW X-mode electron cyclotron heating (ECH). The ECH beam geometry is shown in Fig. 1: 1 MW is injected at the third electron cyclotron harmonic (X3) from the top of TCV and 0.5 MW is injected.
from the low-field side (LFS) at the second harmonic (X2). The absorbed fraction computed by the ray tracing code TORAY-GA [18] is 75% for the X3, primarily in the core region, and 100% for the X2, localized near the plasma edge.

Figure 2 shows plasma signals during an H mode with a SN established between 0.28 and 0.7 s, and a SF+ stationary phase between 0.8 and 1.64 s. ECH is injected from 0.3 to 1.7 s [Fig. 2(d)]. This reproducible discharge featuring both SN and SF+ configurations within the same plasma pulse is used to examine the differences and similarities in the H-mode and ELM behaviors. Operated at low plasma density to avoid the ECH cutoff, these plasmas are well below the Ohmic H-mode TCV density threshold and undergo a transition to H mode only when the ECH power is applied, identified by the characteristic drop in $H_\alpha$ emission [Fig. 2(a)] and the development of an edge transport barrier in the pressure profile measured by Thomson scattering. The H mode features steady ELMs, starting immediately after the transition. Figures 2(b) and 2(c) show the temporal evolution of the volume averaged temperature and the line averaged electron plasma density. The volume averaged plasma temperature increases by $\sim 15\%$ during the SN to SF+ transition as the second X point is moved between the positions shown in Fig. 2. The pedestal temperature does not change [Fig. 5(a)]. The total plasma energy, confinement time, and H factor increase by $\sim 15\%$ in the steady-state SF+ phase. This relatively small enhancement may be consistent with the variation of the global plasma shape parameters (e.g., the $\sim 30\%$ increase in the lower triangularity) between SN and SF+ configurations.

The L-H power threshold and the ELM dynamics are crucial properties of H-mode plasmas and their understanding is regarded as an urgent need for controlled fusion. The L-H–mode threshold power for the two configurations is identified with a sequence of discharges with increasing heating power. Figure 3 shows the minimum heating power necessary to establish an H mode as a function of the volume averaged plasma density $n_e$. Above $n_e \sim 5 \times 10^{19}$ m$^{-3}$, H-mode access is possible with Ohmic heating power alone. The power threshold is similar for the two configurations, so the change in magnetic topology does not appear to influence the H-mode threshold as one might expect from the increase in shear just inside the separatrix [19]. This is an important result since one of the purposes of snowflake divertors is to open a new regime for ELM H modes.

In H modes, ELMs are readily observed as spikes on $H_\alpha$ radiation from the plasma edge. The vertical $H_\alpha$-filtered photodiode, Fig. 2(a), has a field of view that covers all the strike points. A clear change is observed at the SN-SF+ transition with a reduction in the ELM frequency and an...
ELM frequency increases in the amplitude of the $H_\alpha$ peaks and their integrated intensity across the ELM by $\sim 30\%$. The ELMing phases are compared for a sequence of discharges with stepwise increase of the heating power. Figure 4 shows the ELM frequency ($\nu_{ELM}$) versus the input power ($P_{\text{in}}$) for both configurations with quantities averaged over a power step held for 200 ms, i.e., long enough compared to the confinement time and to ensure regular ELM activity. The vertical error bars depict the scatter in the computed ELM confinement time and to ensure regular ELM activity. The significant reduction of $\nu_{ELM}$ with a relatively smaller increase of $\Delta W_{ELM}$ causes a decrease of the normalized ELM power loss ($\nu_{ELM} \times \Delta W_{ELM}/P_{\text{in}}$), changing from 30% for the SN to $\sim 12\%$ for the SF$^+$ configuration.

An analysis of the stability of the plasma edge was undertaken to assess the nature of the ELMs for the two configurations. Figures 5(a) and 5(b) show the temperature and density pedestal profiles for the SN and the SF$^+$ configurations, demonstrating no significant difference in the pedestal profiles, except for the slightly steeper temperature gradient of the SF$^+$ configuration just inside the pedestal region (leading to a 15% increase in $T_{e0}$). The magnetic shear ($s = \frac{\rho_s dq}{dq}$, where $\rho_s$ is the square root of the normalized plasma volume) is computed for the two configurations using the CHEASE code [22] and is shown in Fig. 5(b). The edge bootstrap current, calculated from the electron temperature and density profiles [23], is fully 20%–30%. The ELM behavior is thus indeed strongly modified by the SF$^+$ configuration and results in improved plasma performance. The significant reduction of $\nu_{ELM}$ with a relatively smaller increase of $\Delta W_{ELM}$ causes a decrease of the normalized ELM power loss ($\nu_{ELM} \times \Delta W_{ELM}/P_{\text{in}}$), changing from 30% for the SN to $\sim 12\%$ for the SF$^+$ configuration.

