NSTX

Fusion Energy Sciences

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

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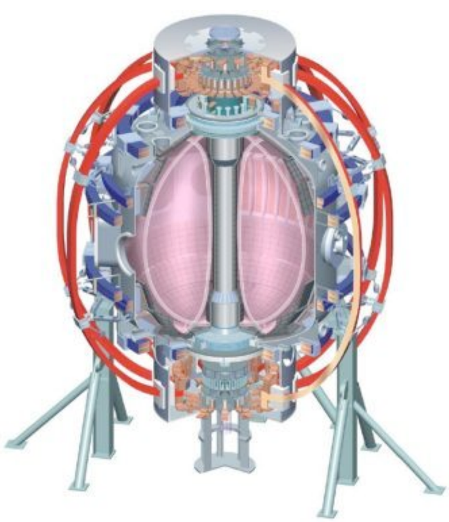
2nd International Symposium on Lithium Applications in Fusion Devices
Princeton, New Jersey
27-29 April 2011



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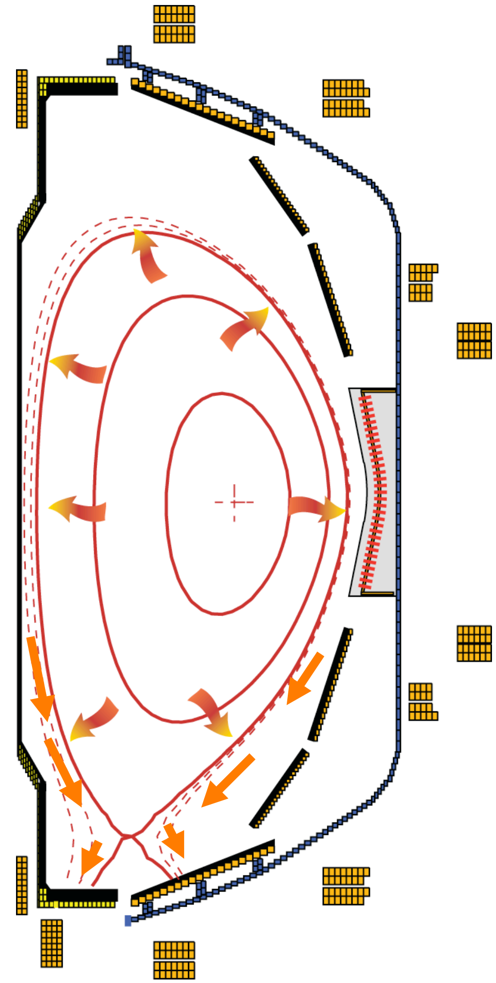
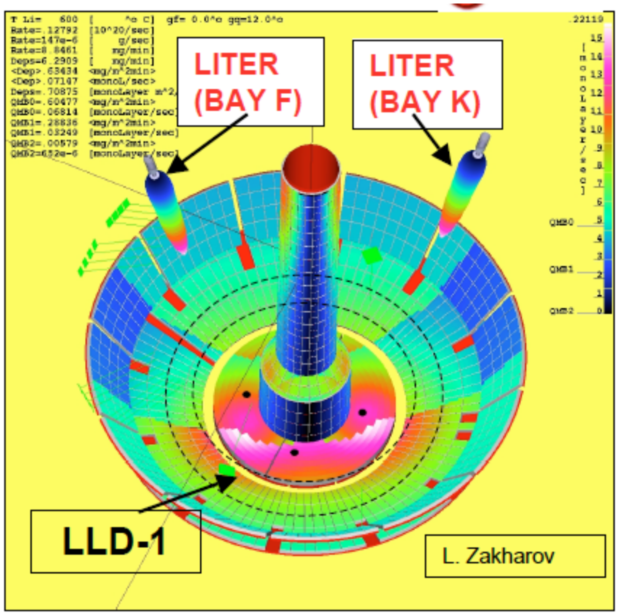
Solid lithium coatings are studied in NSTX for impurity and density control applications

- Access to reduced core collisionality
  - $n_e \sim 0.6\text{-}0.9\ n_G$ for transport, stability, start-up, high non-inductive current fraction scenario studies for future STs (e.g., NSTX-Upgrade)
  - $n_e \sim 0.3\text{-}0.7\ n_G$ 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

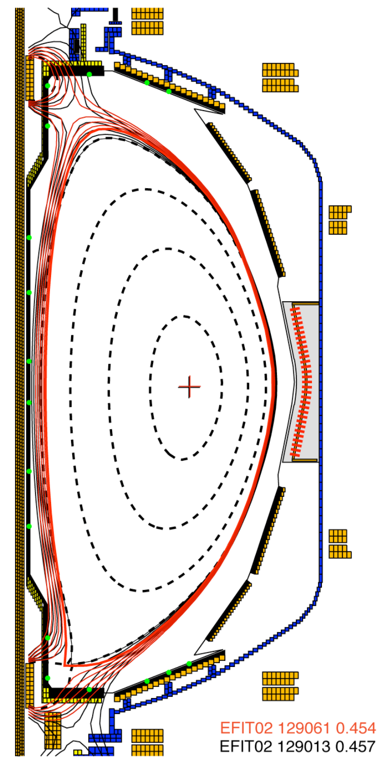
Plasma-surface interactions with solid lithium coatings on graphite plasma-facing components



- 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^o C) and evaporation (significant rate at T > 300^o 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

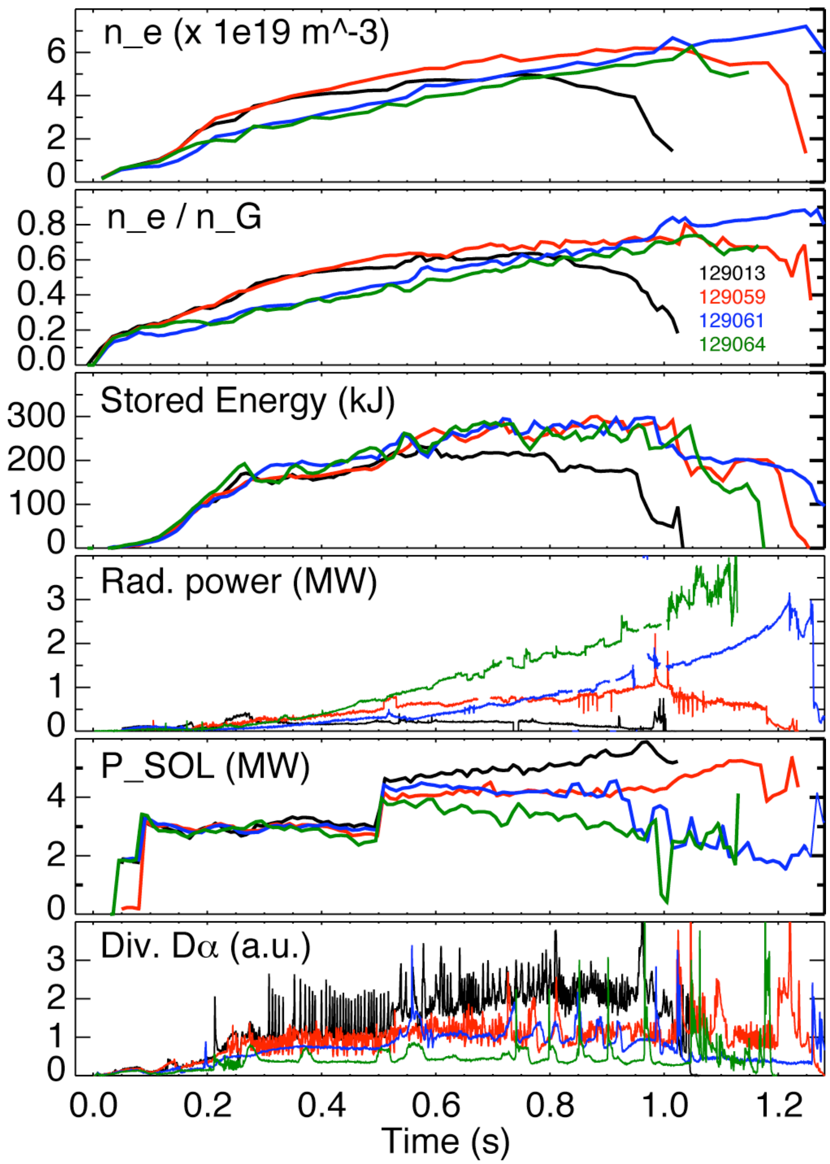
- Pumping and recycling on PFCs
- Lithium influx from PFCs and core lithium density
- Control of divertor carbon influx



- 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

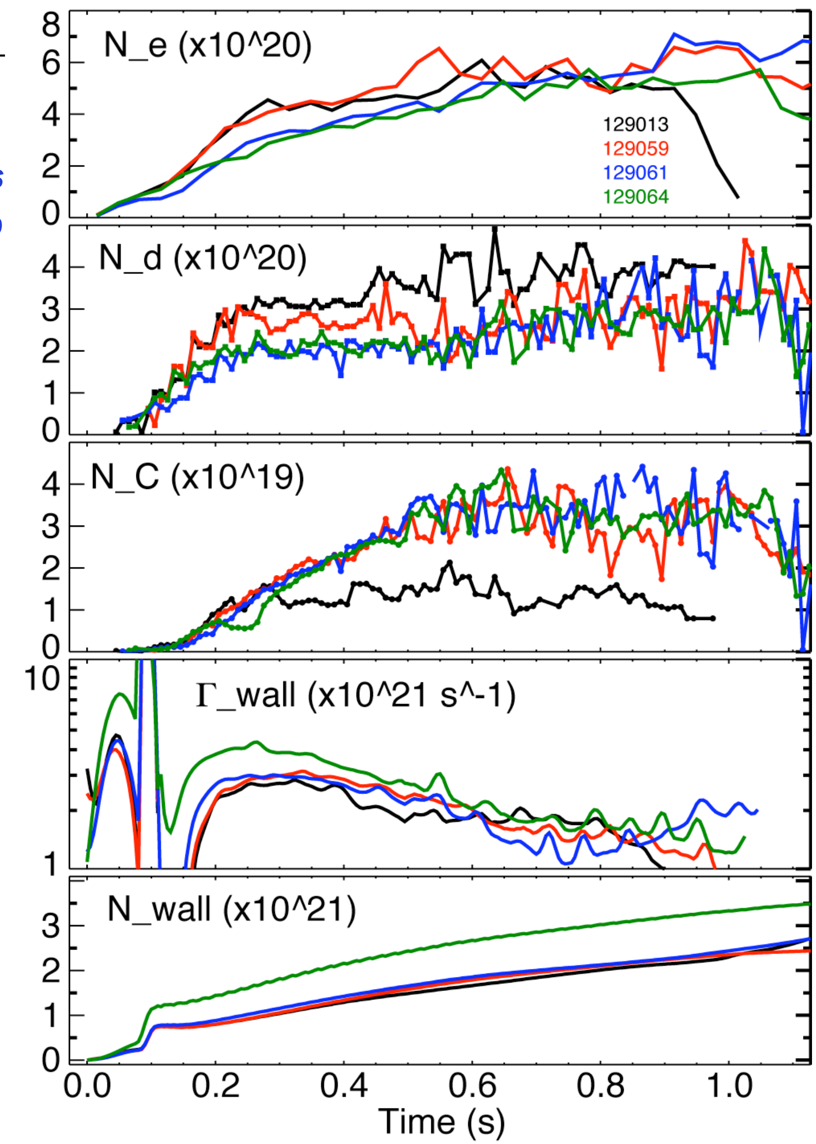
$$\frac{dN_p}{dt} = \Gamma_{gas} + \Gamma_{NBI} + \Gamma_{NBI\_cold} + \Gamma_{NBI\_cryo} + \Gamma_{wall} + \Gamma_{pump} + \frac{dN_n}{dt}$$

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

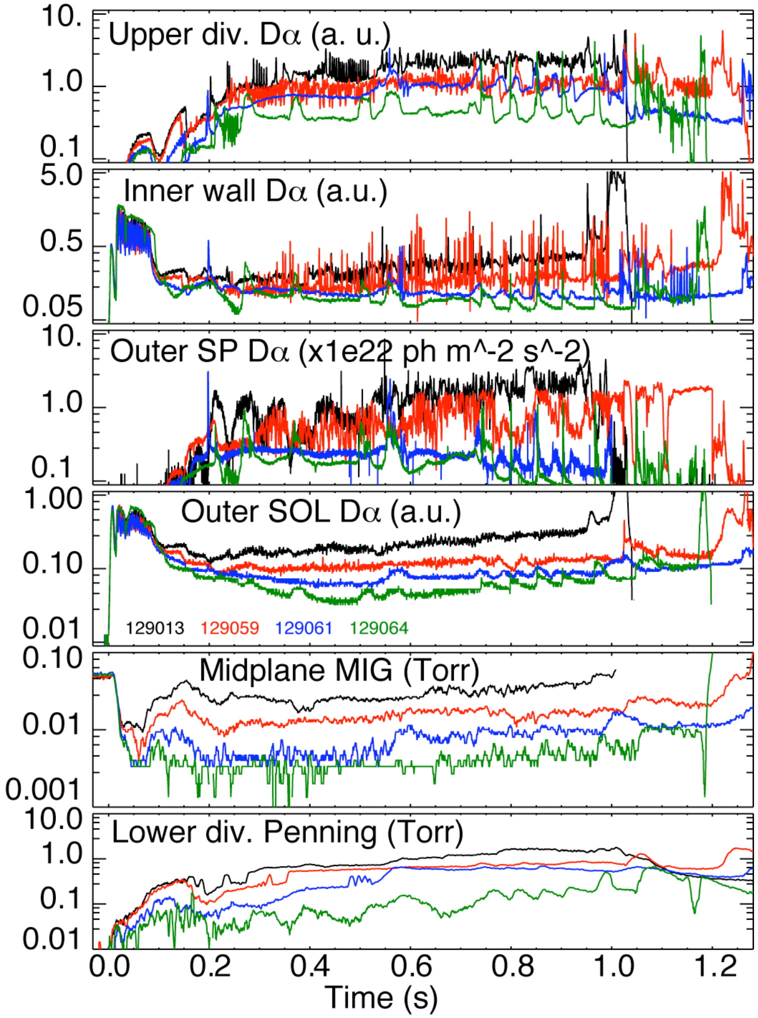
- Particle balance equation
- Particle inventory balance: $N_e = 6\, N_C + N_d$

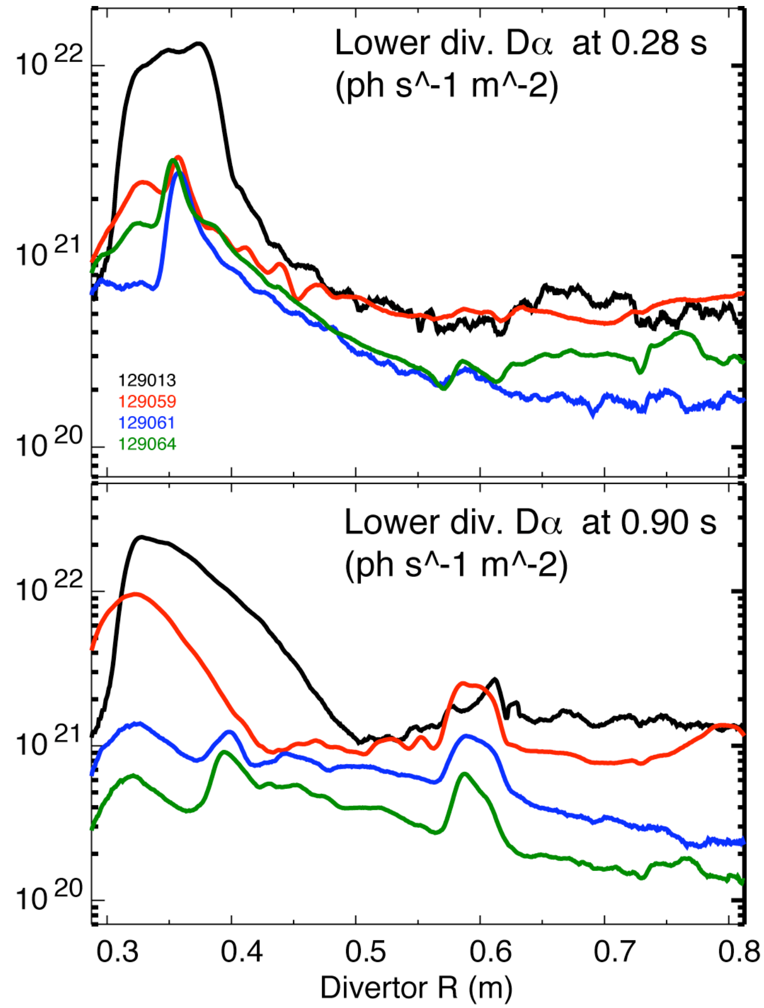
- Continuous pumping
- Cumulative coatings provide higher pumping rate
- Wall in pumping state far from saturation

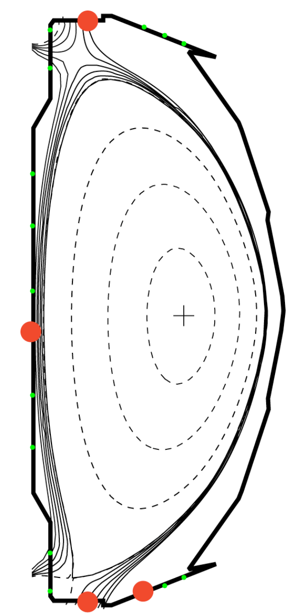
No lithium (129013)
No lithium (129059)
190 mg lithium (129061)
600 mg lithium (129064)



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



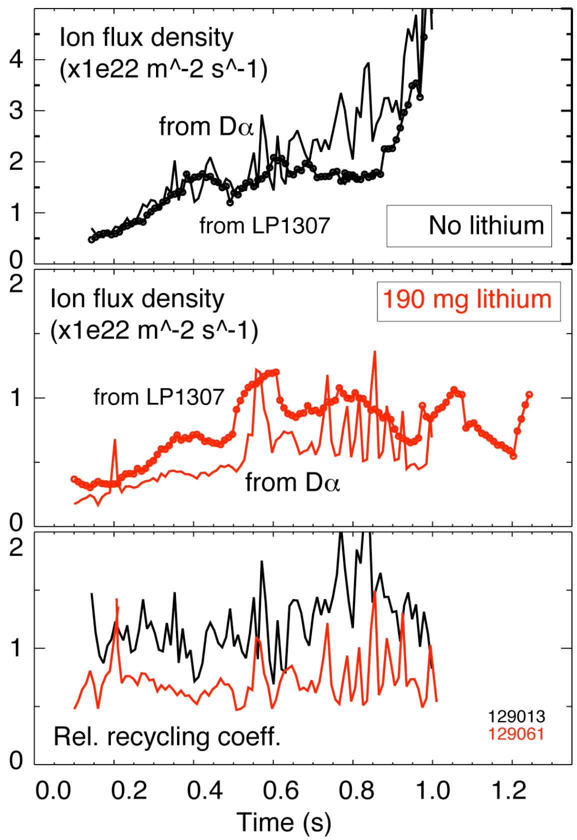


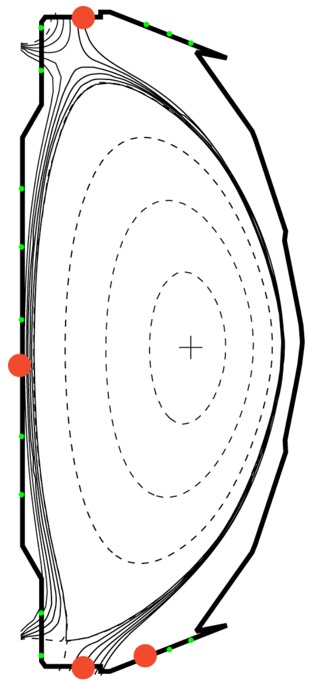


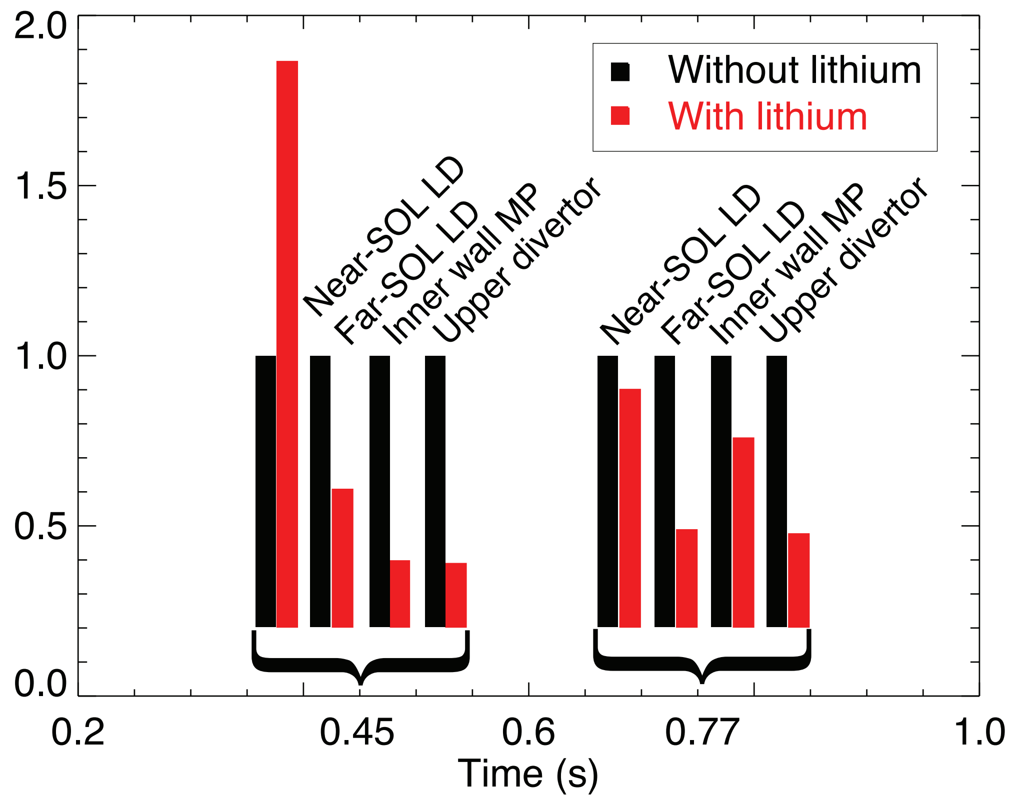
No lithium (129013)
No lithium (129059)
190 mg lithium (129061)
600 mg lithium (129064)

- 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

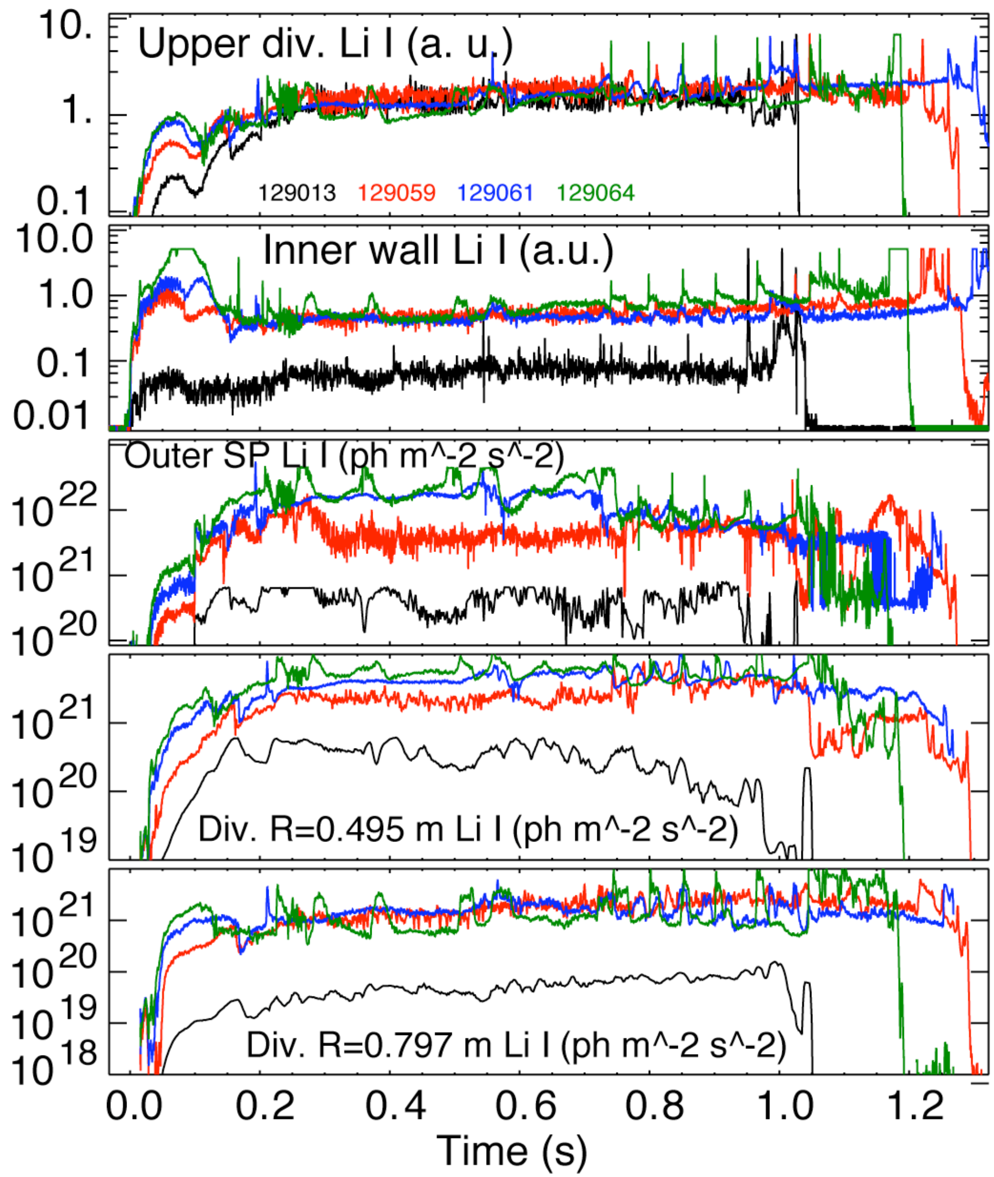
Impact of lithium conditioning was investigated in NBI-heated H-mode discharges

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

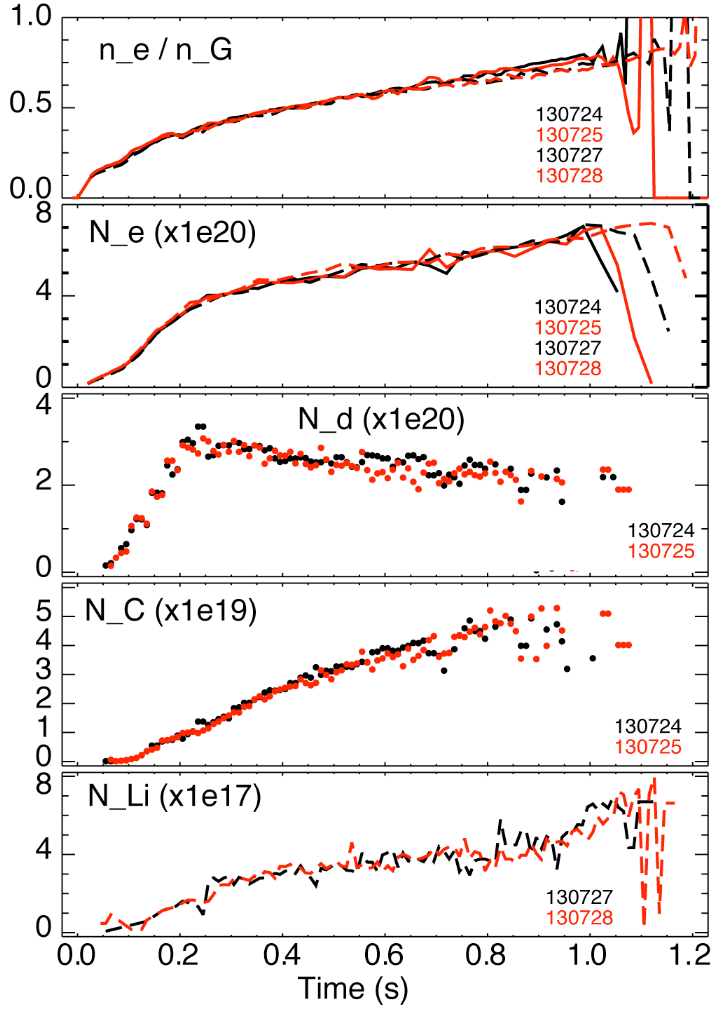
Lithium flux measurements suggest lithium source is in lower divertor, degrades in one discharge

- 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

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

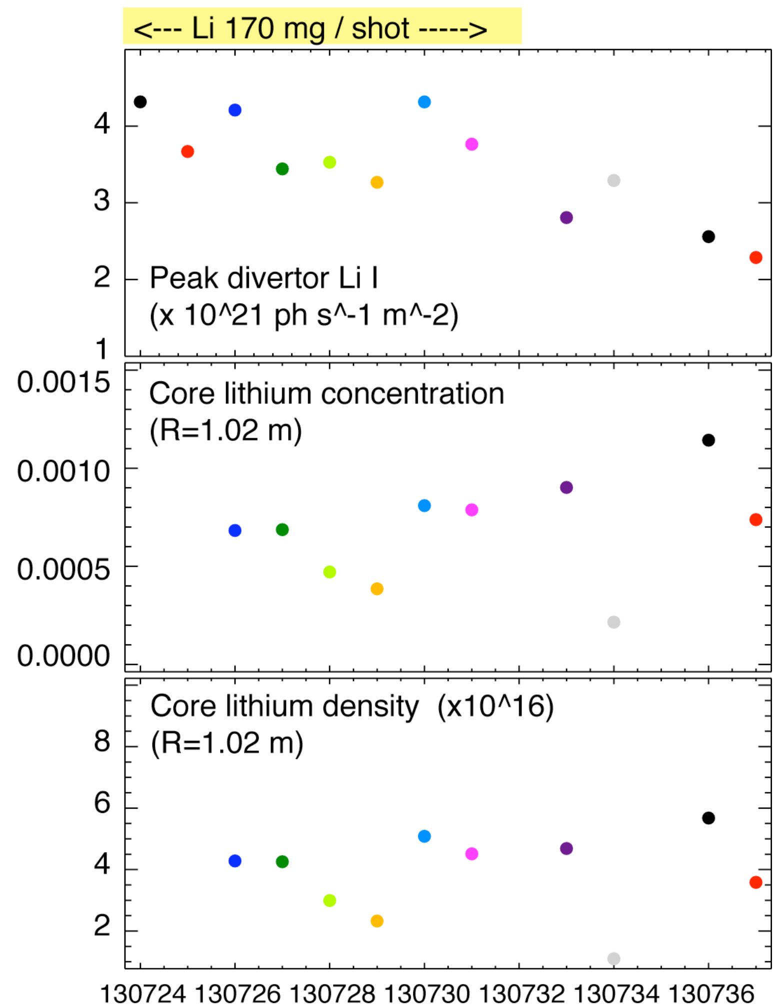


Core lithium density low, does not scale with divertor source, lithium weakly accumulates in core



Impurity density profiles from CHERS

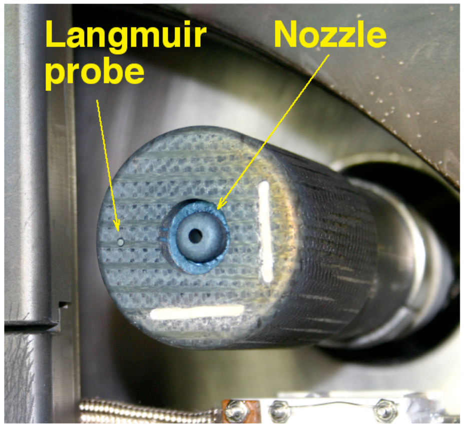
- C VI, n = 8-7, 529.1 nm
- Li III, n = 7-5, 516.7 nm

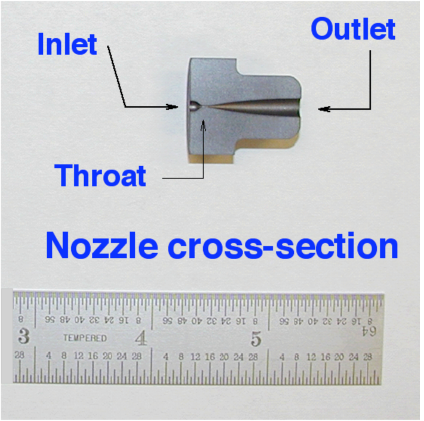


- Lithium screening efficiency high, penetration factor N_{Li} / Γ_{li} ~ 0.0001

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

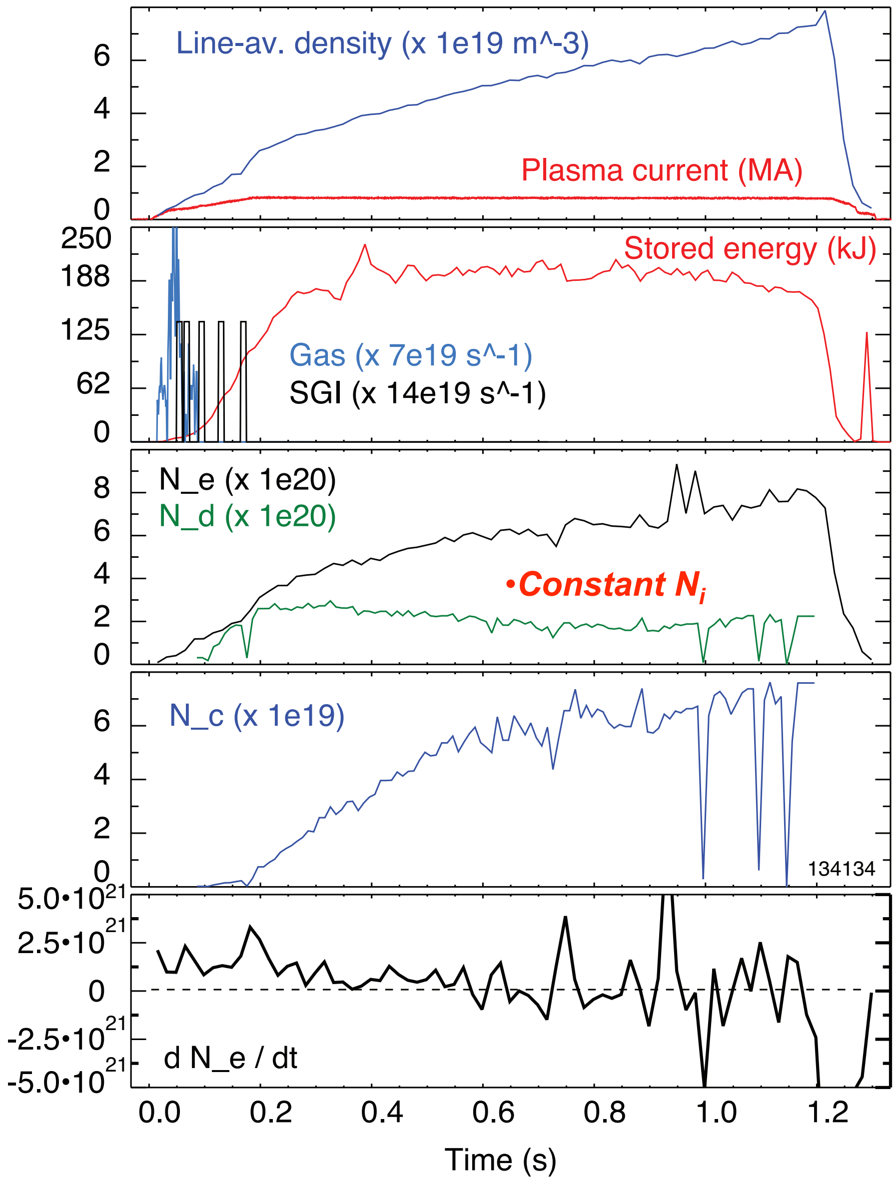
- Ion pumping and recycling fluxes
- Lithium influx from PFCs and core density
- **Fueling and density evolution**

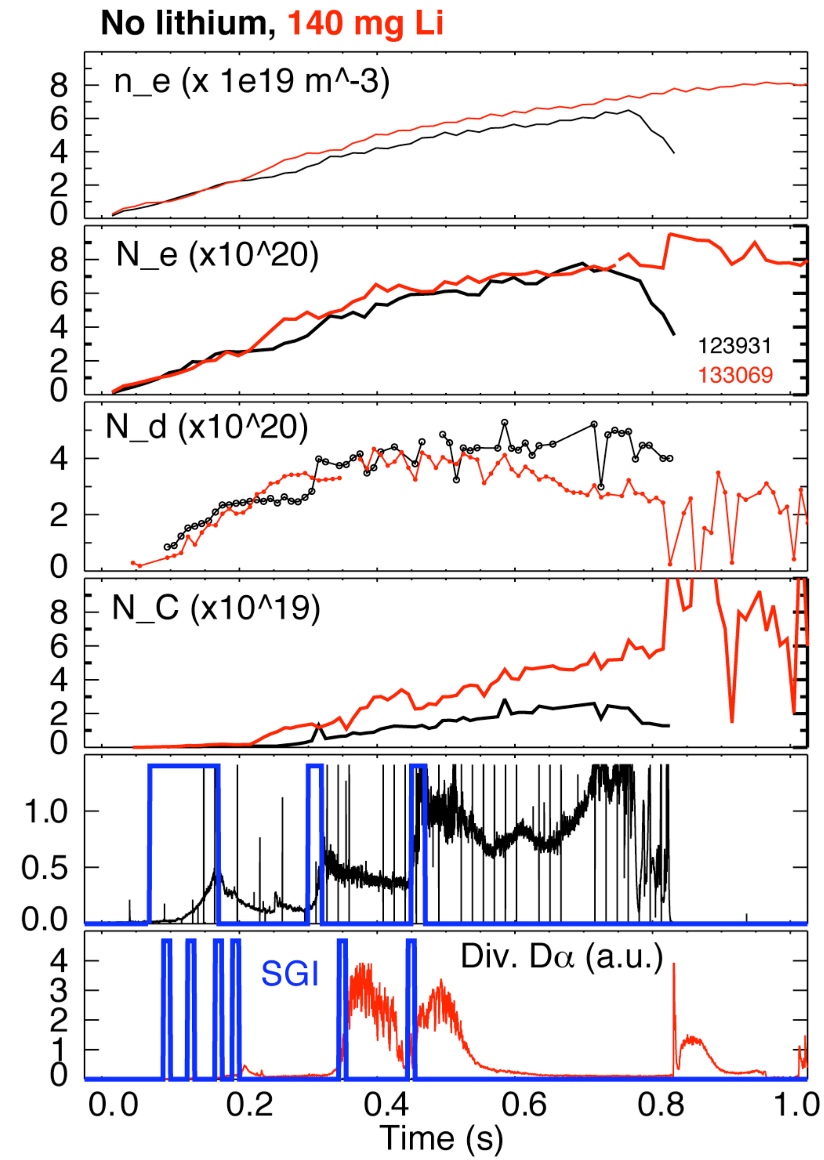




- SGI-U is operated at flow rates 50-250 Torr l /s ($3.5 – 17.5 \times 10^{21}$ s^{-1})
- Supersonic deuterium jet properties:
  - Jet divergence half-angle: 6^o - 25^o (measured)
  - Mach number M = 4 (measured)
  - Estimated: T ~ 60 - 160 K, $n < 5 \times 10^{23}$ m^{-3}, v_{flow} = 2.4 km/s, v_{therm}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

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



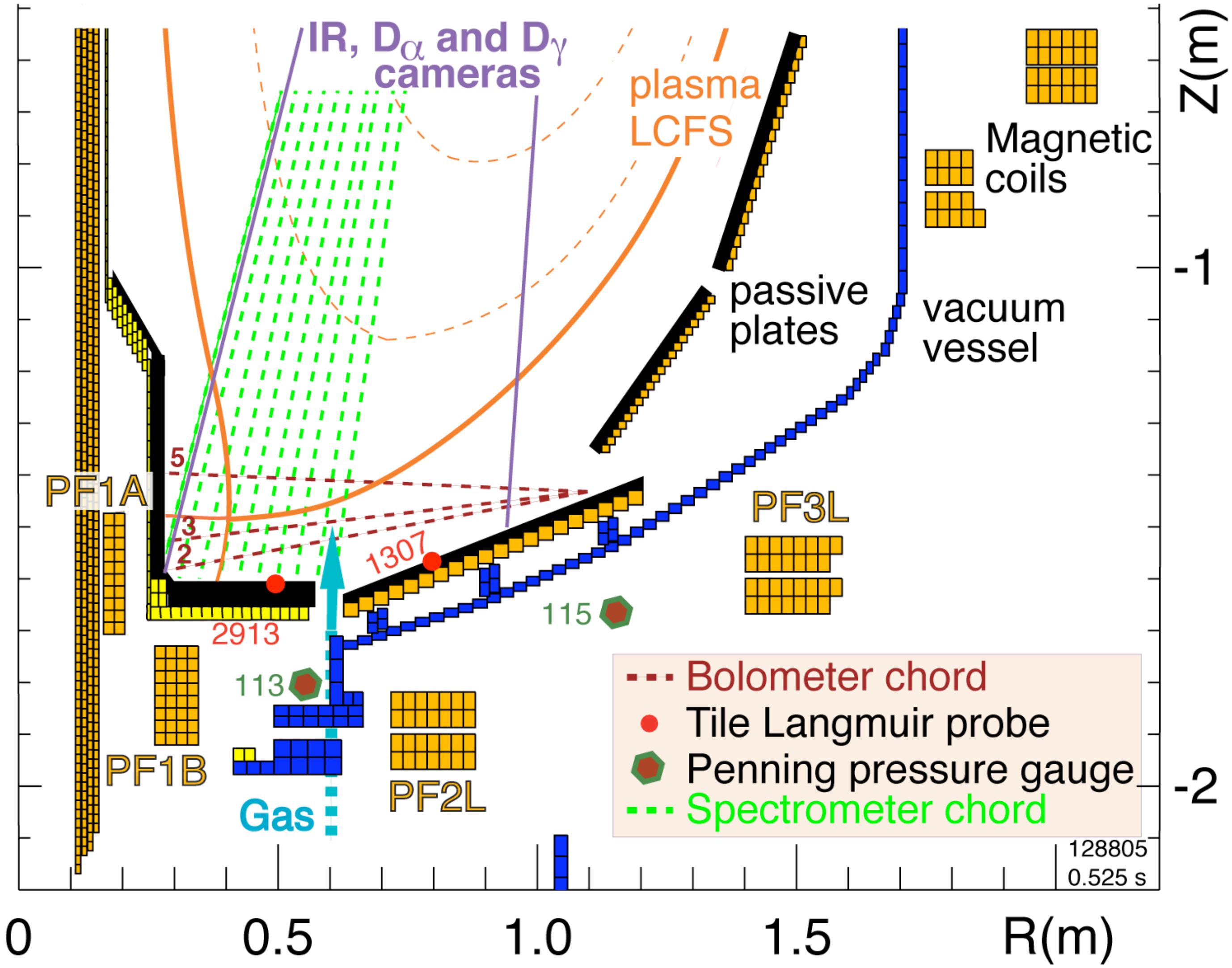


Summary and plans

- 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

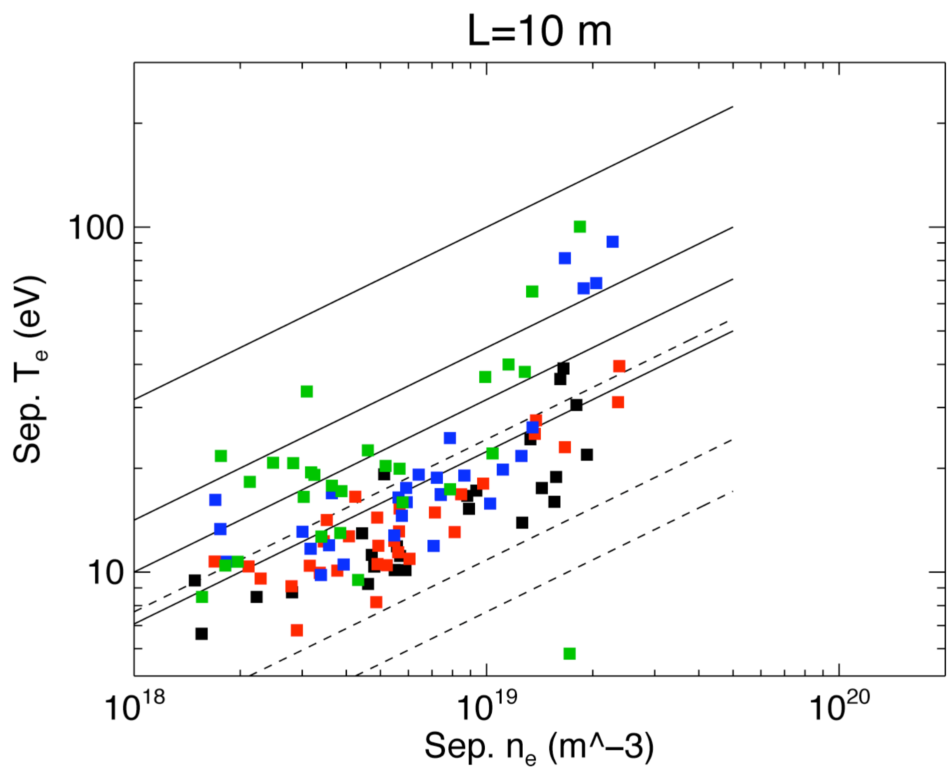


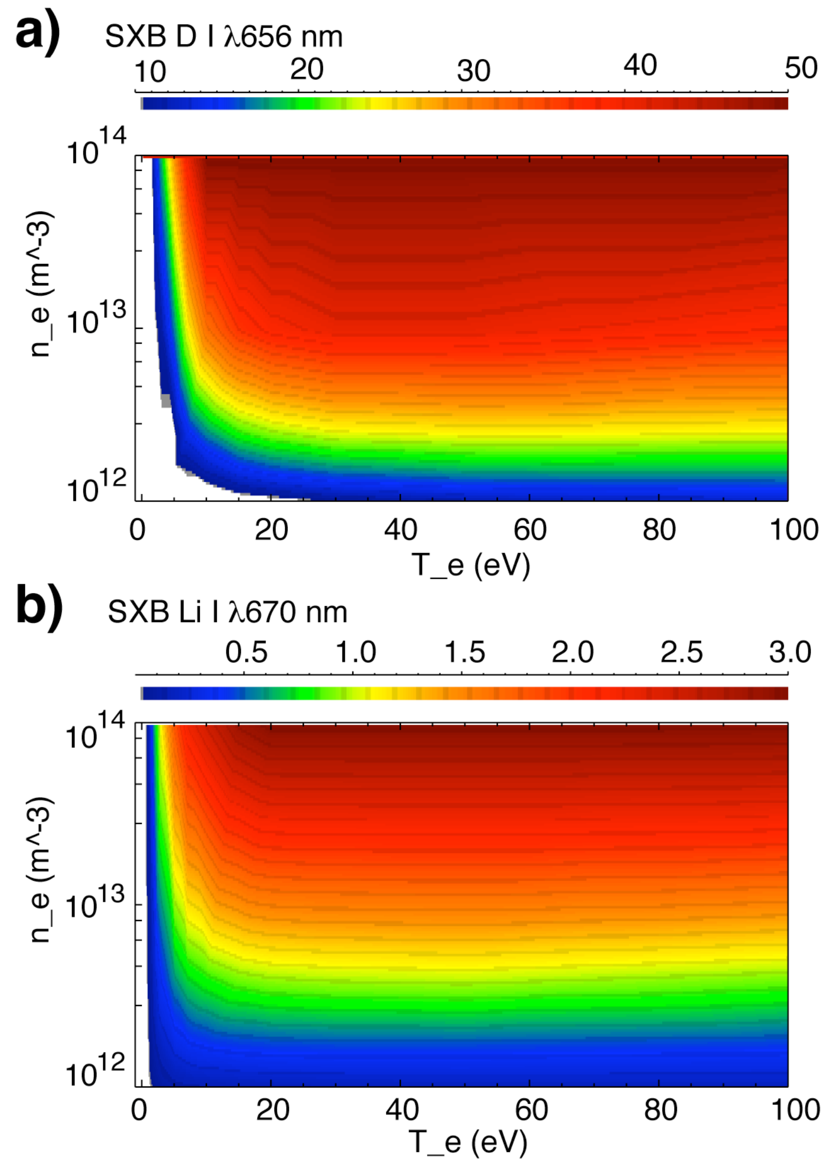
Heat flux mitigation is more challenging in compact divertor of spherical torus

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

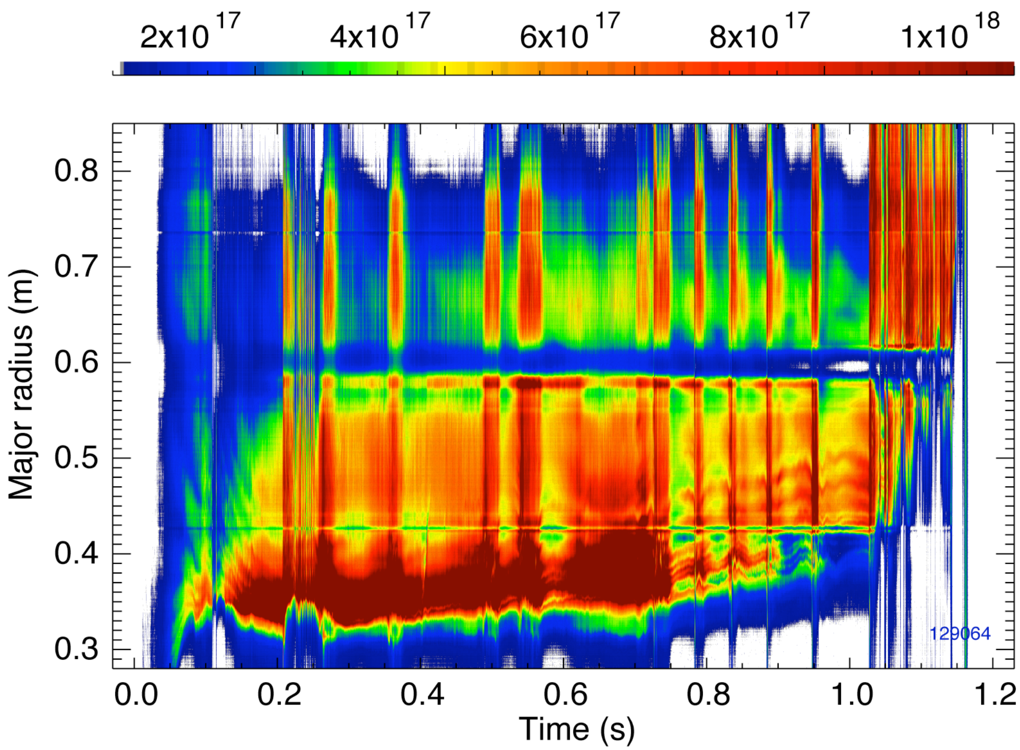


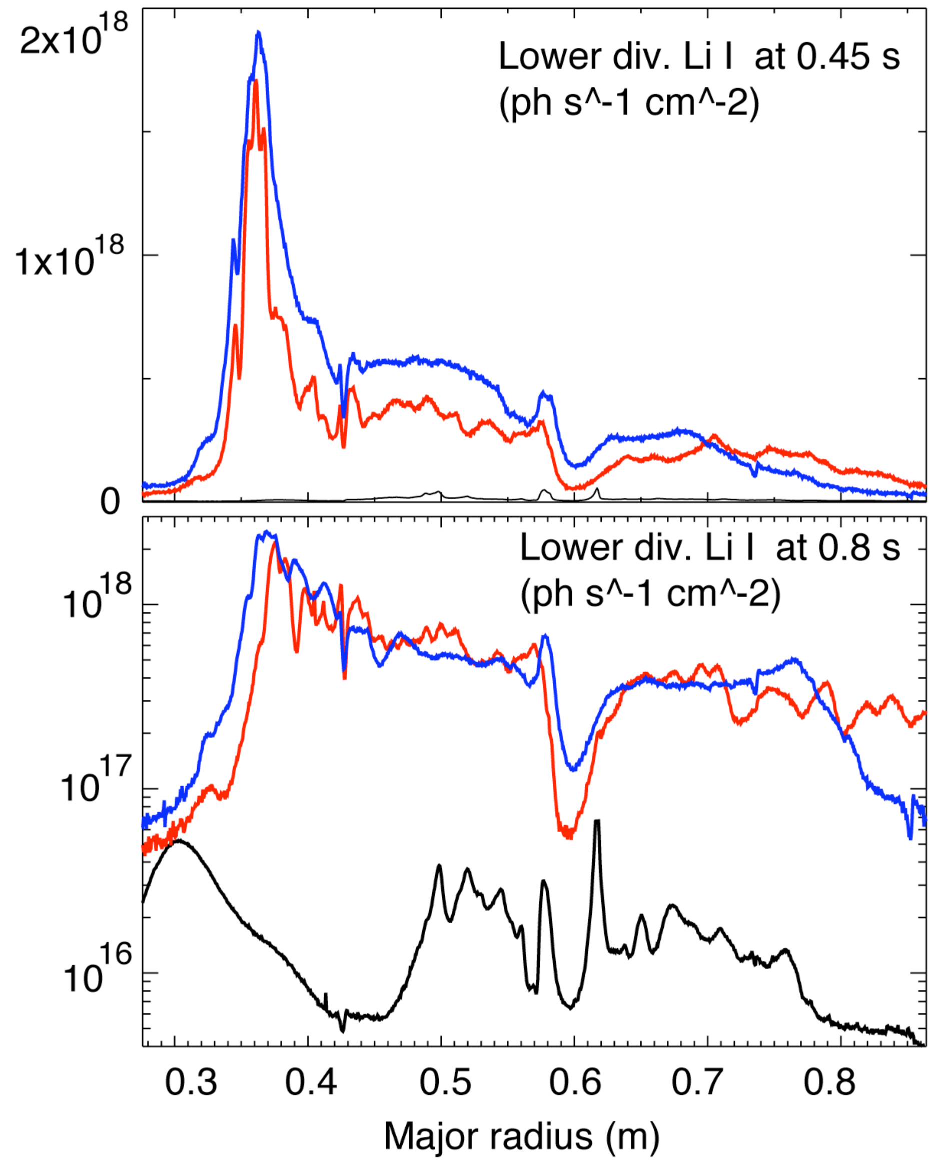


$$\nu_e^* = l_c/\lambda_e$$

- 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 ν_e^*=10

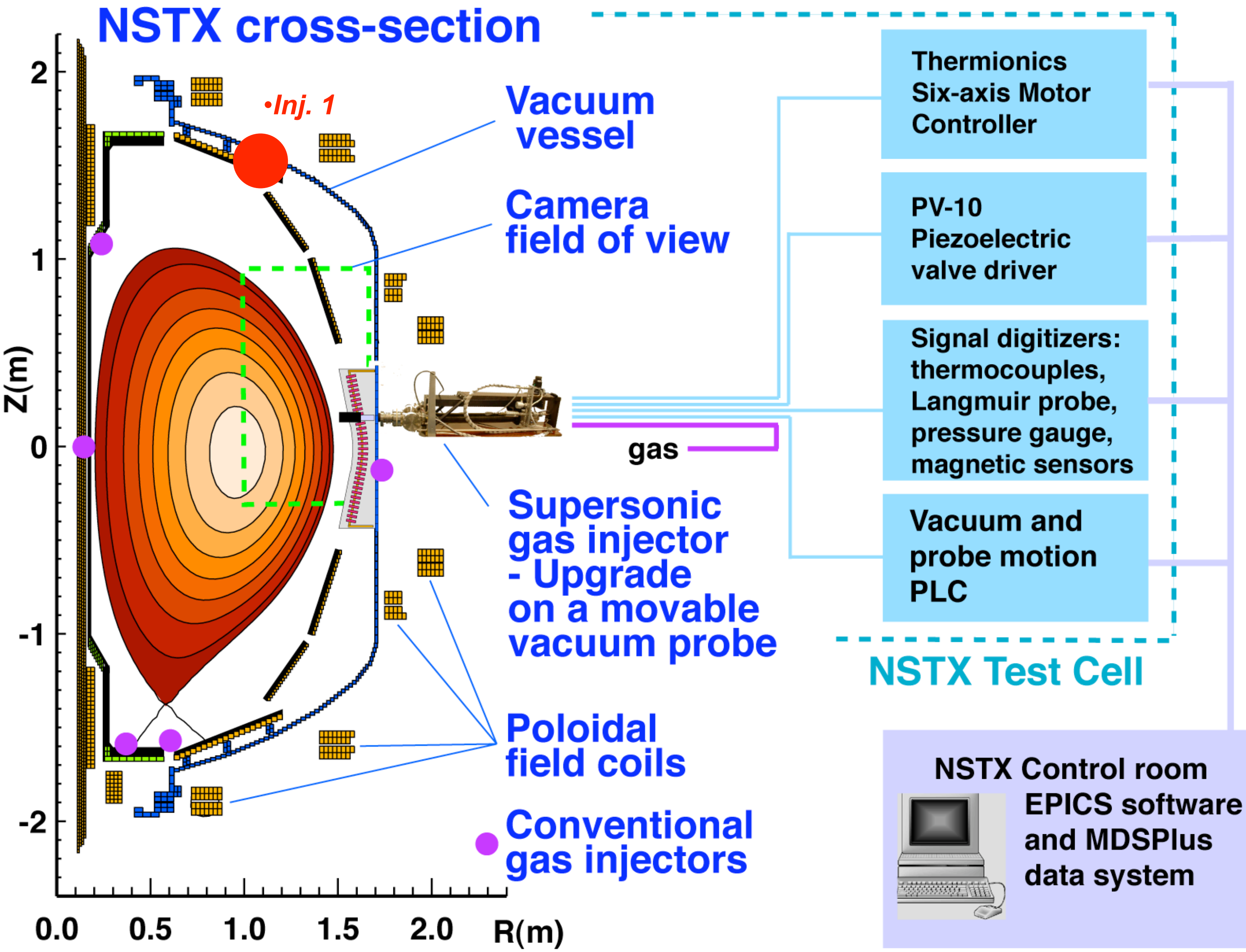
Li I emission profiles are highly peaked suggesting lithium melting in strike point region



