NSTX-U

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Measurements of core lithium concentration in diverted H-mode plasmas of NSTX

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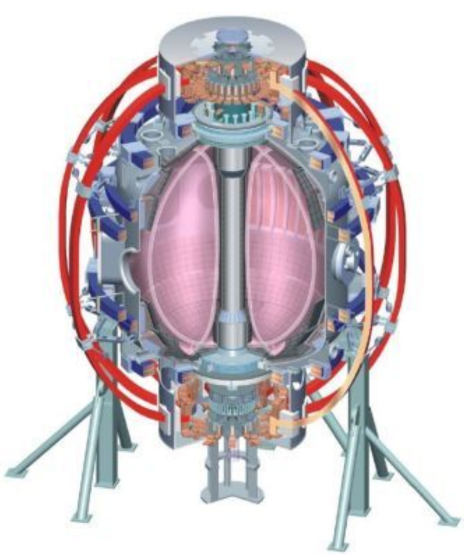

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Abstract

NSTX is exploring the use of lithium as plasma-facing material to handle the large power flux to the wall expected in future fusion devices. Measurements of core lithium concentration $n_{Li}(R)$ have been performed to assess the possible contamination of the core plasma caused by lithium influx. Experimental scenarios representative of the NSTX operating space for diverted H-mode are investigated. In particular, a total of 1.3 kg of lithium was evaporated into the vessel in the 2010 NSTX experimental campaign. In spite of the fact that up to hundreds of milligrams of lithium are introduced in the vessel, n_{Li} remains insignificant in the core. Measured values $n_{Li} \ll 0.1\%$ of the electron density are rather insensitive to variations of toroidal field, plasma current, divertor conditions. No dependence of core lithium concentration on the specific technique utilized for lithium conditioning of the vessel wall is observed.

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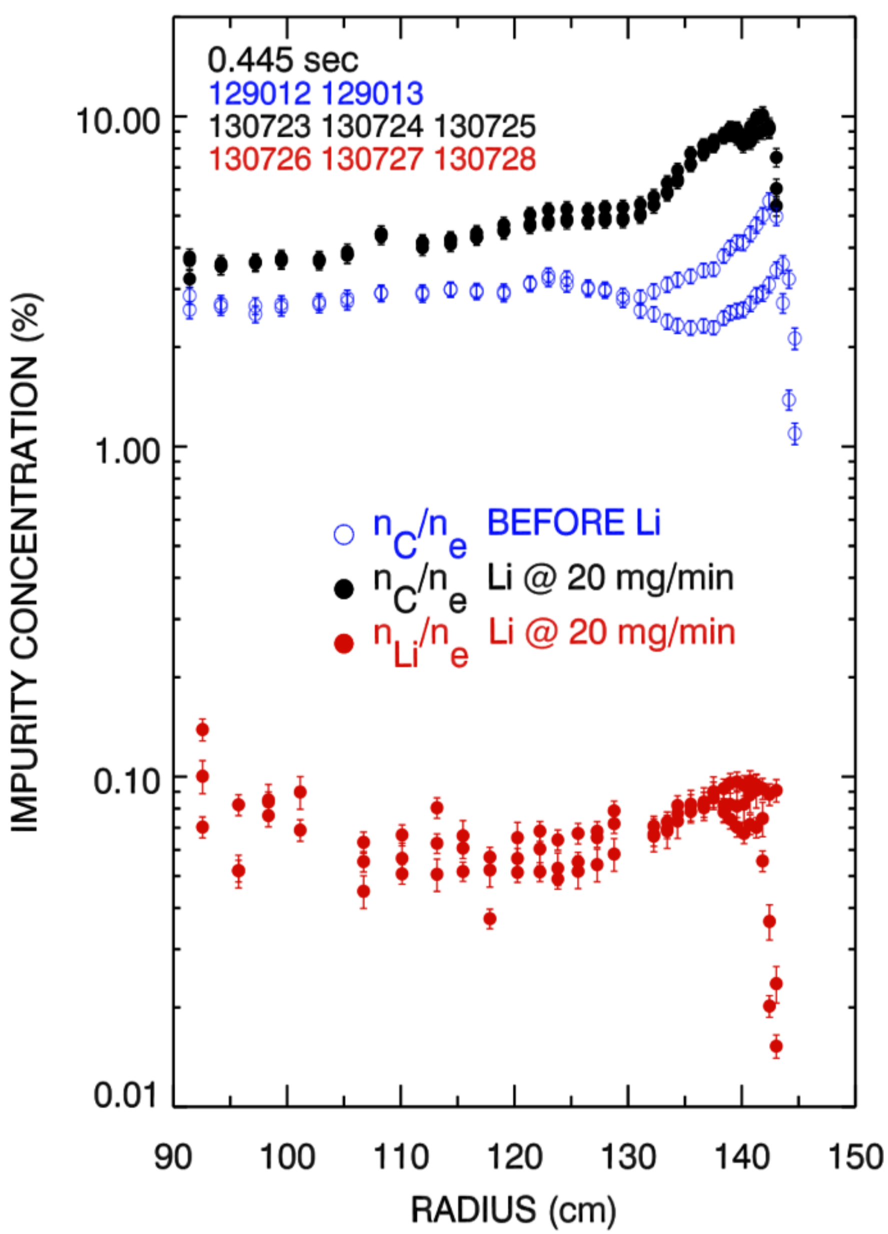
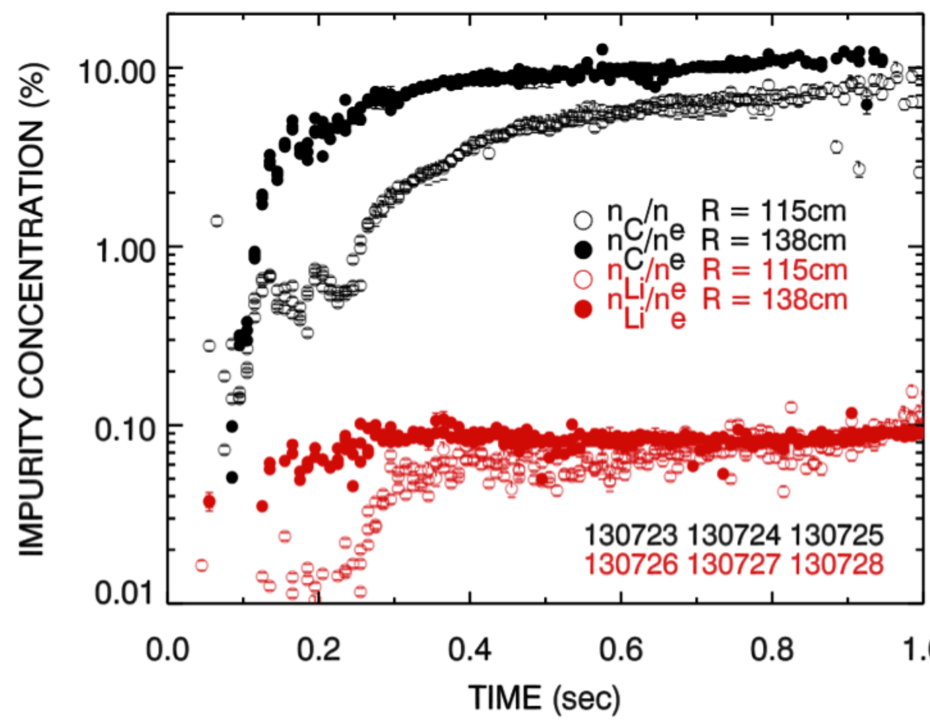
2008 Lithium and Carbon density measurements: extremely low Li concentration and higher C concentration

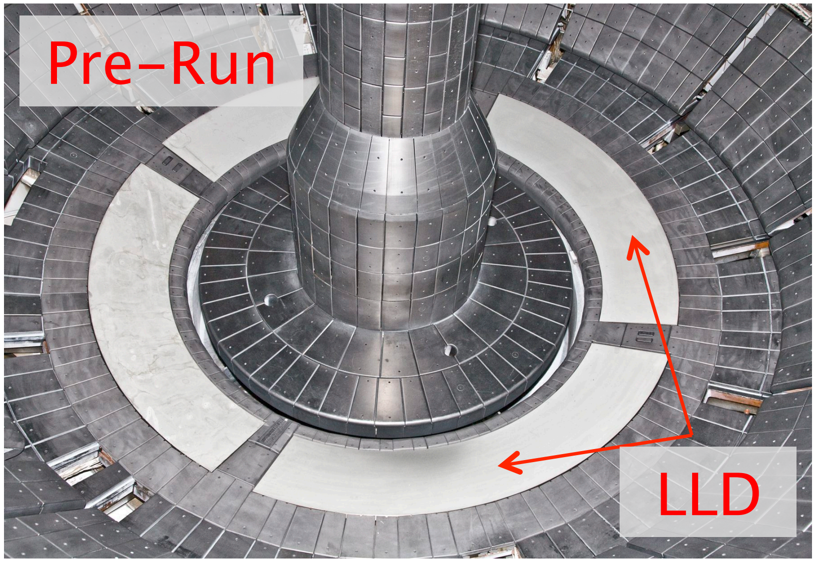


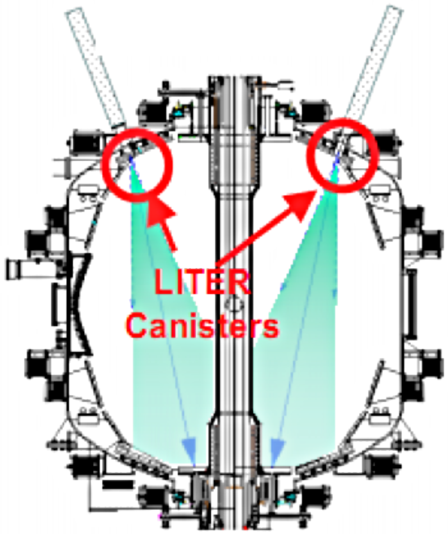
- Impurity density profiles from *toroidal* CHERS
  - C VI, n = 8–7 transition, 529.1 nm
  - Li III, n = 7–5 transition, 516.7 nm
- Lithium concentration much lower than carbon concentration
  - $n_C/n_{Li} \sim 100$
- Carbon increases with Li evaporation

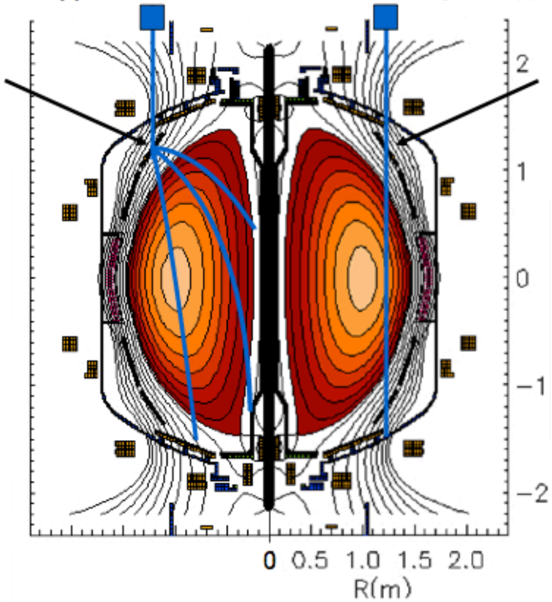
> ***One operating condition (H-mode) measured***



About 1.3 kg of lithium (total) evaporated during 2010 Run







- Lithium conditioning systems
  - LITER evaporation
  - Li Dropper
  - Liquid Lithium Divertor (LLD)

Are 'massive' Lithium evaporations polluting the plasma?