An analysis of the stability of the plasma edge was undertaken to assess the nature of the ELMs for the two configurations. Figures 5(a) and 5(b) show the temperature and density pedestal profiles for the SN and the SF$^+$ configurations, demonstrating no significant difference in the pedestal profiles, except for the slightly steeper temperature gradient of the SF$^+$ configuration just inside the pedestal region (leading to a 15% increase in $T_{e0}$). The magnetic shear ($s = \frac{\rho_s dq}{dq}$, where $\rho_s$ is the square root of the normalized plasma volume) is computed for the two configurations using the CHEASE code [22] and is shown in Fig. 5(b). The edge bootstrap current, calculated from the electron temperature and density profiles [23], is fully 20%–30%. The ELM behavior is thus indeed strongly modified by the SF$^+$ configuration and results in improved plasma performance. The significant reduction of $\nu_{ELM}$ with a relatively smaller increase of $\Delta W_{ELM}$ causes a decrease of the normalized ELM power loss ($\nu_{ELM} \times \Delta W_{ELM}/P_{\text{in}}$), changing from 30% for the SN to $\sim 12\%$ for the SF$^+$ configuration.

An analysis of the stability of the plasma edge was undertaken to assess the nature of the ELMs for the two configurations. Figures 5(a) and 5(b) show the temperature and density pedestal profiles for the SN and the SF$^+$ configurations, demonstrating no significant difference in the pedestal profiles, except for the slightly steeper temperature gradient of the SF$^+$ configuration just inside the pedestal region (leading to a 15% increase in $T_{e0}$). The magnetic shear ($s = \frac{\rho_s dq}{dq}$, where $\rho_s$ is the square root of the normalized plasma volume) is computed for the two configurations using the CHEASE code [22] and is shown in Fig. 5(b). The edge bootstrap current, calculated from the electron temperature and density profiles [23], is fully 20%–30%. The ELM behavior is thus indeed strongly modified by the SF$^+$ configuration and results in improved plasma performance. The significant reduction of $\nu_{ELM}$ with a relatively smaller increase of $\Delta W_{ELM}$ causes a decrease of the normalized ELM power loss ($\nu_{ELM} \times \Delta W_{ELM}/P_{\text{in}}$), changing from 30% for the SN to $\sim 12\%$ for the SF$^+$ configuration.

An analysis of the stability of the plasma edge was undertaken to assess the nature of the ELMs for the two configurations. Figures 5(a) and 5(b) show the temperature and density pedestal profiles for the SN and the SF$^+$ configurations, demonstrating no significant difference in the pedestal profiles, except for the slightly steeper temperature gradient of the SF$^+$ configuration just inside the pedestal region (leading to a 15% increase in $T_{e0}$). The magnetic shear ($s = \frac{\rho_s dq}{dq}$, where $\rho_s$ is the square root of the normalized plasma volume) is computed for the two configurations using the CHEASE code [22] and is shown in Fig. 5(b). The edge bootstrap current, calculated from the electron temperature and density profiles [23], is fully 20%–30%. The ELM behavior is thus indeed strongly modified by the SF$^+$ configuration and results in improved plasma performance. The significant reduction of $\nu_{ELM}$ with a relatively smaller increase of $\Delta W_{ELM}$ causes a decrease of the normalized ELM power loss ($\nu_{ELM} \times \Delta W_{ELM}/P_{\text{in}}$), changing from 30% for the SN to $\sim 12\%$ for the SF$^+$ configuration.

An analysis of the stability of the plasma edge was undertaken to assess the nature of the ELMs for the two configurations. Figures 5(a) and 5(b) show the temperature and density pedestal profiles for the SN and the SF$^+$ configurations, demonstrating no significant difference in the pedestal profiles, except for the slightly steeper temperature gradient of the SF$^+$ configuration just inside the pedestal region (leading to a 15% increase in $T_{e0}$). The magnetic shear ($s = \frac{\rho_s dq}{dq}$, where $\rho_s$ is the square root of the normalized plasma volume) is computed for the two configurations using the CHEASE code [22] and is shown in Fig. 5(b). The edge bootstrap current, calculated from the electron temperature and density profiles [23], is fully 20%–30%. The ELM behavior is thus indeed strongly modified by the SF$^+$ configuration and results in improved plasma performance. The significant reduction of $\nu_{ELM}$ with a relatively smaller increase of $\Delta W_{ELM}$ causes a decrease of the normalized ELM power loss ($\nu_{ELM} \times \Delta W_{ELM}/P_{\text{in}}$), changing from 30% for the SN to $\sim 12\%$ for the SF$^+$ configuration.

