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Recycling, Pumping and Divertor Plasma-Material Interactions with evaporated lithium coatings in NSTX

V. A. Soukhanovskii

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Princeton, NJ, United States
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NSTX

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Recycling, Pumping and Divertor Plasma-Material Interactions with evaporated lithium coatings in NSTX

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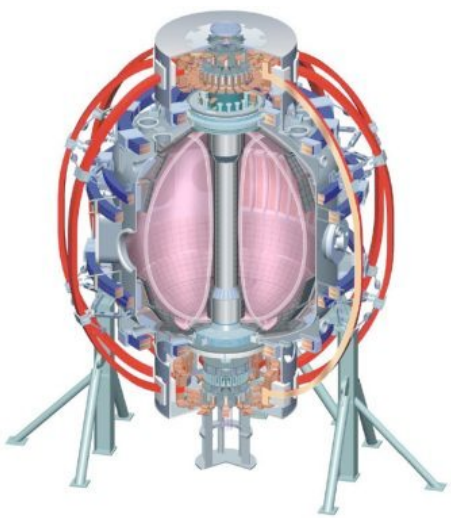

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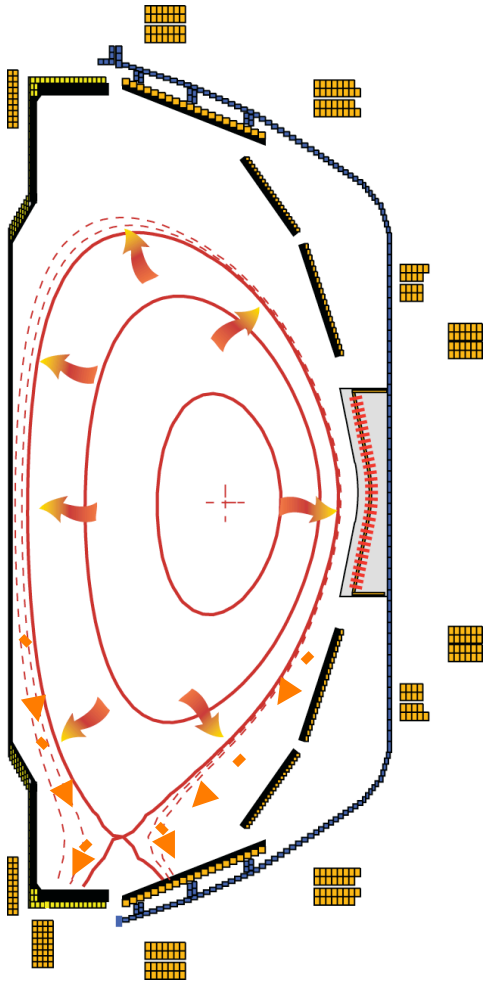
Solid lithium coatings are studied in NSTX for impurity and density control applications

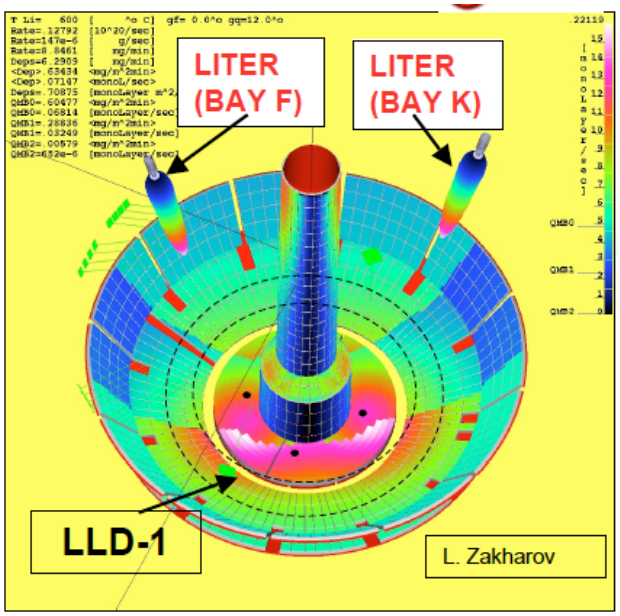
- Access to reduced core collisionality
  - n_e ~ 0.6-0.9 n_G for transport, stability, start-up, high non-inductive current fraction scenario studies for future STs (e.g., NSTX-Upgrade)
  - n_e ~ 0.3-0.7 n_G for adequate NBI current drive efficiency in scenarios relevant to fusion and nuclear science ST-based devices
- Spherical tokamak: compact divertor for power and particle exhaust
- NSTX (Aspect ratio A=1.4-1.5)
  - $I_p \leq 1.4$ MA, $P_{in} \leq 7.4$ MW (NBI), P / R ~ 10
  - $q_{peak} \leq 15$ MW/m^2, $q_{||} \leq 200$ MW/m^2
  - ATJ and CFC graphite tiles as PFCs
  - Typical divertor strike point region $T \leq 500$ C ($q_{peak} \leq 10$ MW/m^2) in 1 s discharges



National Spherical Torus Experiment

Plasma-surface interactions with solid lithium coatings on graphite plasma-facing components

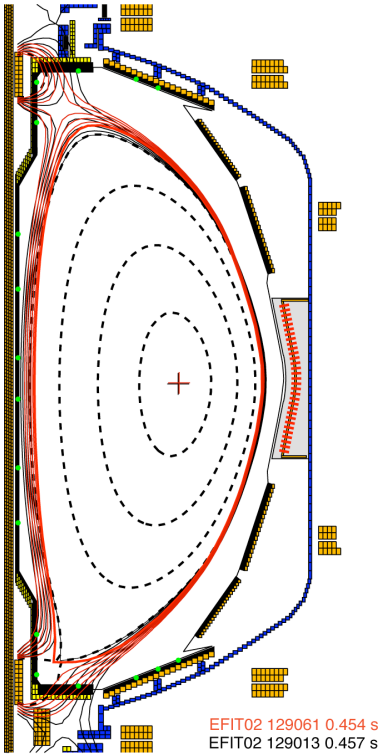
- Solid lithium coatings in NSTX
  - deposited by two lithium ovens (LITERs)
    - oven T= 600-680°C
    - Evaporation rate: 1 mg/min – 80 mg/min
  - divertor coating thickness up to 200-400 nm
  - up to 50 % variation in toroidal thickness
- Interaction of solid lithium coatings with plasma
  - Physical sputtering of lithium atoms
    - by D ions - 2/3 lithium sputtered as Li^+
    - by lithium (self-sputtering) and carbon
  - Re-deposition
  - Melting (T = 180° C) and evaporation (significant rate at T > 300° C)
  - Reaction with D^0 atoms leads to pumping of hydrogenic plasma
    - Coating can bind D with all Li inventory up to a full thickness
    - After saturation - high recycling, low pumping rate
  - Reaction with H_2O, C and O to form various compounds



Impact of lithium conditioning was investigated in NBI-heated H-mode discharges

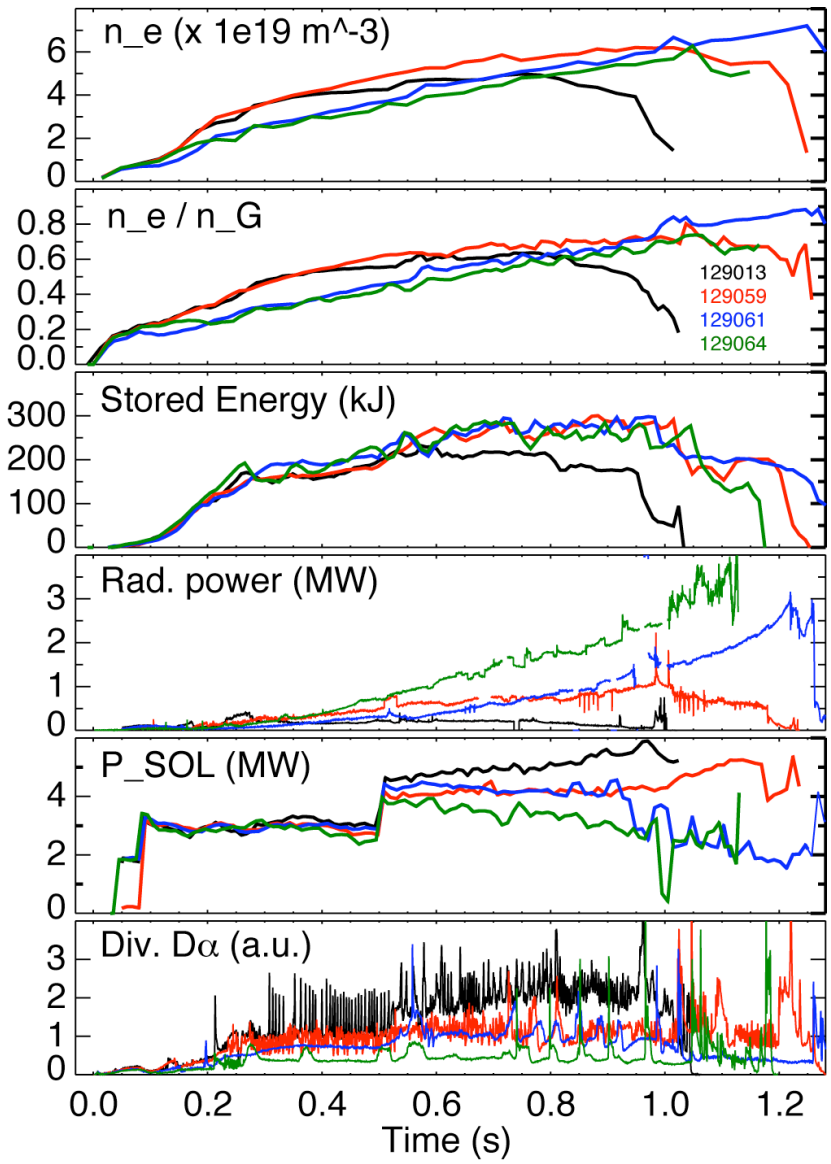
- Pumping and recycling on PFCs
- Lithium influx from PFCs and core lithium density
- Control of divertor carbon influx

- I_p=0.9 MA, B_t=4.5 kG, P_{NBI}=4-6 MW, high κ~2.3, δ~0.6
  - **Discharge without lithium (129013)**
    - boronized carbon, no prior lithium use
  - **Discharge without lithium (129059)**
    - prior use of lithium (~ 20 discharges, ~ 8 g)
  - **Discharge with 190 mg lithium (~ 190 mg total, 129061)**
  - **Discharge with 600 mg lithium (2.2 g total, 129064)**



- Photometrically calibrated filtered cameras and spectrometers, tile-mounted Langmuir probes, neutral pressure gauges
- Γ_{ion} [ion/m^2/s] = 4 π I_λ [ph/m^2/s/sr] S/XB [ion/ph]
  - For deuterium, D_a and D_b ; for lithium, Li I λ=670 nm
  - Outer SOL region only

With lithium, reduced core density operation can be achieved



- n_e/n_G ~ 0.2-0.7
  - N_e and n_e increasing
- W_{MHD} increased
- P_{SOL} decreasing with lithium amount
  - Core P_{rad} increasing
  - $P_{SOL}=P_{OH}+P_{NBI} - P_{rad} - dW/dt - P_{fast\ ion\ loss}$
- ELMs suppressed
  - Pedestal MHD stability modified due to n_e (r) mod.