Outline

- Core Li concentration monitored throughout 2010 Run
- Broad range of operating conditions covered
  - B_ϕ, I_P, aspect ratio/inner gap
  - Different Li conditioning techniques
  - Anomalous events, e.g. Li ‘blobs’ on divertor tiles

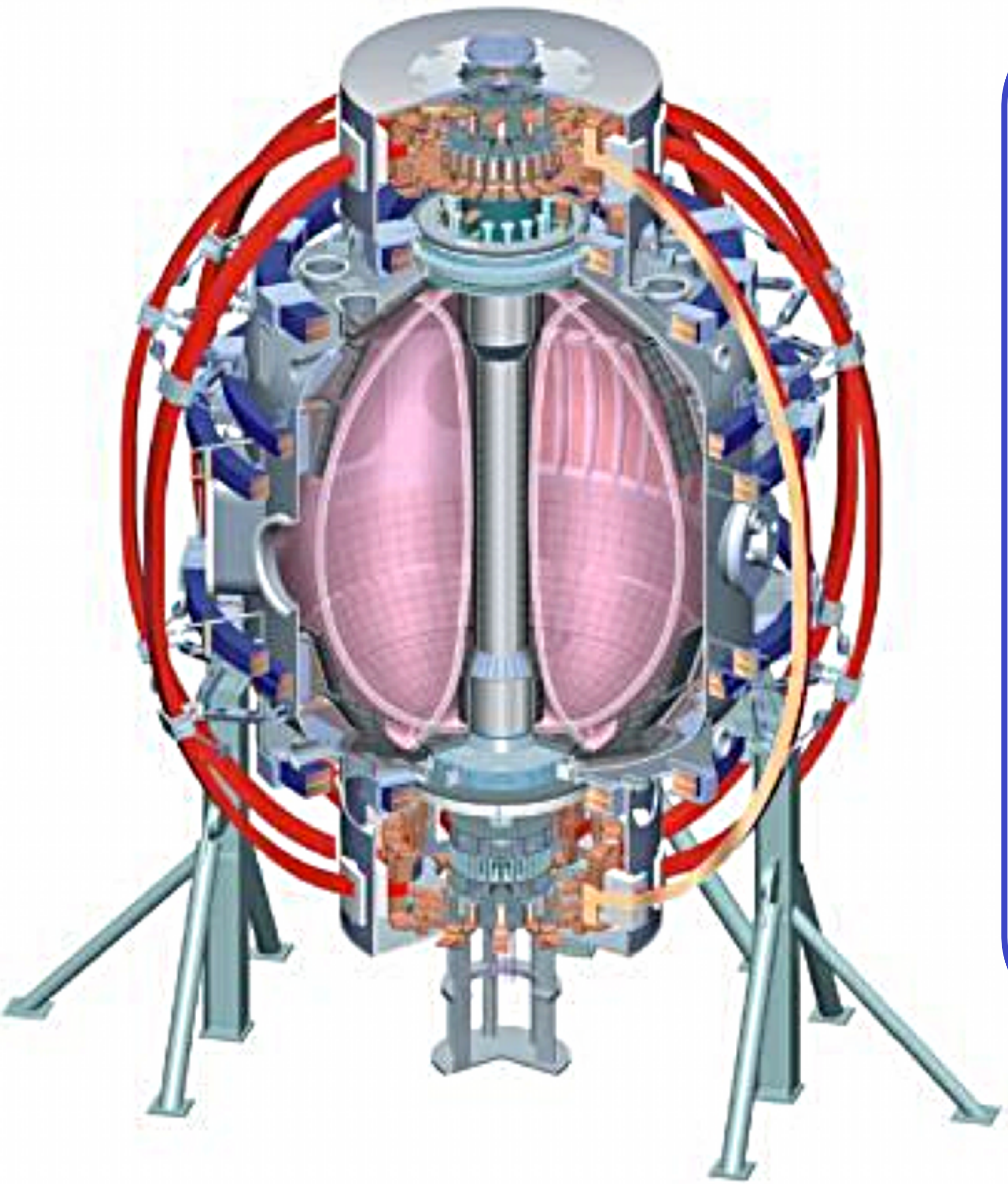
> Plasma configuration has little effect on n_{Li}

> Only systematic dependence observed is on B_ϕ, I_P
  - Attributed to general improvement in confinement

> **Negligible Li concentration is a robust property of NSTX**
  - $n_{Li}/n_e << 0.1\%$
  - Carbon remains dominant impurity even after massive (hundreds of milligrams) Li evaporation
  - ΔZ_{eff} due to lithium ≤ 0.006

Experimental Setup and Analysis techniques

NSTX parameters



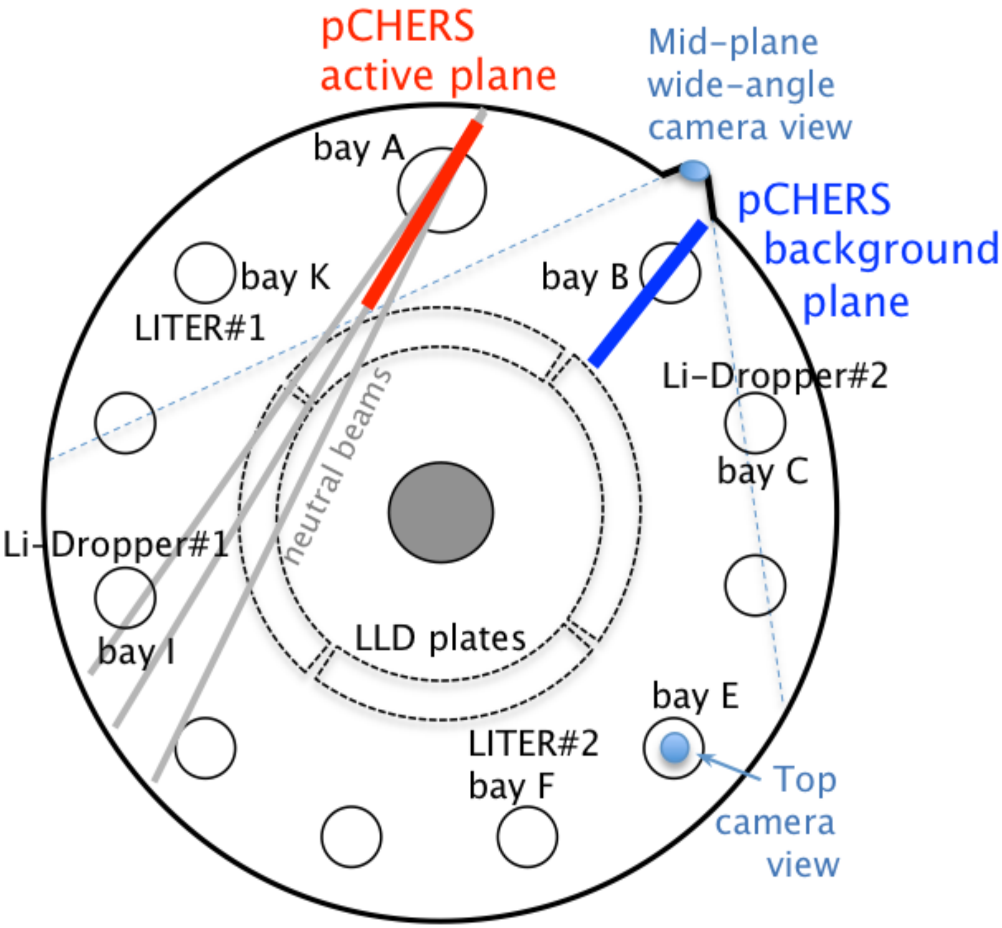
Major radius	0.85 m
Aspect ratio	1.3
Elongation	2.7
Triangularity	0.8
Plasma current	~1 MA
Toroidal field	<0.55 T
Pulse length	<2 s

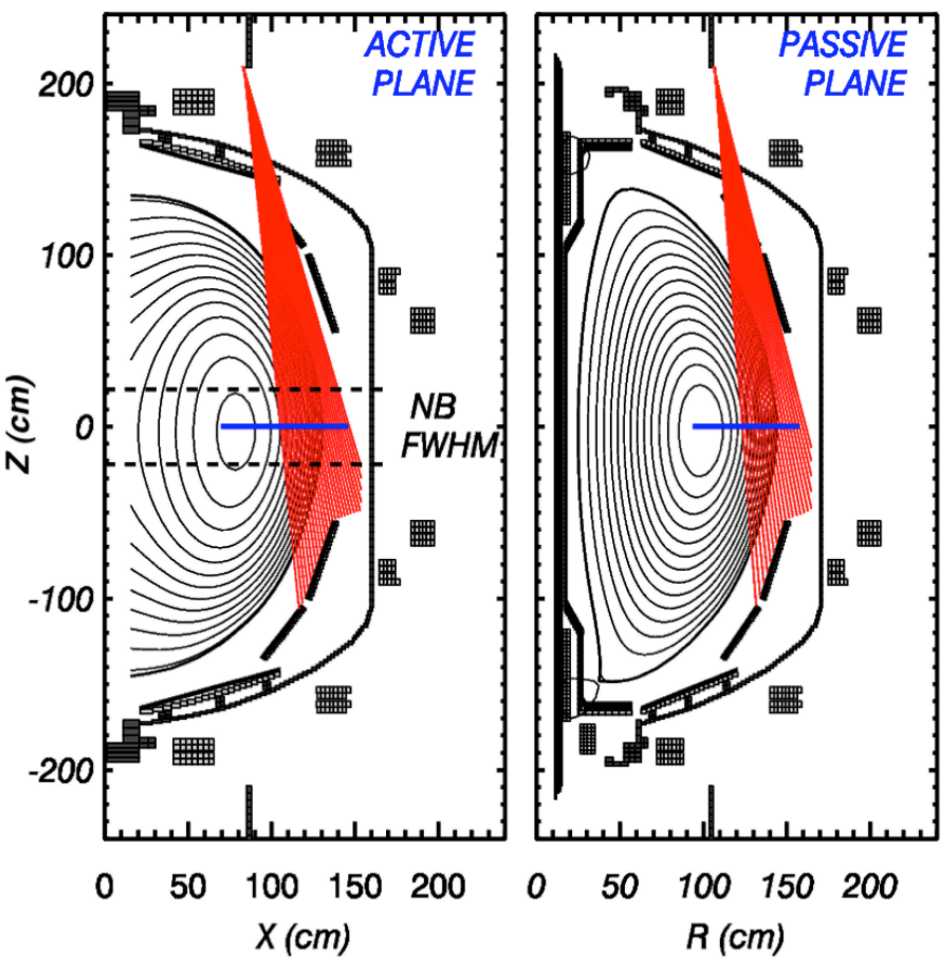
3 Neutral Beam sources:

$P_{NBI} \leq 7$ MW

$E_{injection} \leq 95$ keV

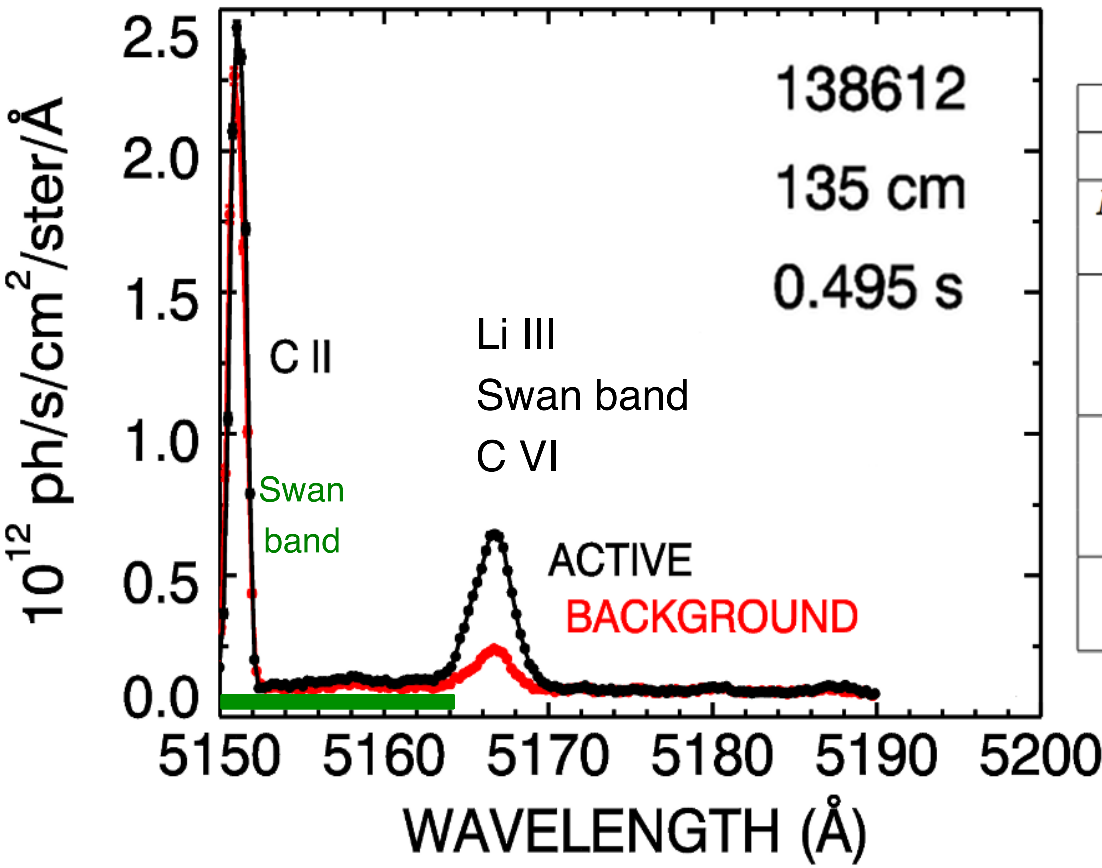
Suite of CHERS diagnostics allowed simultaneous measurements of C, Li on outer midplane in 2010





- Active/passive paired vertical views to remove background
- Monitor Li III line (*n*=7–5) at 516.7 nm
- Interleaved measurements of C VI (*n*=8–7) at 529.1 nm
- Data from mid-radius (R~120 cm) out every 10 ms.

Measured Li III spectrum complicated by low Li III content, blend with C VI, and overlap with C_2 ('Swan') band



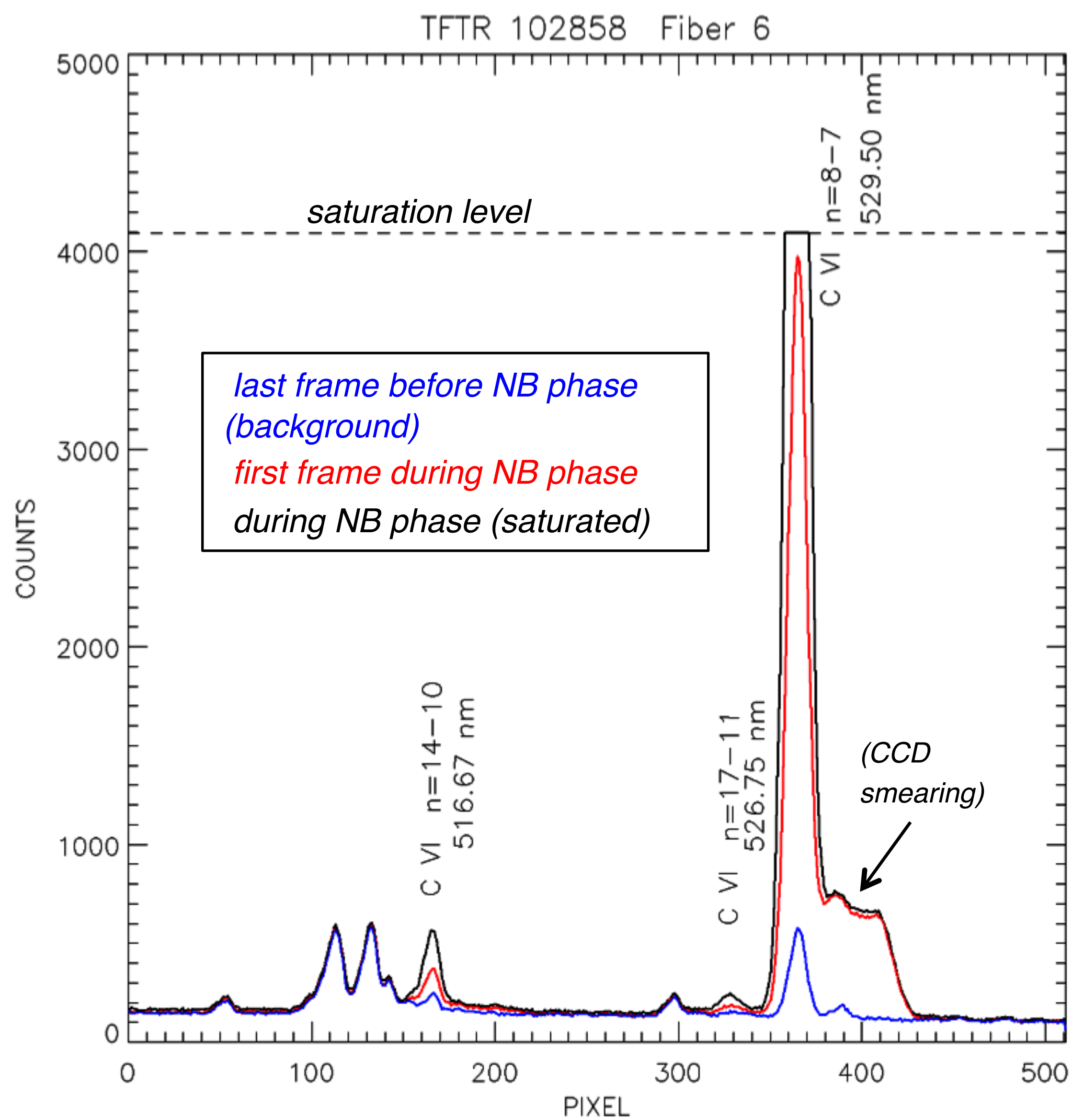
Available diagnostics:

System	CHERS	pCHERS	Li-pCHERS
Views	tangential	vertical	vertical
Measured/derived quantities	n_C, v_{tor} n_i, T_i, Z_{eff}	n_c, v_{pol}	n_{Li} n_{Li}/n_C
Monitored species	C VI	C VI	Li III C VI C II
Monitored lines	5290.5 Å	5290.5 Å	5166.89 Å (Li III) 5166.67 Å (C VI) 5151.1 Å (C II)
Radial coverage	90 – 157 cm	90 – 157 cm	120 – 157 cm

- C VI line (*n*=14–10) at same wavelength as Li III (*n*=7–5)
- Molecular C_2 band (*Swan band*) partly overlaps Li III
- No NSTX lithium-free discharges available to estimate relative brightness of C VI versus Li III

TFTR spectra indicate that C VI (n=14–10) to C VI (n=8–7) *brightness* ratio is ~3.6 %

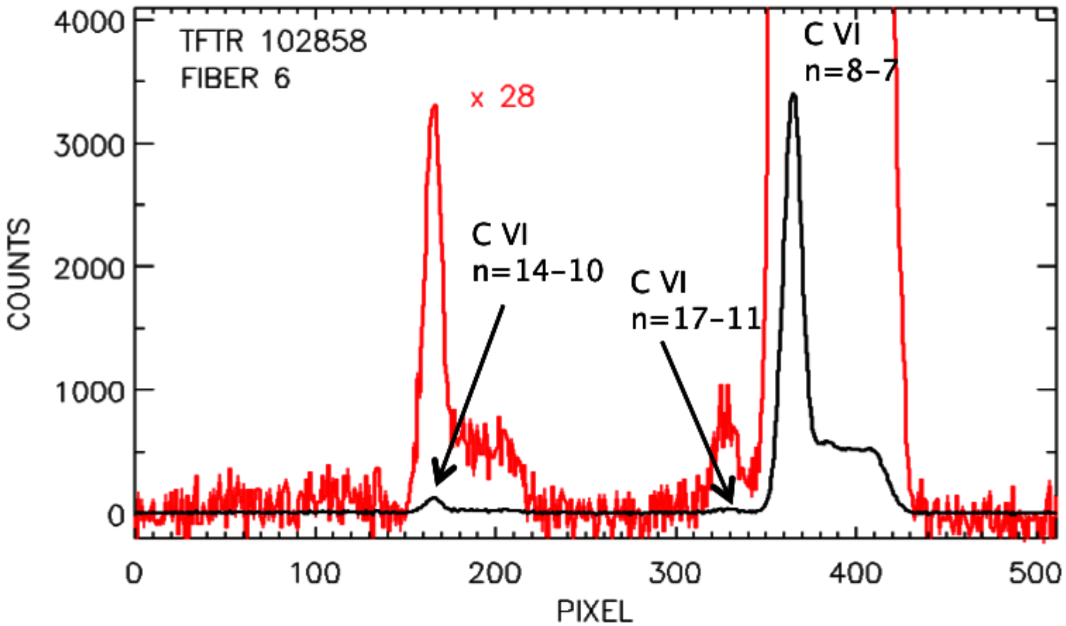
- Data taken during TFTR pCHERS commissioning near beam turn-on
- n_e~1.2 x $10^{19}m^{-3}$, T_i,T_e~ 3 keV
- Measured relative brightness of C VI
  - n=8–7 @ 529.5 nm
  - n=14–10 @ 516.7 nm
  - n=17–11 @ 526.8 nm
- Brightness ratio B_{8-7}:B_{14-10} is 28:1
- Measured ratio provides an estimate for expected C VI (n=14–10) brightness on NSTX
  - Collisional-Radiative (CR) model for CX using n_D=1,2,3 excited donor neutrals under populates upper n levels compared to measurement
  - > *From CR model, expect little variation between these TFTR parameters and NSTX parameters*



About 50% of brightness @516.7nm on NSTX can be due to C VI

Brightness ratios measure n-level population ratios

CX spectra obtained by subtracting pre-beam spectrum from post-beam turn-on spectrum:



- Assuming fully mixed levels, the TFTR measurements imply that the *n*=14 and *n*=17 levels are more populated by charge exchange with the neutral beams that the *n*=8 level
- The CR model using donor neutrals n_D=1,2,3 does *not* adequately populate the upper levels
- Other populating mechanisms, e.g. n_D=4,5,6 , are required to match measured brightness ratio.

$$B \propto A_{ki} N_k$$

N_k is population of n-level k

A_{ki} coefficients for C VI:

$$A_{8-7} = 2.94 \times 10^8$$

$$A_{14-10} = 7.02 \times 10^6$$

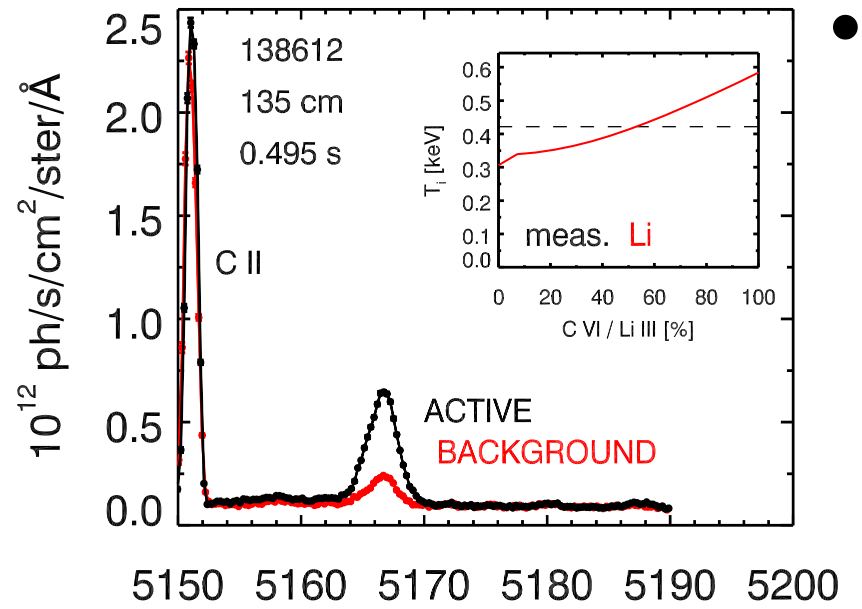
$$A_{17-11} = 2.08 \times 10^6$$

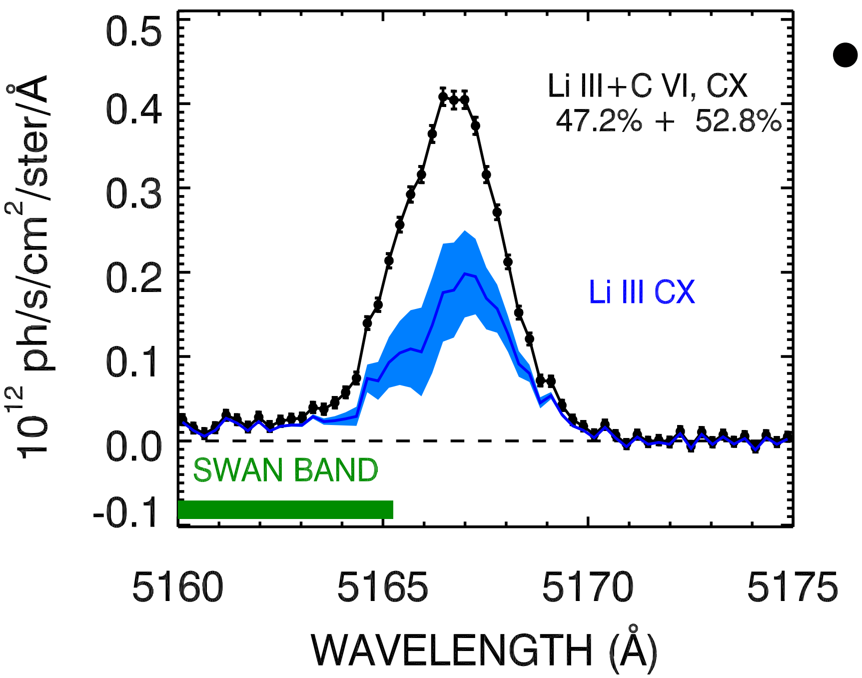
$$\frac{B_{14-10}}{B_{8-7}} = \frac{A_{14-10}}{A_{8-7}} \frac{N_{14}}{N_8} = \frac{1}{28}$$

$$\frac{N_{14}}{N_8} = \frac{B_{14-10}}{B_{8-7}} \frac{A_{8-7}}{A_{14-10}} = 1.5$$

$$\frac{B_{17-11}}{B_{8-7}} \approx \frac{1}{120} \quad \Rightarrow \quad \frac{N_{17}}{N_8} = 1.2$$

Combine information from C-pCHERS and Li-pCHERS to fit composite Li III, C VI and Swan band spectra



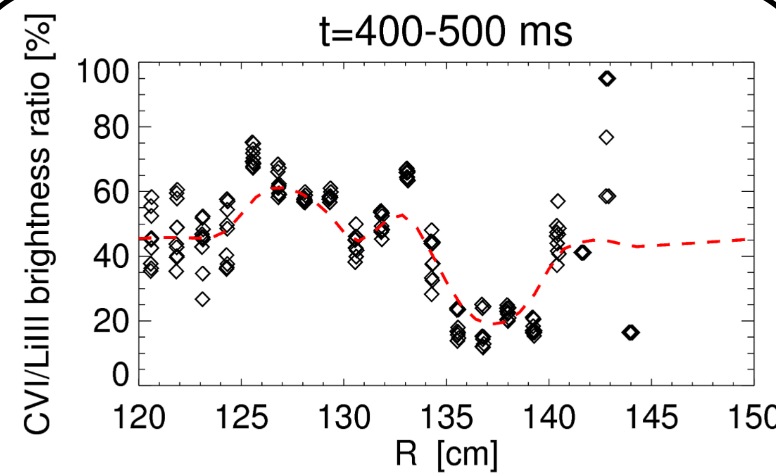


- Fit background-subtracted spectrum, assuming:
  - All species have same T_i
    - Use apparent (line-integrated) T_i from C-pCHERS as reference
  - Fixed wavelength for Swan head-band
  - Known wavelength for C VI (n=14-10) based on C VI (n=8-7) measurement
- Scan ratio of C VI to Li III brightness, infer FWHM ~ $(T_i/m_i)^{1/2}$
  - Inferred T_i for Li III changes with ratio
  - *Look for T_i consistency:*
    - > ***Correct ratio such that $T_{Li}=T_C$***

On average, 50% of brightness is from C VI
Large uncertainties, +/- 25%

Analysis based on line-integrated measurements identifies an *upper limit* for n_{Li}

- Issues:
  - Line-integrated measurement
  - Differences among CX cross sections
  - Variations in Li III / C VI brightness ratio
- Line-integrated analysis used
  - Reduced radial resolution (smearing)
  - Compared to *inverted profiles* (for a subset of discharges) compensating for differences in CX cross sections
  - Assume all emission near Li III wavelength is lithium (i.e. no C VI)
  - Scaled to (absolutely calibrated) toroidal CHERS with actual Carbon density

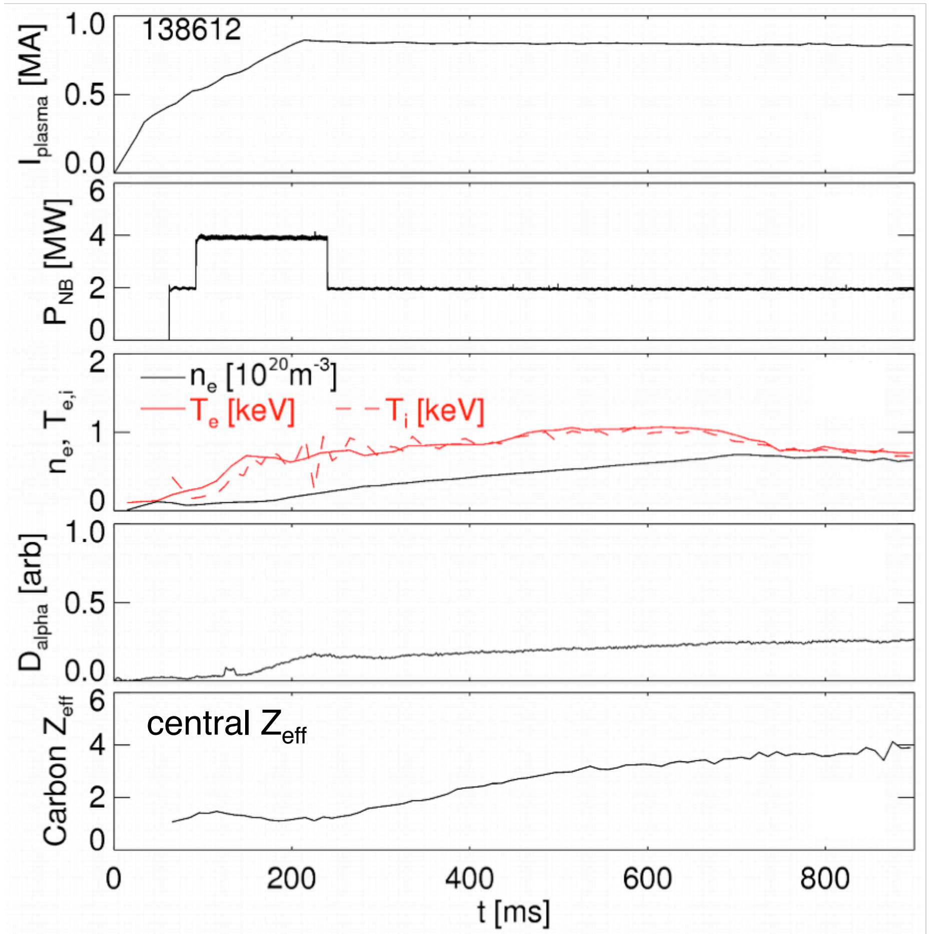


Relative brightness of Li III (n=7–5) compared to C VI (n=14–10) varies with radius