An analysis of the stability of the plasma edge was undertaken to assess the nature of the ELMs for the two configurations. Figures 5(a) and 5(b) show the temperature and density pedestal profiles for the SN and the SF$^+$ configurations, demonstrating no significant difference in the pedestal profiles, except for the slightly steeper temperature gradient of the SF$^+$ configuration just inside the pedestal region (leading to a 15% increase in $T_{e0}$). The magnetic shear ($s = \frac{\rho_s dq}{dq}$, where $\rho_s$ is the square root of the normalized plasma volume) is computed for the two configurations using the CHEASE code [22] and is shown in Fig. 5(b). The edge bootstrap current, calculated from the electron temperature and density profiles [23], is fully 20%–30%. The ELM behavior is thus indeed strongly modified by the SF$^+$ configuration and results in improved plasma performance. The significant reduction of $\nu_{ELM}$ with a relatively smaller increase of $\Delta W_{ELM}$ causes a decrease of the normalized ELM power loss ($\nu_{ELM} \times \Delta W_{ELM}/P_{\text{in}}$), changing from 30% for the SN to $\sim 12\%$ for the SF$^+$ configuration.

An analysis of the stability of the plasma edge was undertaken to assess the nature of the ELMs for the two configurations. Figures 5(a) and 5(b) show the temperature and density pedestal profiles for the SN and the SF$^+$ configurations, demonstrating no significant difference in the pedestal profiles, except for the slightly steeper temperature gradient of the SF$^+$ configuration just inside the pedestal region (leading to a 15% increase in $T_{e0}$). The magnetic shear ($s = \frac{\rho_s dq}{dq}$, where $\rho_s$ is the square root of the normalized plasma volume) is computed for the two configurations using the CHEASE code [22] and is shown in Fig. 5(b). The edge bootstrap current, calculated from the electron temperature and density profiles [23], is fully 20%–30%. The ELM behavior is thus indeed strongly modified by the SF$^+$ configuration and results in improved plasma performance. The significant reduction of $\nu_{ELM}$ with a relatively smaller increase of $\Delta W_{ELM}$ causes a decrease of the normalized ELM power loss ($\nu_{ELM} \times \Delta W_{ELM}/P_{\text{in}}$), changing from 30% for the SN to $\sim 12\%$ for the SF$^+$ configuration.

An analysis of the stability of the plasma edge was undertaken to assess the nature of the ELMs for the two configurations. Figures 5(a) and 5(b) show the temperature and density pedestal profiles for the SN and the SF$^+$ configurations, demonstrating no significant difference in the pedestal profiles, except for the slightly steeper temperature gradient of the SF$^+$ configuration just inside the pedestal region (leading to a 15% increase in $T_{e0}$). The magnetic shear ($s = \frac{\rho_s dq}{dq}$, where $\rho_s$ is the square root of the normalized plasma volume) is computed for the two configurations using the CHEASE code [22] and is shown in Fig. 5(b). The edge bootstrap current, calculated from the electron temperature and density profiles [23], is fully 20%–30%. The ELM behavior is thus indeed strongly modified by the SF$^+$ configuration and results in improved plasma performance. The significant reduction of $\nu_{ELM}$ with a relatively smaller increase of $\Delta W_{ELM}$ causes a decrease of the normalized ELM power loss ($\nu_{ELM} \times \Delta W_{ELM}/P_{\text{in}}$), changing from 30% for the SN to $\sim 12\%$ for the SF$^+$ configuration.

An analysis of the stability of the plasma edge was undertaken to assess the nature of the ELMs for the two configurations. Figures 5(a) and 5(b) show the temperature and density pedestal profiles for the SN and the SF$^+$ configurations, demonstrating no significant difference in the pedestal profiles, except for the slightly steeper temperature gradient of the SF$^+$ configuration just inside the pedestal region (leading to a 15% increase in $T_{e0}$). The magnetic shear ($s = \frac{\rho_s dq}{dq}$, where $\rho_s$ is the square root of the normalized plasma volume) is computed for the two configurations using the CHEASE code [22] and is shown in Fig. 5(b). The edge bootstrap current, calculated from the electron temperature and density profiles [23], is fully 20%–30%. The ELM behavior is thus indeed strongly modified by the SF$^+$ configuration and results in improved plasma performance. The significant reduction of $\nu_{ELM}$ with a relatively smaller increase of $\Delta W_{ELM}$ causes a decrease of the normalized ELM power loss ($\nu_{ELM} \times \Delta W_{ELM}/P_{\text{in}}$), changing from 30% for the SN to $\sim 12\%$ for the SF$^+$ configuration.
FIG. 6 (color online). Temperature $T$ and heat flux $q_{\text{VIR}}$ profiles at the strike point 4 vs the distance from the strike point at the time of the ELM $H_\alpha$ spike. The profiles are coherently averaged over 30 ELMs.

The most striking difference is in the ELM frequency, reduced by a factor 2–3 in the snowflake, while $\Delta W_{\text{ELM}}/W_p$ is increased by only 20%–30%. This opens the way to the study of the effect of the new magnetic topology on ELMs.

The authors gratefully acknowledge valuable discussions with S. Alberti, T. Goodman, Y. Martin, R. A. Pitts, and L. Porte. This work was partly supported by the Fonds National Suisse de la Recherche Scientifique.

References: