Synergy Between Lithium Plasma-Facing Component Coatings and the Snowflake Divertor Configuration in NSTX*

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Poster EXD / P 3-32
13 October 2010

11–16 October 2010
Daejeon, Republic of Korea

IAEA FEC 2010
23rd IAEA Fusion Energy Conference

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* Supported by the U.S. DOE under Contracts DE-AC52-07NA27344, DE AC02-09CH11466, DE-AC05-00OR22725, DE-FG02-08ER54989.

Abstract

The studies of an innovative “snowflake” divertor configuration and evaporated lithium wall and divertor coatings in NSTX provide support to these PMI concepts as viable candidates for future high divertor heat flux tokamaks and spherical tokamak based devices for fusion development applications. Lithium coatings have enabled ion density reduction up to 50 % in NSTX through the reduction of wall and divertor recycling rates. The outer SOL parallel heat transport regime changed from the high-recycling, heat flux conduction-limited to the sheath-limited regime. An enhancement in edge transport and a recycling coefficient of R~0.85 were inferred from interpretive two dimensional multi-fluid edge transport modeling. However, a concomitant elimination of ELMs and an improvement in particle confinement caused impurity accumulations. The “snowflake” divertor (SFD) configuration obtained in NSTX in 0.8 MA 4-6 MW NBI-heated H-mode lithium-assisted discharges demonstrated encouraging impurity control and divertor heat flux handling results. A number of theoretically predicted geometric and radiative properties of the SFD configuration has been confirmed. A very high poloidal flux expansion of the separatrix region in the SFD, as well as a longer connection length, as compared to a standard divertor configuration, led to a partial strike point detachment and the associated peak heat flux reduction. The core carbon density and radiated power were also significantly reduced.

Overview and Summary: High flux expansion area-pumping divertor is studied in NSTX

- **Evaporative lithium coatings on carbon PFCs** modify divertor and SOL
  - Surface pumping reduced ion inventory (density) by up to 50 %
  - Recycling was reduced by up to 50 % in both divertors and wall
  - Local recycling coefficients reduced on inner wall and far SOL, remained similar in the outer strike point region
  - Parallel heat transport regime in the SOL changes from conduction-limited (high-recycling) to sheath-limited (low-recycling)
  - Edge transport enhancement and recycling coefficient R~0.85 concluded from interpretive UEDGE modeling that matched experimental data

- **“Snowflake” divertor configuration** (cf. standard divertor)
  - Obtained with 2 divertor coils and w/ 3 divertor coils for 100-600 ms
  - H-mode confinement maintained with significant reduction in core impurities
  - Significant reduction in peak heat flux (and outer strike point partial detachment)
  - Higher divertor plasma-wetted area A_{wet} and volume (increased P_{rad}, R_{rec}, R_{cx})
  - Excellent candidate divertor solution for future high divertor heat flux devices

Various techniques considered for SOL / divertor $q_{||}$ and q_{pk} control

- **Divertor heat flux mitigation solutions:**

$$q_{pk} \simeq \frac{P_{heat}\,(1-f_{rad})f_{out/tot}f_{down/tot}(1-f_{pfr})\sin\alpha}{2\pi R_{SP} f_{exp}\lambda_{q_{||}}}$$

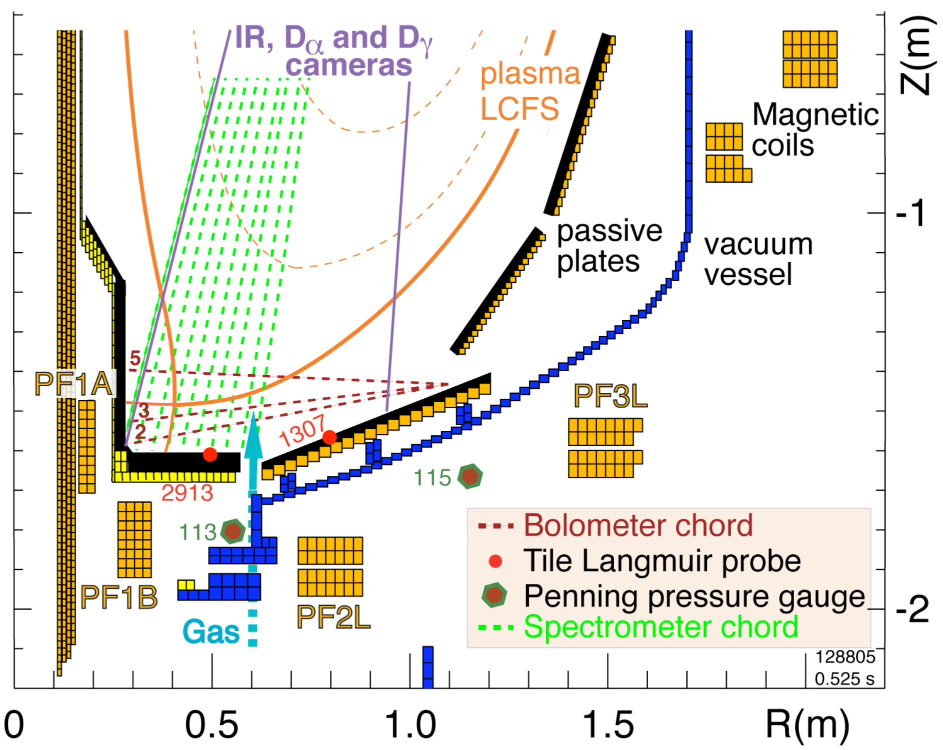
  - ✓ Divertor geometry (poloidal flux expansion)
  - ✓ Strike point sweeping
  - ✓ Radiative divertor (or radiative mantle)
  - ✓ Divertor plate tilt and divertor magnetic balance

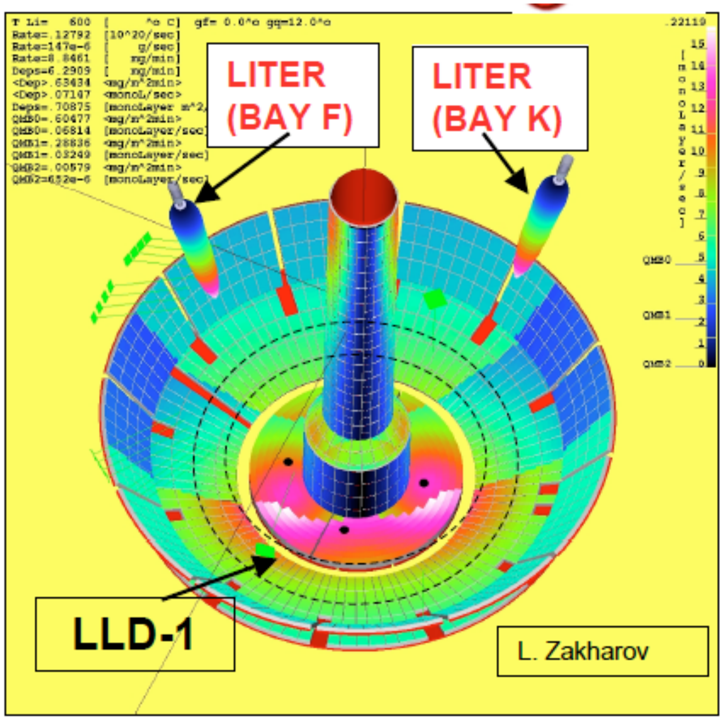
$$f_{exp} = \frac{(B_p/B_{tot})_{MP}}{(B_p/B_{tot})_{OSP}}$$

$$A_{wet} = 2\pi R\, f_{exp}\, \lambda_{q_{||}}$$

- **Candidate solutions must**
  - **be compatible with good core plasma performance (H-mode confinement, MHD, ELM regime, density)**
  - **be compatible with particle control (e.g., cryopump, lithium)**
  - **scale to very high q_{peak} (15 - 80 MW/m^2) for future devices**

Open divertor geometry enables well-diagnosed divertor configuration studies and area pumping by lithium coatings





- **NSTX plasma facing components**
  - ATJ and CFC graphite tiles
- **Lithium pumping**
  - Through LiD formation
  - Solid coating bind D up to a full 200-400 nm thickness
- **Impurity (Li, C) generation**
  - Sputtering by D ions, Self-sputtering, Evaporation

- Two lithium evaporators (LITERs)
- Typical Operating Conditions
  - Capacity: 90 g Li
  - Oven Temp: 600-680°C
  - Rate: 1mg/min - 80mg/min

Ion density is reduced by up to 50 % in 4-6 MW H-mode discharges by lithium conditioning

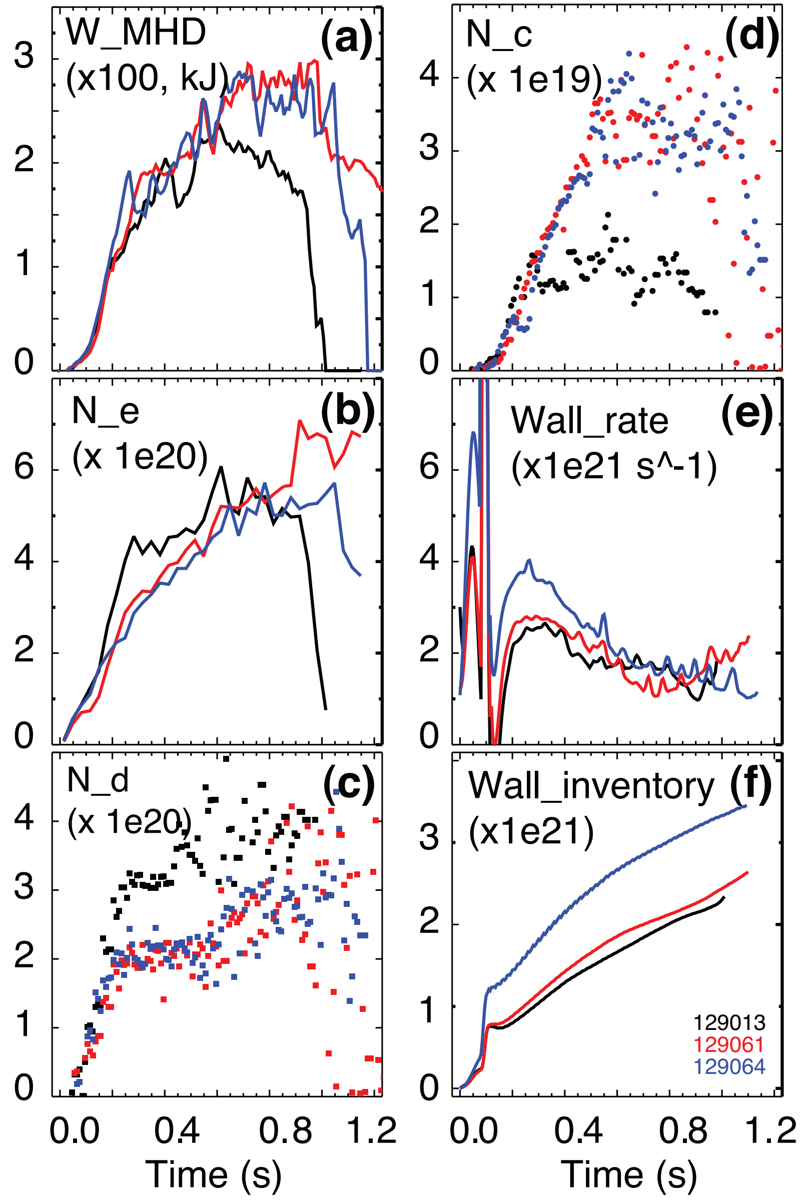
- Particle balance model
  - Continuous pumping throughout a discharge
  - cumulative coatings provide higher pumping rate
  - Wall in pumping state far from saturation

$$\frac{dN_p}{dt} = \Gamma_{gas} + \underbrace{\Gamma_{NBI} + \Gamma_{NBI\_cold}} + \Gamma_{NBI\_cryo} + \Gamma_{wall} + \Gamma_{pump} + \frac{dN_n}{dt}$$

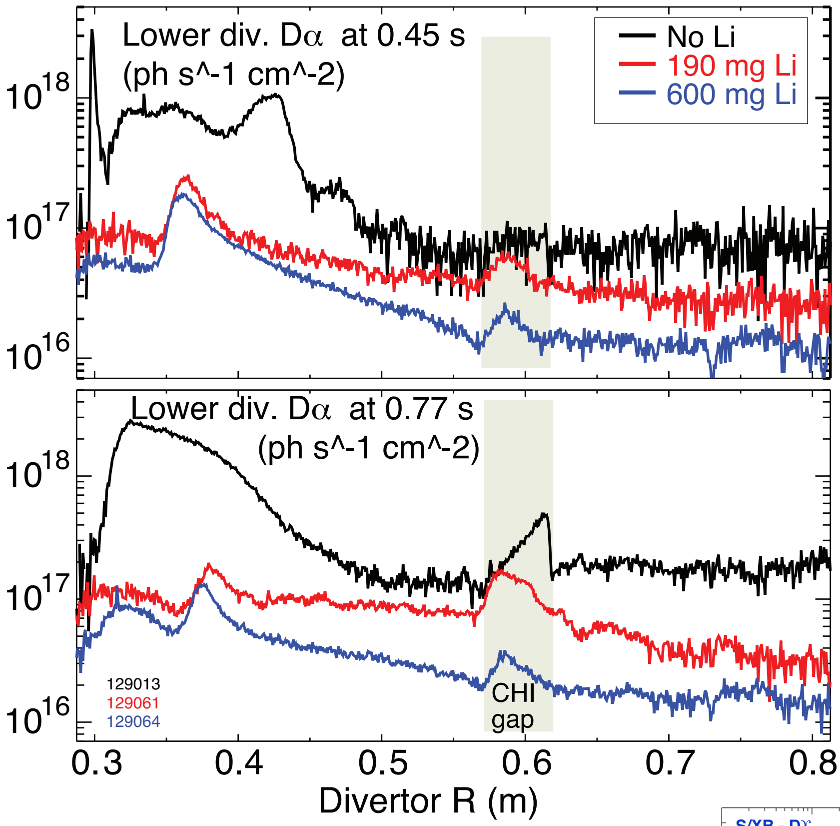
Change in ion inventory	*Gas feed rate*	*NBI fueling rate*	*NBI cryopump rate*	*Wall loading rate*	*Turbo. pump rate*	*Neutrals build-up rate*

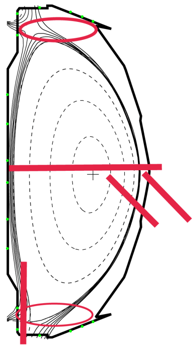
- Particle inventory balance: $N_e = 6\,N_C + N_i$
- 0.9 MA, 4.5 kG, 4-6 MW NBI
- High κ~2.3, δ~0.6 shape
- Biased DN with δr_{sep} ~-6mm

No lithium (129013)
190 mg Lithium (129061)
600 mg lithium (129064)



Lithium conditioning had a profound and cumulative effect on poloidal recycling flux profile





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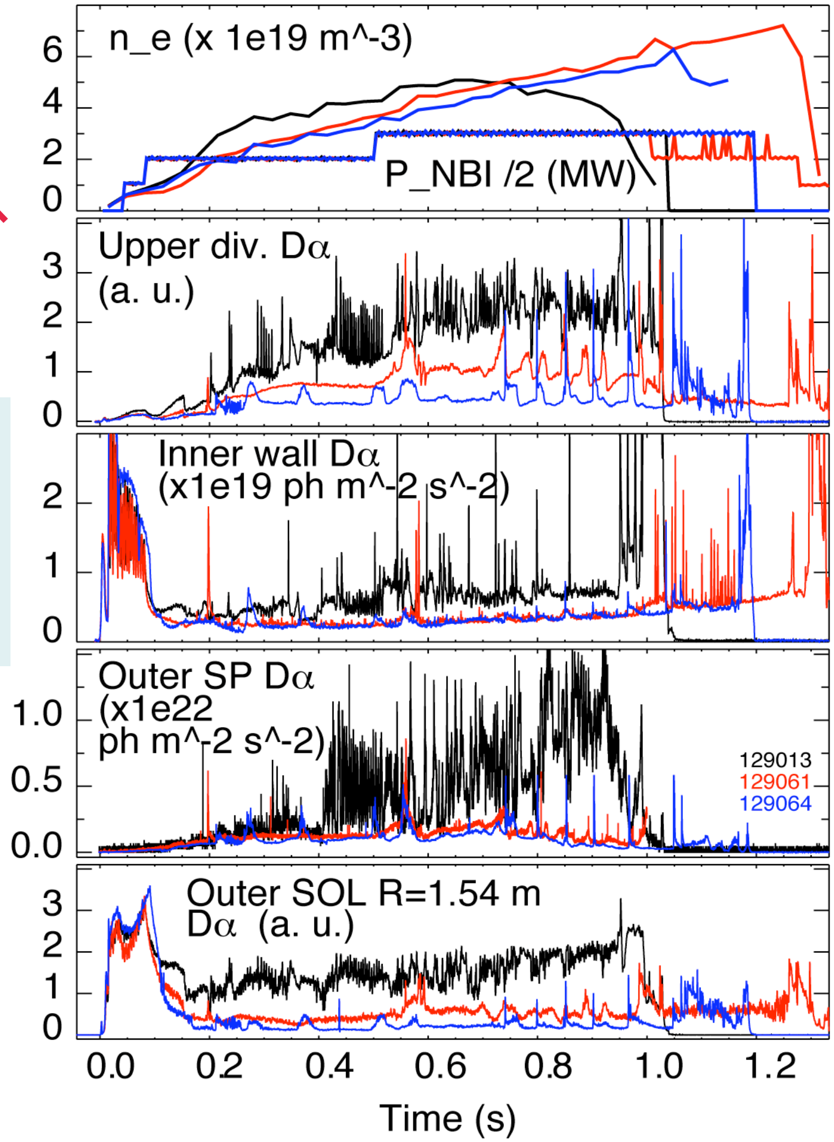
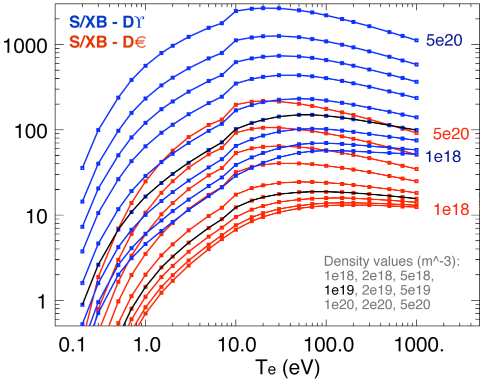
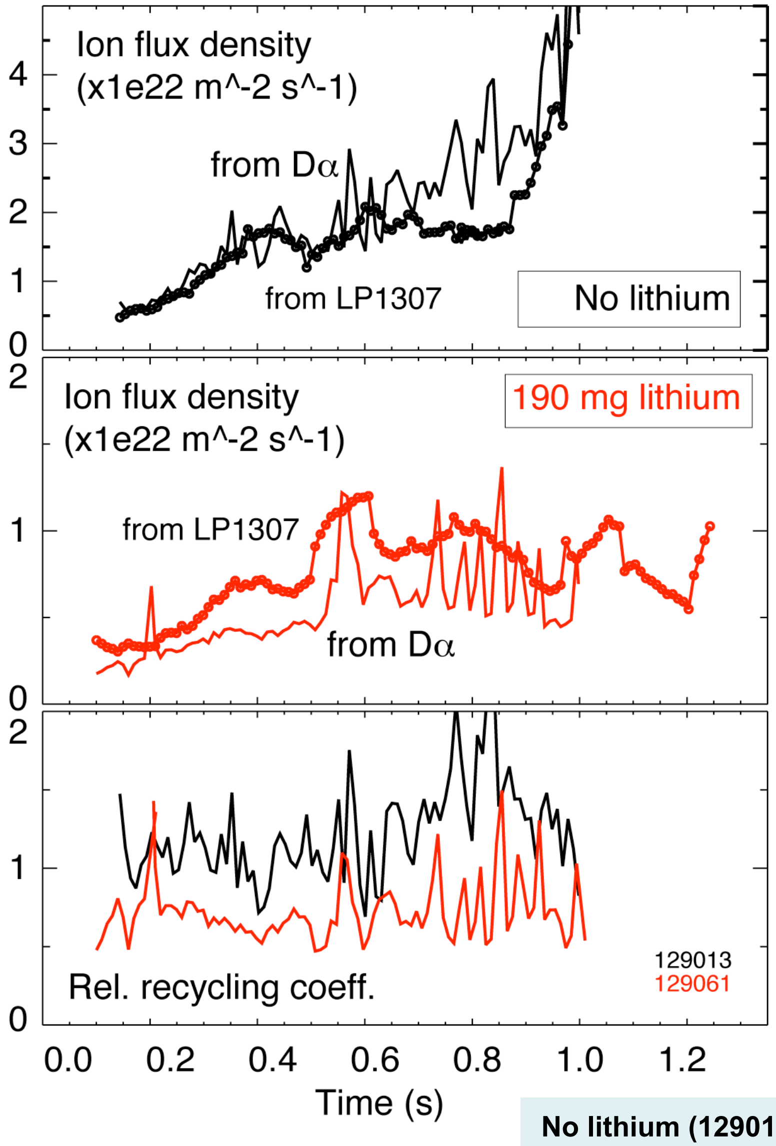
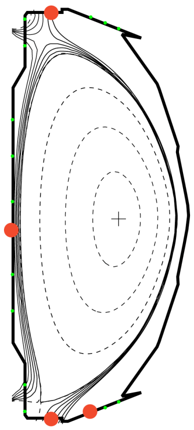


$$\Gamma_{recy} \sim SX/B\ I_{D\alpha}$$



Lithium conditioning reduced local ion recycling coefficients on PFCs except in the near-SOL region





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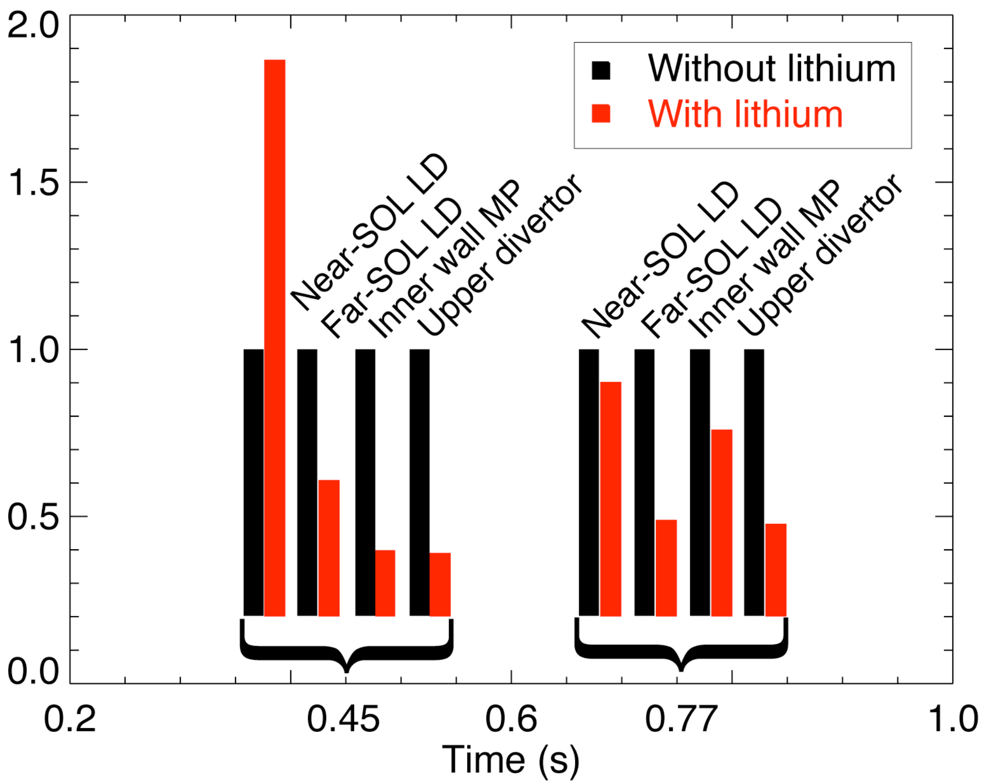
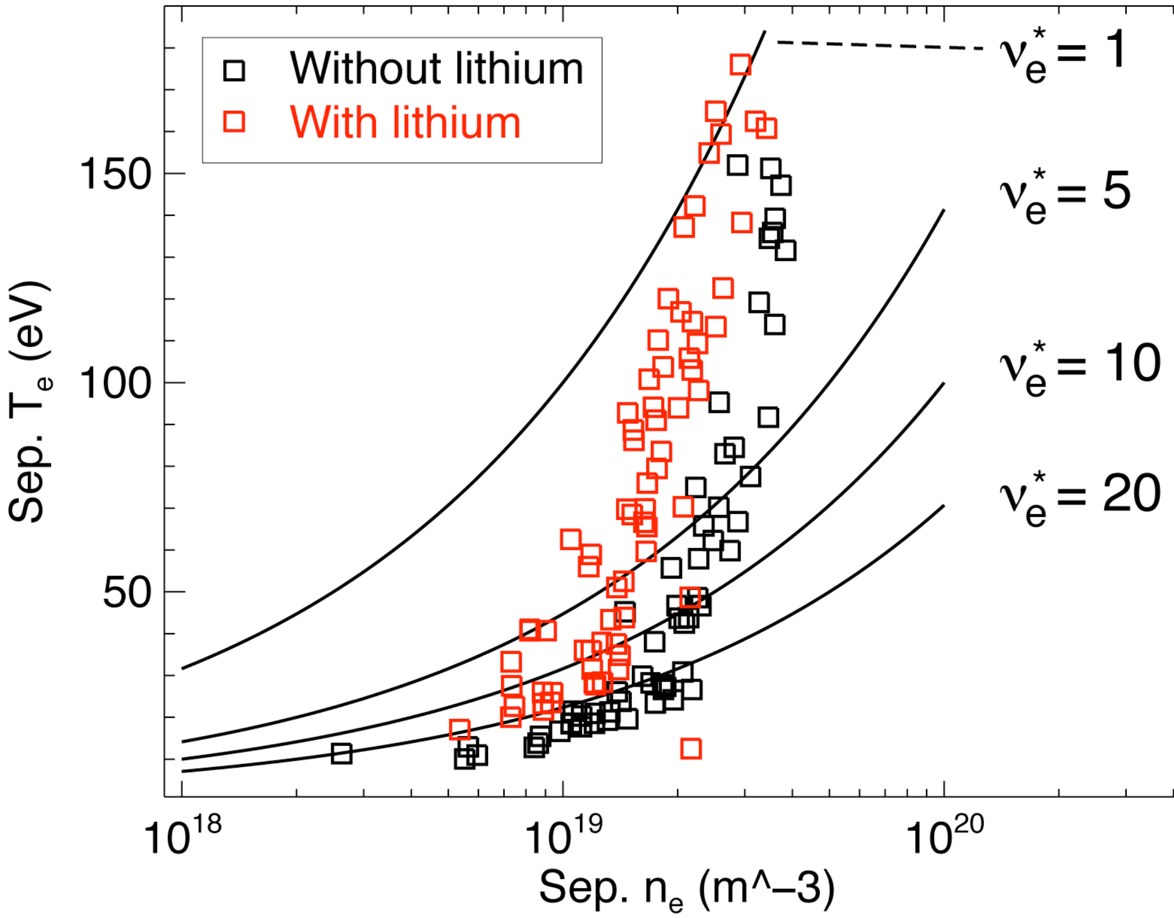


- Local recycling $R_{local}=\Gamma_i^{out} / \Gamma_i^{in}$
  - Ion flux into LLD Γ_i^{in} is measured by Langmuir Probes (LPs)
  - Ion outflux Γ_i^{out} estimated from measured Dα fintensity and S/XB (ionizations/photon) coefficient from ADAS

A transition from conduction-limited to sheath-limited parallel SOL heat transport regime is observed with lithium

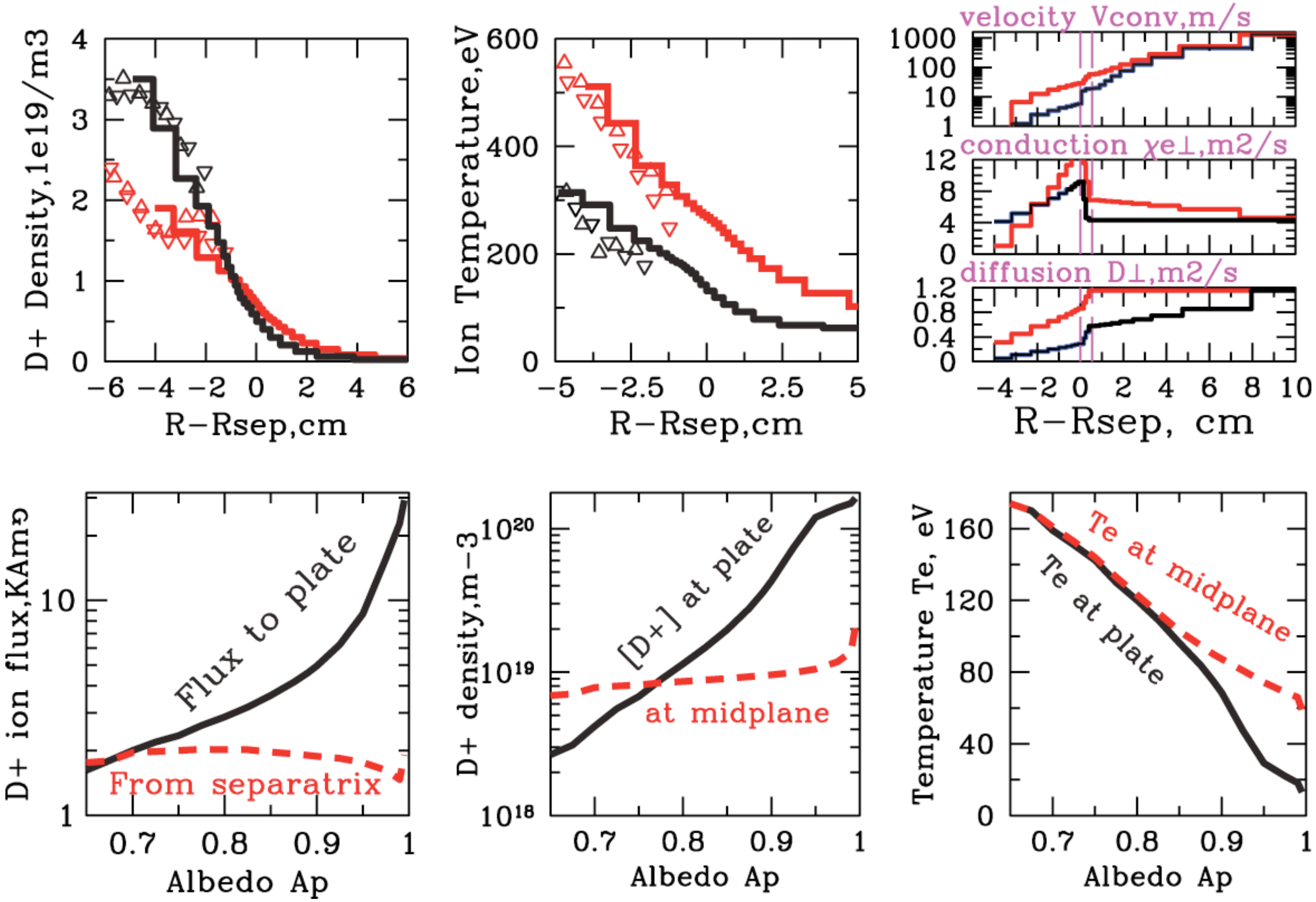


$$\nu_e^* = l_c/\lambda_e$$

- l_c=10 m – typical connection length
- λ_e – electron mean free path

- $\nu_e^*=10^{-16}\, n_e\, l_c\, /\, T_e$
- Borderline between sheath-limited and conduction-limited at ν_e^*=10

2D edge transport code UEDGE suggests enhanced edge transport and R~0.85 with lithium

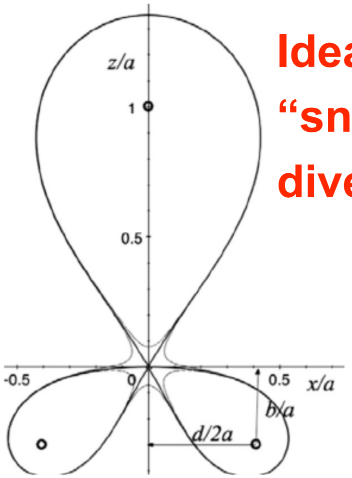


Theory predicts attractive divertor geometry properties in "snowflake" divertor configuration

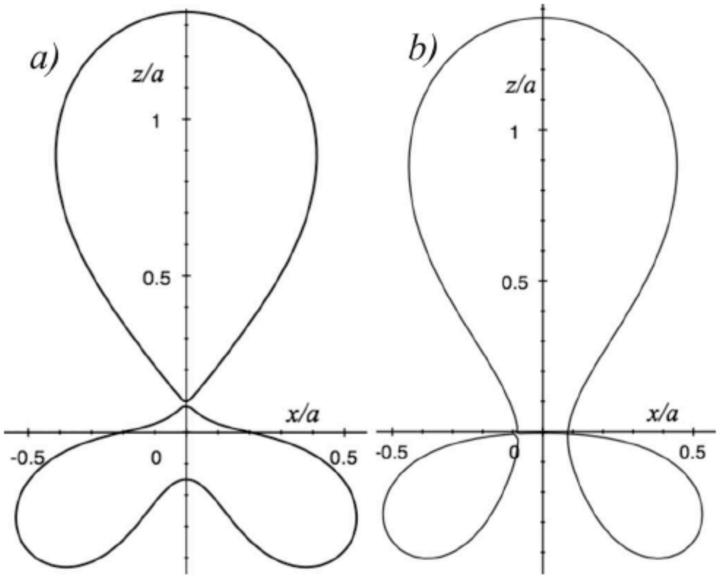
- Proposed by D. D. Ryutov (LLNL)
  - Phys. Plasmas 14, 064502 (2007)
  - 34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.31F, D-1.002 (2007)
  - Phys. Plasmas, 15, 092501 (2008)
  - Paper IC/P4-8 at IAEA FEC 2008

- SFD is obtained by creating a second-order poloidal null in the (lower) divertor **with existing divertor coils**

- Predicted properties (cf. standard divertor)
  - Larger low B_p region around X-point
  - Larger plasma wetted-area A_{wet} , flux expansion f_{exp}
  - Larger X-point connection length L_x
  - Larger effective divertor volume V_{div}
  - X-point flux tube squeezing – barrier for turbulence?
  - ELM control (increased edge magn. shear) ?

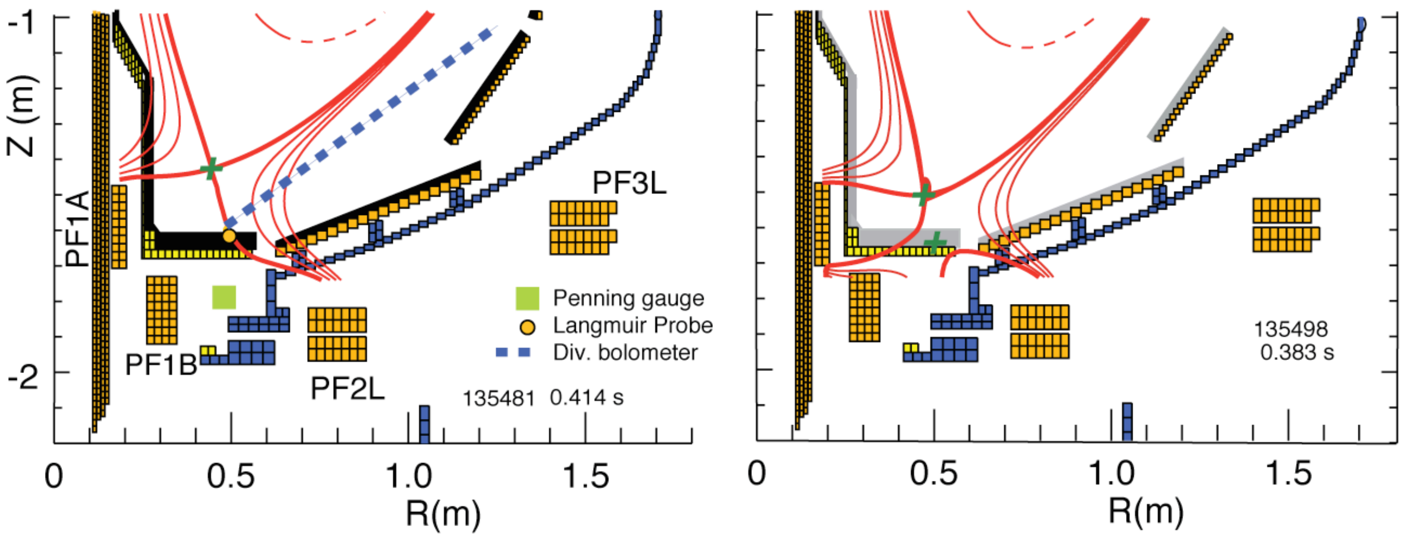


Ideal "snowflake" divertor

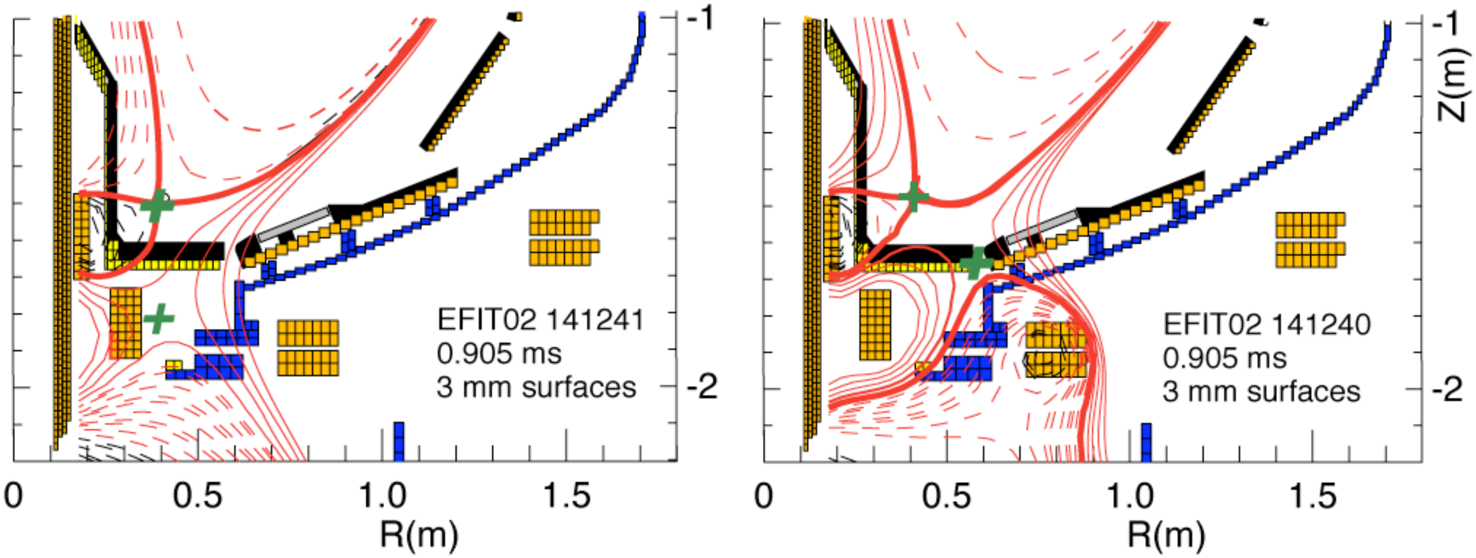


"snowflake"-plus "snowflake"-minus divertor configurations

“Snowflake” divertor configurations are obtained in NSTX with two and with three divertor coils

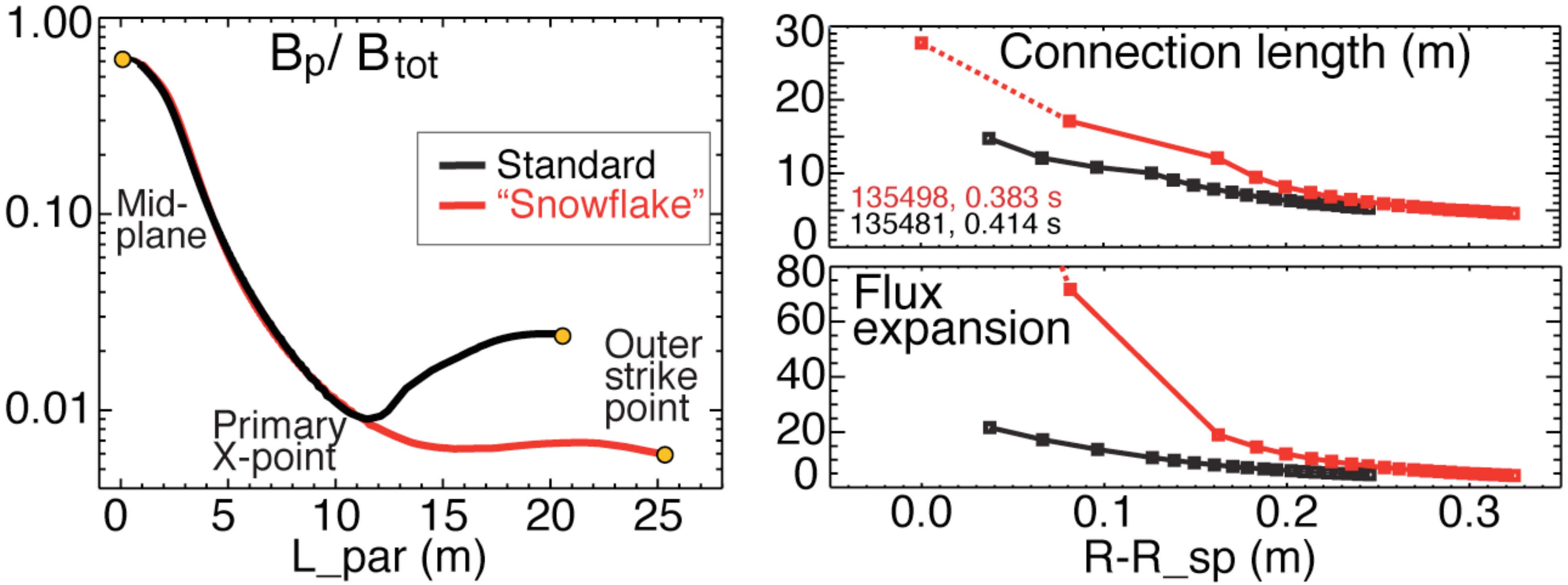


Standard divertor configuration (δ ~0.55-0.60) is transformed into “Snowflake” divertor with **two coils**



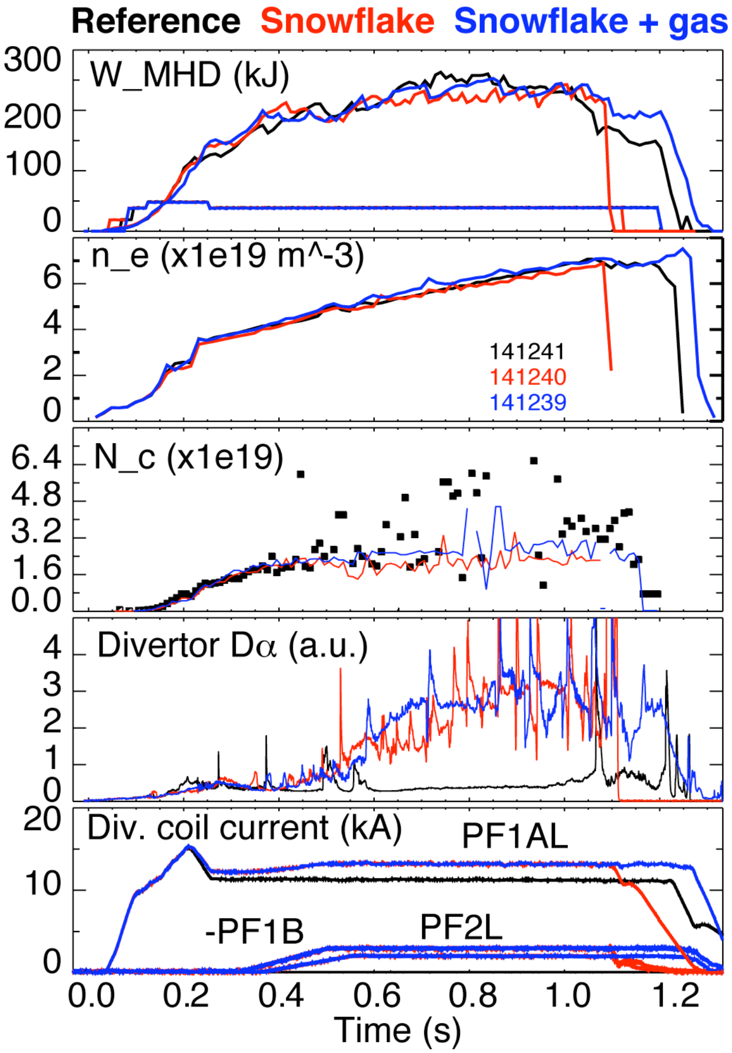
Standard high-δ divertor configuration is transformed into “Snowflake” divertor with **three coils**

Poloidal flux expansion and connection length are increased by up to 90 % in “snowflake” divertor

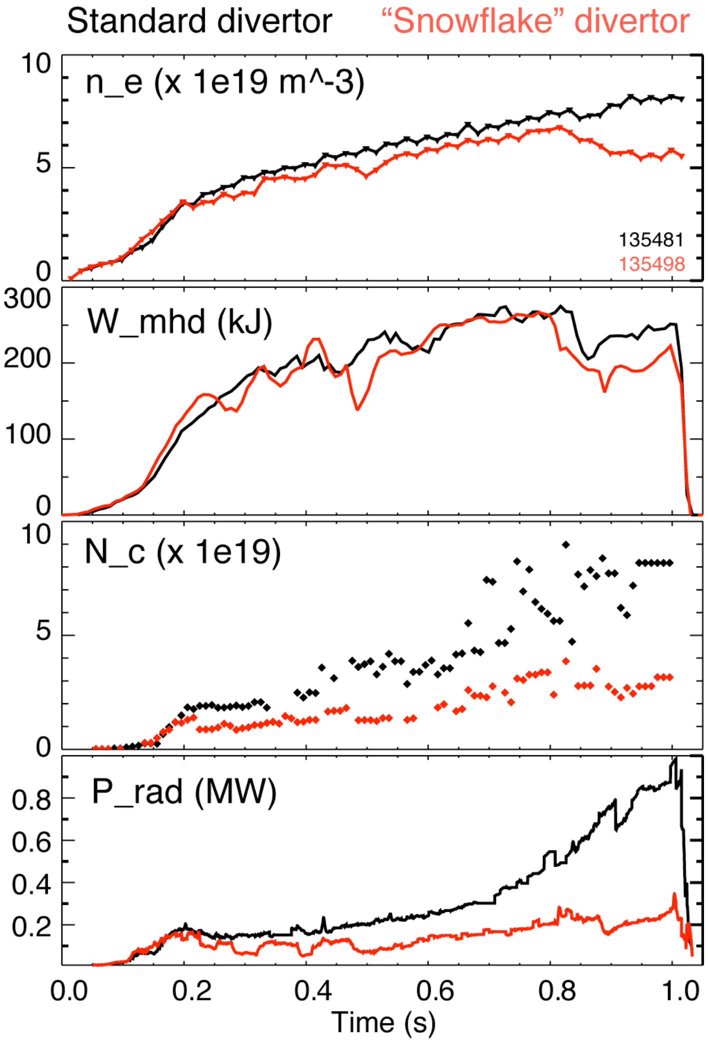


- In “snowflake” divertor
  - Plasma-wetted area (flux expansion) higher by up to 90 %
  - L_x longer (thus f_{PFR} and V_{div} higher)
- These properties observed in first 2-3 mm of SOL λ_q when mapped to midplane

H-mode confinement retained with “snowflake” divertor, core P_{rad} and N_C reduced by up to 75 %



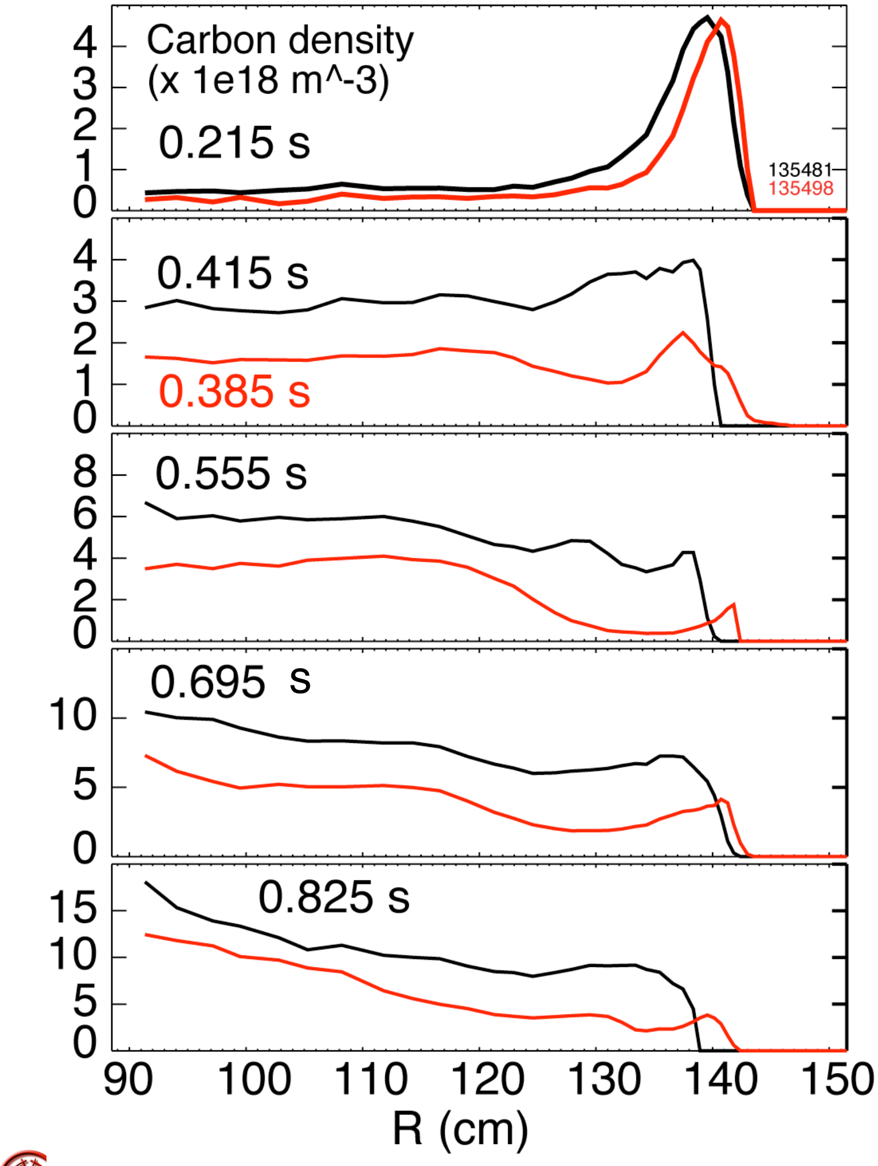
3-coil “snowflake”



2-coil “snowflake”

- Used 80-100 mg evaporated lithium
- 0.8 MA, 4 MW ELM-free H-mode discharges had impurity accumulation
- Core impurity reduction in “snowflake” divertor discharges may be due to
  - Divertor sputtering source reduction
  - Better impurity entrainment in SOL flow
  - Edge inward convection reduction

Core carbon density profiles show drastic reduction of carbon in ELM-free “snowflake” discharges