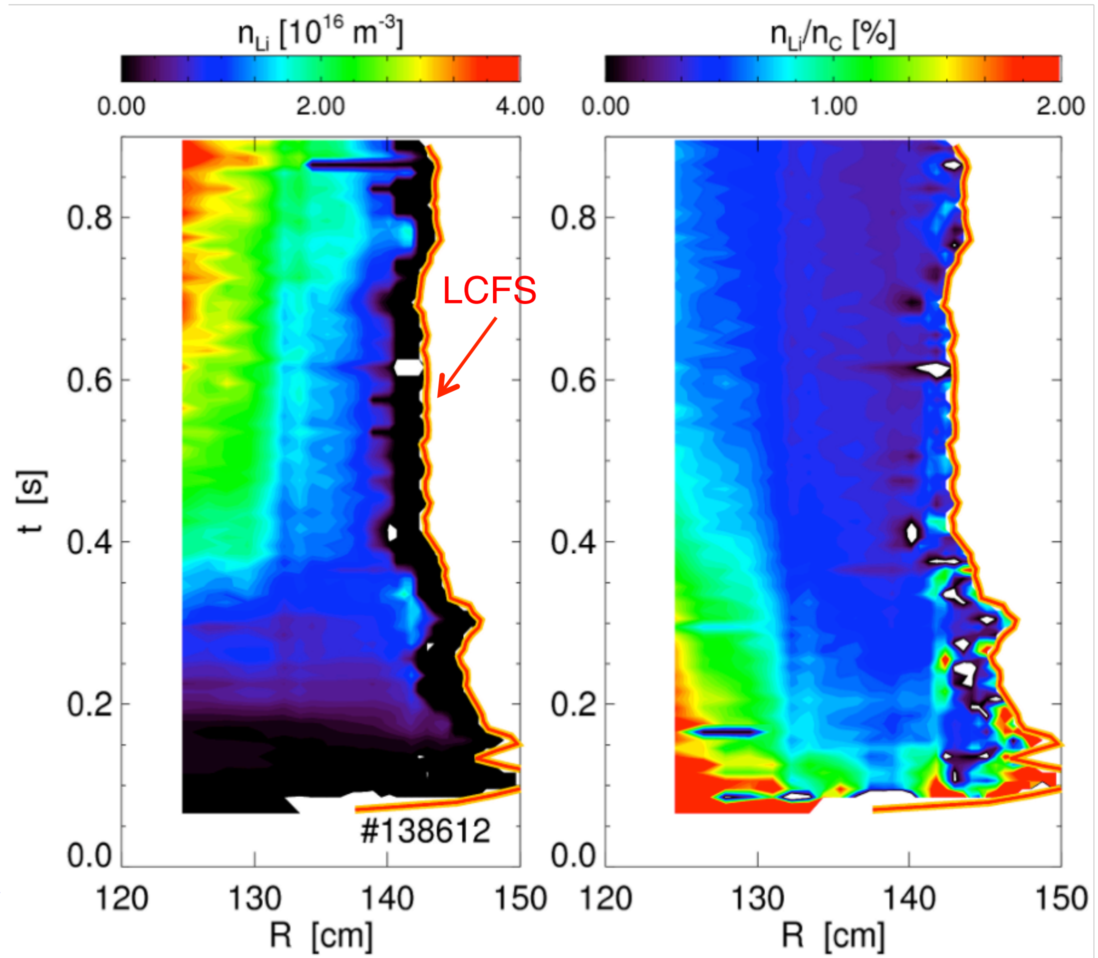
- Results *without* corrections for C VI/Li III brightness ratio shown in the following viewgraphs
  - **Upper limit for n_{Li}**
  - \> **Actual lithium density (concentration) could be 2–4 times smaller than what shown hereafter**

Scans of Toroidal Field, Plasma Current, Aspect Ratio

Typical H-mode, moderate NB power discharge shows only trace amounts of lithium in the core

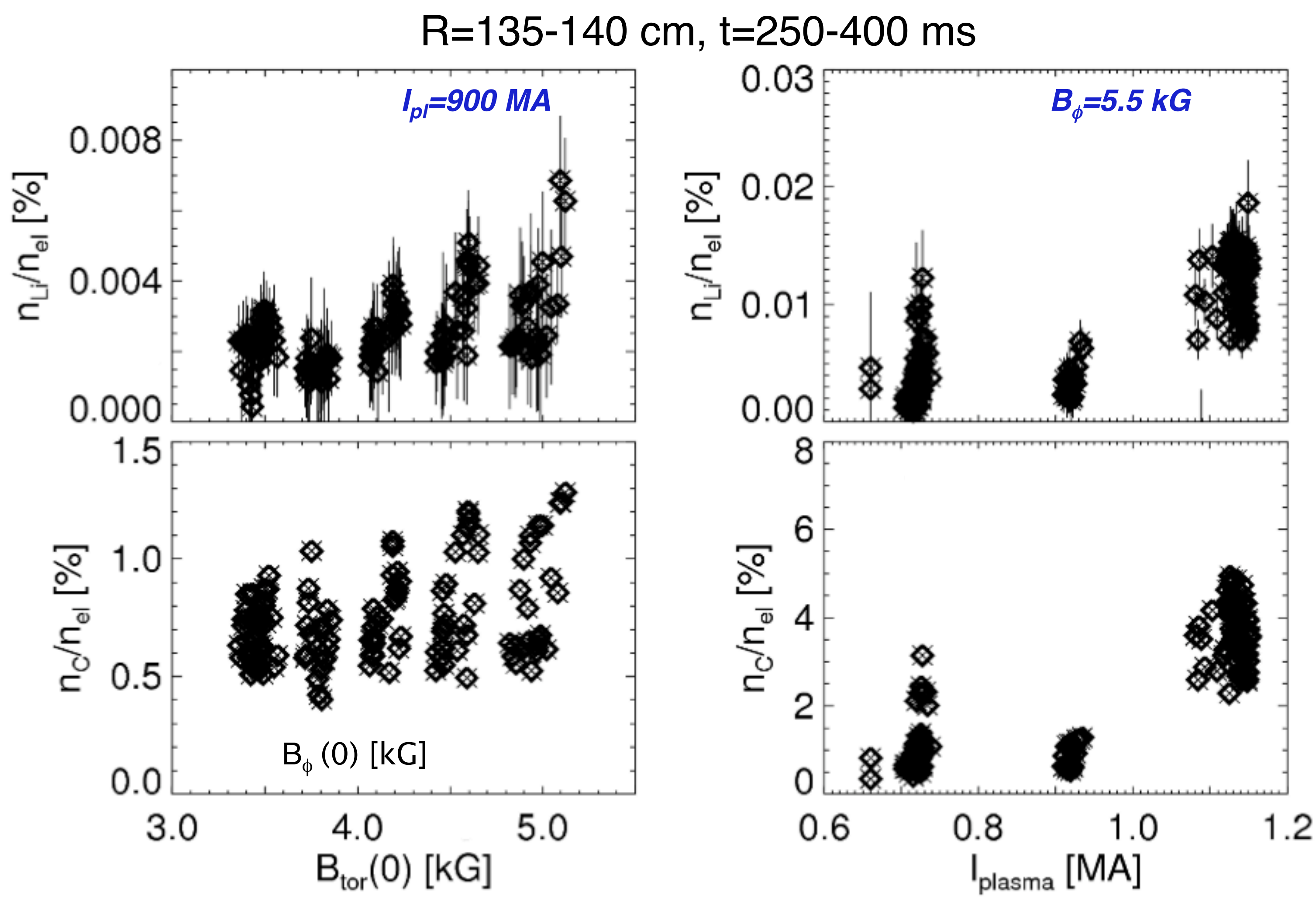


- ELM-free, 800 kA discharge
- Usual increase in Z_{eff} during the pulse



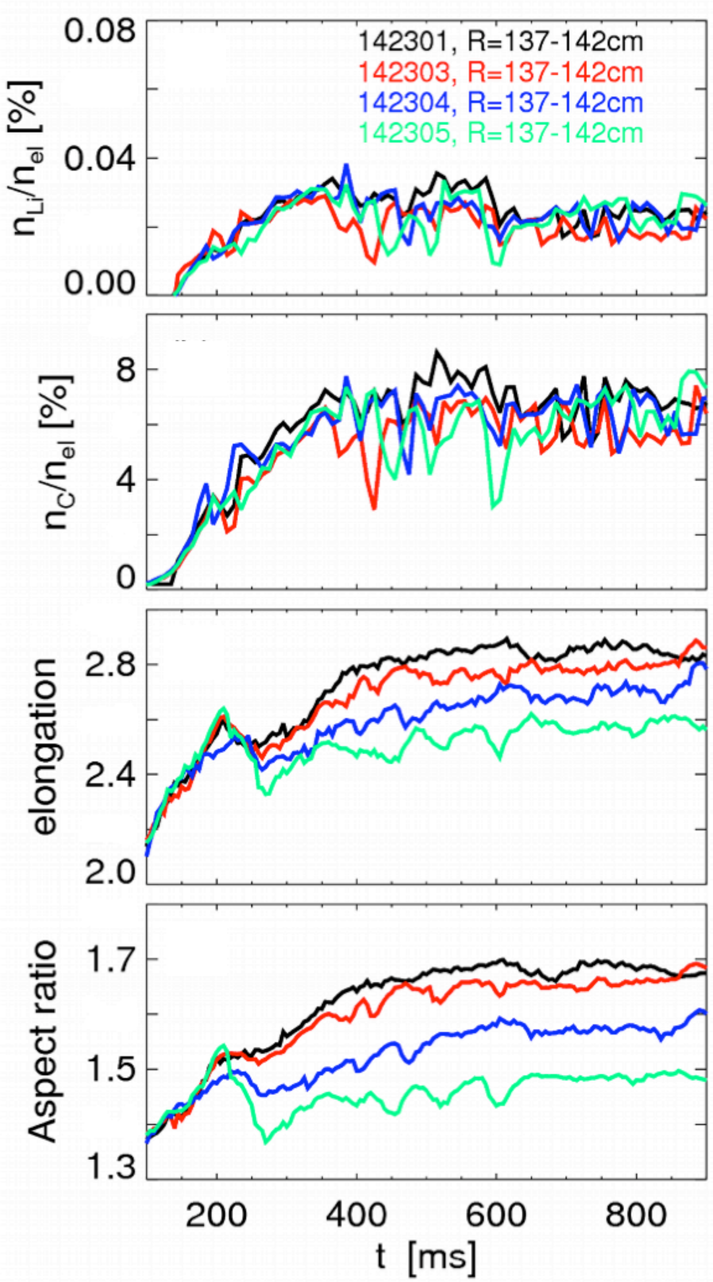
- Lithium density increases in time, but remains low
  - **Max 2% of carbon density**
  - **<<0.1% of electron density**

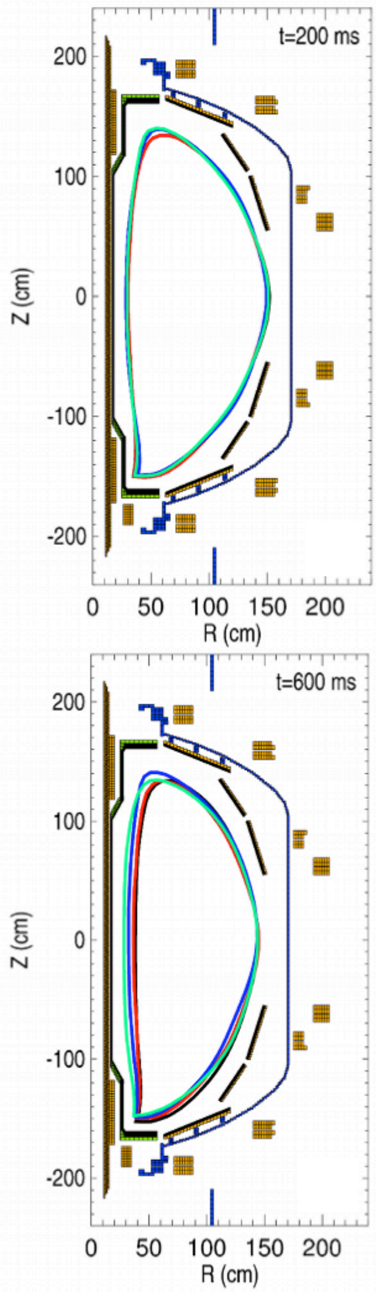
Both lithium and carbon relative concentrations increase with toroidal field and plasma current



- Better confinement expected for higher B_ϕ, I_P
- Increasing Li, C concentration with plasma current; weak trend with B_ϕ
- Extremely low Li concentration projected for higher B_ϕ with NSTX-U

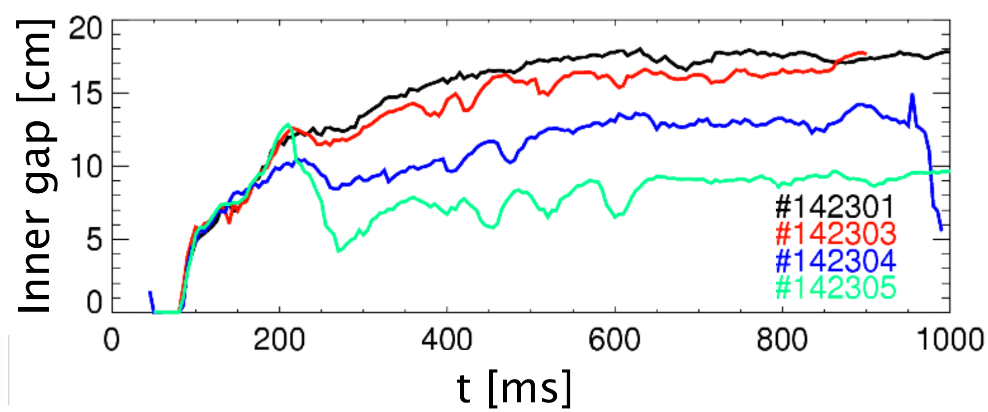
Aspect ratio/ Inner gap scan shows no effect on average Lithium – and Carbon – concentrations





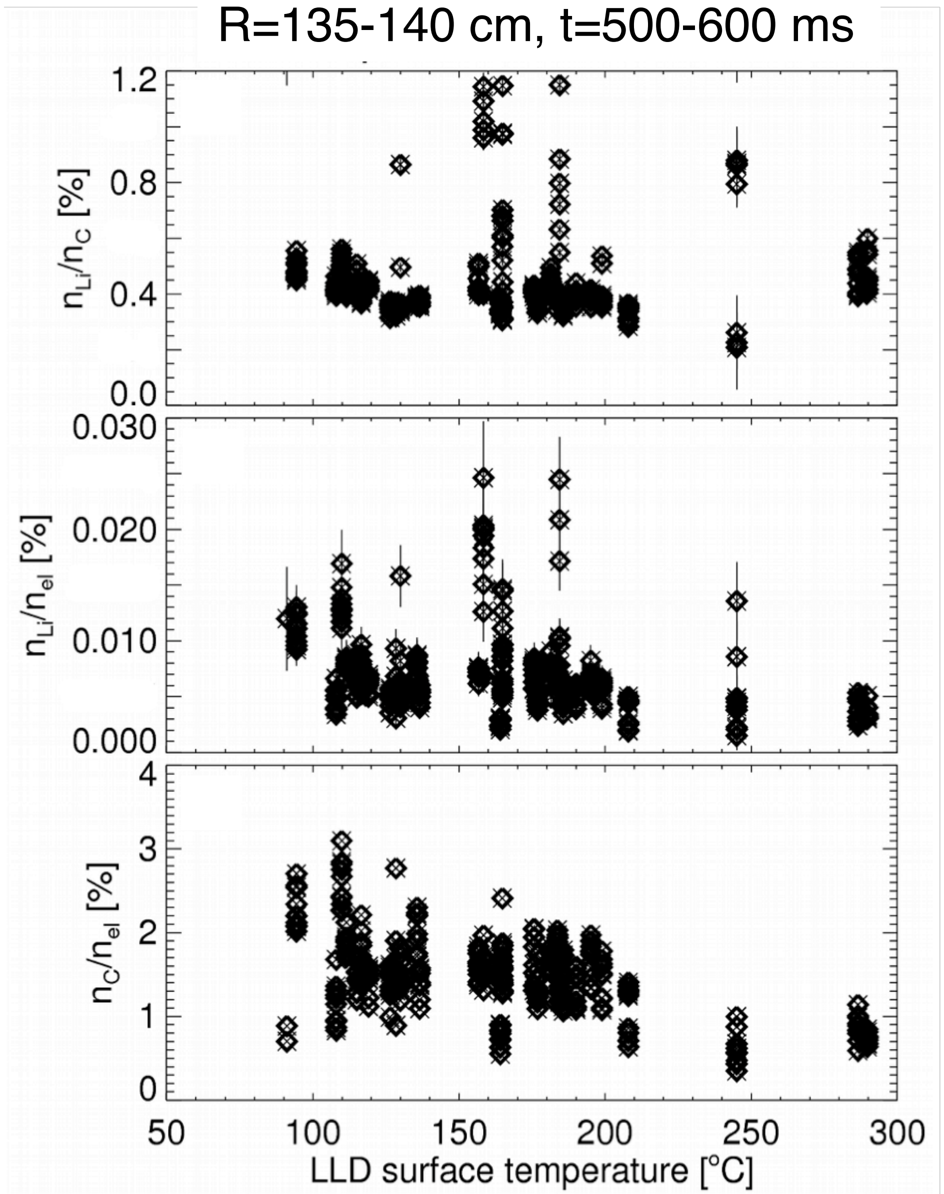
- ***Are lithium/carbon sputtered in from the center stack?***
- Four discharges analyzed
  - All start the same way
  - Inner gap/aspect ratio modified after ~200 ms
  - Other parameters change at the same time (elongation, bottom gap, etc.)

>No variation of n_{Li} observed among shots
  - Slight decrease of n_{Li} in time
  - Carbon seems to saturate
  - Lithium concentration low (< 0.04%)



Dependence on Lithium Conditioning: LITER, Li-Dropper, LLD

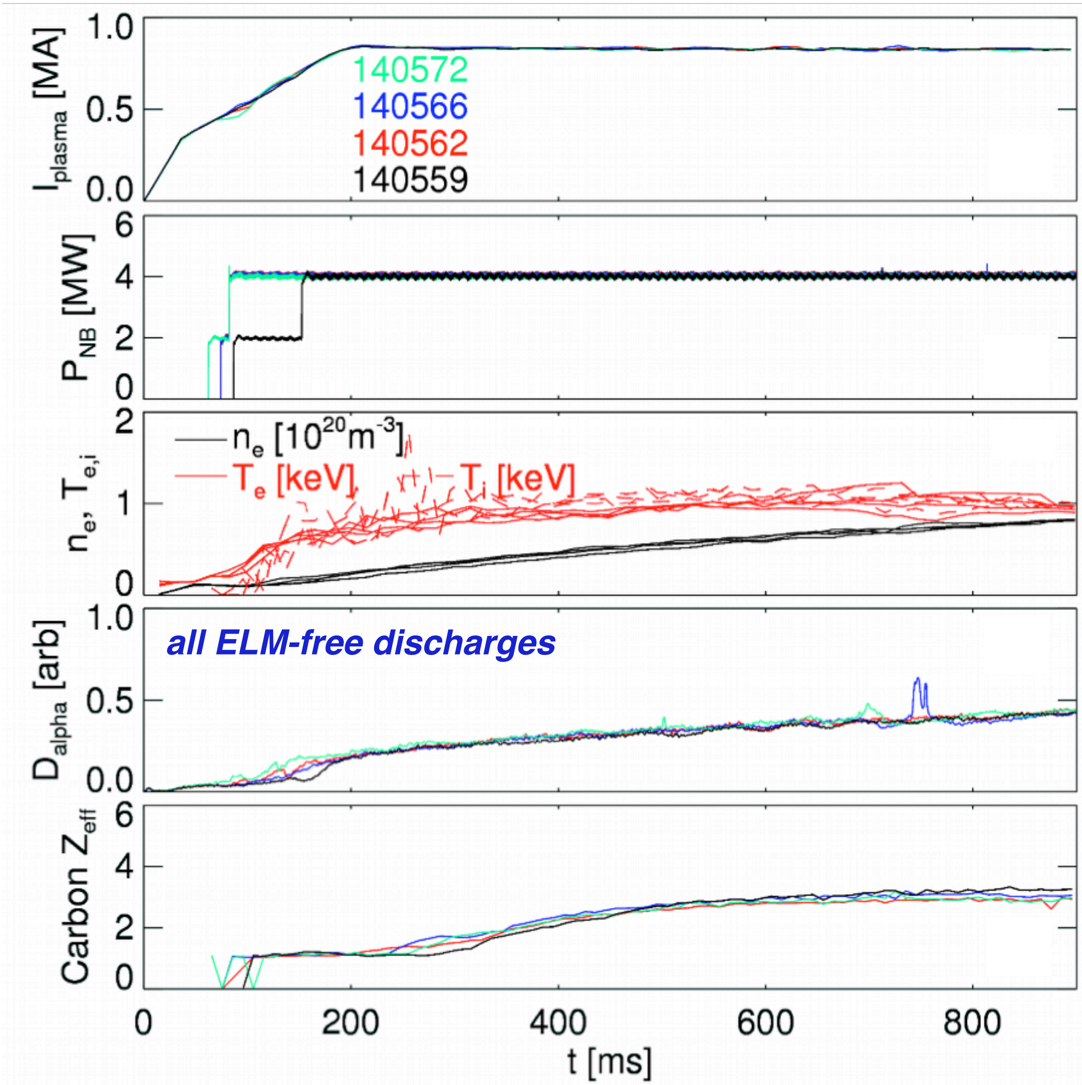
LLD well above Li melting temperature does not affect significantly Lithium and Carbon core concentration



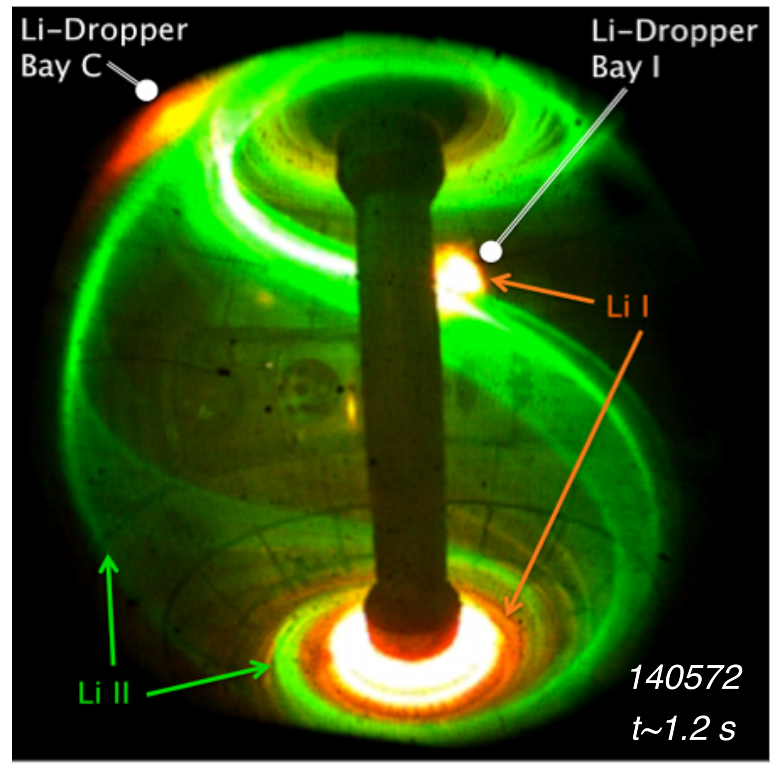
shots: 142488 - 142522

- LLD temperature increased from 90°C to 290°C
  - 'Passive' heating from plasma, increase ~10°C/shot
- No clear systematic change in lithium/carbon concentrations
  - Slight decrease above 200°C, but fueling also changed
- Cumulative effects of lithium evaporation dominant?
  > Look for changes with Li introduced *during* shot

‘LITER-only’ and ‘LITER plus Li-Dropper’ discharges show different edge features, but similar overall parameters

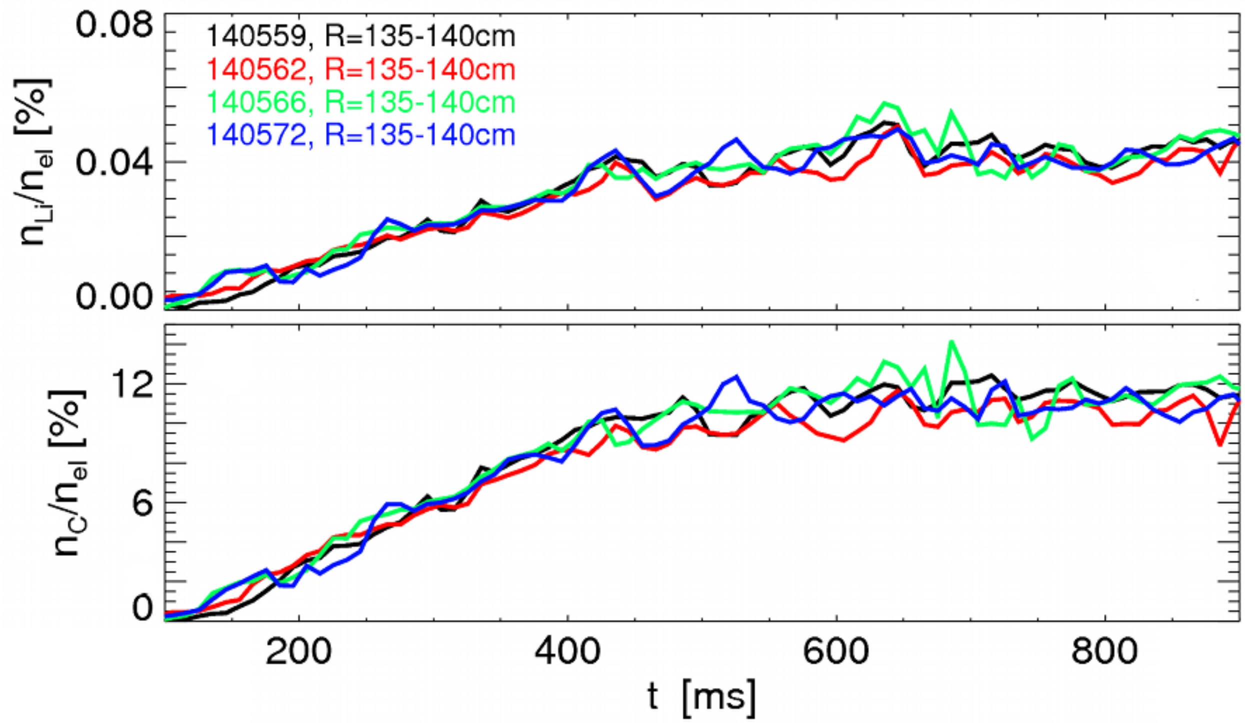


shot no.	*LITER*	*Li-Dropper*
140559	240 mg	—
140562	240 mg	240 mg + 240 mg/s × 1.2 s
140566	240 mg	0 mg + 100 mg/s × 1.1 s
140572	120 mg	240 mg + 120 mg/s × 1.2 s



Comparable amount of lithium inserted from LITER (pre-shot) and from Li-Dropper (pre/during shot)

Both carbon and lithium concentrations saturate in time; evolution is independent of conditioning technique

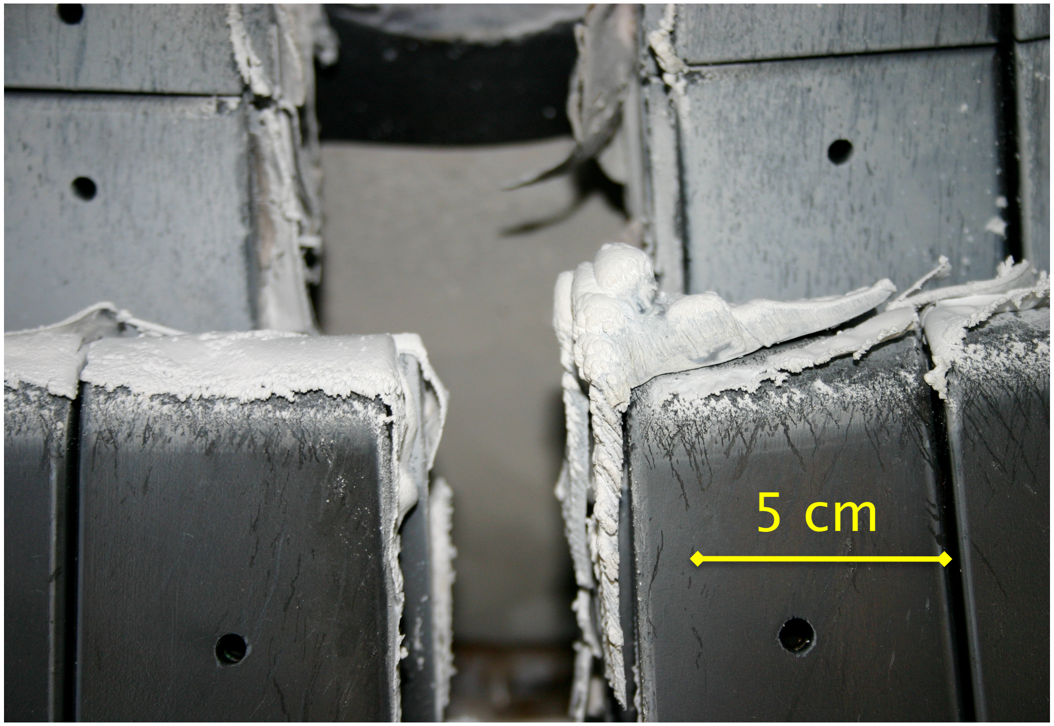


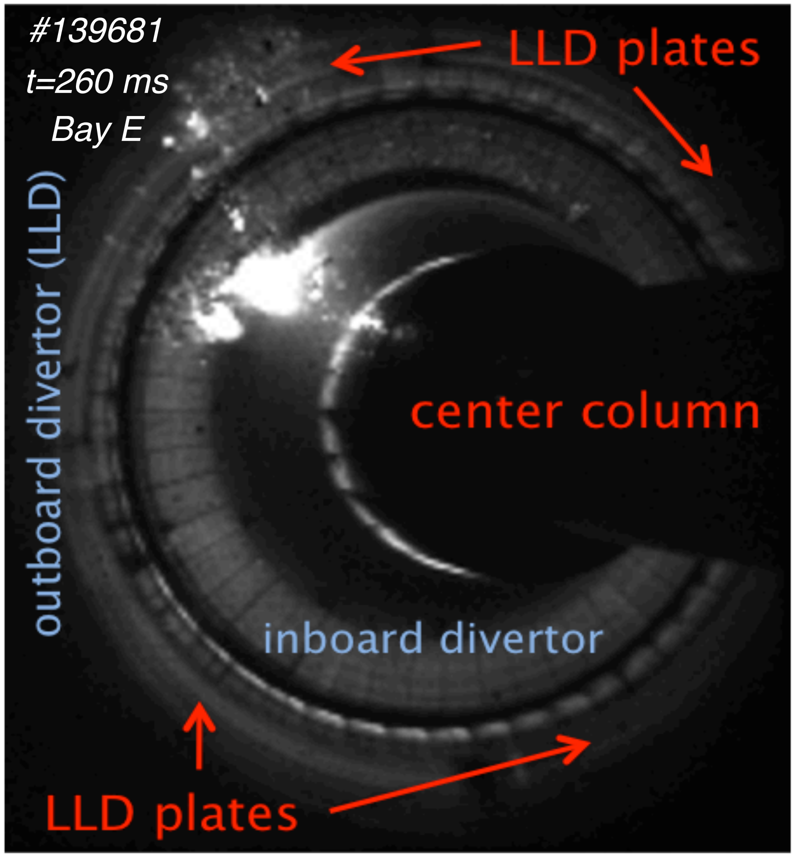
Typical Lithium operating conditions show low lithium core concentration, $n_{Li}/n_e < 0.1\%$

- Very similar discharges
  - Same configuration, same parameters (n_e,T_e): clean comparison
- Large Carbon content: edge Z_{eff} = 4–5 after 400 ms
- Lithium saturates to n_{Li} / n_e~0.04%
- **Investigation of C (and Li) sources and transport in progress**
  - **Li transport (trends & scalings) consistent with Neo-classical impurity transport**
  - **See poster EX/P3-34 by F. Scotti et al., "*Study of Core Transport of Intrinsic Impurities in ELM-free NSTX Discharges with Lithium Wall Conditioning*"**

Anomalous Events affecting Li influx

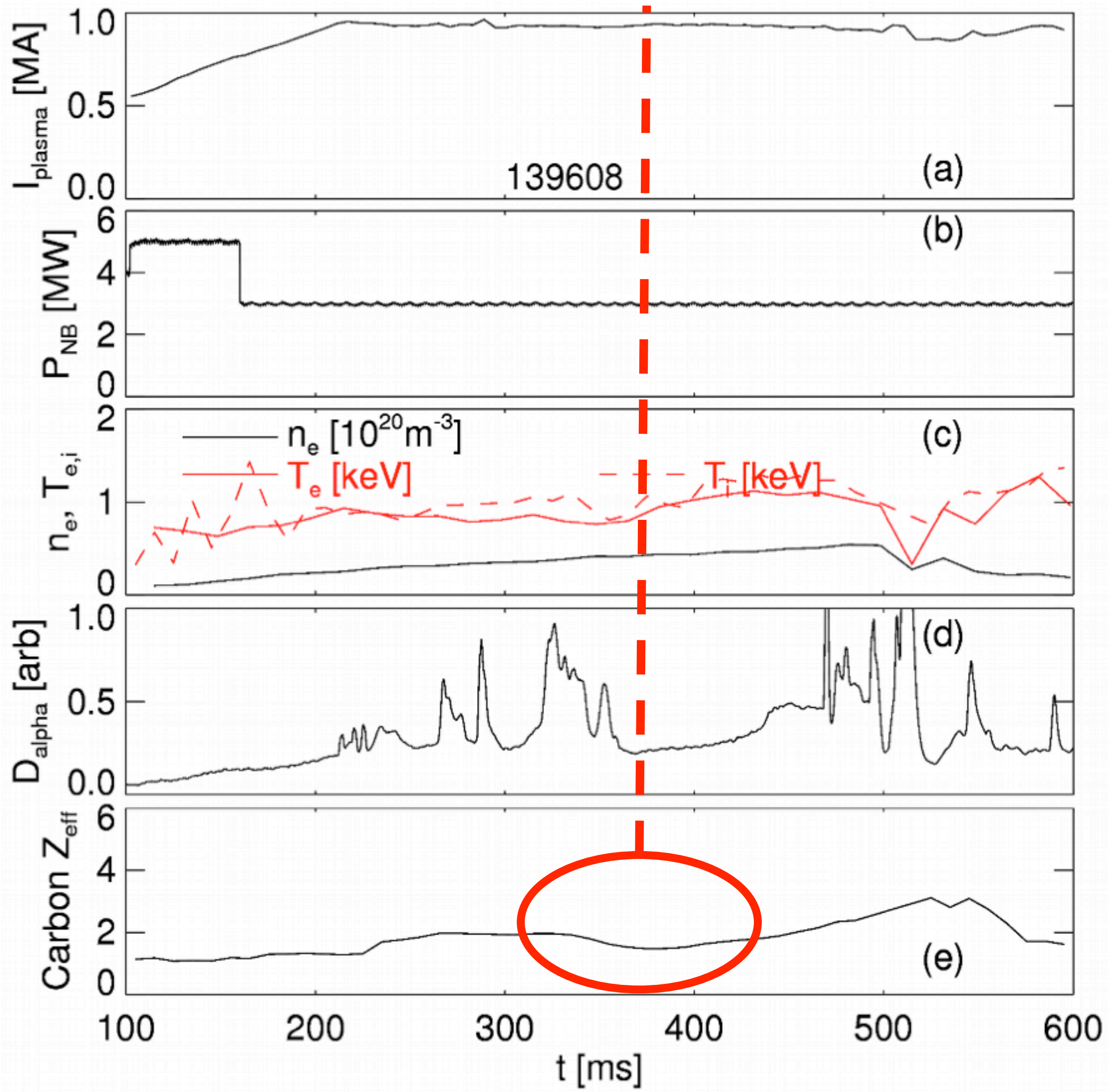
Li "*blob*" on divertor floor interacts with NSTX plasmas

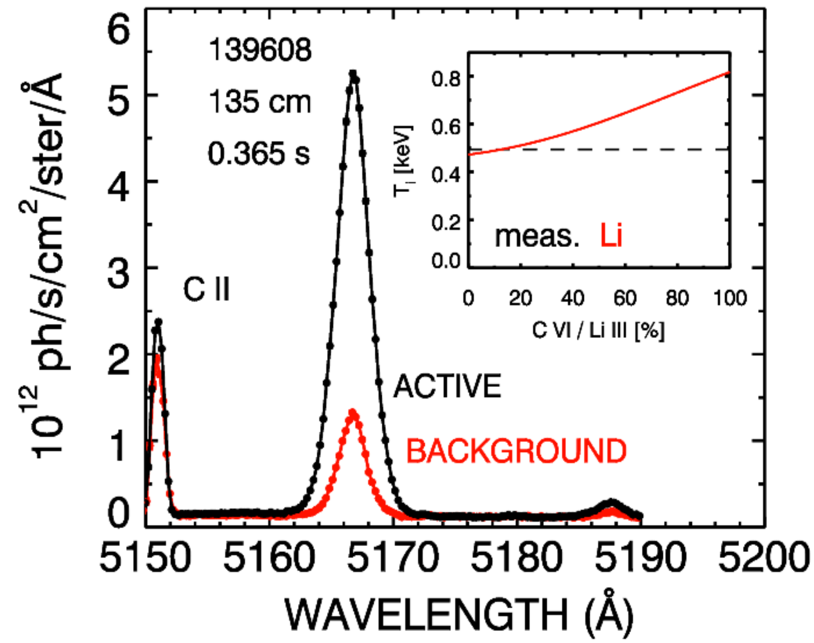


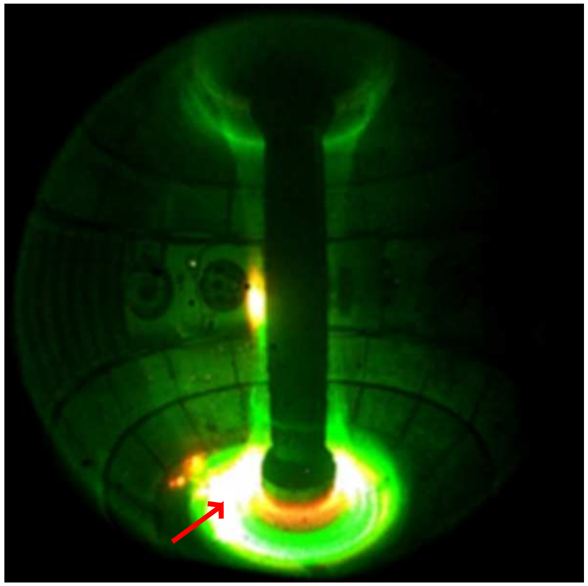


- Source of "blob" probably accumulation of Li mass near evaporator throat
- Plasma transiently and intermittently interacts strongly with Li blob
- Break up of macroscopic Li material when near strike point

Plasma survives after first interaction with Li blob, followed by increase in core Li concentration

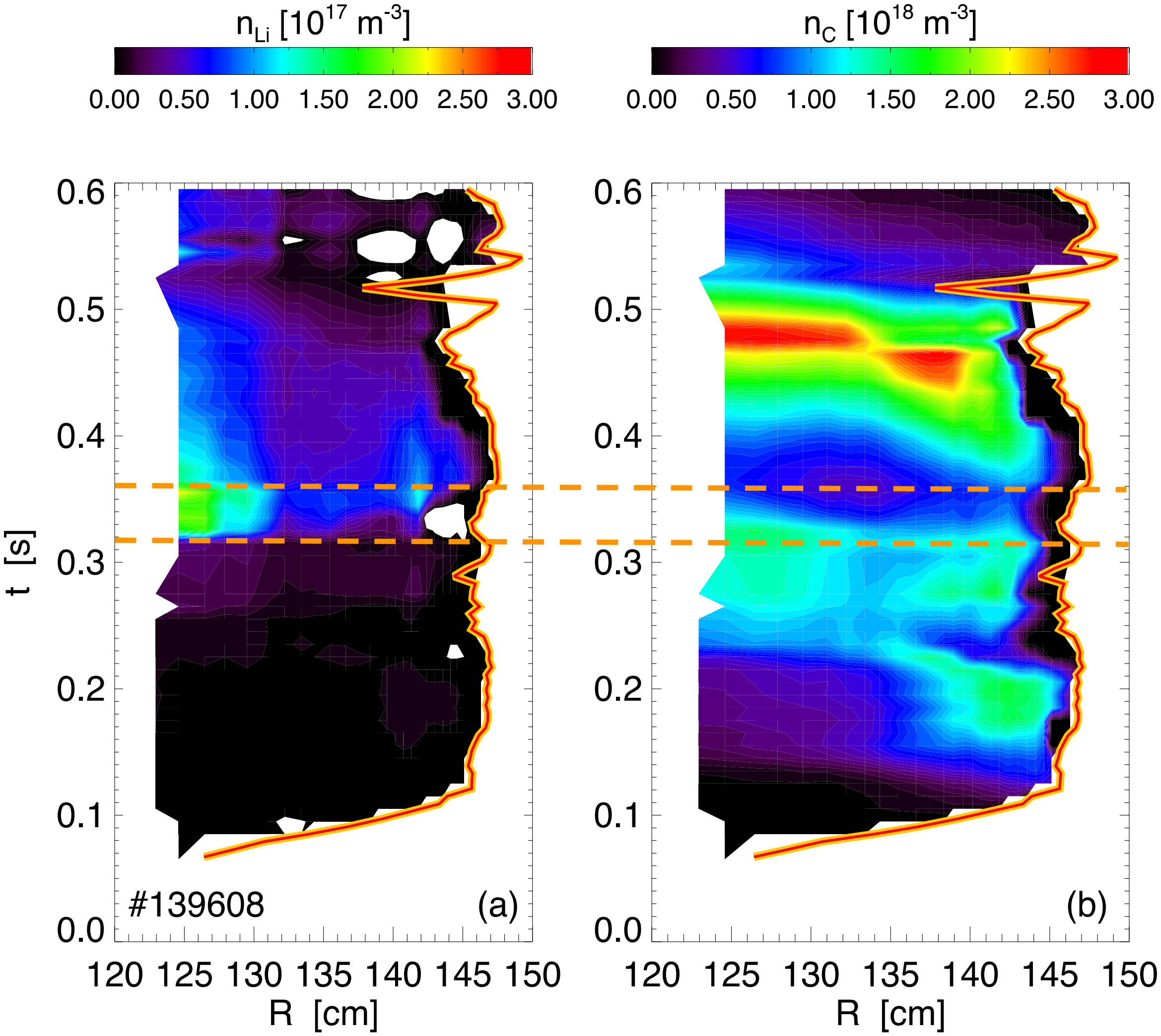






- Li-pCHERS spectrum around 360 ms dominated by Li
- **Carbon transiently decreases, n_C/n_e~1% or less (low for NSTX)**

Lithium "blob" transiently changes impurity content with n_{Li}/n_e~0.2% and an overall decrease in carbon.



- Large, localized Lithium source can transiently lead to higher n_{Li} in the core (as opposed to evaporated lithium or small granules)
- More similar to 'pellet', but completely un-controlled
- Transient decrease in Carbon content coincides with increase in Lithium content

The Lithium content increases with influx from "blob", but still remains extremely low

Summary

- Core Li concentration monitored throughout 2010 Run
- Broad range of operating conditions covered
  - B_{tor}, I_{pl}, aspect ratio/inner gap; different Li conditioning techniques
  - Anomalous events, e.g. Li blobs on divertor
  - (Plasma shape, ELMs, large MHD modes – not shown here)

> Plasma configuration has little effect on n_{Li}

> Only systematic dependence observed is on B_{tor}, I_{pl}
  - Attributed to general improvement in confinement

> **Negligible Li concentration is a robust property of NSTX**
  - $n_{Li}/n_e << 0.1\%$
  - **Carbon remains dominant impurity even after massive (hundreds of milligrams) Li evaporation**

- Investigation of C (and Li) sources and transport in progress
- High C concentration represents a barrier for Li influx?
  - Li transported outward by scattering on heavier C ions
  - > **See poster EX/P3-34 by F. Scotti et al., "*Study of Core Transport of Intrinsic Impurities in ELM-free NSTX Discharges with Lithium Wall Conditioning*"**

see also : M. Podestà et al., Nucl Fusion 52 033008 (2012)