No lithium (129013)
No lithium (129059)
190 mg lithium (129061)
600 mg lithium (129064)

Impact of lithium conditioning was investigated in NBI-heated H-mode discharges

- **Ion pumping and recycling fluxes**
- Lithium influx from PFCs and core density
- Fueling and density evolution

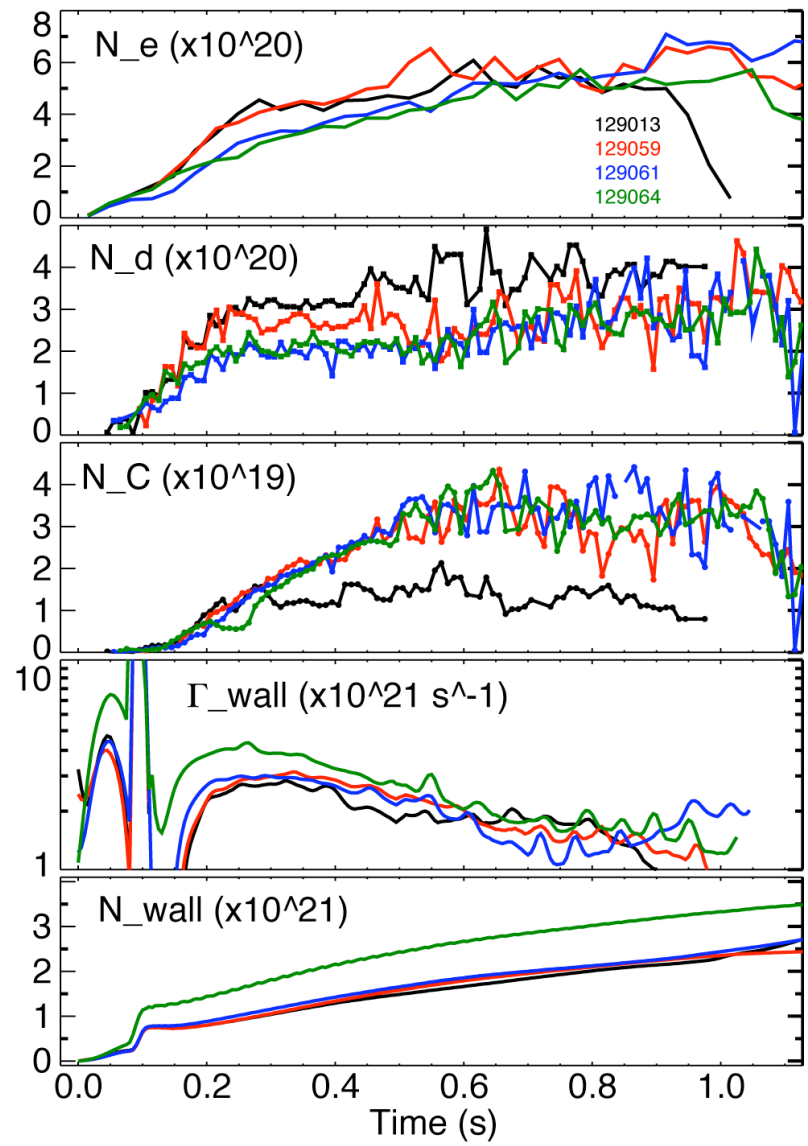
Ion density was reduced by up to 50 % by lithium conditioning in NSTX

$$\frac{dN_p}{dt} = \Gamma_{gas} + \Gamma_{NBI} + \Gamma_{NBI_cold} + \Gamma_{NBI_cryo} + \Gamma_{wall} + \Gamma_{pump} + \frac{dN_n}{dt}$$

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

- Particle balance equation
- Particle inventory balance: $N_e = 6\,N_C + N_d$

- Continuous pumping
- Cumulative coatings provide higher pumping rate
- Wall in pumping state far from saturation



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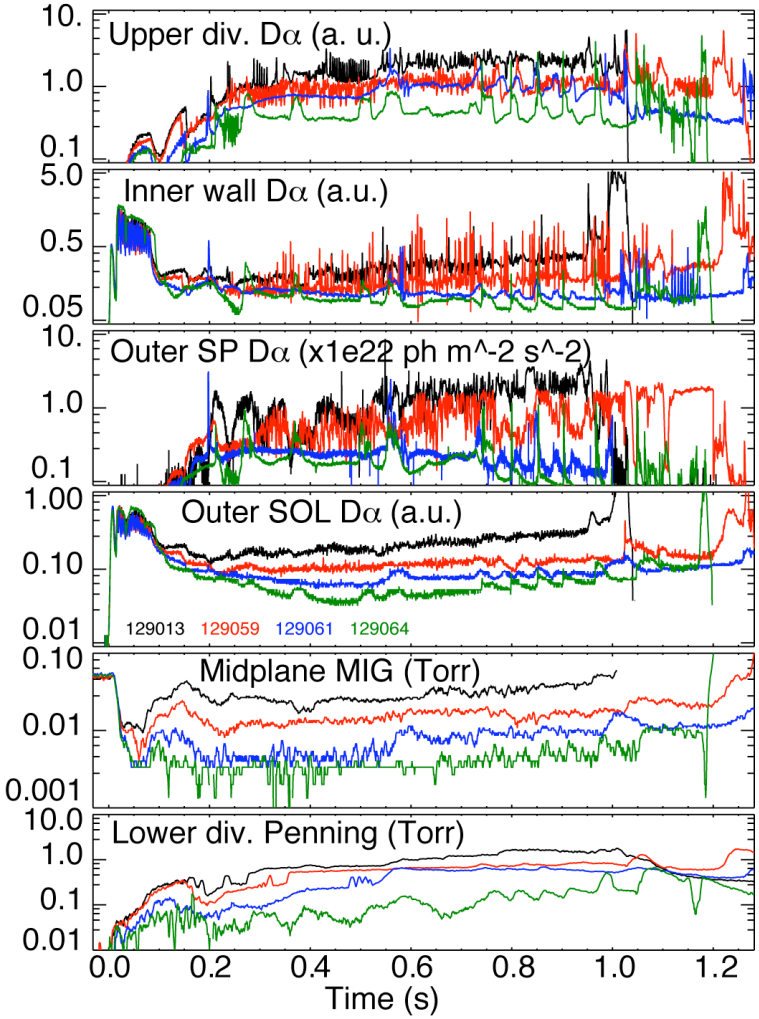
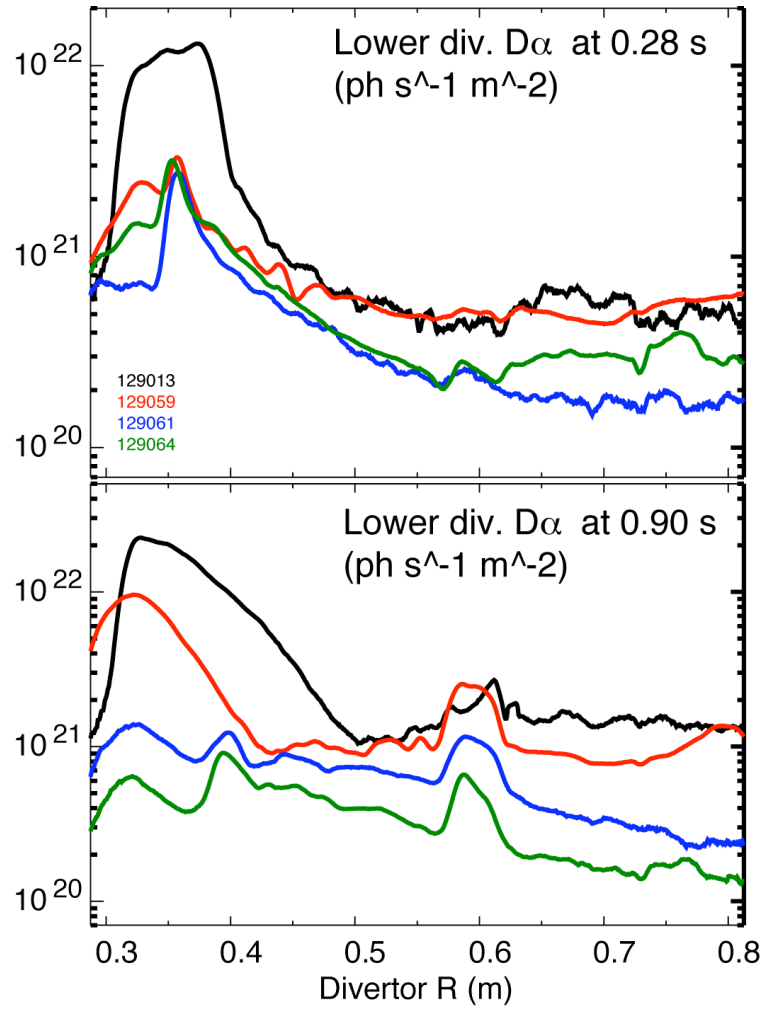
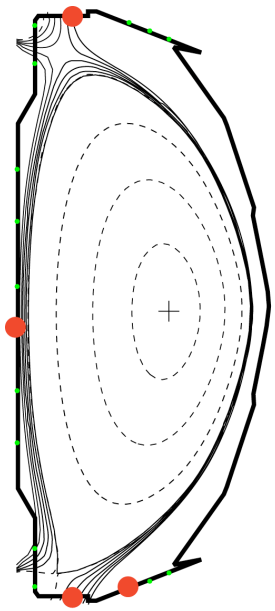
600 mg lithium (129064)

Edge neutral pressure and recycling on PFCs reduced, most strongly in lower divertor







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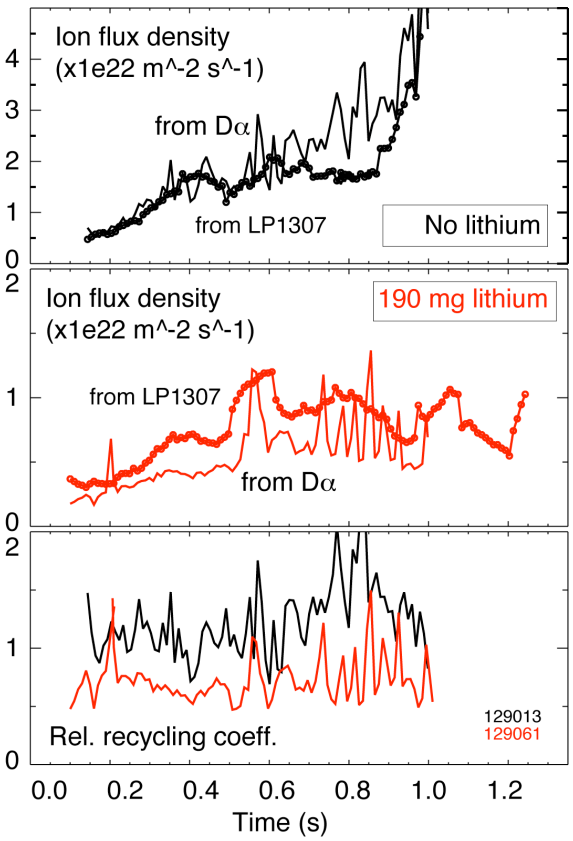
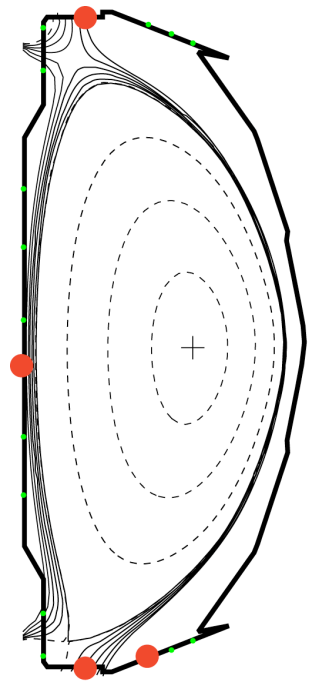
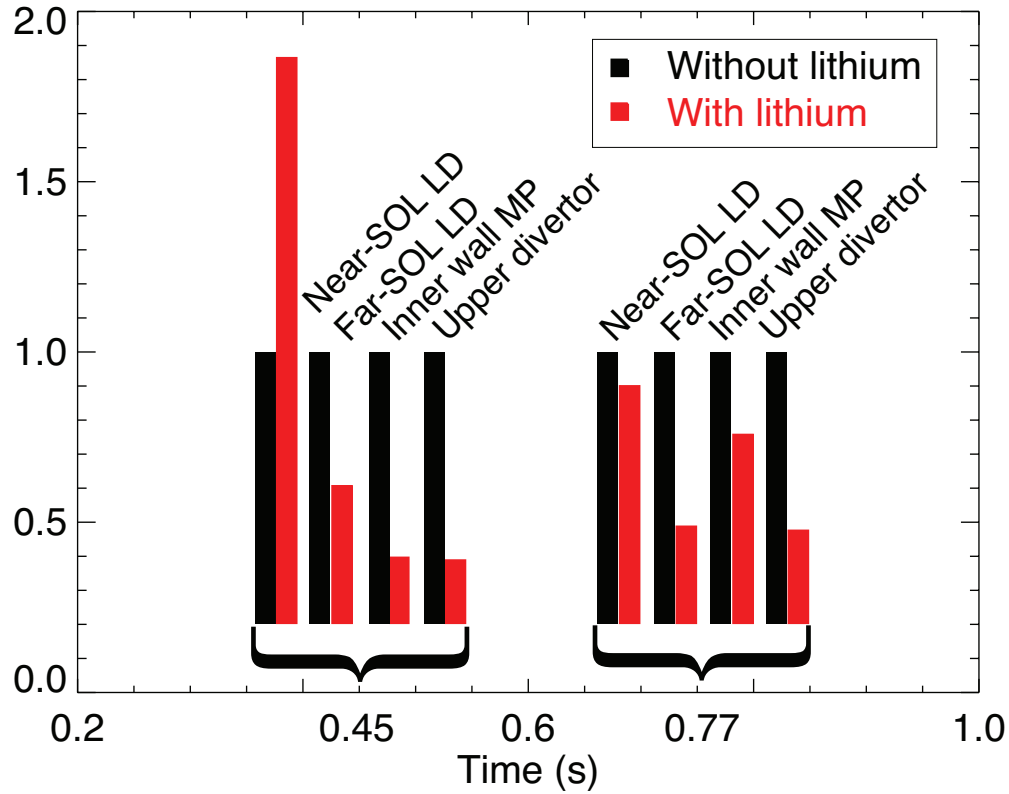
600 mg lithium (129064)

- Divertor ionization source reduced by up to 50 %

Local relative recycling coefficients reduced on all PFCs but in the near-SOL / strike point region







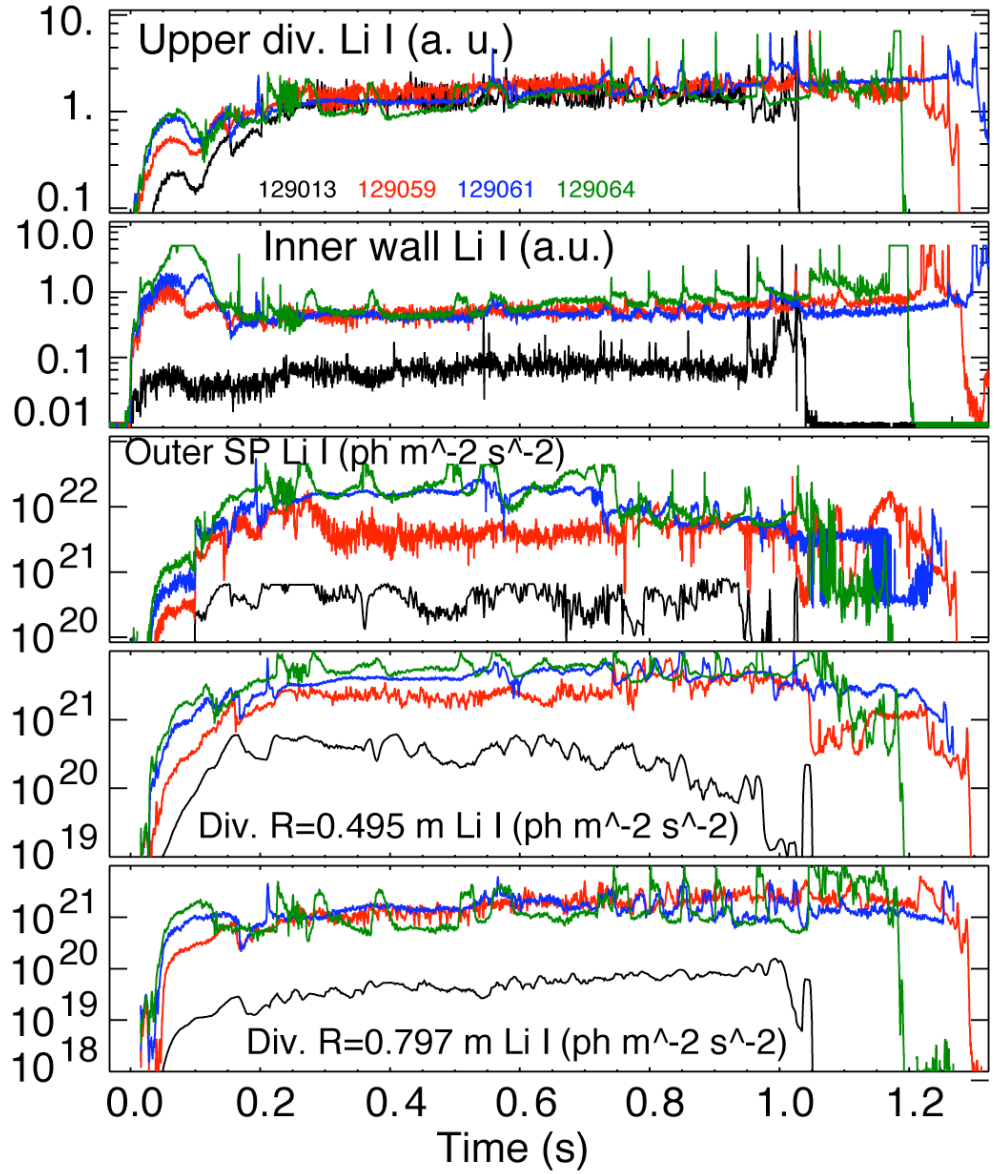
- Local recycling coefficient $R_{local}=\Gamma_i^{out} / \Gamma_i^{in}$
  - Ion flux into surface Γ_i^{in} is measured by Langmuir Probes (LPs)
  - Ion outflux Γ_i^{out} estimated from measured Dα intensity and S/XB (ionizations/photon) coefficient from ADAS

Impact of lithium conditioning was investigated in NBI-heated H-mode discharges

- Ion pumping and recycling fluxes
- **Lithium influx from PFCs and core lithium density**
- Fueling and density evolution

Lithium flux measurements suggest lithium source is in lower divertor, degrades in one discharge

- Strong scaling of lithium fluxes with evaporated amount in early phase on all PFCs
  - In later phase, no scaling in upper divertor, inner wall and far SOL
- In near SOL and strike point, strong scaling until end of discharge (cumulative effect)
- Large difference between "no lithium" reference discharges



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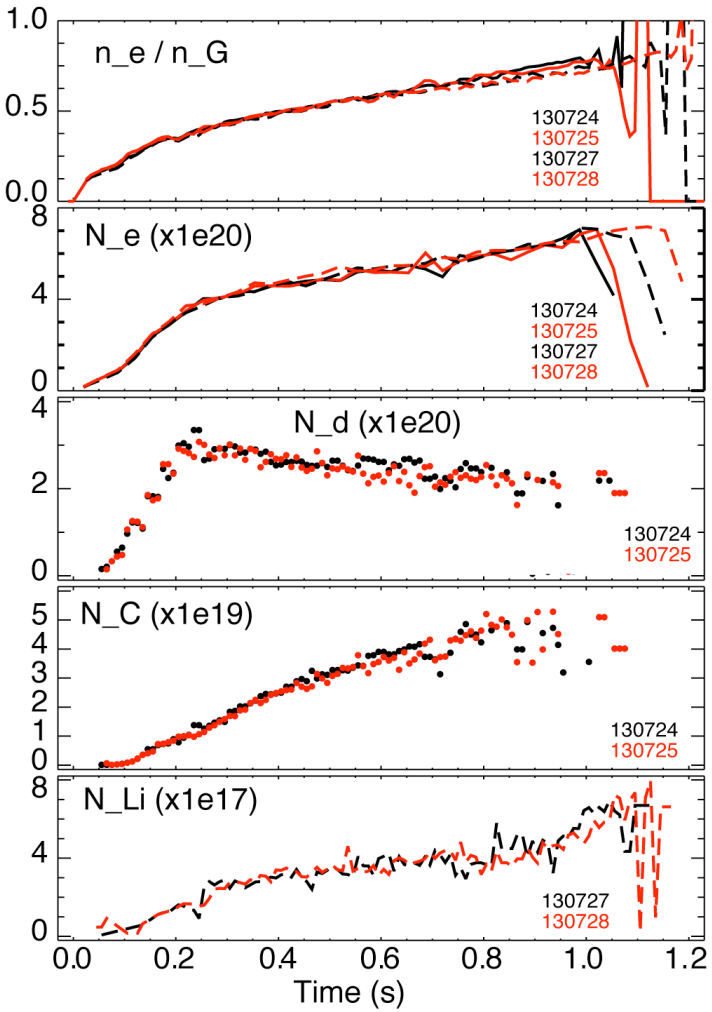
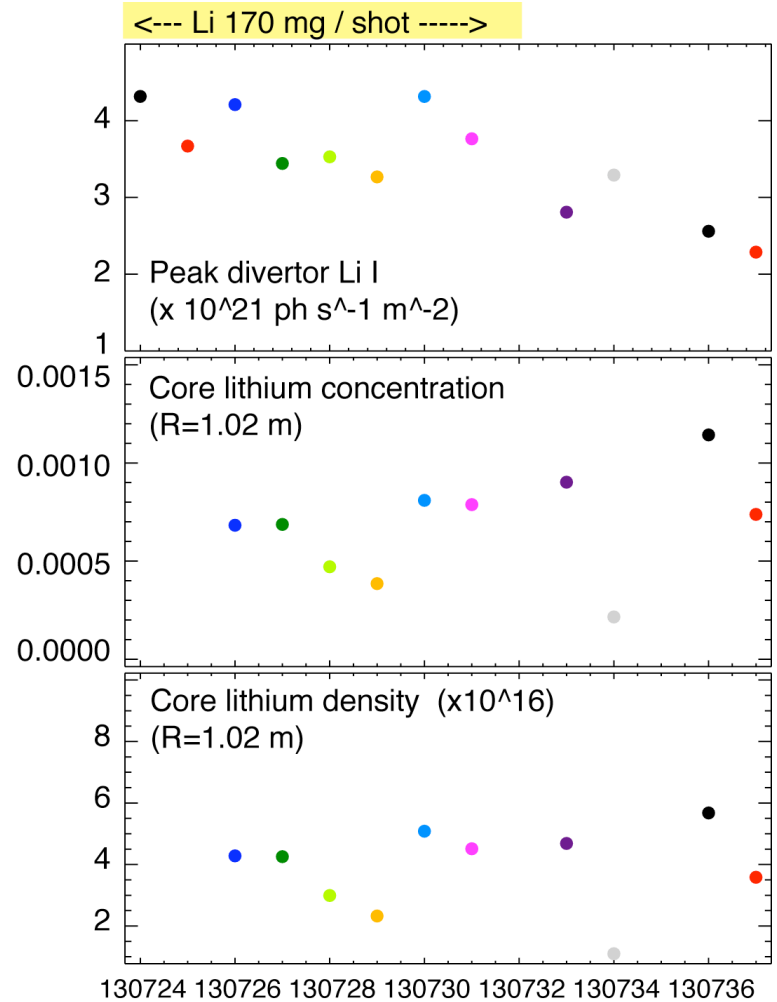
190 mg lithium (129061)
600 mg lithium (129064)

Core lithium density low, does not scale with divertor source, lithium weakly accumulates in core



Impurity density profiles from CHERS

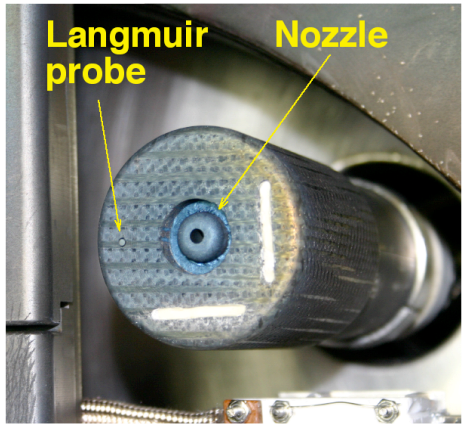
- C VI, n = 8-7, 529.1 nm
- Li III, n = 7-5, 516.7 nm

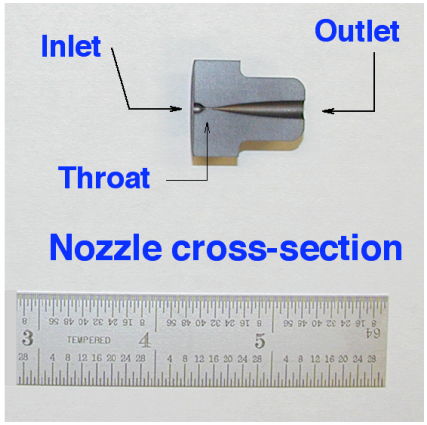


- Lithium screening efficiency high, penetration factor N_{Li} / Γ_{li} ~ 0.0001

Impact of lithium conditioning was investigated in NBI-heated H-mode discharges

- Ion pumping and recycling fluxes
- Lithium influx from PFCs and core density
- **Fueling and density evolution**

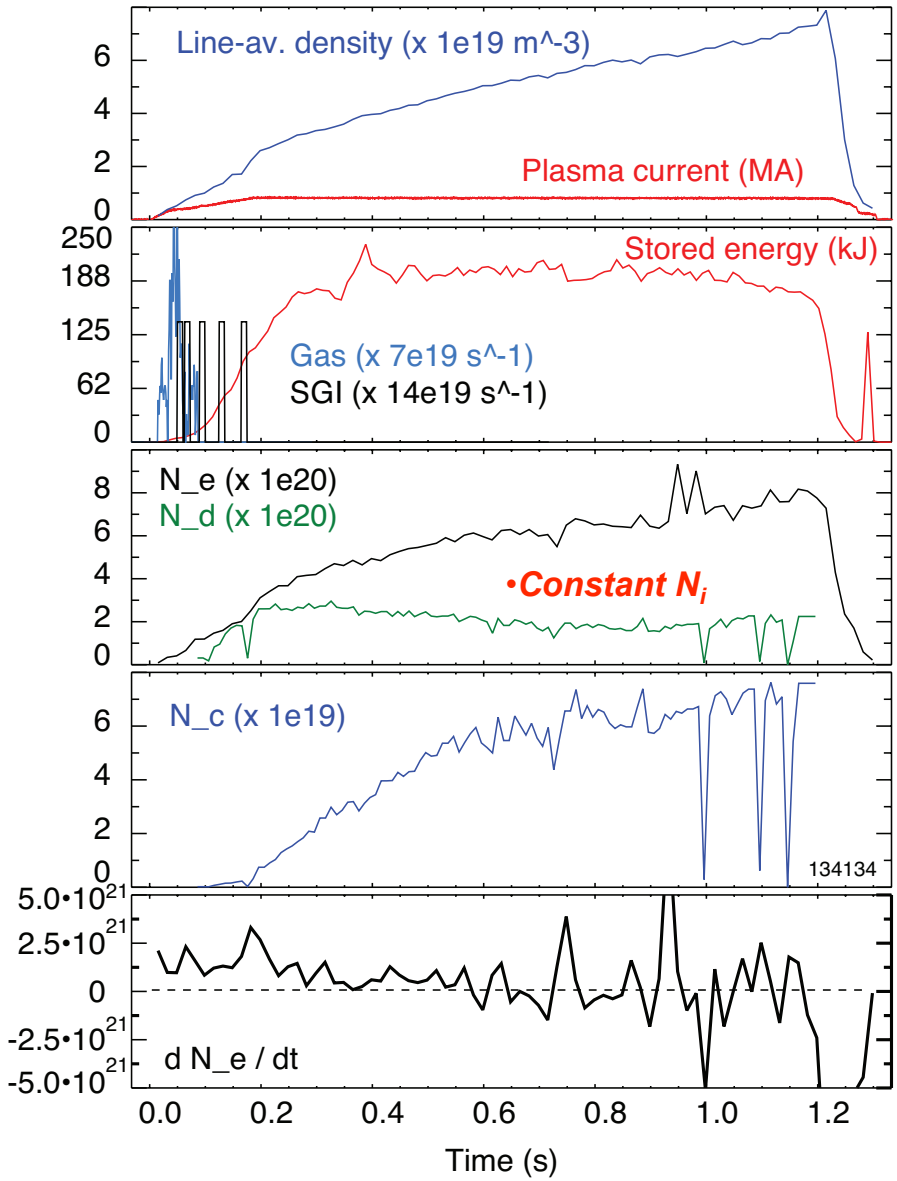


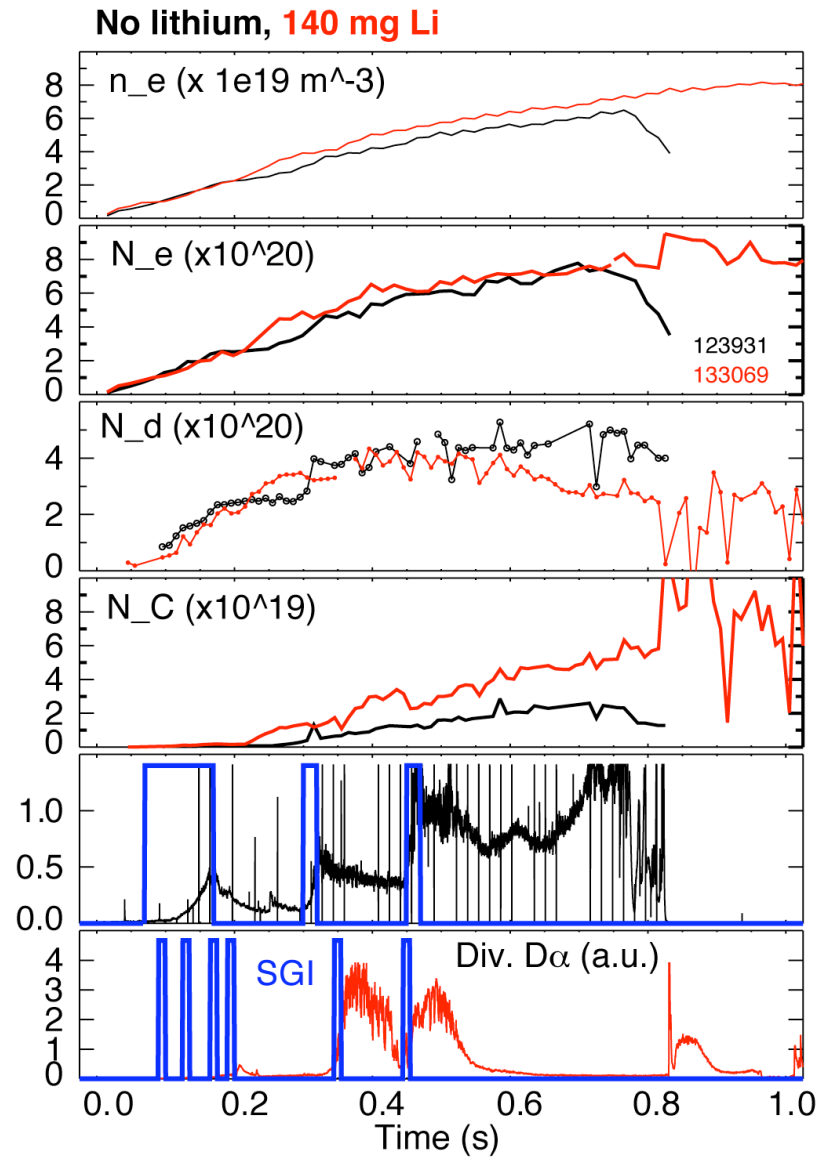


- SGI-U is operated at flow rates 50-250 Torr l /s ($3.5 – 17.5 \times 10^{21}$ s^{-1})

- Supersonic deuterium jet properties:
  - Jet divergence half-angle: 6° - 25° (measured)
  - Mach number M = 4 (measured)
  - Estimated: T ~ 60 - 160 K, $n < 5 \times 10^{23}$ m^{-3}, v_{flow} = 2.4 km/s, v_{therm} ~ 1.1 km/s
  - Nozzle Re = 6000

A long pulse H-mode discharge scenario with SGI fueling and controlled N_i was developed



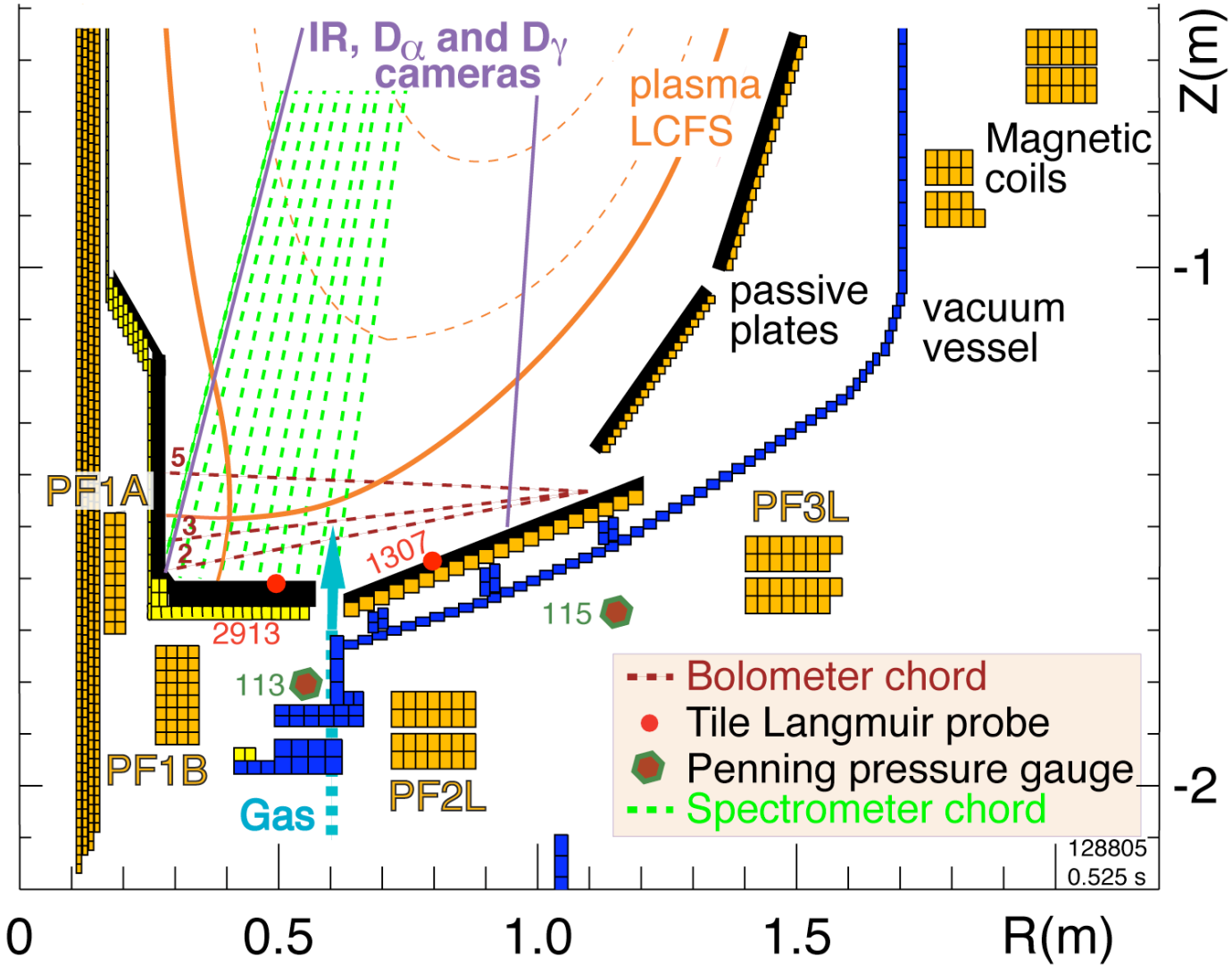


Summary and plans

- Lithium coatings are investigated in NSTX for impurity and density control
  - Divertor surface pumping reduce ion density (inventory) by up to 50 %
  - Pumping effect lasts ~ 1-2 discharges due to lithium coating degradation
  - Plasma has some (but weak) memory of prior lithium evaporations
  - Lithium coatings lead to reduced recycling, strong effect on divertor and pedestal plasma
  - Exploring synergy between solid lithium pumping and efficient fueling by supersonic gas injector
  - This study when completed will provide a basis for comparison between solid lithium coatings on graphite and molybdenum (planned for 2011-2012)

Backup

NSTX divertor diagnostics

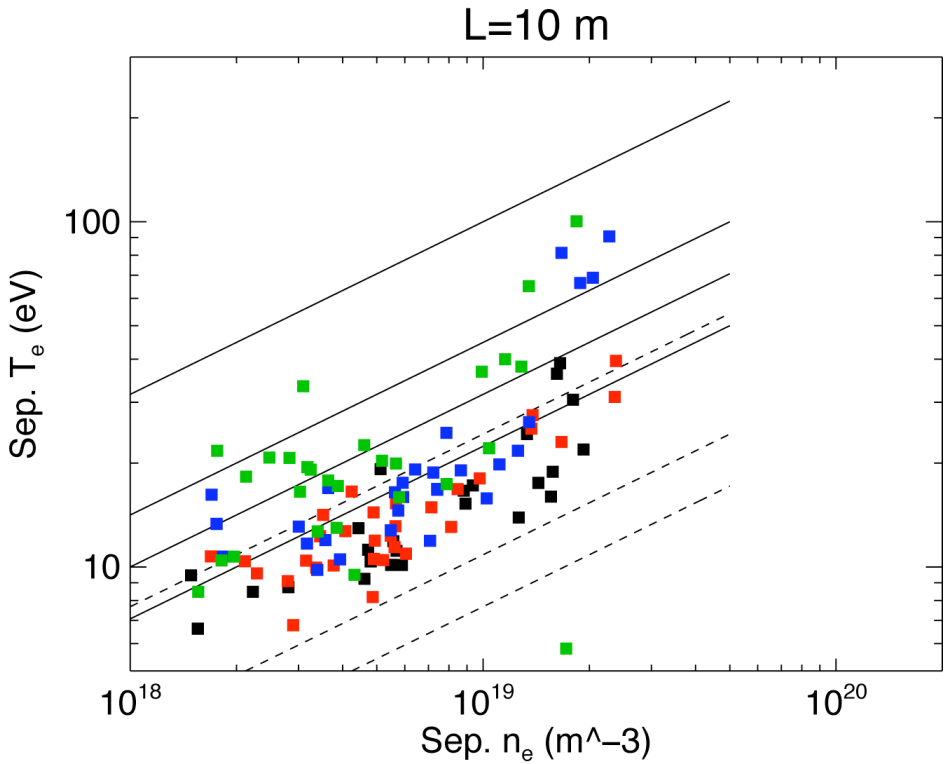


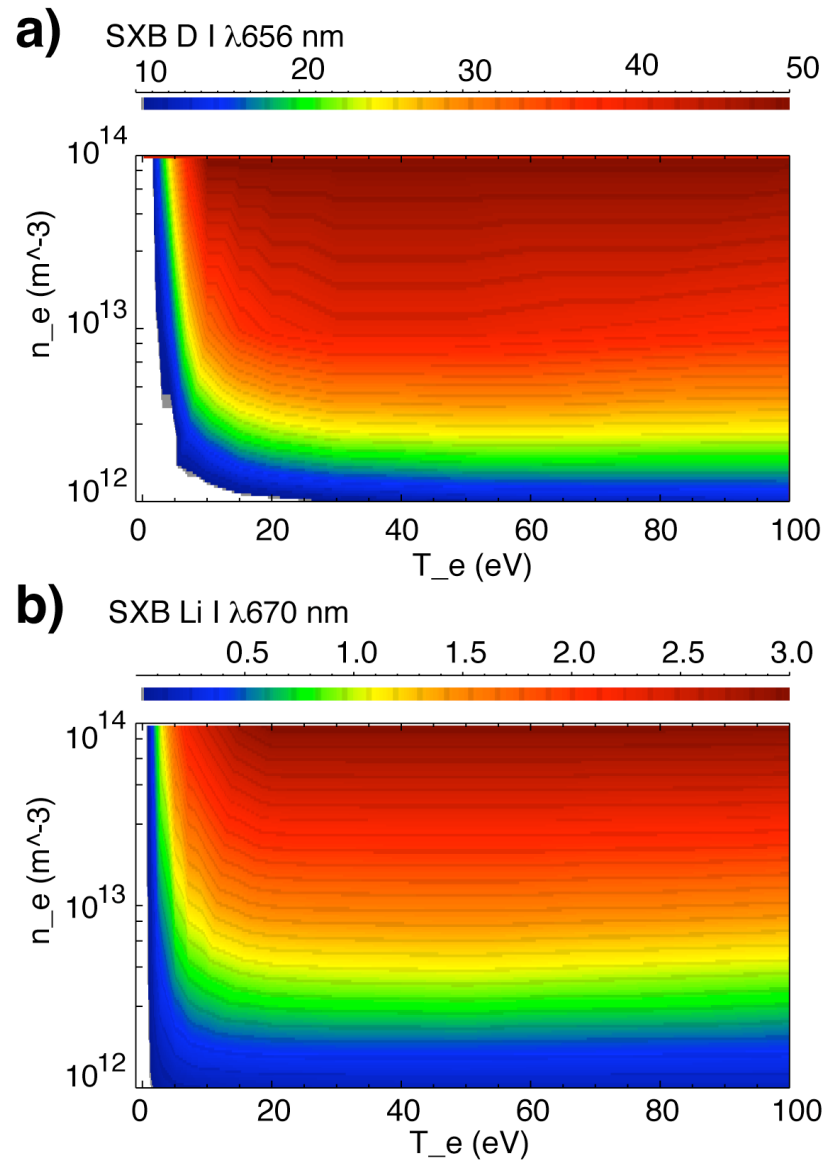
Heat flux mitigation is more challenging in compact divertor of spherical torus

- NSTX
  - I_p = 0.7-1.4 MA, t_{pulse} < 1.5 s, P_{in} ≤ 7.4 MW (NBI)
  - ATJ and CFC graphite PFCs
  - P / R ~ 10
  - q_{pk} ≤ 15 MW/m^2
  - $q_{||}$ ≤ 200 MW/m^2

Quantity	NSTX	DIII-D
Aspect ratio	1.4-1.5	2.7
In-out plasma boundary area ratio	1:3	2:3
X-point to target parallel length L_x (m)	5-10	10-20
Poloidal magnetic flux expansion f_{exp} at outer SP	5-30	3-15
Magnetic field angle at outer SP (deg.)	1-10	1-2

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

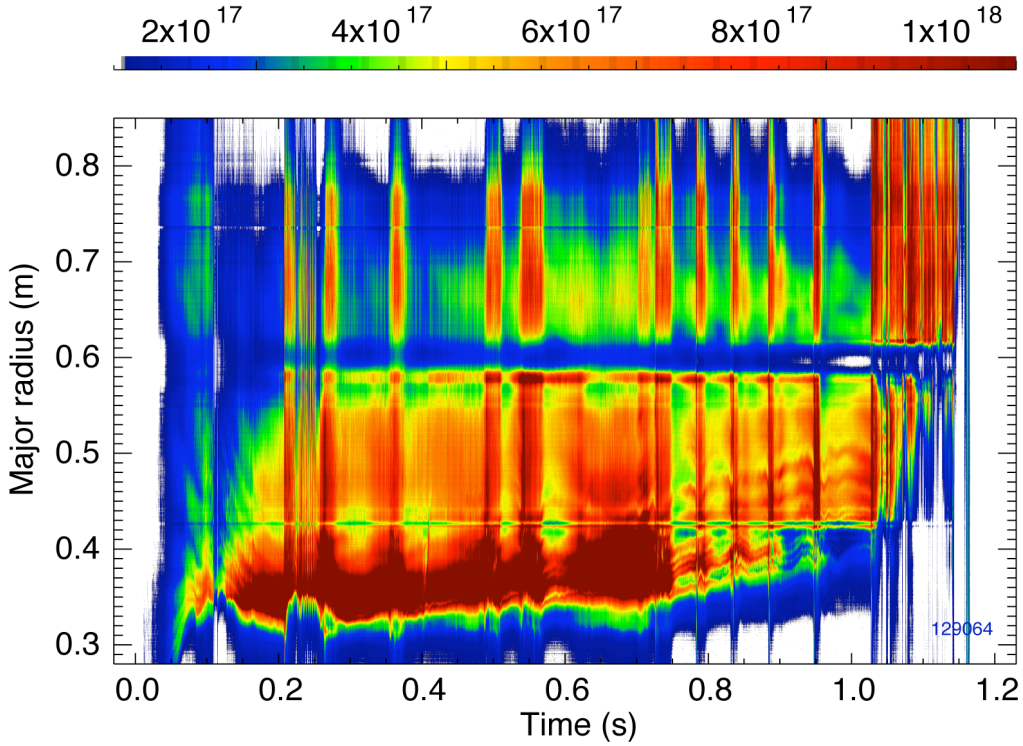


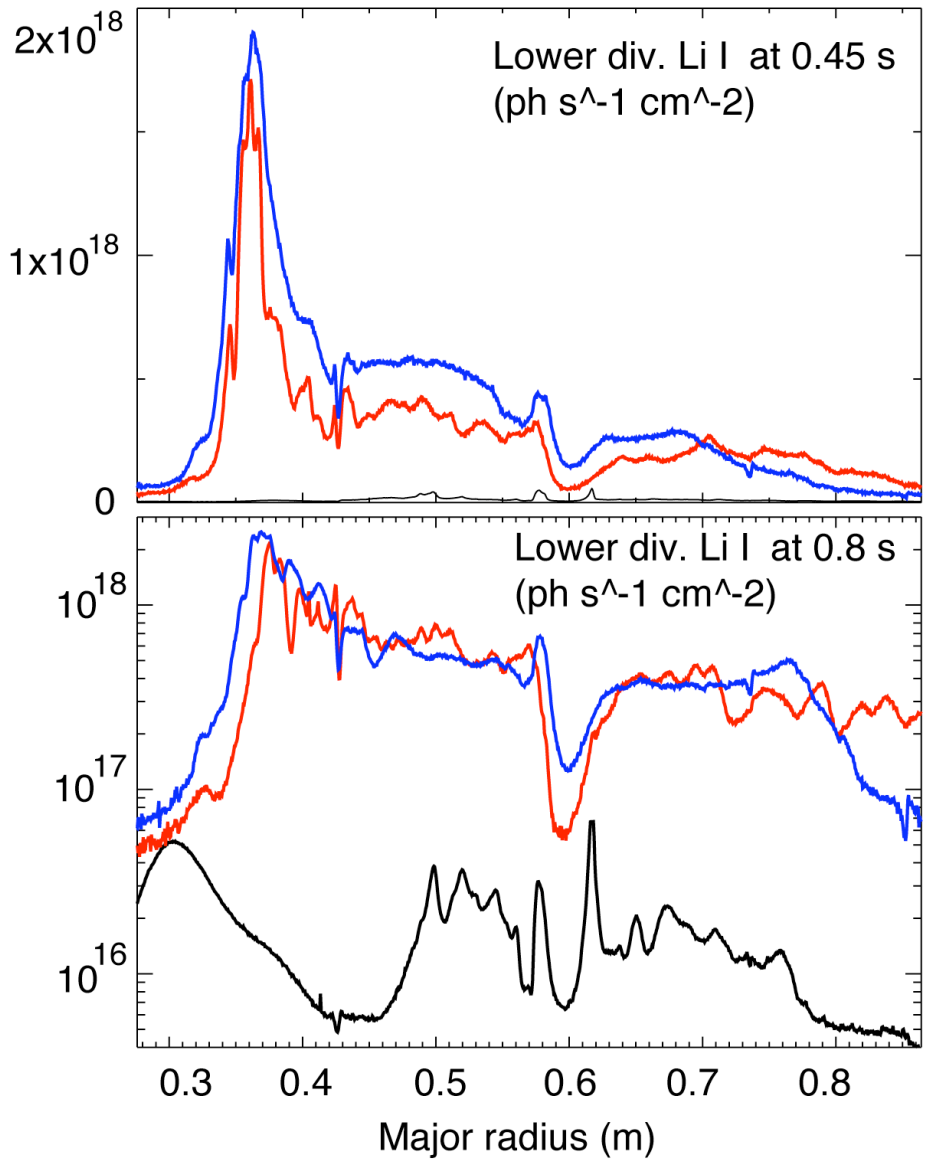


$$\nu_e^* = l_c / \lambda_e$$

- 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 $\nu_e^*=10$

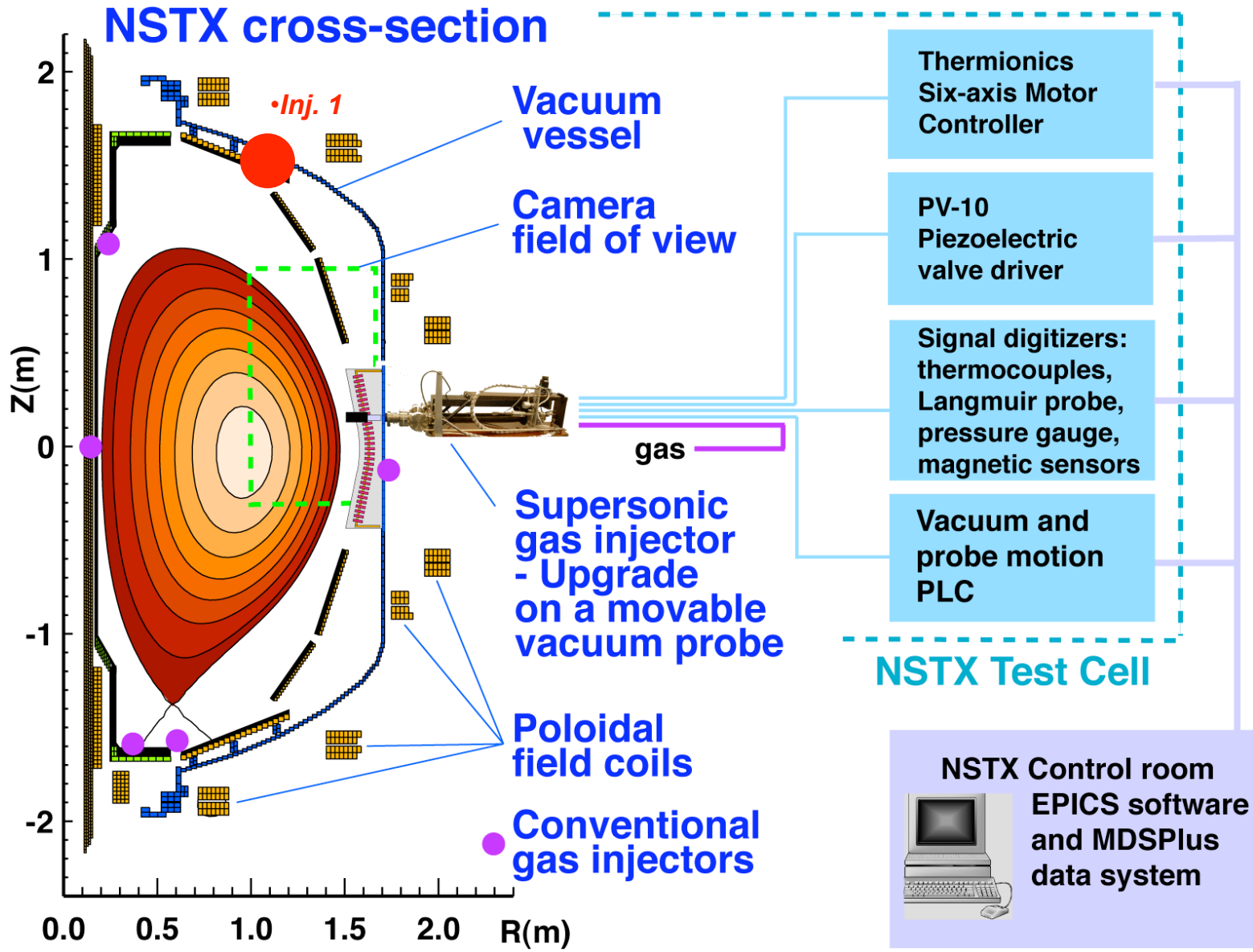
Li I emission profiles are highly peaked suggesting lithium melting in strike point region



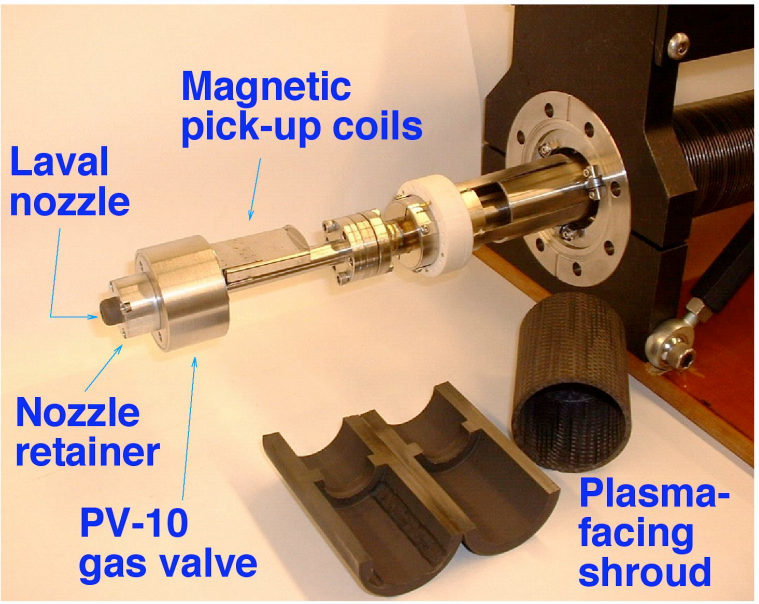


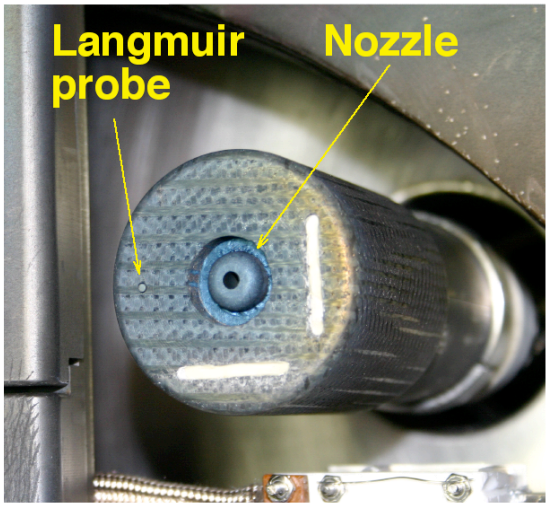
No lithium (129013)
190 mg Lithium (129061)
600 mg lithium (129064)

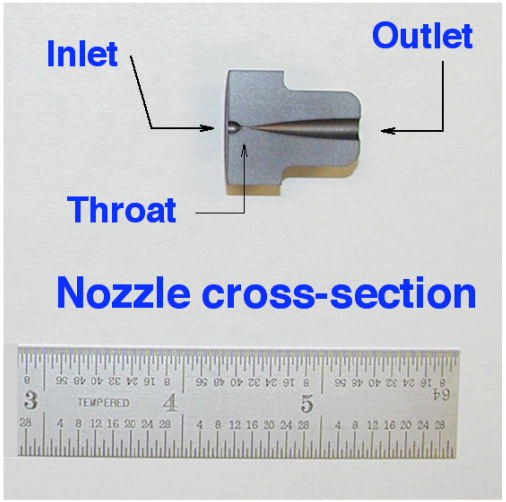
Supersonic gas injector is a complex computer-controlled high gas pressure apparatus



Supersonic gas injector consists of Laval nozzle and piezoelectric valve

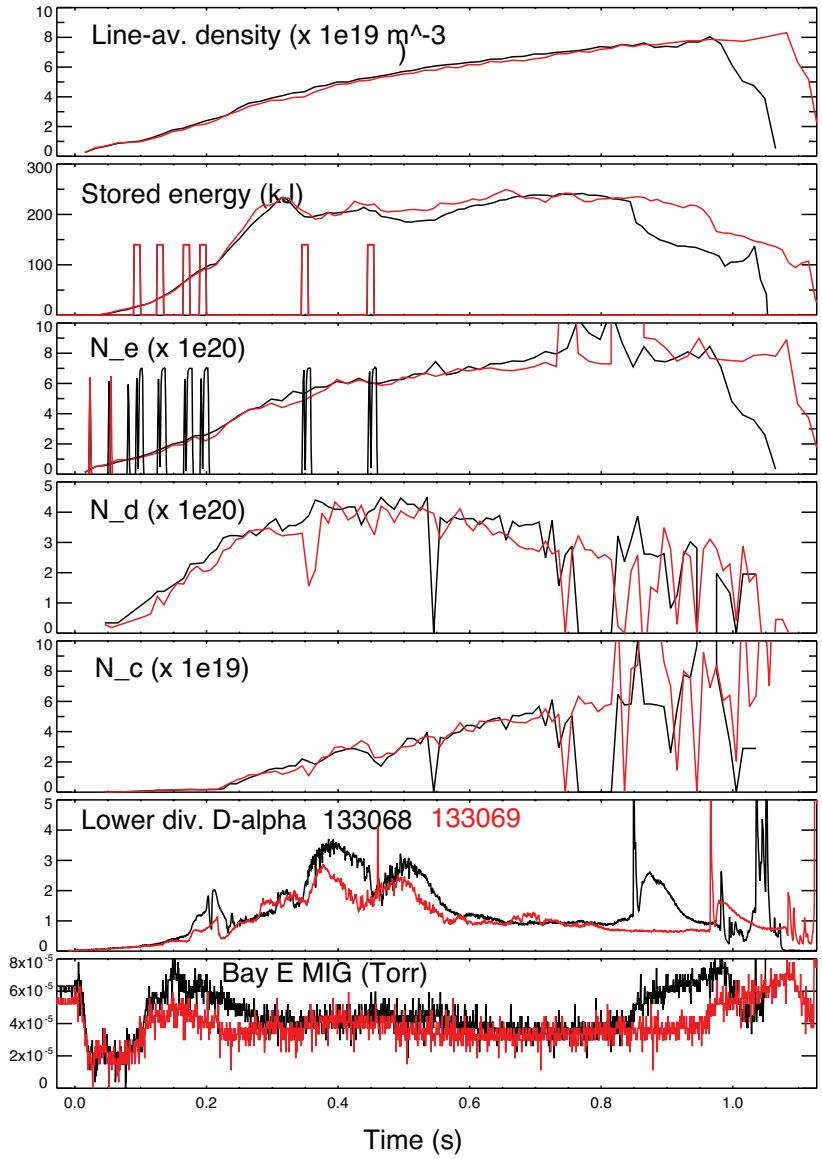




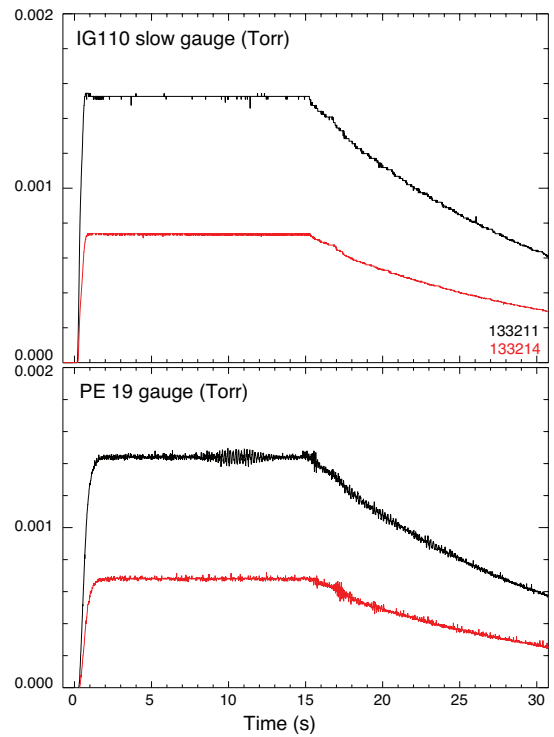


- SGI-U is operated at flow rates 50-250 Torr l /s ($3.5 – 17.5 \times 10^{21}$ s^{-1})
- Supersonic deuterium jet properties:
  - Jet divergence half-angle: 6° - 25° (measured)
  - Mach number M = 4 (measured)
  - Estimated: T ~ 60 - 160 K, $n < 5 \times 10^{23}$ m^{-3}, v_{flow} = 2.4 km/s, v_{therm} ~ 1.1 km/s
  - Nozzle Re = 6000

SGI fueling results in higher fueling efficiency, lower edge neutral pressure



- Comparison between **SGI** and **conv. gas injection** was only possible by 1) matching density in 1 MA, 6-4 MW discharges; 2) comparing gas injection rate and total gas inventory



Divertor with lithium coatings provides pumping – but what about impurity and heat flux handling ?

- On-going study of impurity sources and impurity parallel and radial transport in SOL and pedestal
  - Talk by F. Scotti
- Carbon sources: wall and divertor, physical and chemical sputtering
- Reduce physical sputtering yield by lowering divertor temperature
  - $E_i = 2kT_i + 3\,Z_i\,kT_e$
  - $E_i \sim 50 – 300$ eV -> $Y_C \sim 0.01$
  - Need to obtain $E_i \leq$ 20-40 eV ($T_e \leq 5$ eV)
- Low T_e divertor operation established in NSTX
  - Divertor gas puffing
  - Snowflake divertor

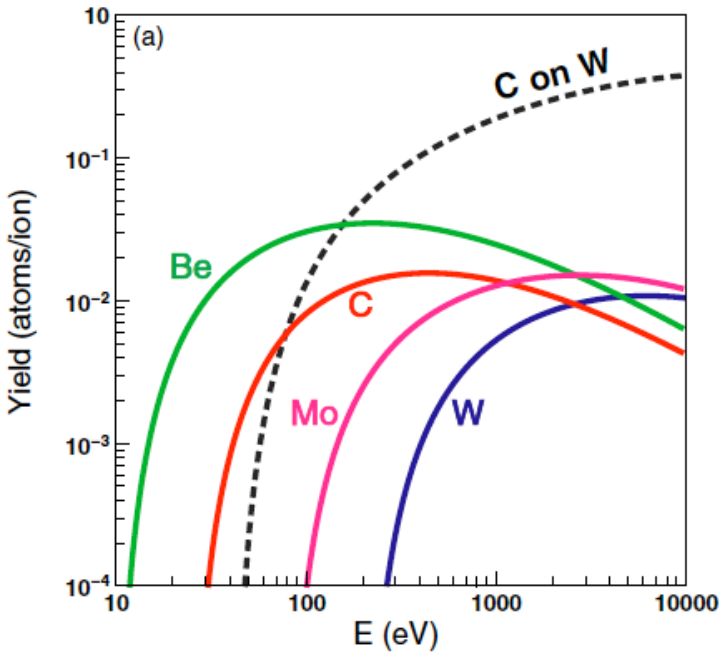
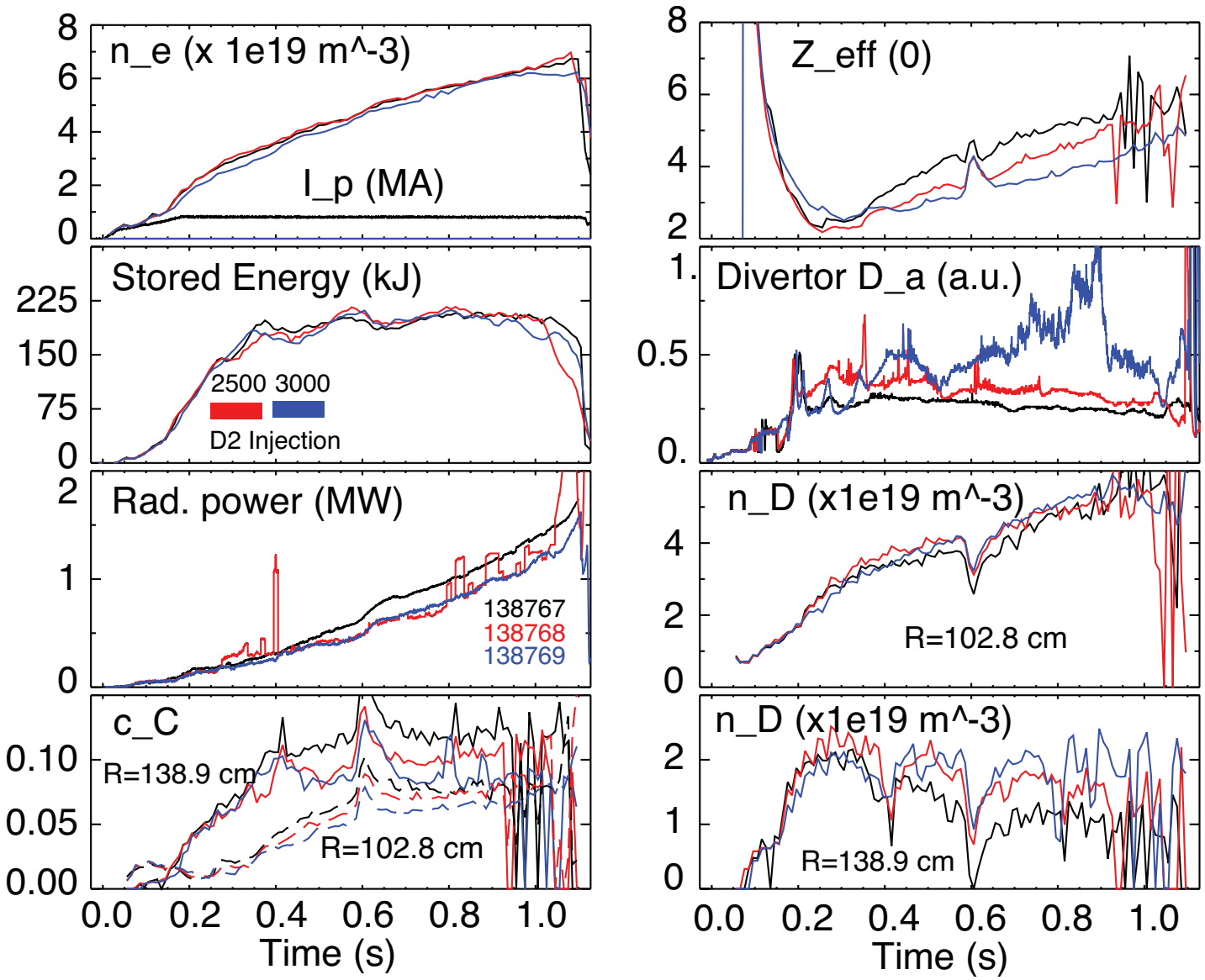


Figure from R. A. Pitts et. al, PPCF (2005) B303

Divertor D_2 puffing used to reduce divertor carbon source and core carbon concentration



Various techniques developed for reduction of heat fluxes $q_{||}$ (divertor SOL) and q_{peak} (divertor target)

$$q_{peak} \simeq \frac{P_{SOL}(1 - f_{rad}) f_{geo} \sin\alpha}{2\pi R_{SP} f_{exp} \lambda_{q_{||}}}$$

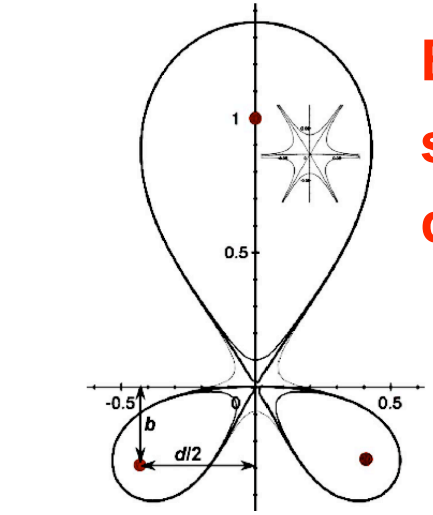
$$A_{wet} = 2\pi R \, f_{exp} \, \lambda_{q_{||}}$$

