“Snowflake” divertor configuration in NSTX*

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Poster P 1-28
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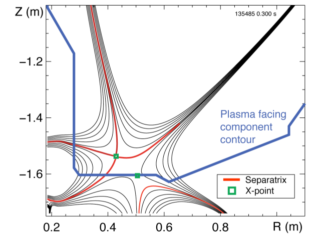
Abstract

Spherical tokamaks (STs), a magnetic fusion confinement concept with low aspect ratio ($A < 2$), are viewed as potentially attractive devices for fusion development applications complementary to large aspect ratio tokamaks. The compact geometry of the ST divertor and the requirement of low normalized density (~ (0.5-0.7) x n_G) operation for increased neutral beam current drive efficiency define a unique edge transport regime with much greater demands on divertor and first-wall particle and heat flux handling. At present, candidate strategies for steady-state mitigation of divertor heat and particle loads in tokamaks include both the passive techniques, such as divertor geometry and magnetic balance, and active techniques, such as radiative divertors, field ergodization and strike point sweeping.

A novel divertor configurtion, called the “snowflake“ divertor (SFD), has been recently proposed and shown theoretically to offer significant benefits for the plasma material interface [1-4]. The SFD uses a second-order X-point created by merging, or bringing close to each other, two first-order X-points of a standard divertor (SD) configuration. The possibility of SFD has been demonstrated through modeling for DIII-D and NSTX [4] and in experiments on TCV [5]. We report on the first experiments in NSTX that obtained the SFD for periods of 50-150 milliseconds and confirmed many of the predicted SFD benefits. When compared to the high-triangularity (δ=0.7-0.8) SD configuration in NSTX [6], the obtained SFD configuration with medium triangularity (δ~0.65) had a connection length longer by factors of 1.5-2, and a poloidal magnetic flux expansion at the outer strike point higher by factors of 2-3. The 4-6 MW NBI-heated discharges with SFD maintained H-mode properties withoutl degradation of stored energy and confinement. Divertor heat flux profiles showed a large reduction in peak heat flux during the SFD periods. Divertor radiation due to carbon impurity was significantly increased in the SFD. A large volume recombination region with T_e ~ 1.5 eV, n_e > 2-6 x 10^{20} m^{-3} developed, while ion flux to the divertor plate reduced, suggesting a partial detachment of the strike point region. As in previous divertor detachment experiments in NSTX [6], the core carbon density was reduced by up to 50 %. A critical SFD issue is magnetic control of the positions of the two X-points [1-4]. The experiments on NSTX provided insights on further SFD magnetic control optimization.

[1] D. D. Ryutov, 34th EPS Conf. on Plasma Phys., Warsaw, 2 - 6 July 2007 ECA Vol.31F, D-1.002 (2007)
[2] D. D. Ryutov, Phys. Plasmas 14, 64502 (2007)
[3] D. D. Ryutov *et al*., Phys. Plasmas 15, 092501 (2008)
[4] D. D. Ryutov *et al*., Paper IC/P4-8, 22st IAEA FEC, Geneva, Switzerland, 10/2008
[5] F. Piras et al., Plasma Phys. Control. Fusion 51 (2009) 055009
[6] V. A. Soukhanovskii *et al*., Phys. Plasmas 16, (2009); V. A. Soukhanovskii *et al*., Nuc. Fusion 49, 095025 (2009)

Overview and Summary



- "Snowflake" divertor configuration – a promising solution for divertor heat flux mitigation in future fusion plasma devices
- "Snowflake" divertor configuration (cf. standard divertor)
  - Higher flux expansion (increased divertor A_{wet})
  - Higher divertor volume (increased P_{rad}, R_{rec}, …)
  - Magnetic control
- In recent NSTX experiments
  - "snowflake" divertor was generated with 2 divertor coils
  - all predicted "snowflake" divertor geometry properties confirmed
  - H-mode confinement maintained
  - "snowflake" divertor led to outer strike point partial detachment
    - significant reduction in peak heat flux
    - reduction of core impurities

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

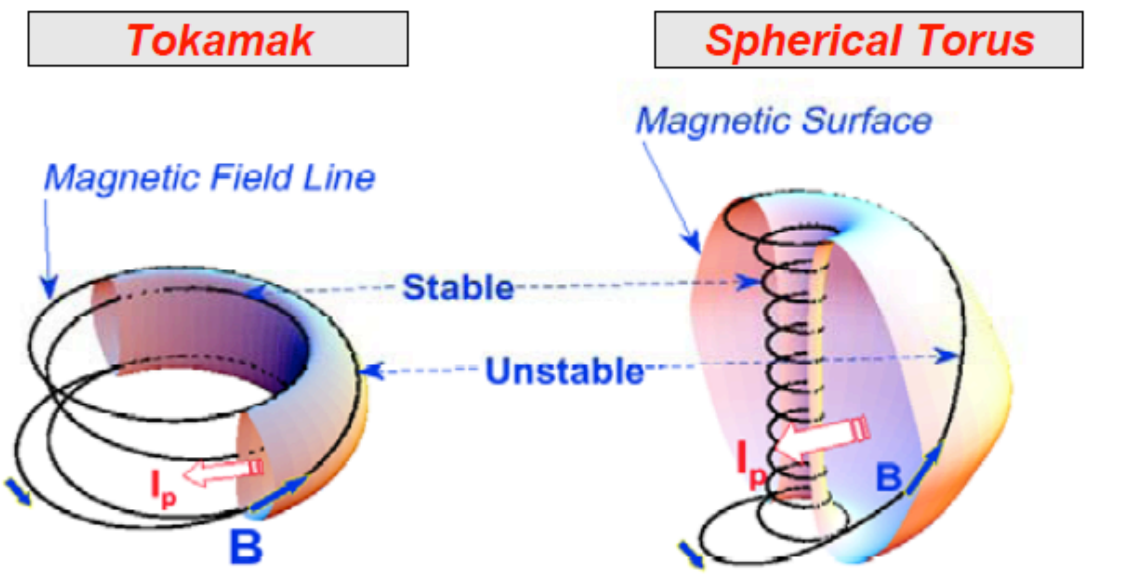
$$f_{exp} = \frac{(B_p/B_{tot})_{MP}}{(B_p/B_{tot})_{OSP}}$$

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

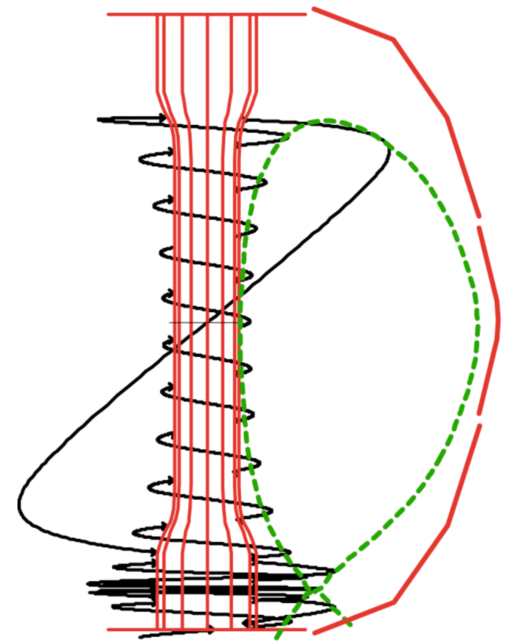
- **Candidate solutions**
  - **be compatible with good core plasma performance (H-mode confinement, MHD, ELM regime, density) and particle control**
  - **scale to very high q_{peak} (15 - 80 MW/m^2) for future devices**

SOL / divertor geometric properties are different in spherical tori and large aspect ratio tokamaks

	NSTX high κ, δ	Tokamak
Aspect ratio	1.4-1.5	2.7
In-out SOL area ratio	1:3	~ 2:3
Parallel connection length $L_{\|\|}$, MP to target (m)	8-12	30-80
$L_{\|\|}$, X-point to target (m)	5-8	10-20
Angle at target (deg)	2-5	1-2



R/a=2.5-4, κ=1.5-2, q_e=3-5 R/a=1.1-1.6, κ=2-3, q_e=6-15

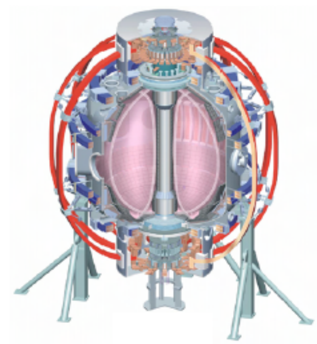


Divertor heat flux mitigation is key for present and future fusion plasma devices

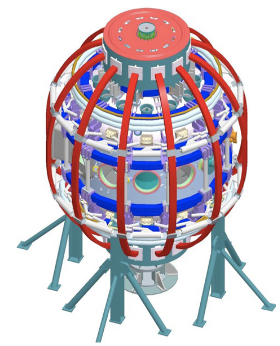
- ST / NSTX goals:
  - Study high beta plasmas at reduced collisionality
  - Access full non-inductive start-up, ramp-up, sustainment
  - Prototype solutions for mitigating high heat & particle flux

- In an ST, modest $q_{||}$ can yield high divertor q_{pk}
  - in NSTX, $q_{||}$= 50-100 MW/m^2 and q_{pk}=6-15 MW/m^2 **(Poster P2-65 by T. Gray, R. Maingi)**
  - Large radiated power and momentum losses are needed to reduce $q_{||}$

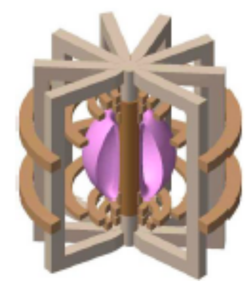
- In NSTX, partially detached divertor regime is accessible only
  - in highly-shaped plasma configuration with high flux expansion divertor (high plasma plugging efficiency, reduced $q_{||}$)
  - modest divertor D_2 injection still needed



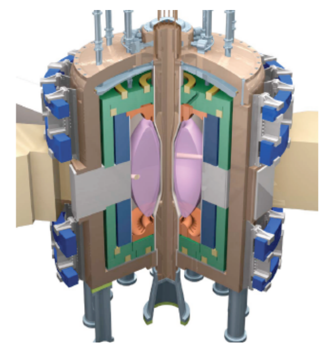
NSTX



NSTX-U



ST-based Plasma Material Interface (PMI) Science Facility

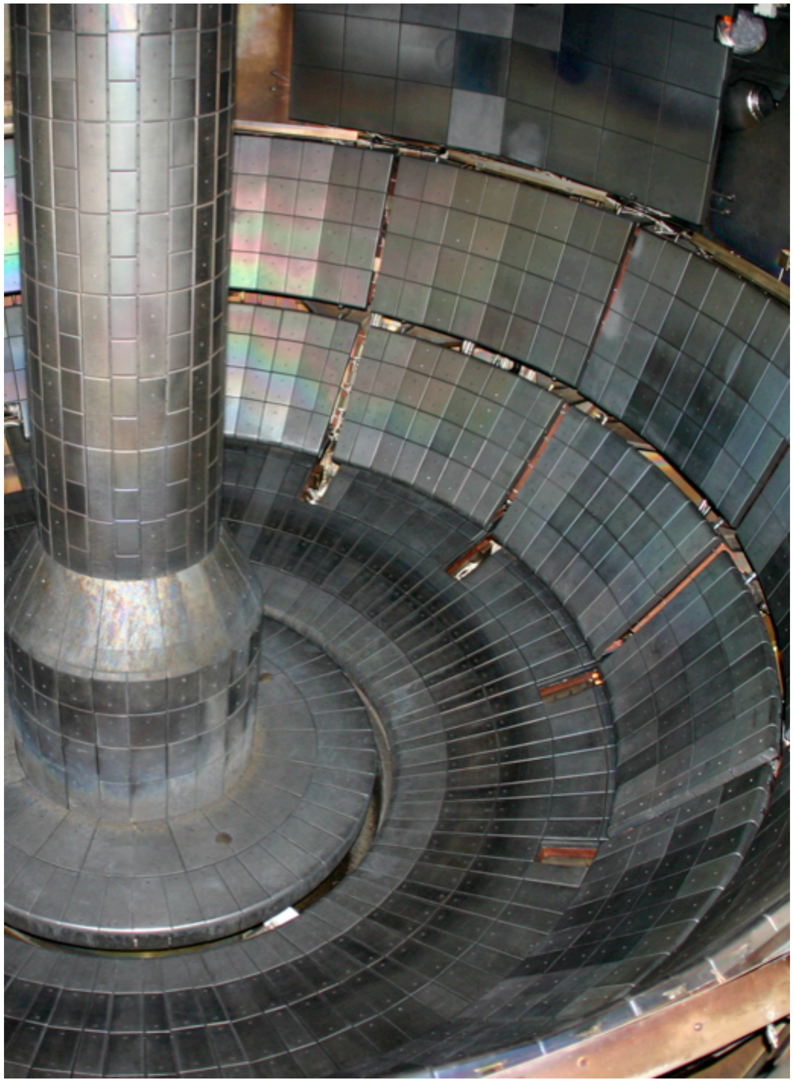


ST-based Fusion Nuclear Science (FNS) Facility

Open geometry enables flexibility in divertor configurations and plasma shaping in NSTX

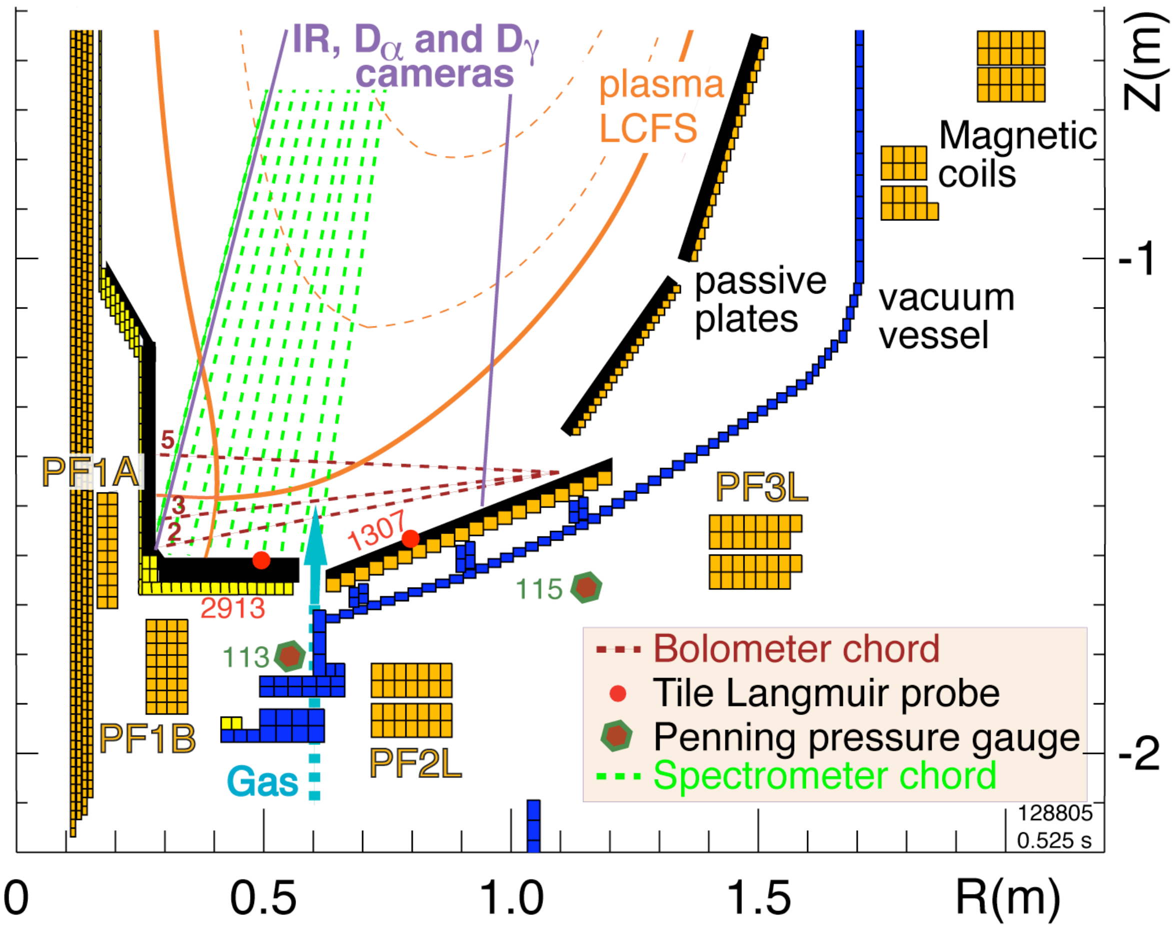
- Plasma facing components
  - ATJ and CFC tiles
  - Carbon - erosion, sputtering
  - Max P_{rad} fraction limited by carbon radiation efficiency
  - Typical divertor tile temperature in 1 s pulses $T < 500$ C ($q_{peak} \leq 10\text{-}15$ MW/m^2)

- No active divertor pumping
  - Evaporated lithium coatings 80-100 g per discharge for reduced recycling and performance improvements



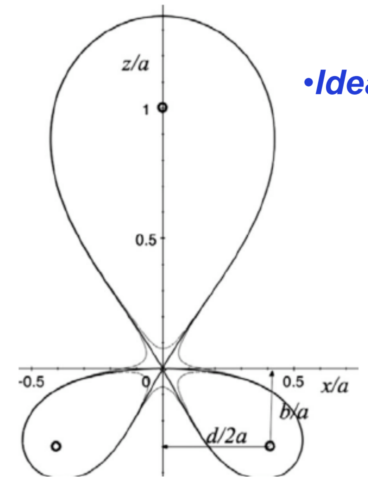
Multiple diagnostic measurements are analyzed to elucidate on divertor physics in NSTX

- Diagnostic set for divertor studies:
  - IR cameras
  - Bolometers
  - Neutral pressure gauges
  - Tile Langmuir probes
  - Dα, Dγ filtered CCD arrays
  - UV-VIS spectrometer (10 divertor chords)
- Midplane Thomson scattering and CHERS systems
- Divertor gas injector
  Γ_{gas} = 20-200 Torr l / s

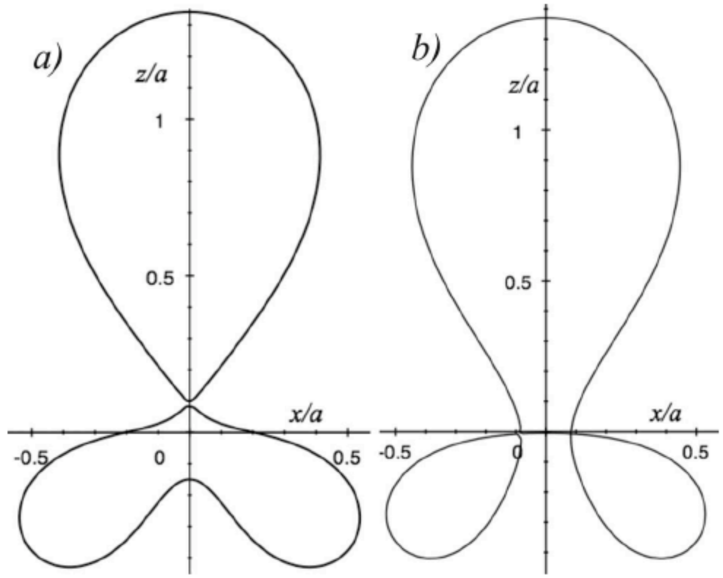


Theory predicts attractive divertor geometry properties in “snowflake” divertor configuration

- “Snowflake” divertor (SFD) configuration proposed and studied theoretically by D. D. Ryutov (LLNL)
  - Phys. Plasmas 14, 064502 (2007)
  - Phys. Plasmas, 15, 092501 (2008)
  - 34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.31F, D-1.002 (2007)
  - 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
  - Low B_p in X-point region
  - Large A_{wet} , f_{exp}
  - Large L_x, V_{div}
  - Null-point flux tube squeezing – barrier for turbulence?
  - ELM control (increased edge magn. shear) ?

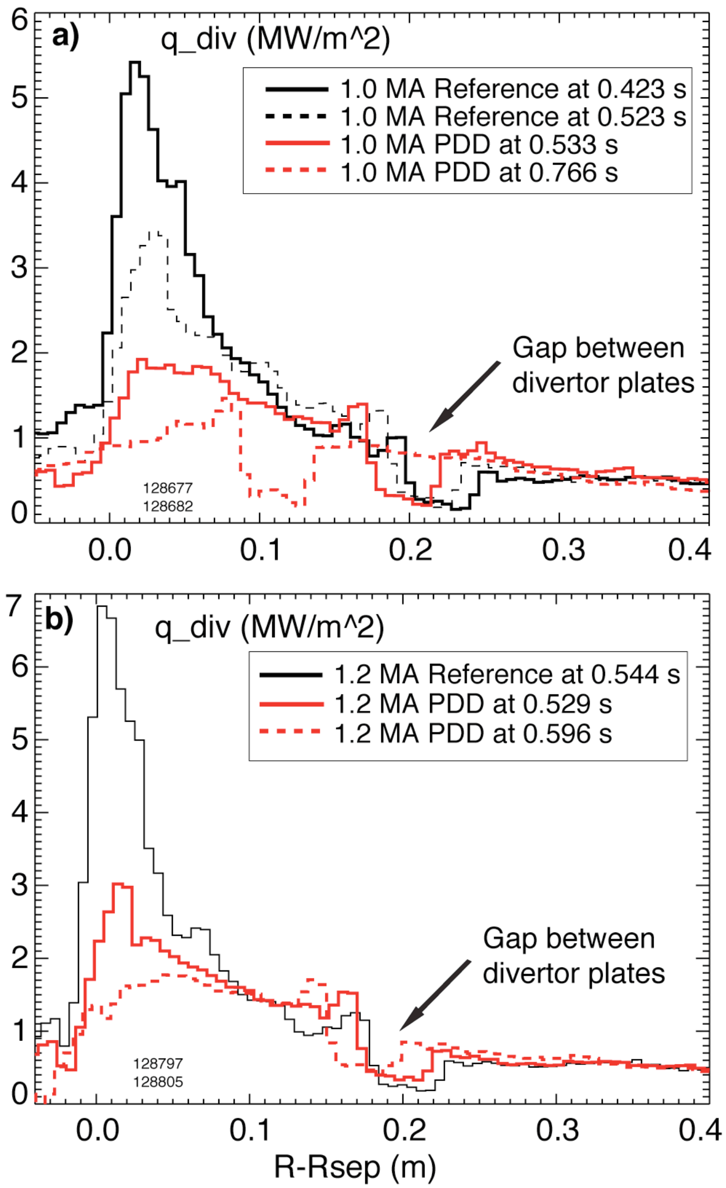


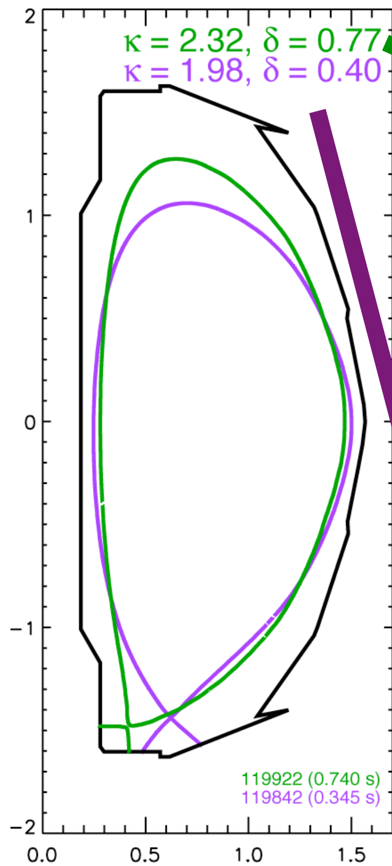
•Ideal SFD

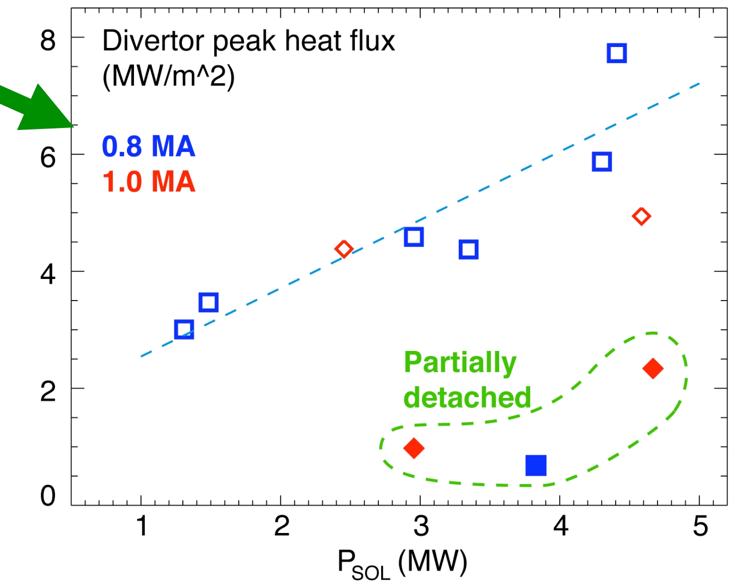


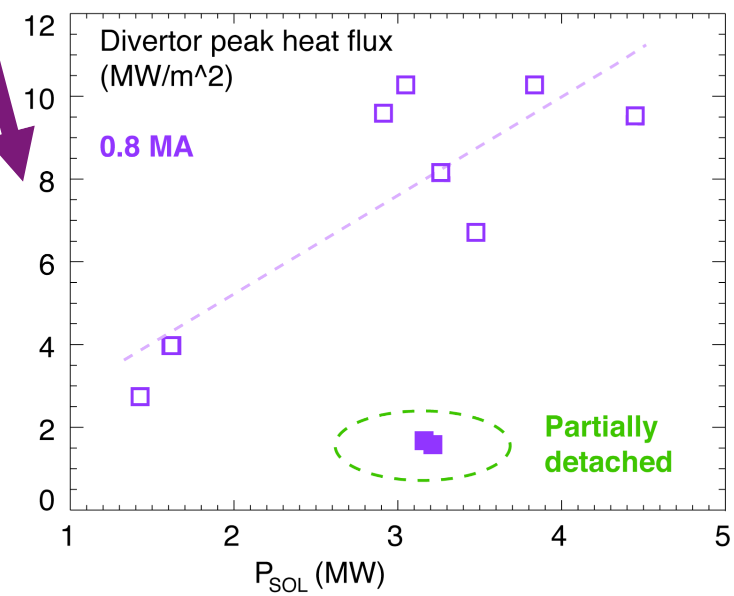
•SFD-plus and SFD-minus

NSTX experiments have already demonstrated benefits of high flux expansion divertor



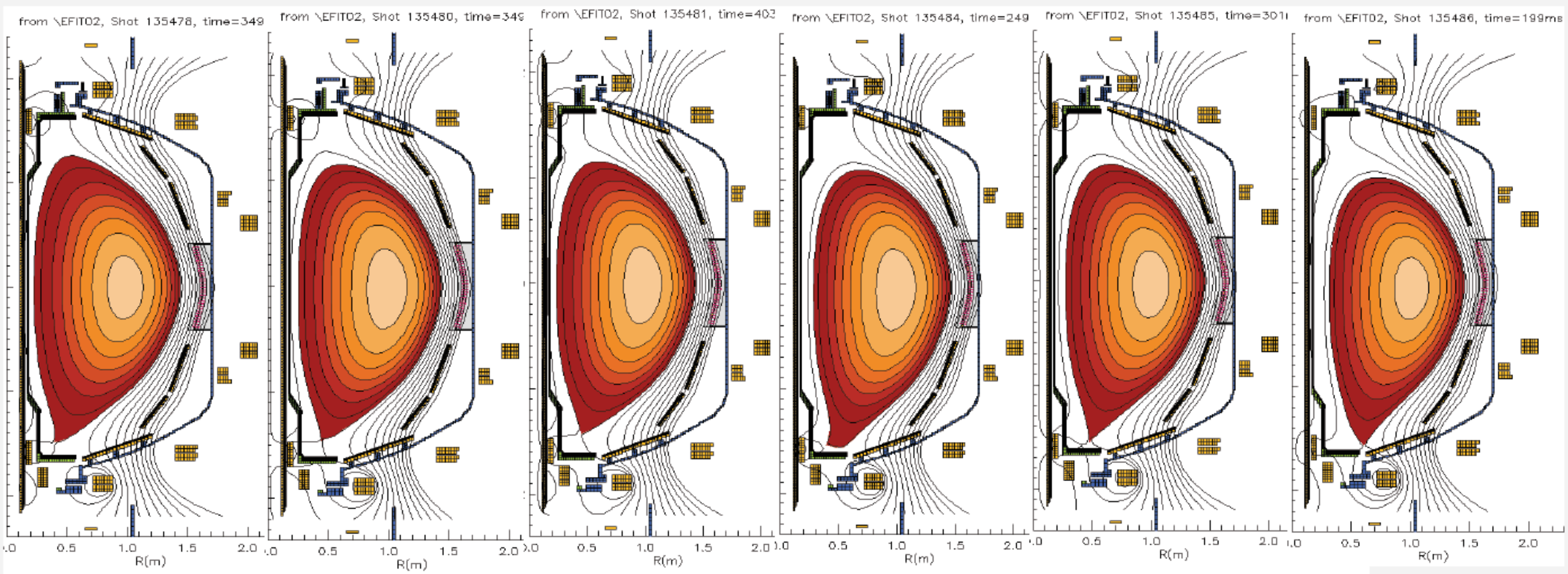






- **Poster P2-65 by T. Gray, R. Maingi**
- SOUKHANOVSKII, V. A. et al., Phys. Plasmas 16 (2009) 022501
- SOUKHANOVSKII, V. et al., Nucl. Fusion 49 (2009) 095025

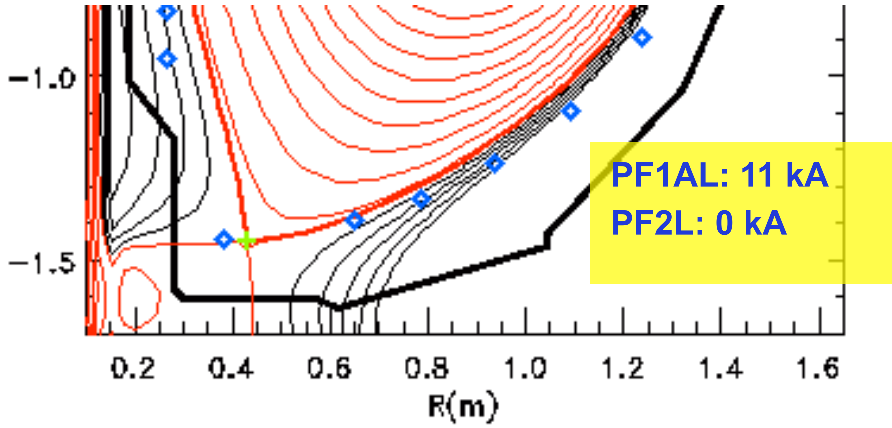
Three lower divertor coils can be used for divertor configurations with various δ, X-pt, R_{OSP}

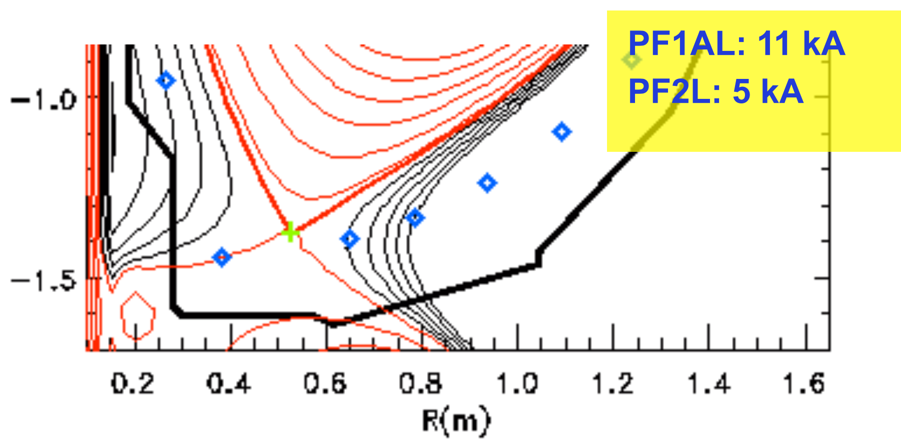


Snowflake scan from 44 to 73 cm

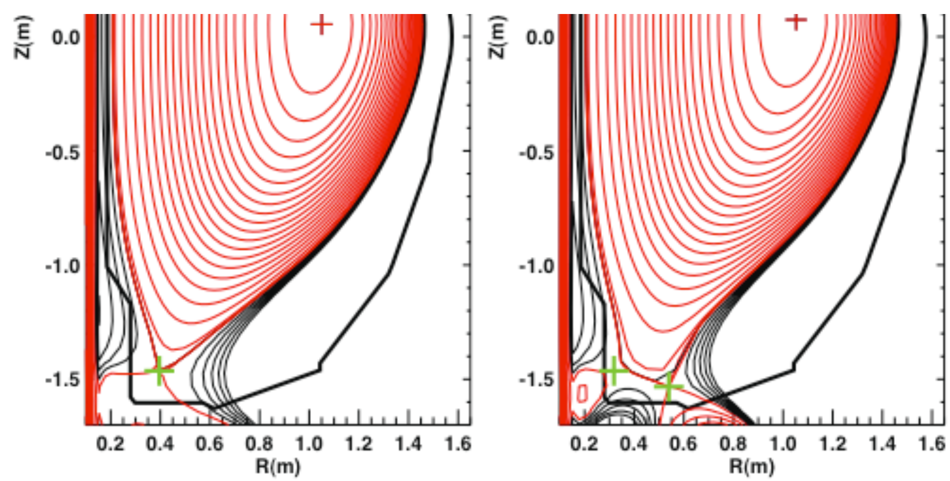
- Presently use two divertor coils in PCS
  - PF1A for inner strike point control
  - PF2L for outer strike point control

ISOLVER code was used to scan strike point positions and divertor coil currents for “snowflake” configuration





- ISOLVER - predictive free-boundary axisymmetric equilibrium solver developed by J. E. Menard
  - normalized pressure and current profiles and boundary shape as input
  - matches a specified plasma current and β,
  - computes coil currents as output

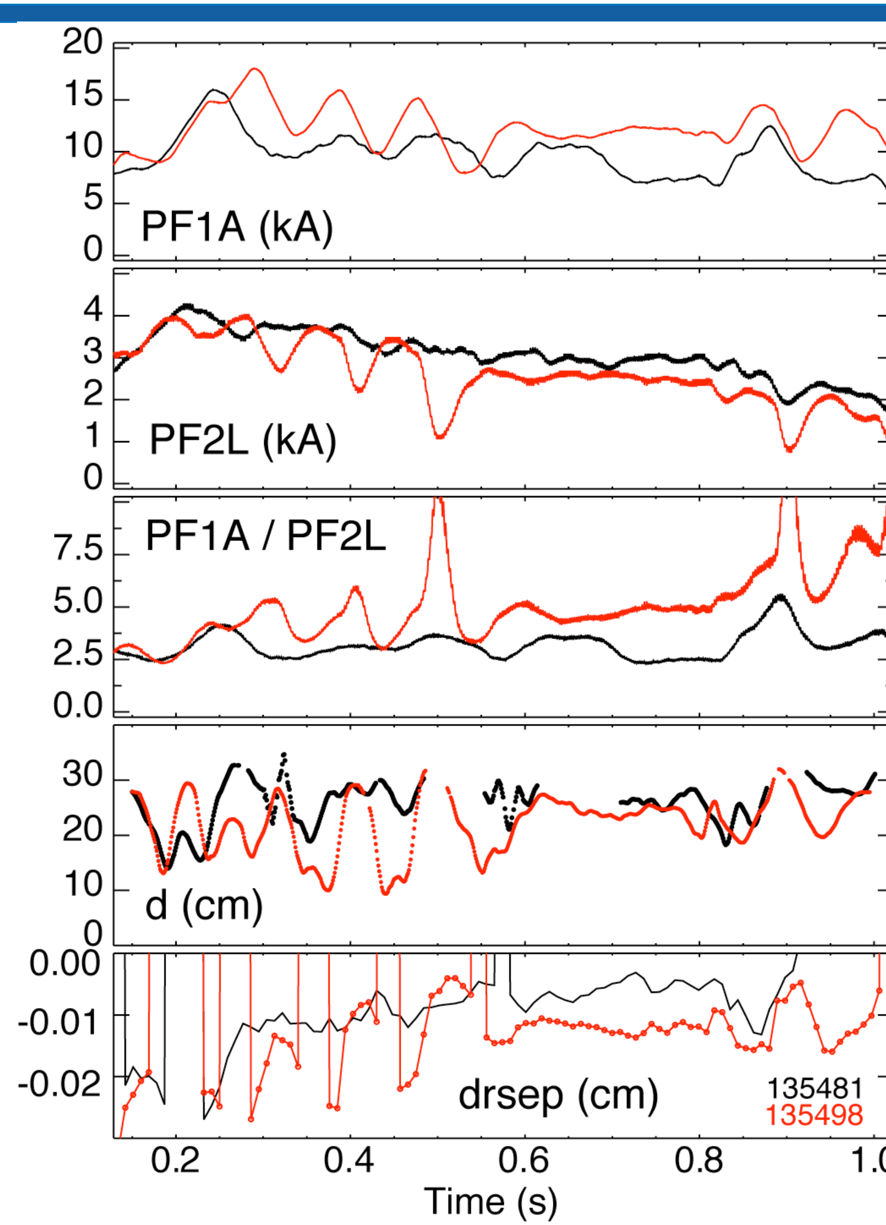


In experiment, controlled outer strike point scan produced "snowflake" divertor configurations

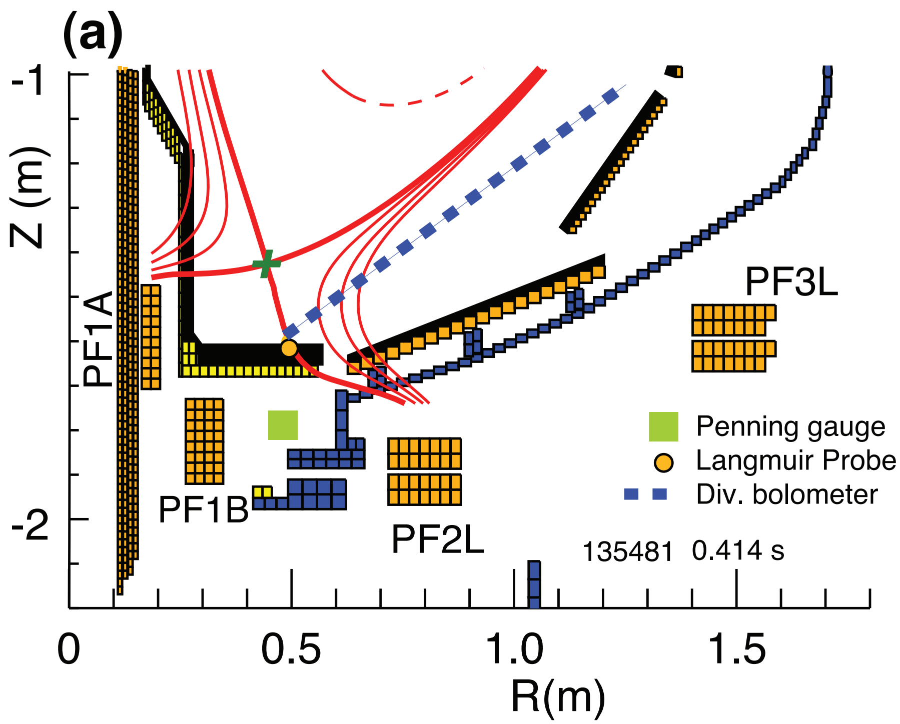
- Scanned OSP between 0.44 to 0.73 m

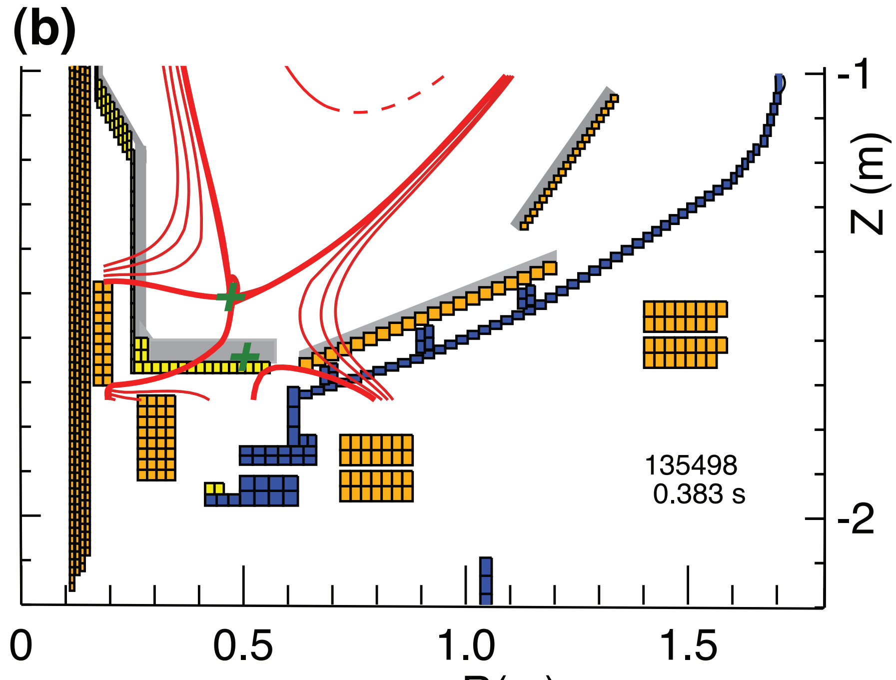
- Best "snowflake" configurations were obtained with requested R_{OSP} ~ 0.55 m (not necessarily actual R_{OSP})

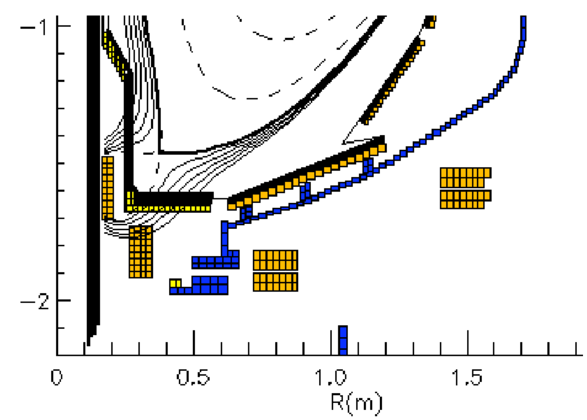
- "Snowflake" configuration was obtained when null-point separation ***d*** decreased to below 20 cm

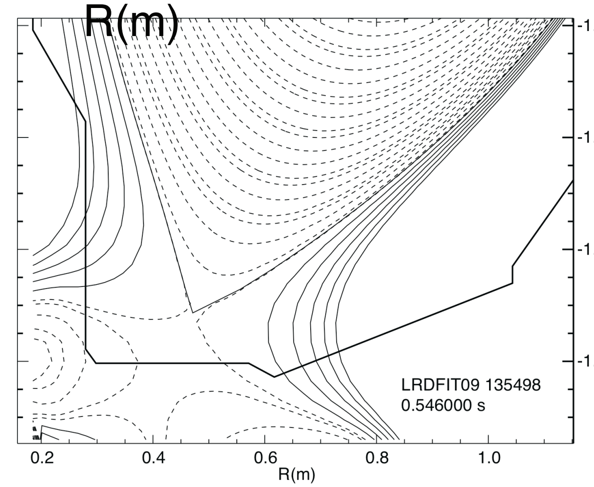


"Snowflake" divertor favorably compares to medium-δ and high-δ standard divertors

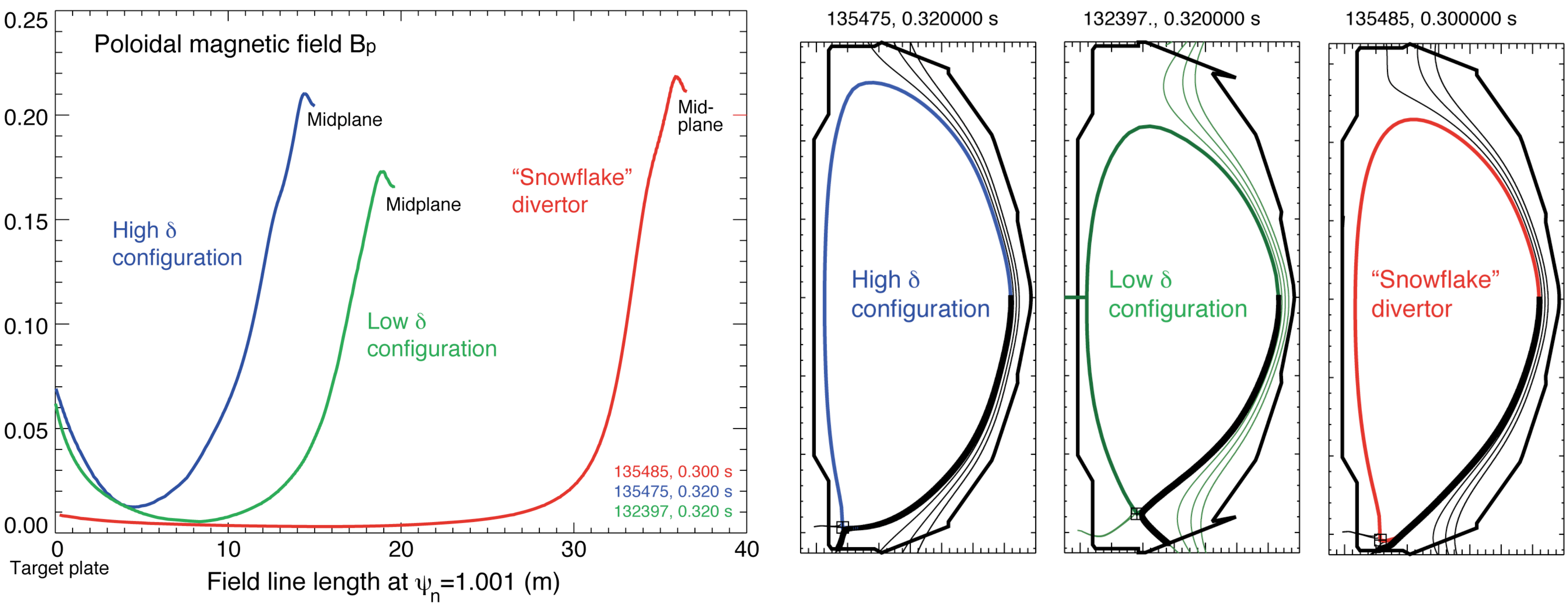






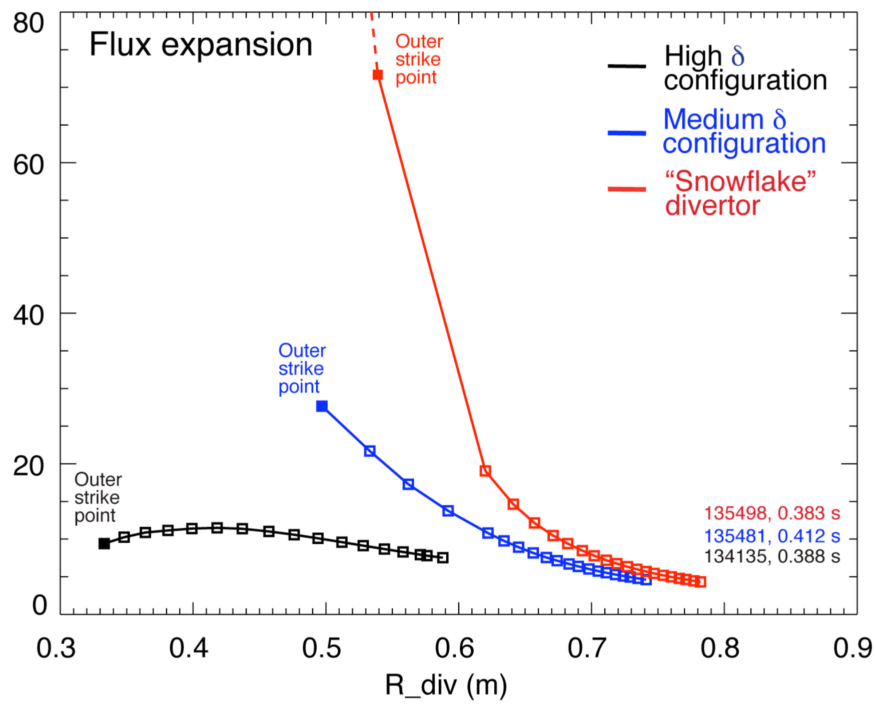


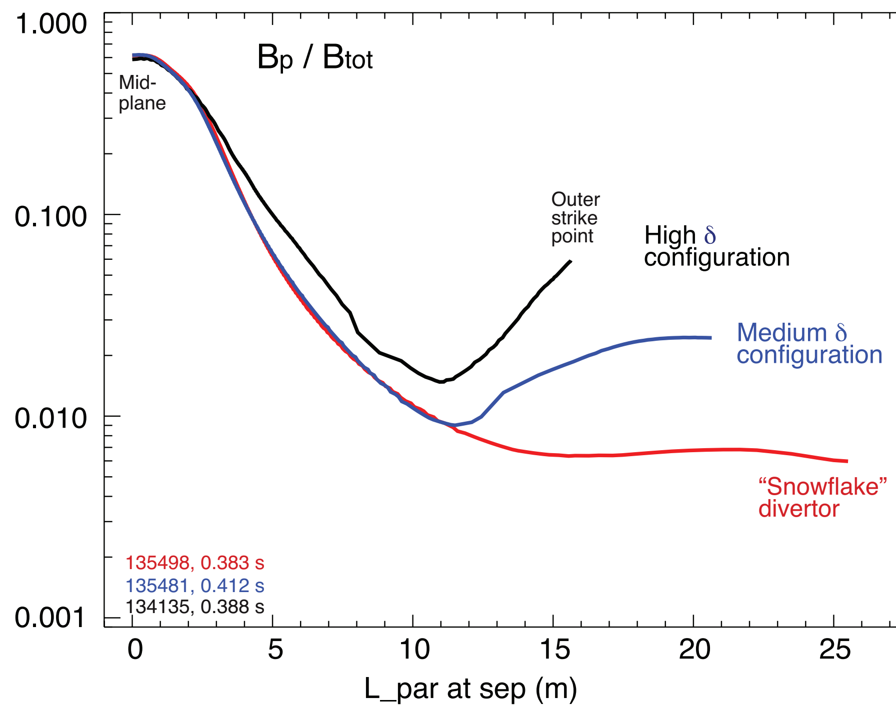
SFD configuration shows highest flux expansion at strike point and longest connection length

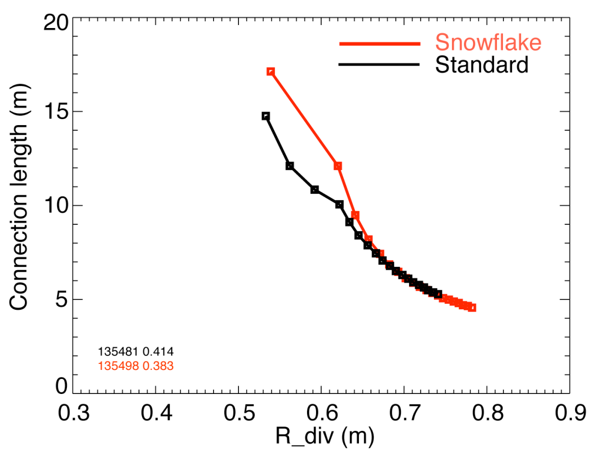


Configuration	Flux expansion	L_x (m)	L_{tot} (m)
SFD	68	16.3	36.5
Low δ	4.5	8.4	19.5
High δ	10	4.5	15.0

Theoretically predicted geometrical properties of the snowflake divertor configuration are confirmed in NSTX







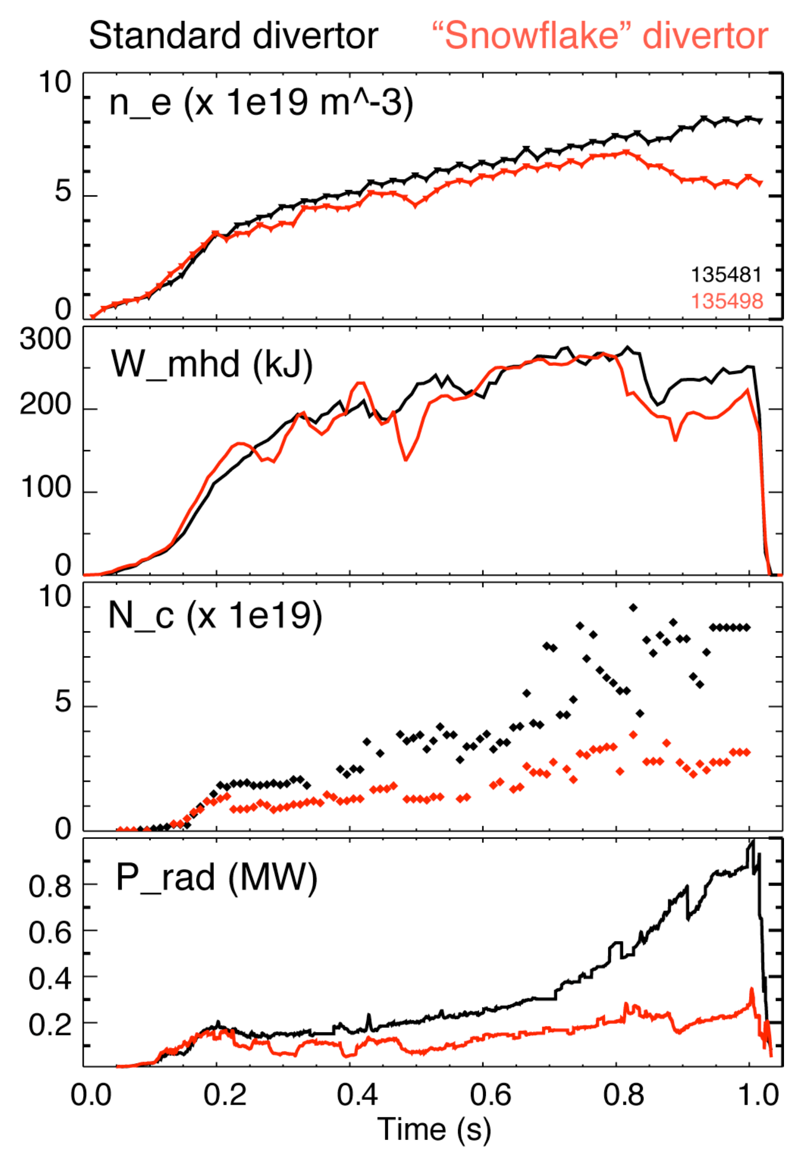
- In "snowflake" divertor
  - Plasma-wetted area (flux expansion) higher
  - L_x longer (thus f_{PFR} and V_{div} higher)
- These properties observed in first 2-3 mm of SOL λ_q

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

- Used 80-100 g evaporated lithium per discharge for wall conditioning

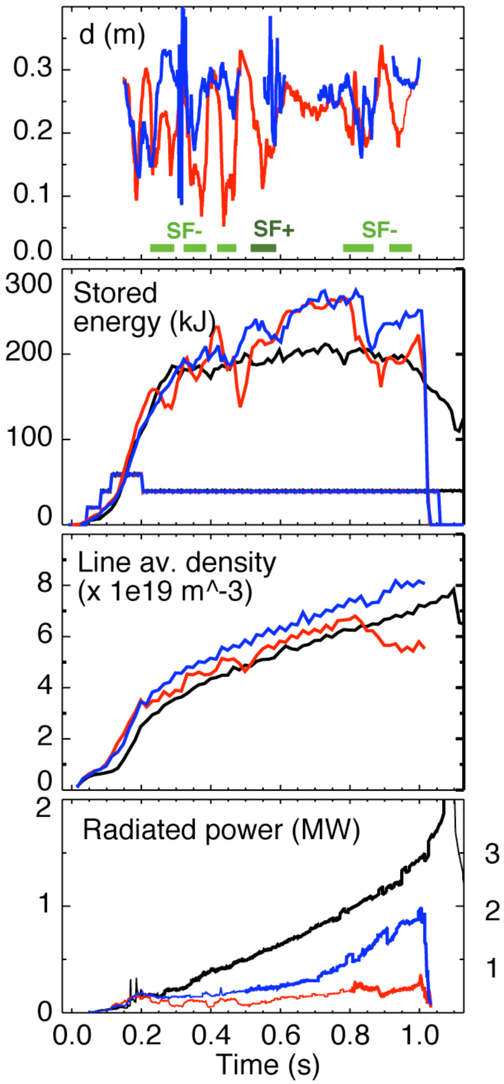
- ELM-free H-mode discharges had impurity accumulation

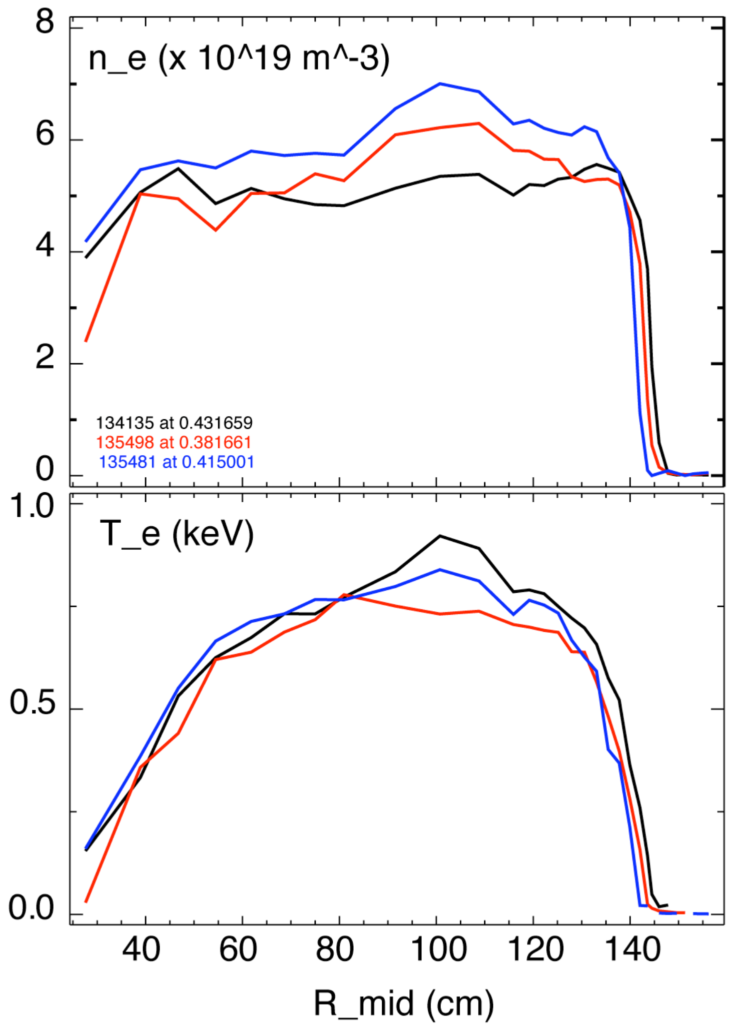
- In "snowflake" divertor discharges
  - Divertor sputtering source reduction (?)
  - Edge confinement degradation (?)



Less carbon accumulation and lower n_e in H-mode "ears" in "snowflake" divertor discharges

Divertor configurations: **High-**, **Medium-triangularity**, **Snowflake**

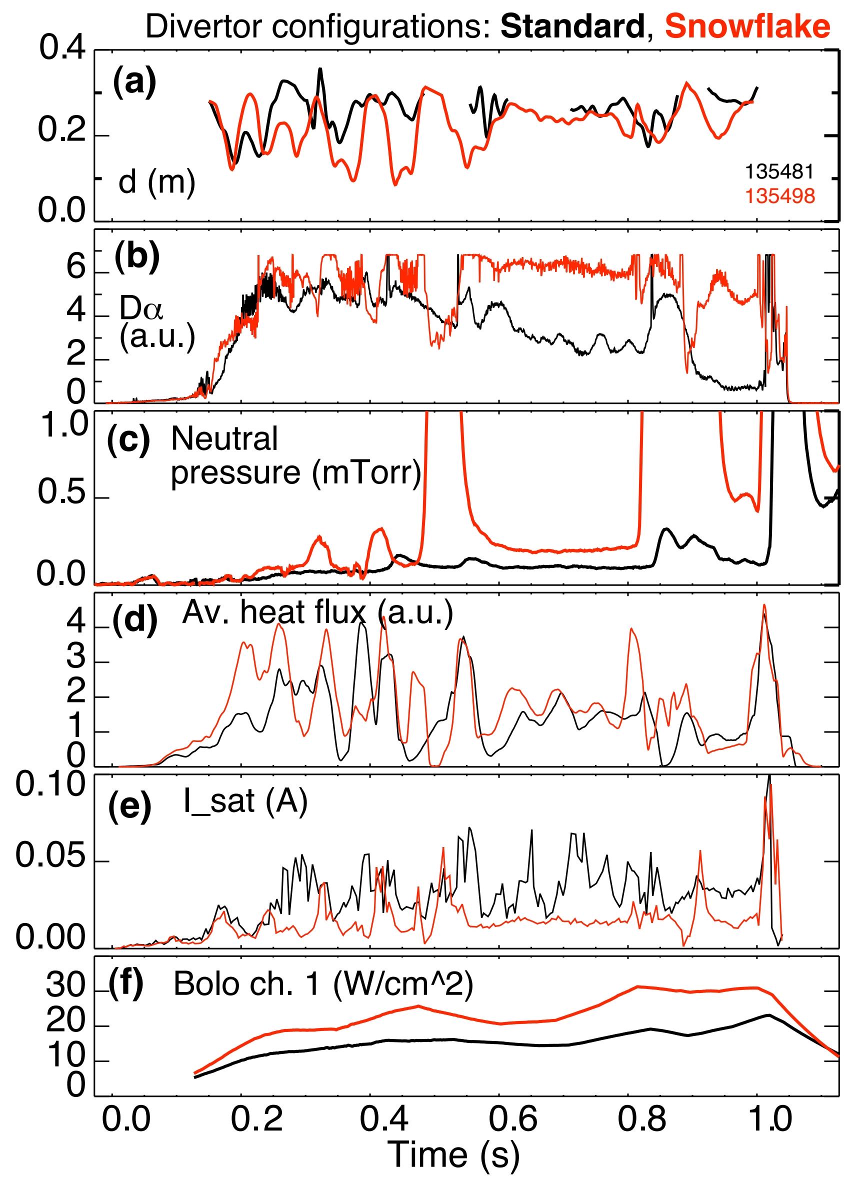




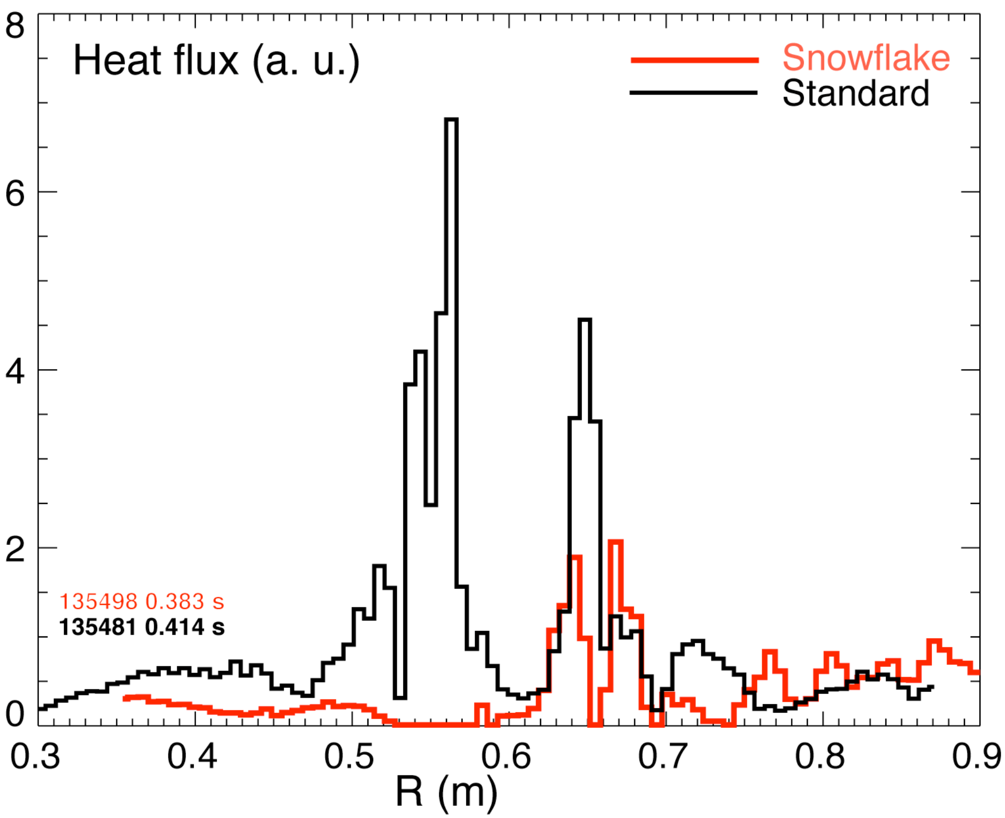
- Different edge $n_e(R)$ due to significant n_C reduction
- Future work – edge stability analysis

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, $n_e \geq 2e14$ m^{-3}
  - Increase in divertor P_{rad}
  - Increase in 3-body recombination rate
  - Increase in neutral pressure

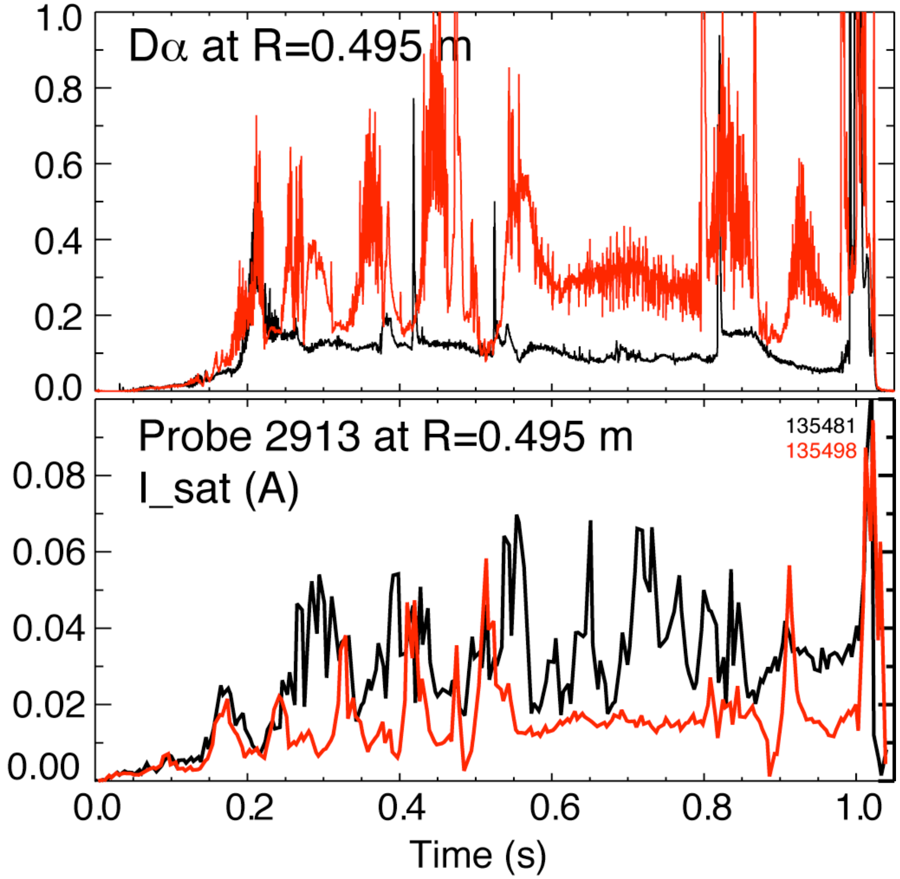


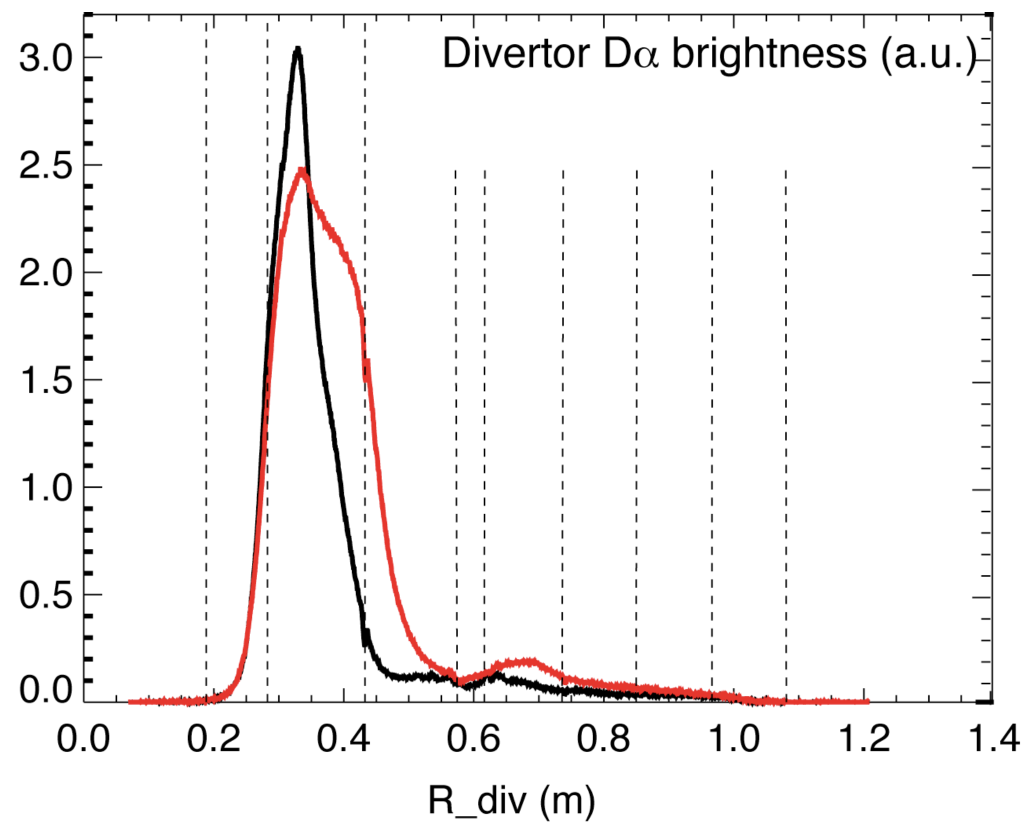
Significant reduction of heat flux observed in "snowflake" divertor



- Divertor peak heat flux well correlated with null-point separation ***d***
- Reduction observed in 2-3 mm region (mapped to midplane) adjacent to separatrix
- Uncalibrated IR camera data due to lithium coatings

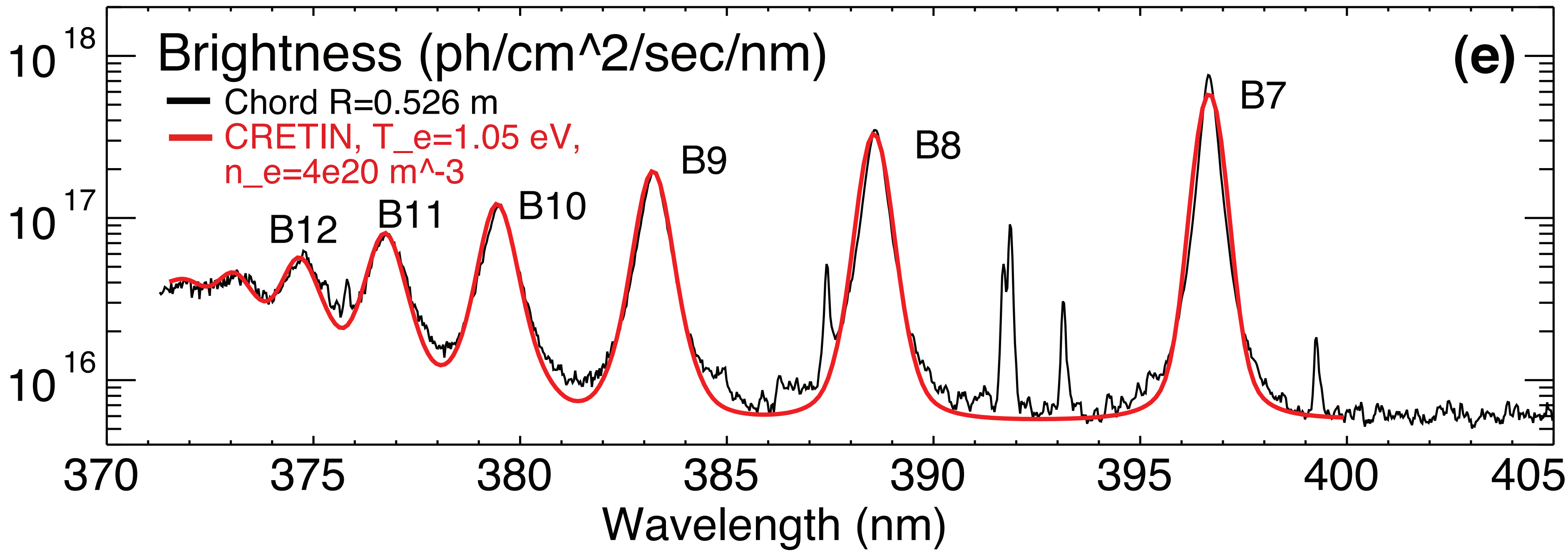
Balmer line emissions suggest large increase in recombination rate in “snowflake” divertor





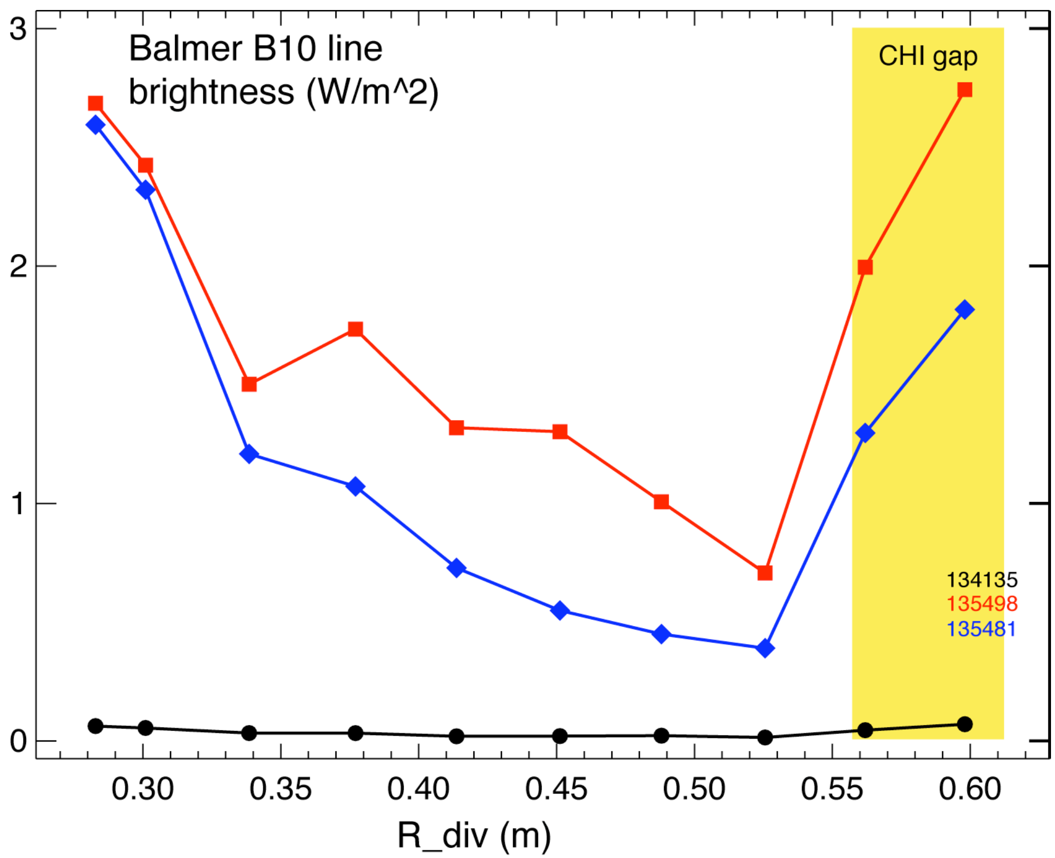
- Divertor D_α emission
  - Increase in radiating zone width
  - Brightness increase (due to recombination) correlated with Langmuir probe I_{sat} decrease (due to particle flux reduction)

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



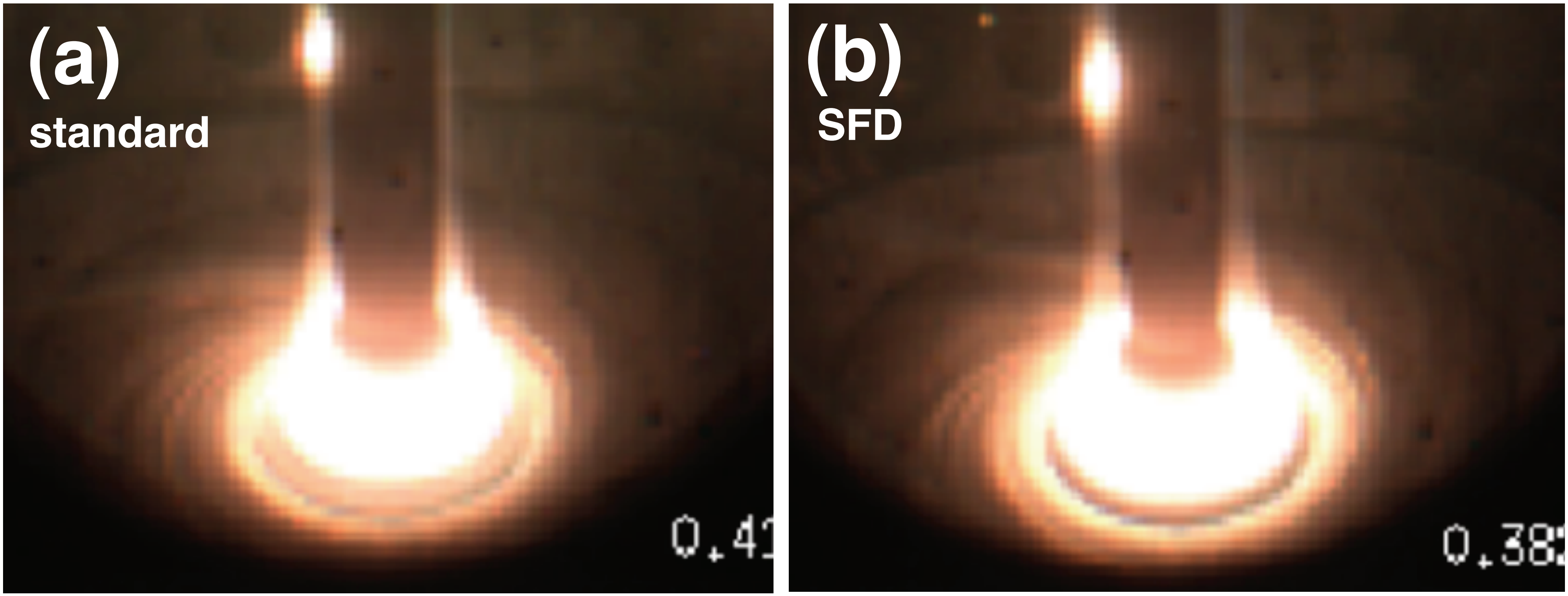
- Balmer series spectra modeled with CRETIN; Spectra sensitive to
  - Line intensity <-> Recombination rate
  - Te <-> Boltzman population distribution
  - ne <-> Line broadening due to linear Stark effect from ion and electron microfield
- T_e=0.8-1.2 eV, n_e=2-7 x 10^{20} m^{-3} inferred from modeling

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



- In "snowflake" divertor and high-δ configurations, B10 emission is from outer SOL, in medium-δ configuration, B10 emission is mostly from PFR region
- Increase in divertor n_e despite lithium conditioning that reduces recycling

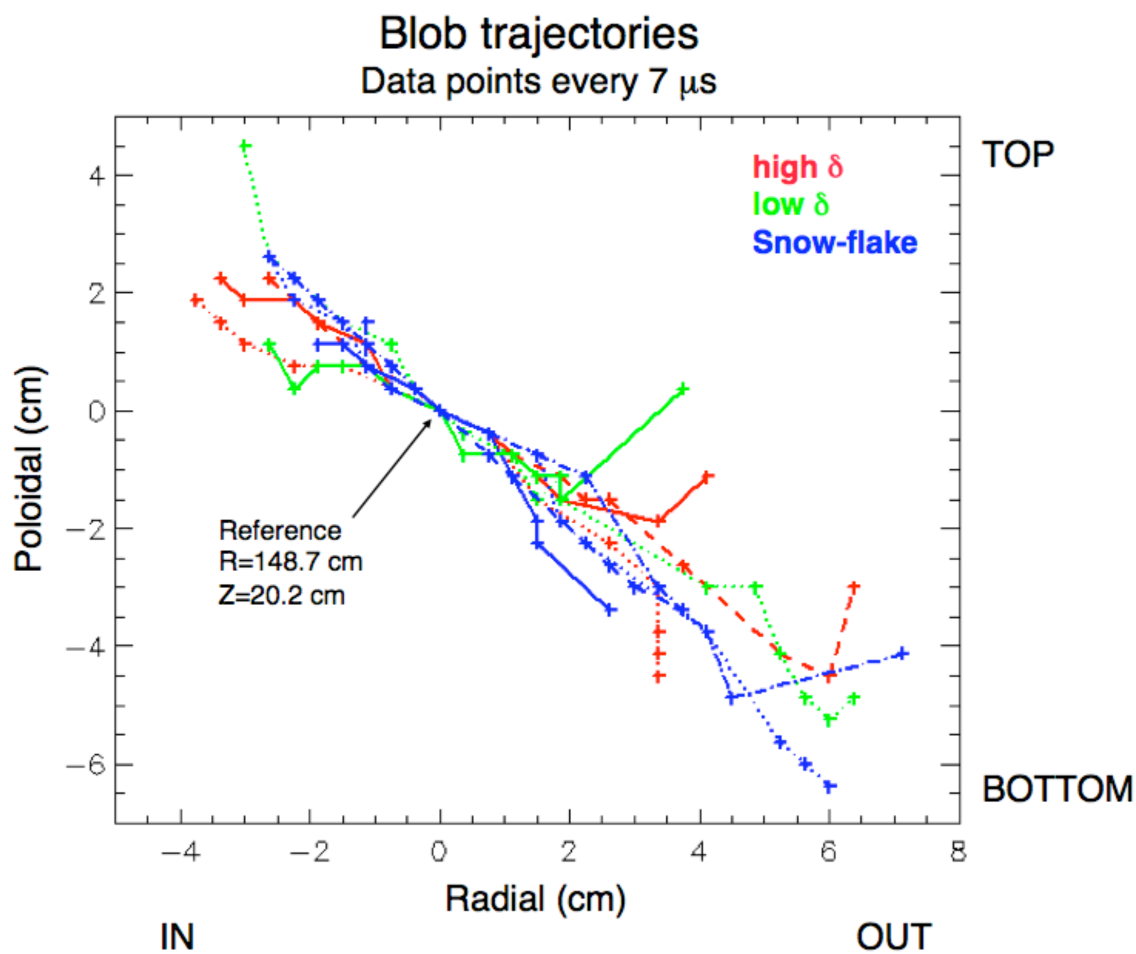
Divertor camera images show formation of extended radiation zone in "snowflake" divertor



- Visible camera images
- Zone extent correlated with divertor configuration

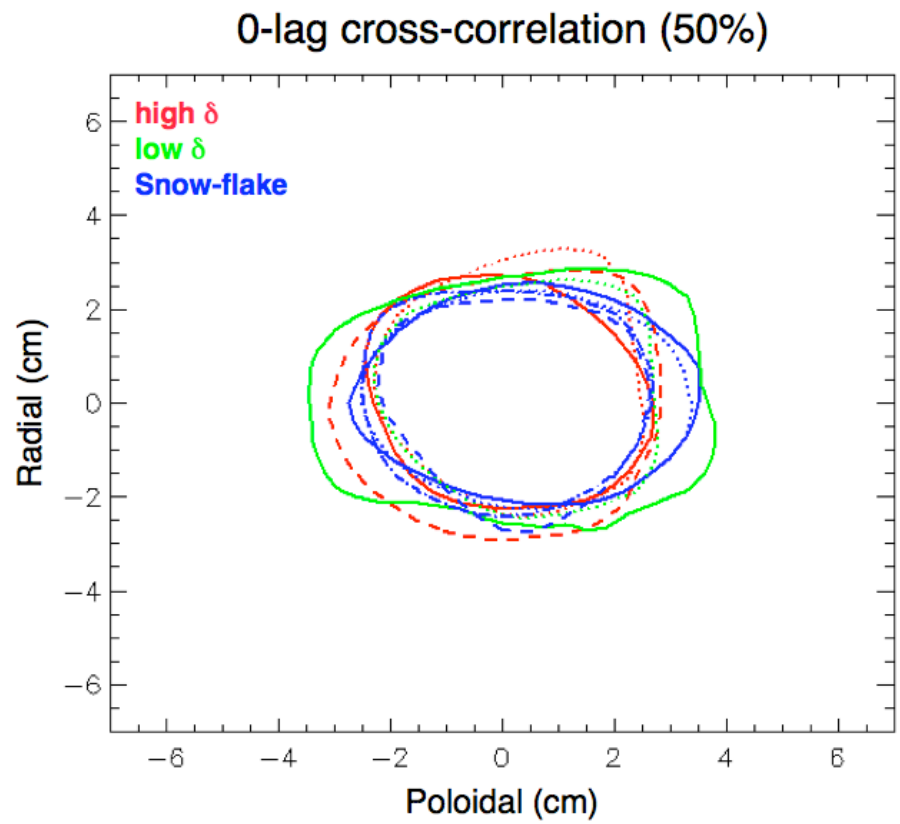
SOL blobs move radially at the same velocity regardless of divertor configuration

- Data from gas puff imaging diagnostic
- The "average" trajectories from the time-delayed cross correlations: each data point is the location of the maximum in the delayed cross correlation (relative to the reference point in the SOL).
- The time delays used are integer multiples of the framing time (7us).



Blob sizes appear to be similar in "snowflake" and standard divertor configurations

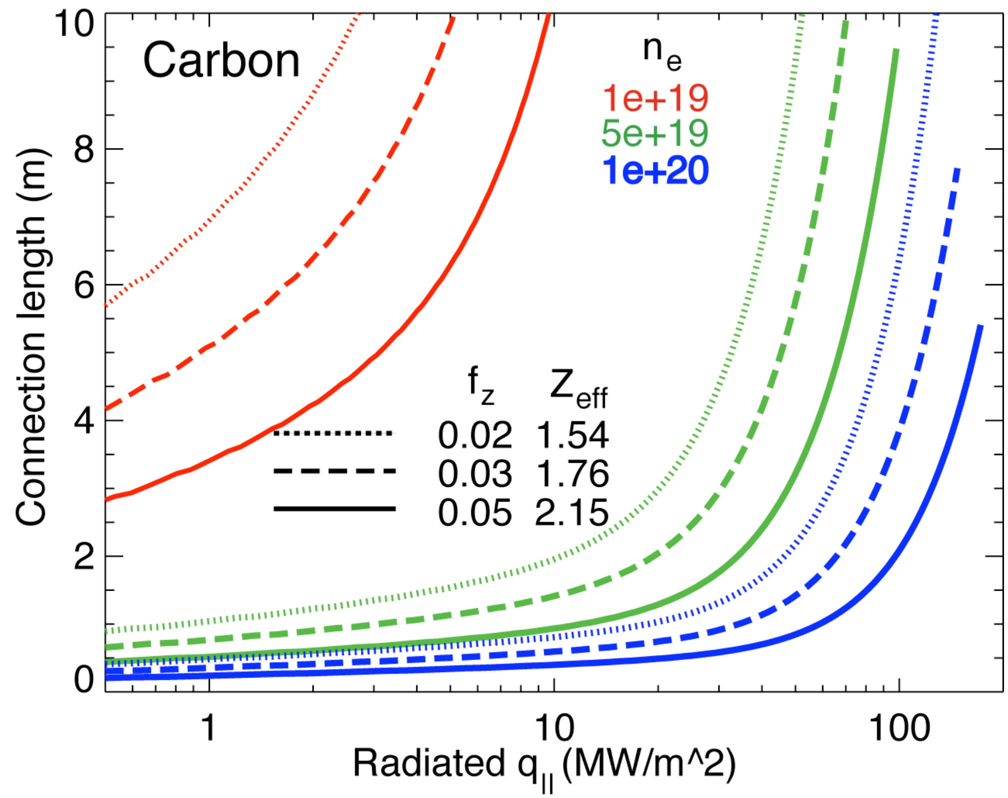
- The first page is 50% contour plot of the 0-lag cross-correlation between a reference point in the SOL and all other points in the images.
- The poloidal and radial auto-correlation lengths are a sub-set of this data.
- The net result: in all cases blobs are ~4cm FWHM in both radial and poloidal dimension.



High f_{rad} can be achieved with carbon in "snowflake" divertor at high n_e and longer L_x

- 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 1e-3 s



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

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

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

- Fraction of $q_{||}$ to be radiated is a function of L_x for given impurity
  - high f_{rad} only where L_x longest

- 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: $\tau_{ion} \leq 1$ ms

- Parallel momentum and power balance:

•CX & elastic recombination

$$\frac{d}{ds}(m_i n v^2 + p_i + p_e) = -m_i(v_i - v_n)S_{i-n} + m_i v S_R$$

•Rad. power

$$\frac{d}{ds}((-\kappa T_e^{5/2}\frac{dT_e}{ds}) + n v_{||}(\frac{5}{2}(T_i + T_e) + \frac{1}{2}m_i v_{||}^2 + I_0)) = S_E$$

Future plans

- Magnetic control of “snowflake” divertor
  - RT-control of 2nd null-point with PCS
  - Use of PF1B for control
- Transport and turbulence characterization
- Edge stability characterization
- Scaling with power

- Plans for NSTX-U
  - Additional divertor coil PF1C
    - flux expansion variation with fixed X-point height and strike-point location
  - Development of PMI solutions to address
    - 2-3x higher input power
    - 30-50% reduction in Greenwald fraction
    - 3-5x longer pulse duration