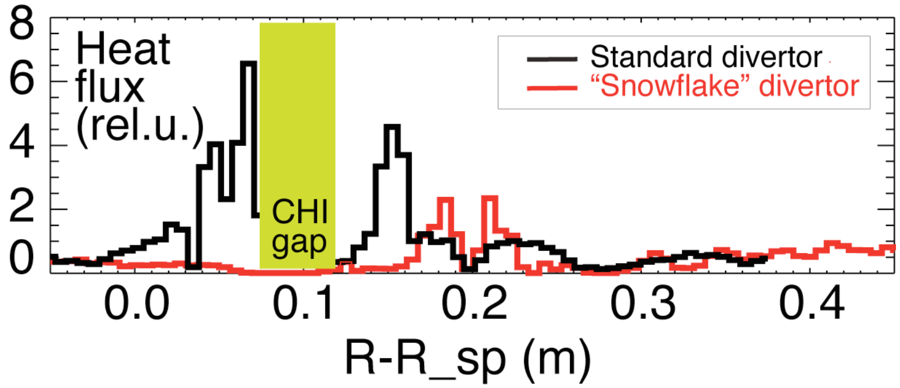

Divertor configurations: **Standard**, **Snowflake**

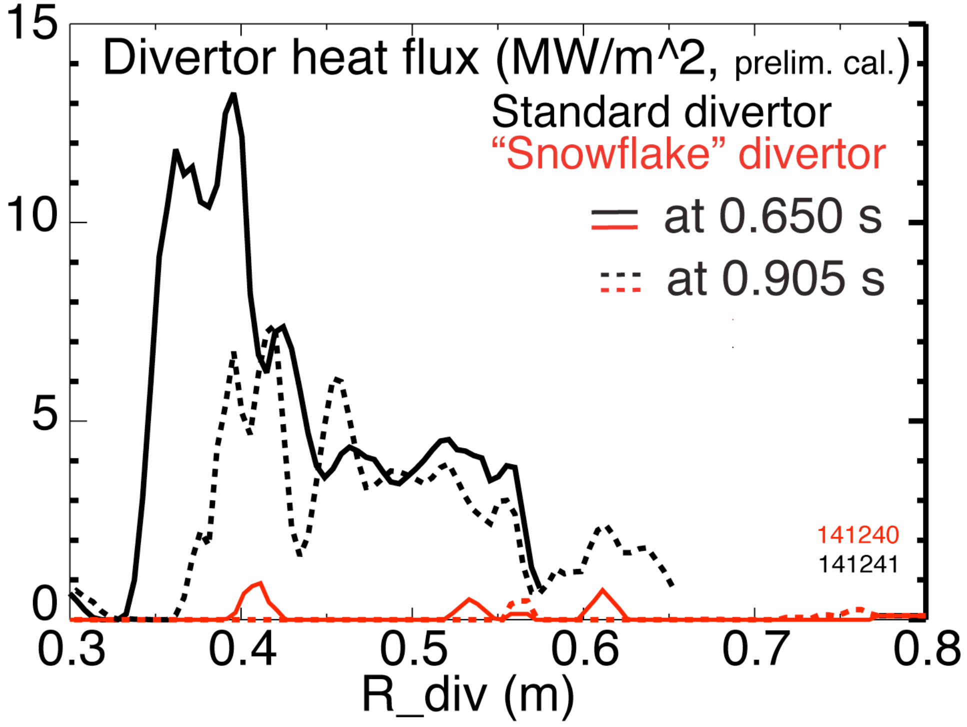
- Core impurity reduction in “snowflake” divertor discharges may be due to
  - Divertor sputtering source reduction
  - Better impurity entrainment in SOL flow
  - Edge inward convection reduction

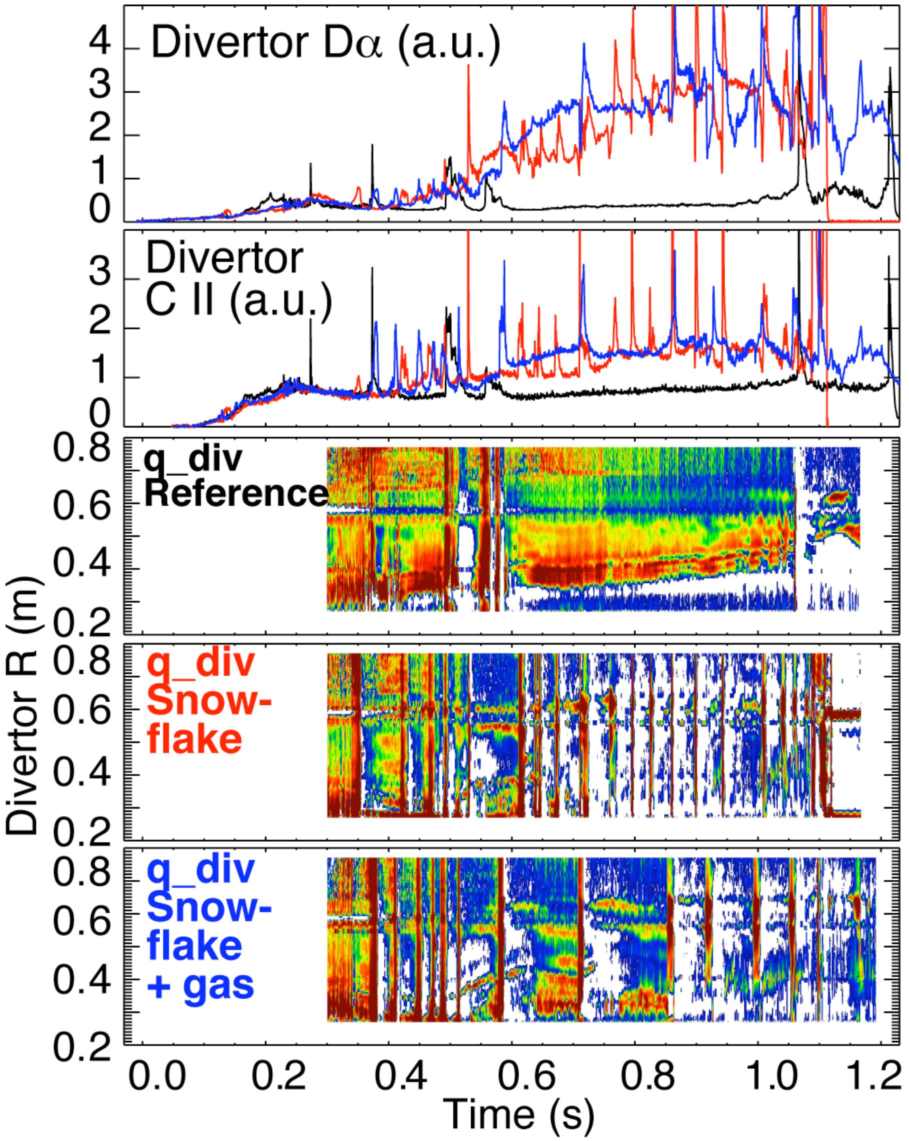
- Impurity transport modeling in progress to understand the dominant cause of n_C reduction

- Carbon density from Charge Exchange Recombination Spectroscopy system

Significant reduction of peak heat flux observed in “snowflake” divertor



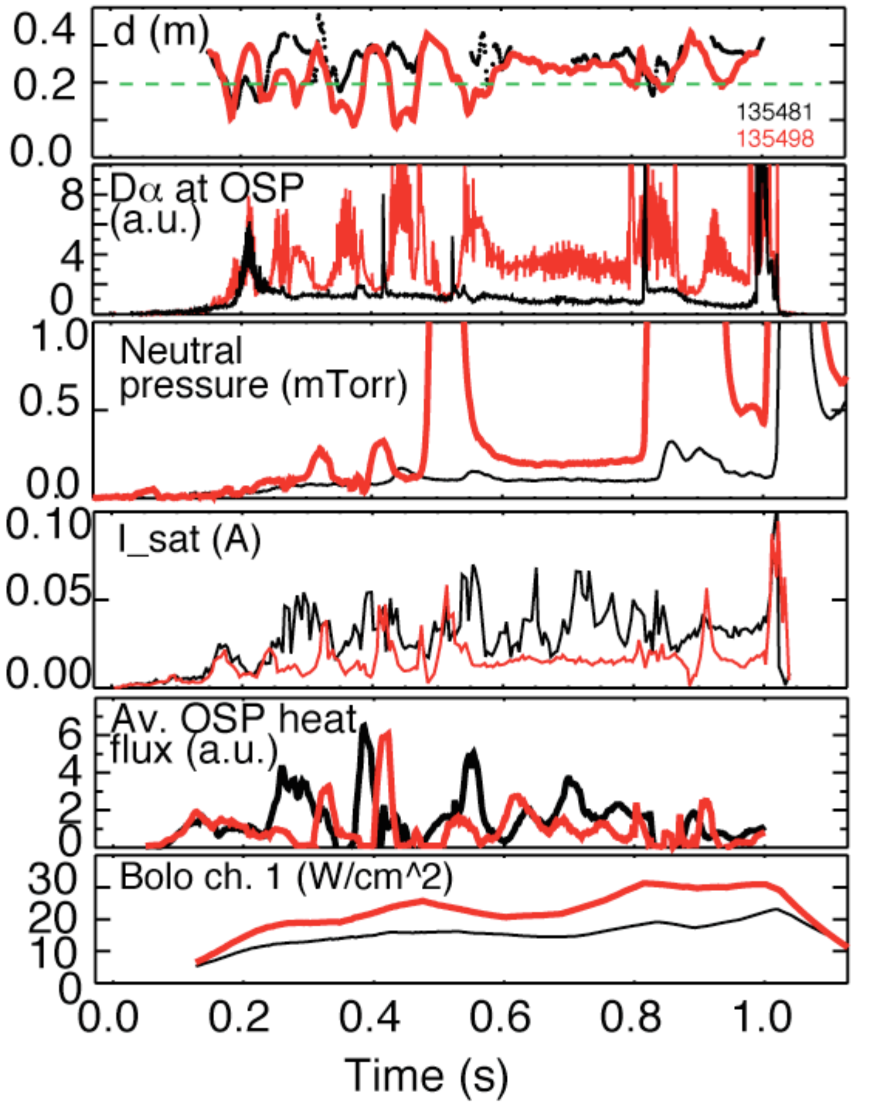




Partial detachment of outer strike point region observed in “snowflake” divertor discharges