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

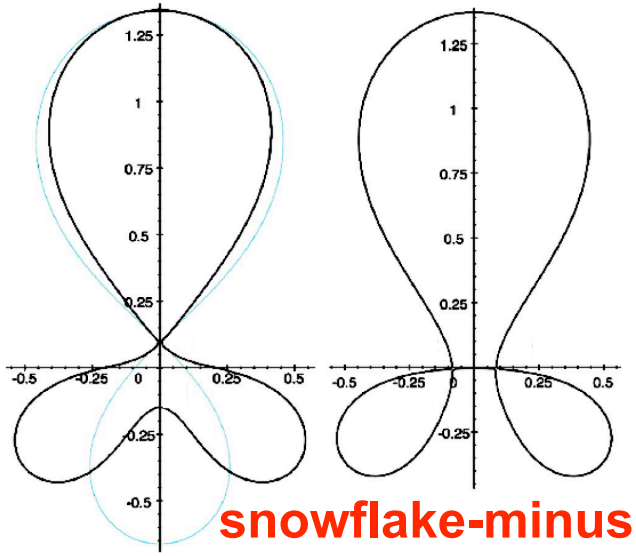
- Promising divertor peak heat flux mitigation solutions:
  - Divertor geometry
    - poloidal flux expansion
    - divertor plate tilt
    - magnetic balance
  - Radiative divertor
- Recent ideas to improve standard divertor geometry
  - X-divertor (M. Kotschenreuther *et. al*, IC/P6-43, IAEA FEC 2004)
  - Snowflake divertor (D. D. Ryutov, PoP 14, 064502 2007)
  - Super-X divertor (M. Kotschenreuther *et. al*, IC/P4-7, IAEA FEC 2008)

Attractive divertor geometry properties predicted by theory in snowflake divertor configuration

- Snowflake divertor
  - Second-order null
    - $B_p \sim 0$ and *grad* $B_p \sim 0$; $B_p \sim r^2$
      (Cf. first-order null: $B_p \sim 0$; $B_p \sim r$)
  - Obtained with existing divertor coils (min. 2)
  - Exact snowflake topologically unstable
- 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}
  - Increased edge magnetic shear
- Experiments
  - TCV (F. Piras *et. al*, PRL 105, 155003 (2010))



Exact snowflake divertor



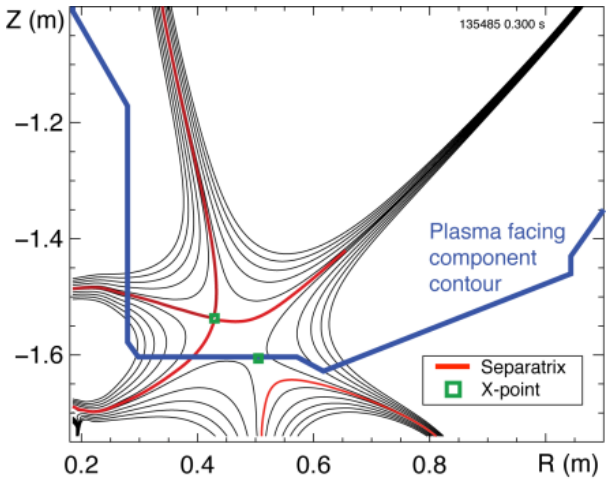
snowflake-minus

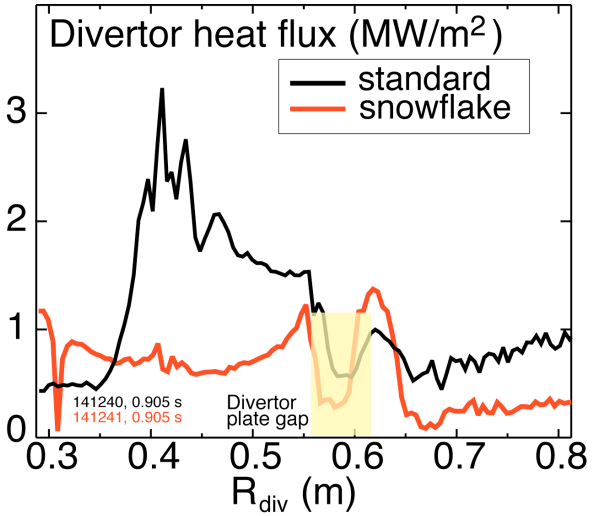
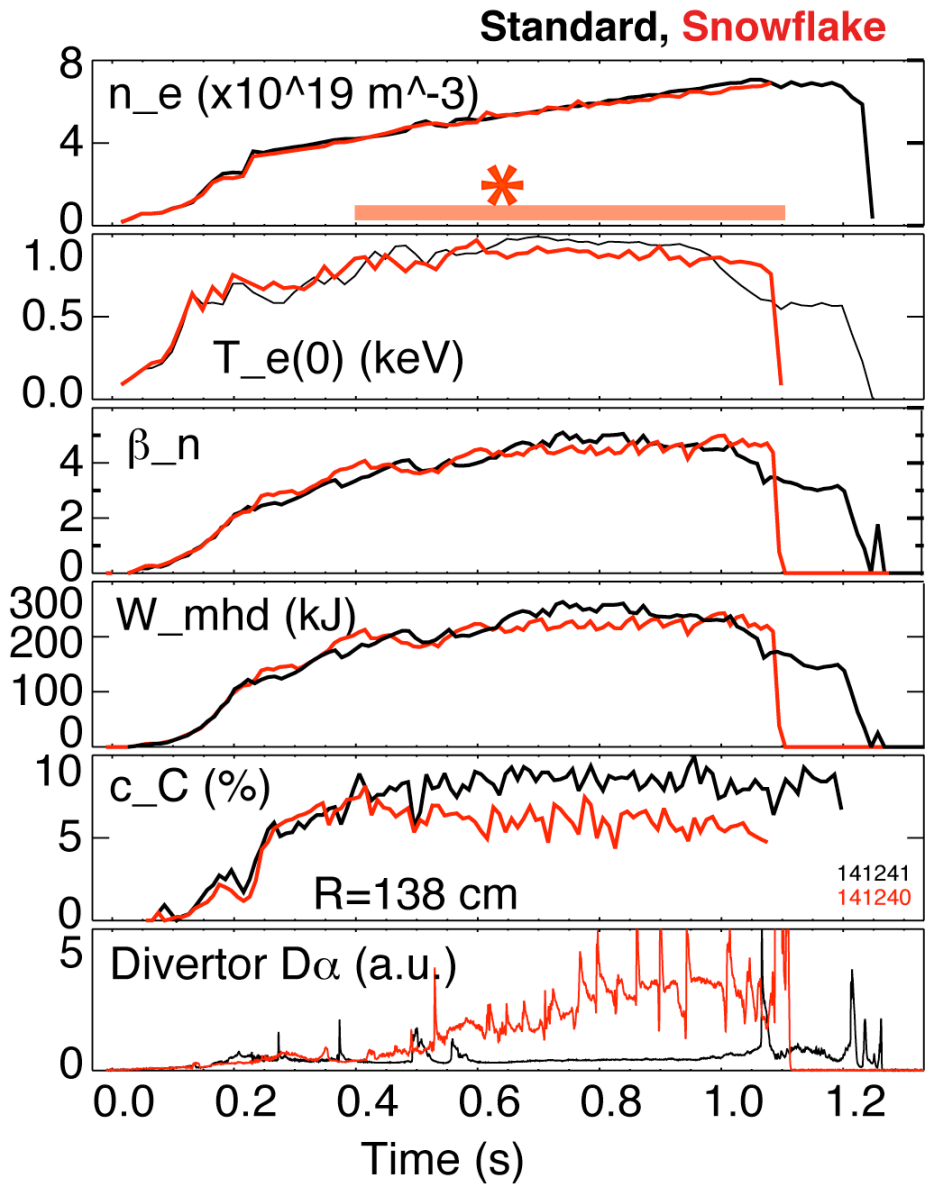
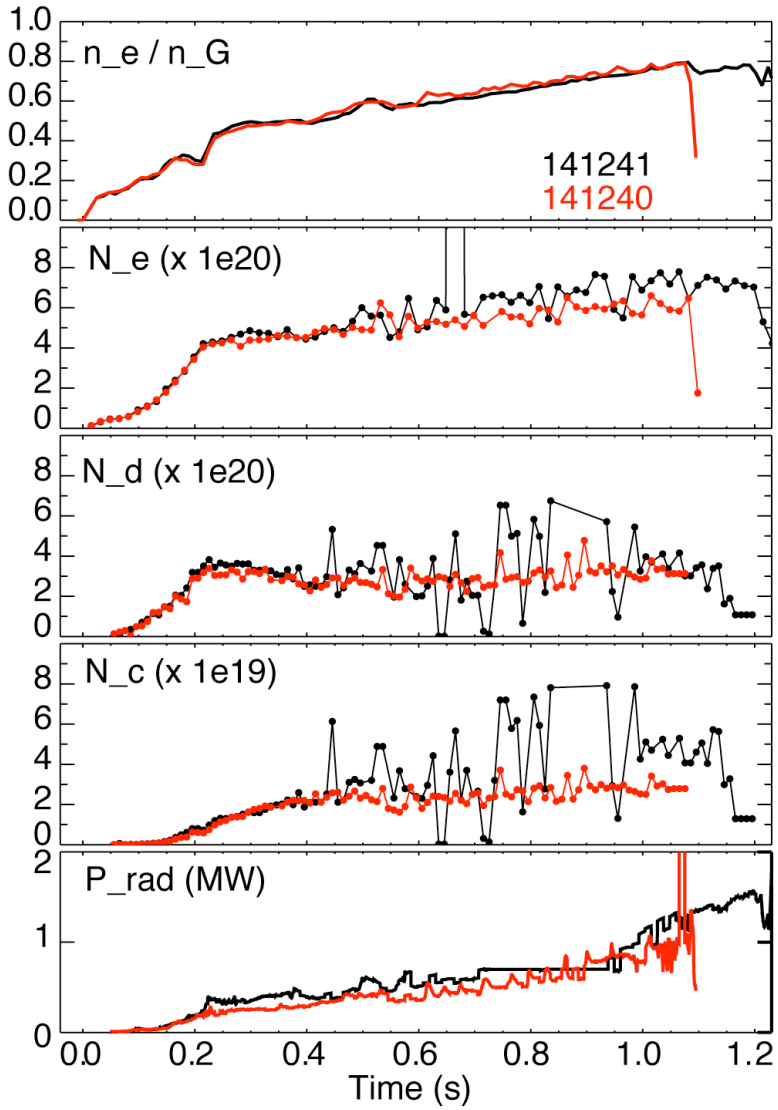
snowflake-plus

D. D. Ryutov, PoP 14, 064502 2007

NSTX studies suggest the snowflake divertor configuration may be a viable solution for present and future tokamaks

- Snowflake divertor configuration (c.f. standard divertor)
  - Higher plasma-wetted area (due to higher magnetic flux expansion)
  - Higher connection length and divertor volume
- In NSTX discharges:
  - Steady-state snowflake up to 600 ms
  - Good H-mode confinement (H98(y,2) ~ 1)
  - Reduced core/pedestal carbon concentration
  - Change in pedestal MHD stability and ELMs
  - Significant reduction in divertor heat flux
    - steady-state peak heat flux (from 4-8 to -0.5-1 MW/m^2)
    - Reduction in ELM heat and particle flux





Core impurity reduction while maintaining constant D inventory with snowflake divertor