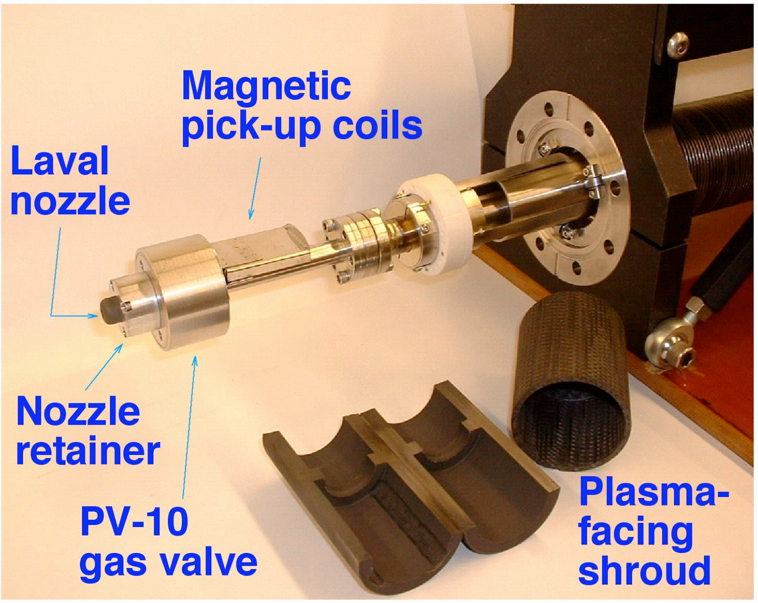


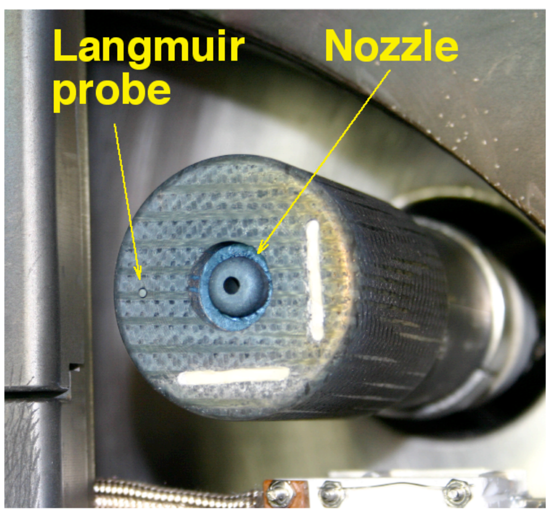
No lithium (129013)
190 mg Lithium (129061)
600 mg lithium (129064)

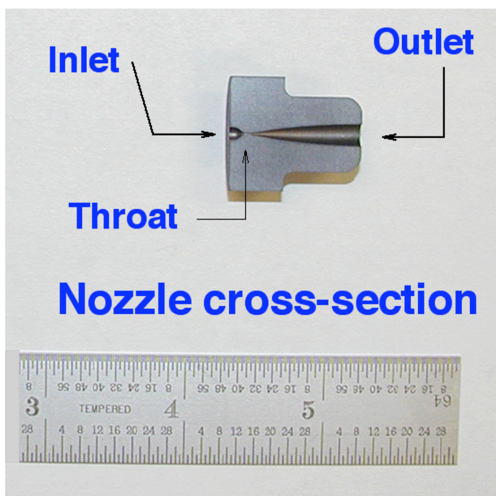
Supersonic gas injector is a complex computer-controlled high gas pressure apparatus



Supersonic gas injector consists of Laval nozzle and piezoelectric valve



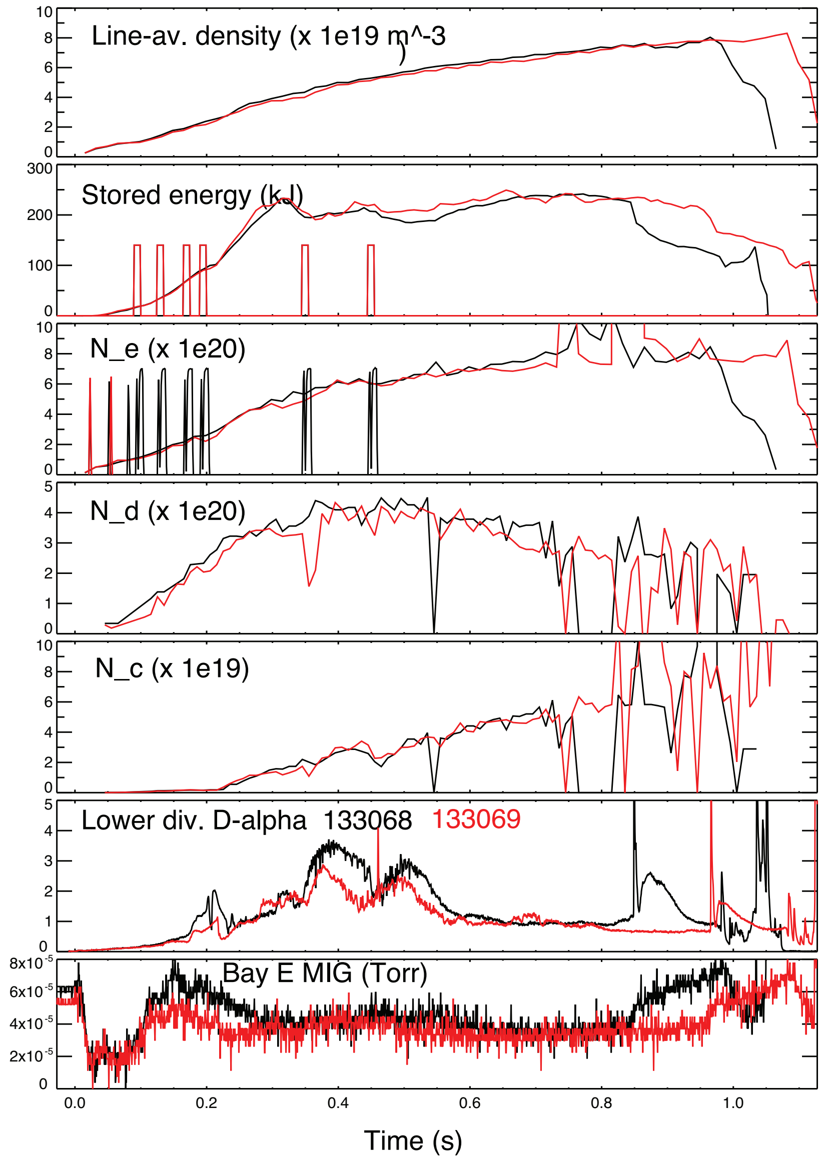




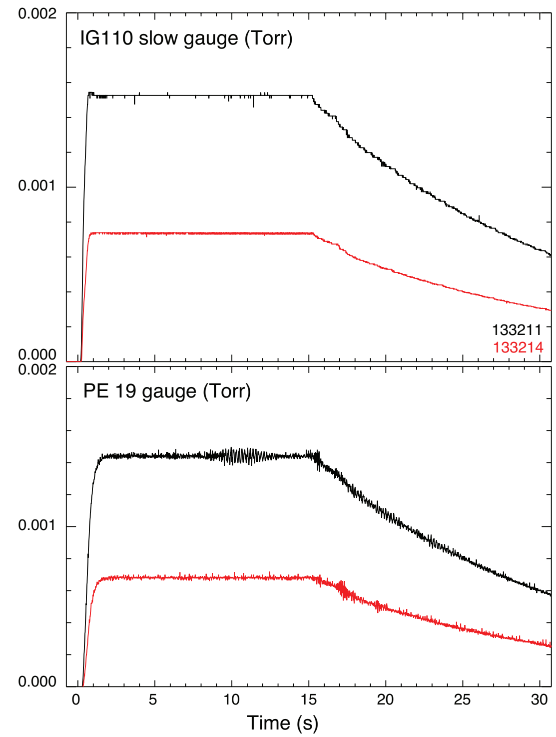
- SGI-U is operated at flow rates 50-250 Torr l /s ($3.5 – 17.5 \times 10^{21}$ s^{-1})

- Supersonic deuterium jet properties:
  - Jet divergence half-angle: 6^o - 25^o (measured)
  - Mach number $M = 4$ (measured)
  - Estimated: T ~ 60 - 160 K, $n < 5 \times 10^{23}$ m^{-3}, $v_{flow} = 2.4$ km/s, $v_{therm} \sim 1.1$ 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 $E_i \leq 20\text{-}40$ eV ($T_e \leq 5$ eV)
- Low T_e divertor operation established in NSTX
  - Divertor gas puffing
  - Snowflake divertor