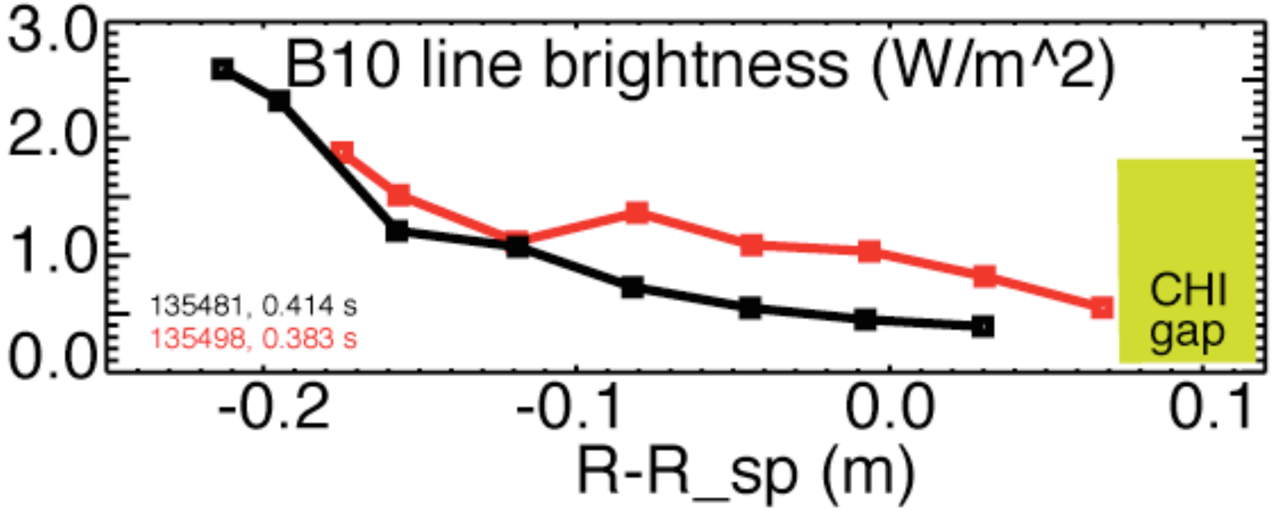
- Signs of partial detachment observed in “snowflake” divertor
  - Loss of parallel pressure
  - Heat and particle flux reduction at the plate
  - $T_e \leq 1.6$ eV, $n_e \leq 4\text{x}10^{20}$ m^{-3}
  - Increase in divertor P_{rad}
  - Increase in 3-body recombination rate
  - Increase in neutral pressure

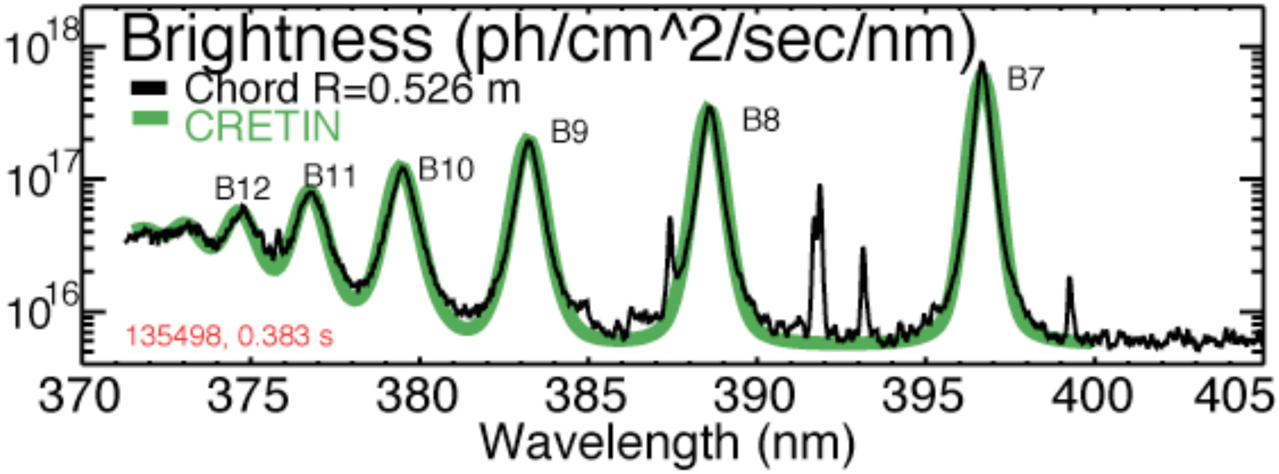
Divertor configurations: **Standard**, Snowflake



High-*n* Balmer line emission measurements suggest high divertor recombination rate, low T_e, high n_e

- Balmer series spectra modeled with CRETIN; Spectra sensitive to
  - Line intensity <-> Recombination rate
  - T_e <-> Boltzman population distribution
  - n_e <-> Line broadening due to linear Stark effect from ion and electron microfield



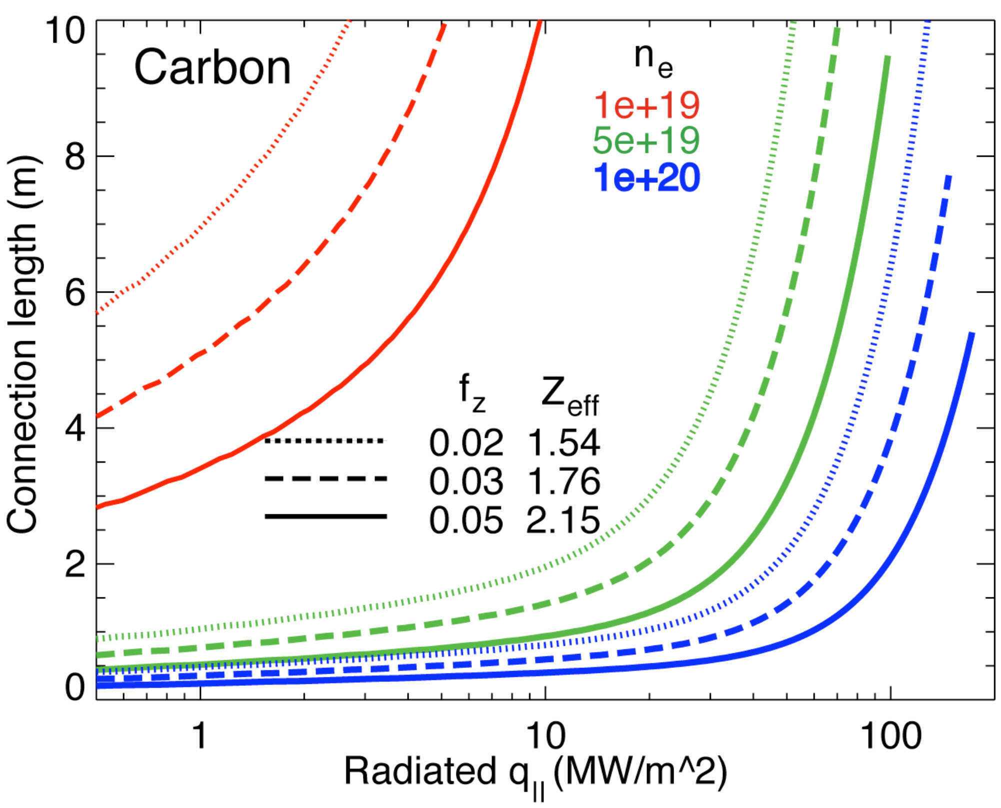


- T_e=0.8-1.2 eV, n_e=2-7 x 10^{20} m^{-3} inferred from modeling

Volumetric power and momentum losses are increased due to geometry in “snowflake” divertor

- Hulse-Post non-coronal radiative cooling curves for low Z impurities for n_0/n_e, n_e-τ_{recy}
- Calculate max $q_{||}$ that can be radiated
- Express max $q_{||}$ as function of distance from heat source for range of f_z (Post JNM 220-222, 1014 (1995))
- Power losses due to deuterium P_{rad} and ionization not considered
- For NSTX, use n_0 = 0.1 % and

  n_e-τ_{recy} = n_e x 1 ms
- Electron-ion recombination rate depends on divertor ion residence time
  - Ion recombination time: τ_{ion}~ 1−10 ms at T_e =1.3 eV
  - Ion residence time: $\tau_{ion} \leq$ 3-6 ms



$$q_{||} = -\kappa_0 T_e^{5/2} \frac{\partial T_e}{\partial x}$$

$$\frac{\partial q_{||}}{\partial x} = -n_e n_z L_Z(T_e)$$

Outlook and future plans

- **Good synergy between ion pumping by lithium and divertor heat flux reduction and impurity screening by the “snowflake” divertor is demonstrated**
  - Sheath-limited divertor regime with lithium simulates high heat flux divertors in future devices
  - High flux expansion divertor pumping
  - Studying compatibility of ”snowflake” divertor with liquid lithium divertor module (H. W. Kugel et. al, FTP/3-6R)
- **NSTX-Upgrade**
  - Development of divertor solutions to address
    - 2-3x higher input power
    - Projected peak divertor heat fluxes up to 24 MW/m^2 (T. K. Gray EXD/P3-13)
    - Up to 30 % reduction in Greenwald fraction
    - 3-5 x longer pulse duration
  - Additional divertor coil PF1C
    - Flux expansion variation with fixed X-point height