# Snowflake Divertor Configuration Effects on Pedestal Stability and Edge Localized Modes in NSTX and Preparations for Snowflake Divertor Research on NSTX Upgrade.

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Analysis of snowflake (SF) divertor [1] experiments in NSTX [2] show that the SF divertor can increase edge magnetic shear and modify pressure profiles of the H-mode pedestal enabling pedestal stability control while maintaining good H-mode confinement ($H_{98y2}$~1). The scrape-off layer (SOL) geometry modifications lead to reduced peak plasma-facing component (PFC) temperature via significant additional dissipation and partitioning of ELM heat fluxes. The possibility of MHD stability and ELM control with the SF configuration was proposed theoretically [3] and studied with edge fluid and turbulence transport modeling [4-6]. Steady-state divertor heat flux mitigation in future tokamaks is envisioned via a combination of radiative divertors and divertor magnetic and plate geometries, however, mitigation of large ELMs is still an unresolved issue. The unmitigated ELM energy density up to 5-14 MJ-m$^{-2}$ poses a significant risk for PFCs and cannot be mitigated by radiative buffering [7].

The SF divertor configuration uses a second-order poloidal field null, or two nearby first order nulls, for a large region of low poloidal field $B_p$ in the divertor [1]. Existing divertor coils have been used for steady-state SF divertor configurations in H-mode discharges in NSTX ($I_p$=0.9 MA, $P_{SOL}$~3 MW, and $B\times\nabla B$ down). The SF formation in NSTX was always accompanied by radiative divertor detachment. Previous analysis focused on divertor geometry effects on inter-ELM heat transport in the radiative SF divertor [2]. This work addresses the pedestal ELM stability and ELM heat transport and heat deposition in the radiative SF divertor with low-Z impurities.

ELM control strongly depends on proximity of the pedestal stability operating point to edge toroidal current density (peeling mode) and edge pressure gradient (ballooning mode) limits. Recent stability analysis of the highly-shaped discharges with lithium conditioning in NSTX [8] confirmed that pedestal stability operating condition was close to the kink/peeling boundary with the standard divertor, and ELMs were stabilized by changes in pedestal pressure gradient and current density profile resulting from lithium conditioning [9]. With the SF divertor and lithium conditioning, large ELMs ($f_{ELM}$=12–35 Hz, $\Delta W_{MHD}/W_{MHD}$=5–10%) were destabilized. Furthermore, additional $CD_4$ seeding in the SF divertor (and with lithium conditioning) stabilized these SF-induced large ELMs and resulted in H-mode regime with very small ELMs (Fig. 1). Core confinement was slightly reduced. Initial profile analysis suggests that the pedestal was returned to pre-lithium conditions with the radiative SF divertor, and back with additional gas seeding. Planned linear MHD stability

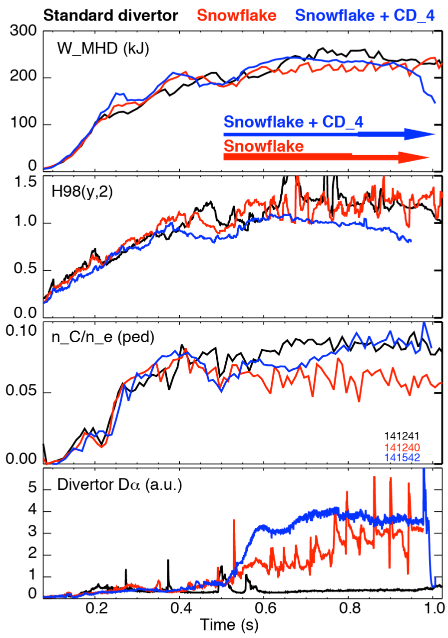


**Fig. 1. Comparison of plasma stored energy, H98(y,2) factor, pedestal carbon concentration, and divertor Dα (ELMs) in H-mode discharges with the standard divertor, and snowflake divertor with and without $CD_4$ seeding.**

calculations will help understand the destabilization mechanism. ELM-free induced impurity accumulation was arrested with the SF configuration, e.g., carbon concentration was reduced by 30-50% in the pedestal. SF-induced ELMs may provide a way of controlling impurity accumulation in lithium-conditioned discharges in NSTX-U [10].

A reduction of ELM-induced divertor peak temperature $T_{surf}$ (and heat flux) in the SF divertor (cf. standard divertor) was noted in NSTX experiments [2]. A transient (ELM) heat pulse causes a divertor $T_{surf}$ rise $\Delta T \sim \Delta W_{div}/(A\tau^{1/2})$, where $\Delta W_{div}$ is the total deposited energy, $A$ is the ELM-wetted area, and $\tau$ is the deposition time, proportional to the pedestal thermal ion transit time to the strike point $\tau_{||}=L_{mp-sp}/c_{ped}$, where $c_{ped}$ is the ion sound speed and $L_{mp-sp}$ is the connection length. The transit time $\tau_{||}$ is longer in the SF geometry due to $L_{mp-sp}$ being greater by 80% [2]. Longer $L_{mp-sp}$ can also result in a temporal dilution of the energy pulse and its peak reduction [3,5]. It is found that the divertor ELM energy density $\Delta W_{div}/A$ is reduced due to 1) reduction of $\Delta W_{div}$ due to additional dissipative losses; 2) splitting $\Delta W_{div} / A$ between additional SF strike points, a key SF property [1]. Divertor profiles before and at peak ELM times are compared for the SF and standard geometries in Fig. 2. Heat is transported to the primary and secondary strike points in the SF configuration. During an ELM heat pulse in the SF divertor, C III and C IV radiation fill the entire divertor volume (cf. narrow radial SOL region in the standard divertor). Plasma slab model with coronal impurity radiation [11] calculations indicate that it is possible to dissipate ELM energy of 10-20 kJ through carbon radiation, charge exchange and elastic collision losses via a longer loss length. ELMs do not "burn through" the SF divertor plasma in NSTX, the SF divertor remains in low-temperature, high density recombining state. This effect was also observed in radiative SF divertor in DIII-D [12].

In summary, the SF divertor configuration can modify pedestal and ELM characteristics via a larger area of low poloidal field in the divertor region and the associated modifications in magnetic and geometric properties both inside and outside the separatrix, as demonstrated in NSTX experiments. The modifications are generally beneficial and can be further developed into ELM control scenarios and an ELM mitigation technique. New SF divertor experiments that are planned on NSTX Upgrade [10] will focus on the outstanding issues in SF physics, including pedestal stability, null-region churning mode stability and growth-rate scaling, steady-state and ELM heat transport studies, and highly radiative scenarios with low-Z and medium-Z seeding and high-Z PFCs [13].

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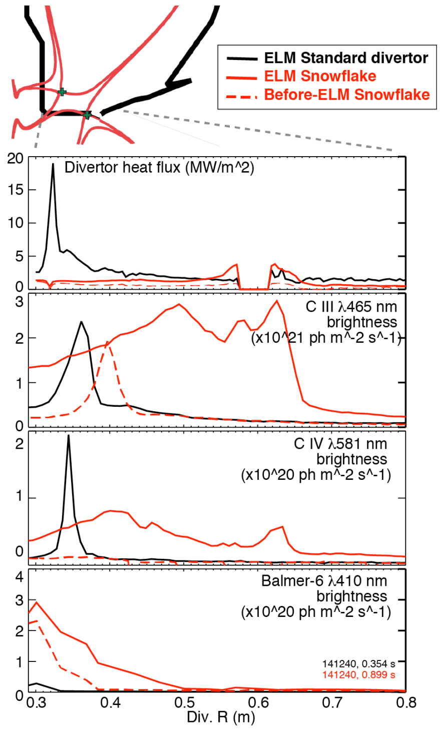


**Fig. 2. Comparison of divertor profiles in the standard attached and radiative snowflake divertors at peak ELM times and before an ELM.**