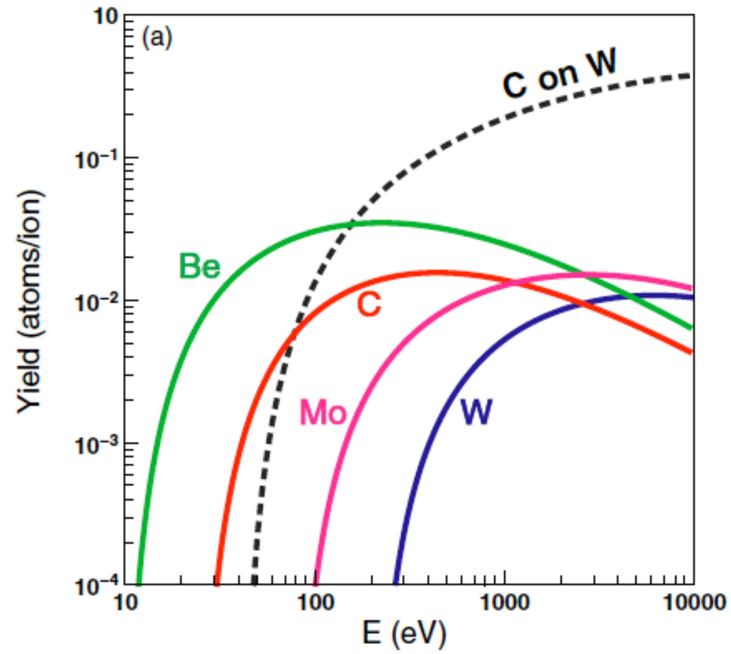
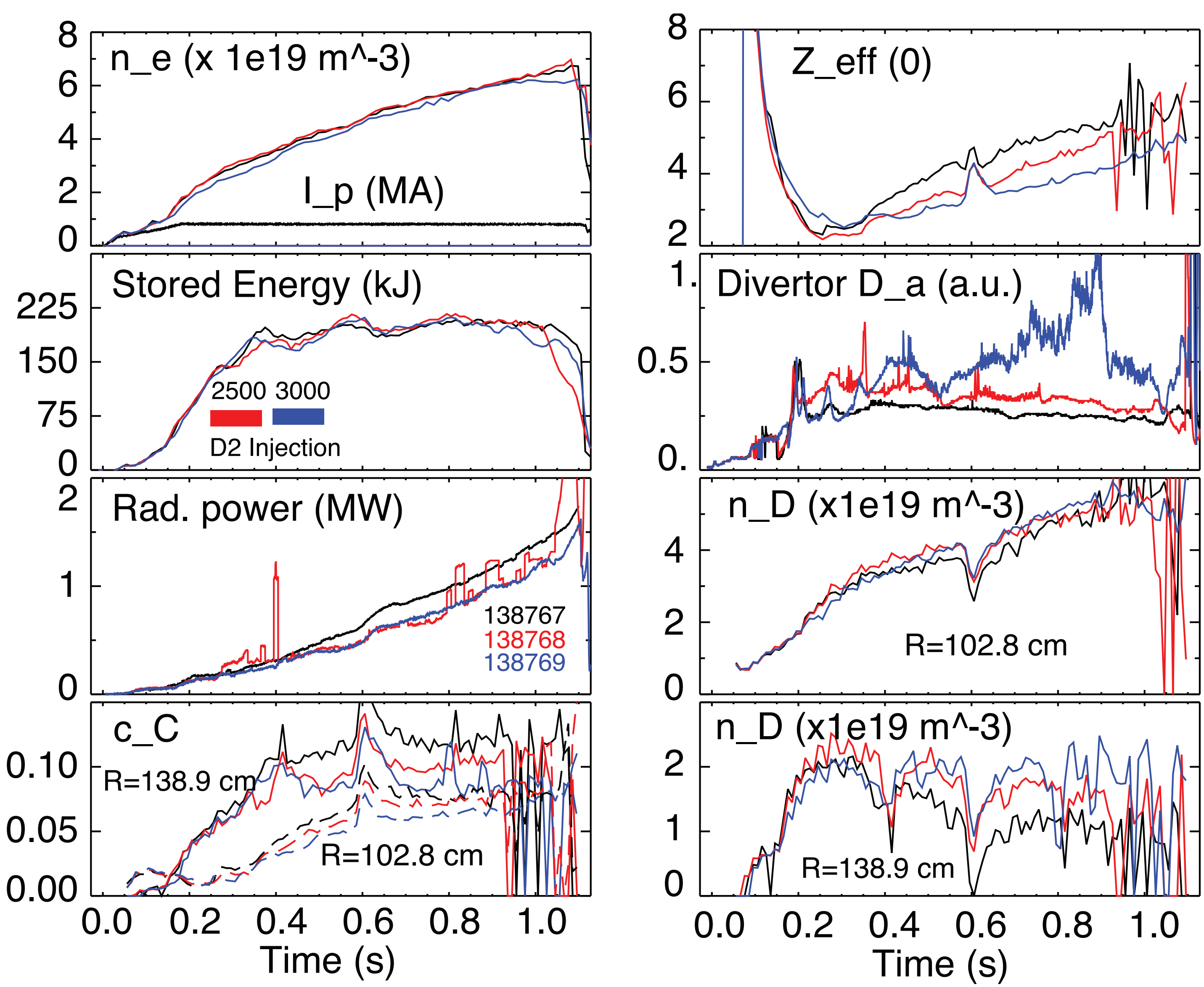


Figure from R. A. Pitts et. al, PPCF (2005) B303

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)

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

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

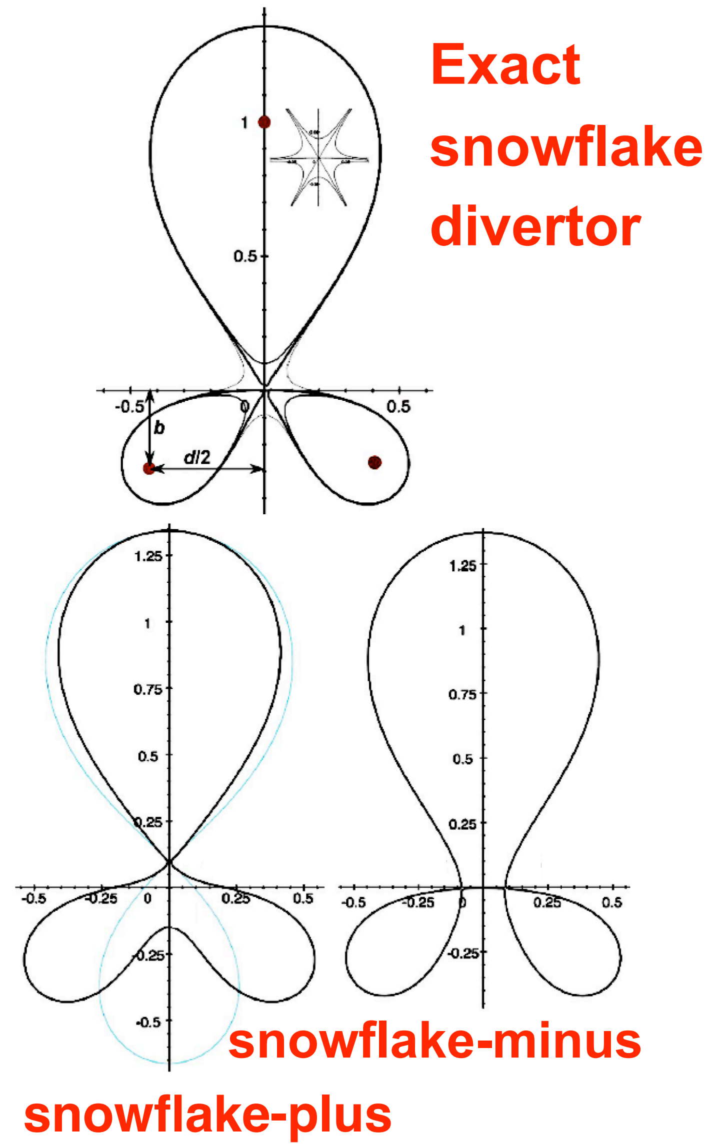
$$f_{exp} = \frac{(B_p/B_{tot})_{MP}}{(B_p/B_{tot})_{OSP}}$$

- 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* $B_p \sim 0$; $B_p \sim r^2$

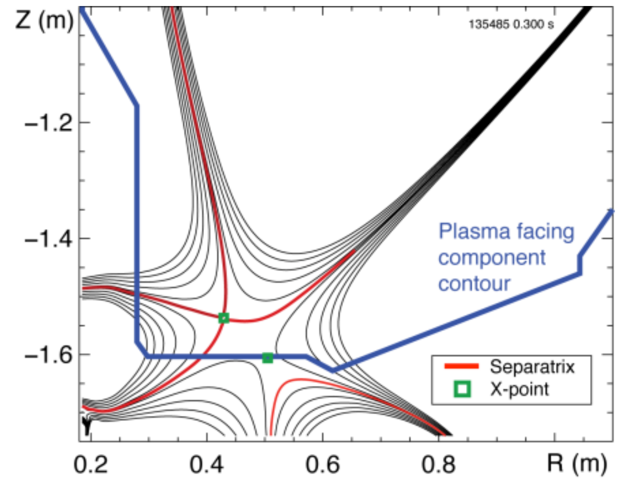
      (Cf. first-order null: $B_p \sim 0$; $B_p \sim r$)
  - Obtained with existing divertor coils (min. 2)
  - Exact snowflake topologically unstable
- Predicted properties (cf. standard divertor)
  - Larger low B_p region around X-point
  - Larger plasma wetted-area A_{wet} (flux expansion f_{exp})
  - Larger 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))

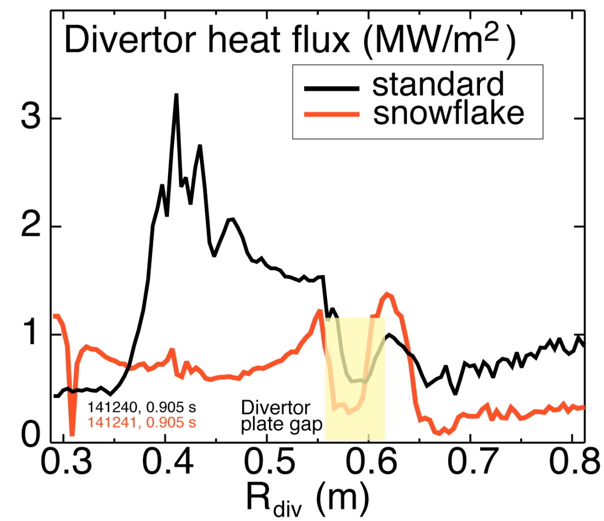


D. D. Ryutov, PoP 14, 064502 2007

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