NSTX Supported by U.S. DEPARTMENT OF ENERGY Office of Science

Modeling of Balmer series deuterium spectra with the Cretin code for diagnosing inner divertor re-attachment threshold in NSTX discharges with lithium coatings

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APS-DPP Conference 2009
Atlanta, GA

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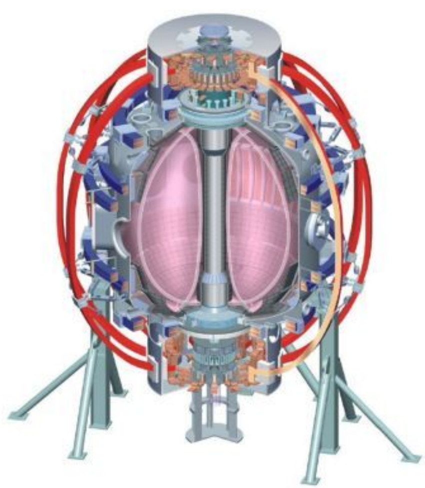

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Abstract

Application of evaporated lithium coatings on graphite divertor tiles in NSTX led to a reduction of divertor recycling.

The inner divertor electron density and recombination rate were also drastically reduced, suggesting that the normally detached inner divertor re-attached in many lithium-assisted ELM-free H-mode discharges.

This observation was based on the divertor brightness profiles of Stark-broadened ultraviolet spectral lines from the Balmer series n = 2-7…12 transitions.

To understand the divertor transport regimes with reduced recycling and the density thresholds for both the inner divertor detachment and X-point MARFE formation, we are developing a simulation of the NSTX divertor spectra in a realistic viewing geometry using the Cretin code. The non-local thermodynamic equilibrium radiation transport code Cretin uses a 1-D plasma model with neutral diffusion and line shape calculations based on the quasi-static ion microfield approximation and a binary electron impact collision model.

*Work supported by the U.S. DOE under Contracts DE-AC52- 07NA27344 and DE-AC02-09CH11466.

Outline & Summary

• Introduction: NSTX divertor regimes strongly modified with Lithium deposition.

• SOL Five Point Model was used to simulate inner divertor regimes with reduced recycling due to Li coatings:

- Increase in T_e and reduction in n_e at the target
- Suggests re-attachment of the inner leg.

• NLTE radiation transport code CRETIN was used to simulate Balmer series deuterium spectra in NSTX inner divertor.

• Stark broadening from n=10 Balmer line was used to estimate n_e in the inner divertor based on:

- Quasi-static ion microfield approximation
- Binary electron impact collision model.

• Post Li inner divertor plasmas show reduced recombination, higher T_e and reduced n_e, consistent in both fluid and spectroscopic analysis.

Divertor in STs and NSTX

- Spherical Tokamak (ST) Divertor Geometric Features:
  - small surface to volume ratio and plasma wetted area
  - short connection length
  - strong inner/outer heat flux asymmetry

- Achievement of dissipative regimes (radiative/detached) is challenging

BUT

- Potential CTF application: heat/particle fluxes potentially comparable to reactor

- NSTX:
  - Symmetric upper and lower divertor with graphite tiles
  - Open geometry: flexibility in plasma shaping
  - No active pumping: secular core density rise
  - Outer divertor: generally attached, high gas puffing to partially detach
  - Inner divertor detaches early in the discharge ($n_{e\text{-}core}$>2-3·10^{19} m^{-3})

Lithium as PFC in NSTX

• Lithium used on NSTX as a PFC: pellets injection or evaporative deposition on the divertor plates. Next step in FY2010: Liquid Lithium Divertor module.

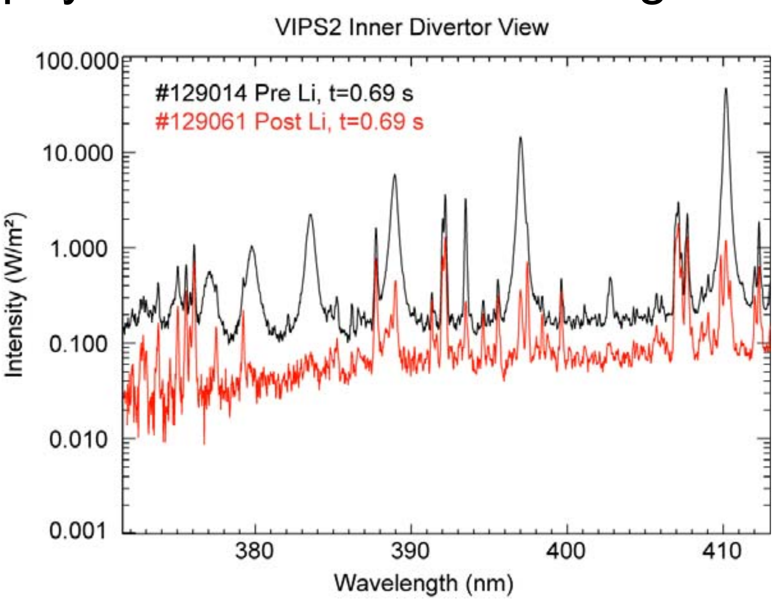
• Lithium capability of pumping hydrogen offers a potential solution for density control.

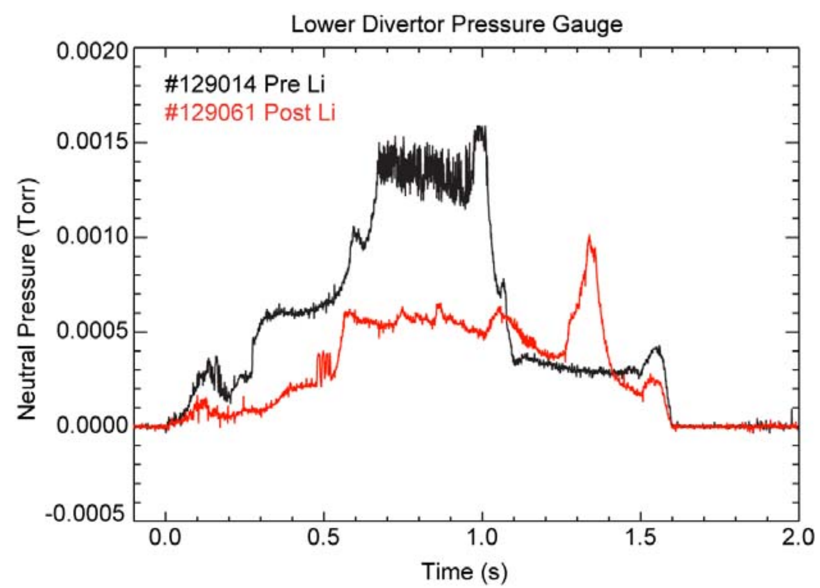
• Performance improvements in reduced recycling regimes with Li deposition:

- ELMs suppression,
- improvement of energy confinement and plasma performance,
- higher pedestal T_e and T_i (flatter T profile)

Research Motivation: Experimental Observation of Inner Divertor Re-attachment After Li Deposition

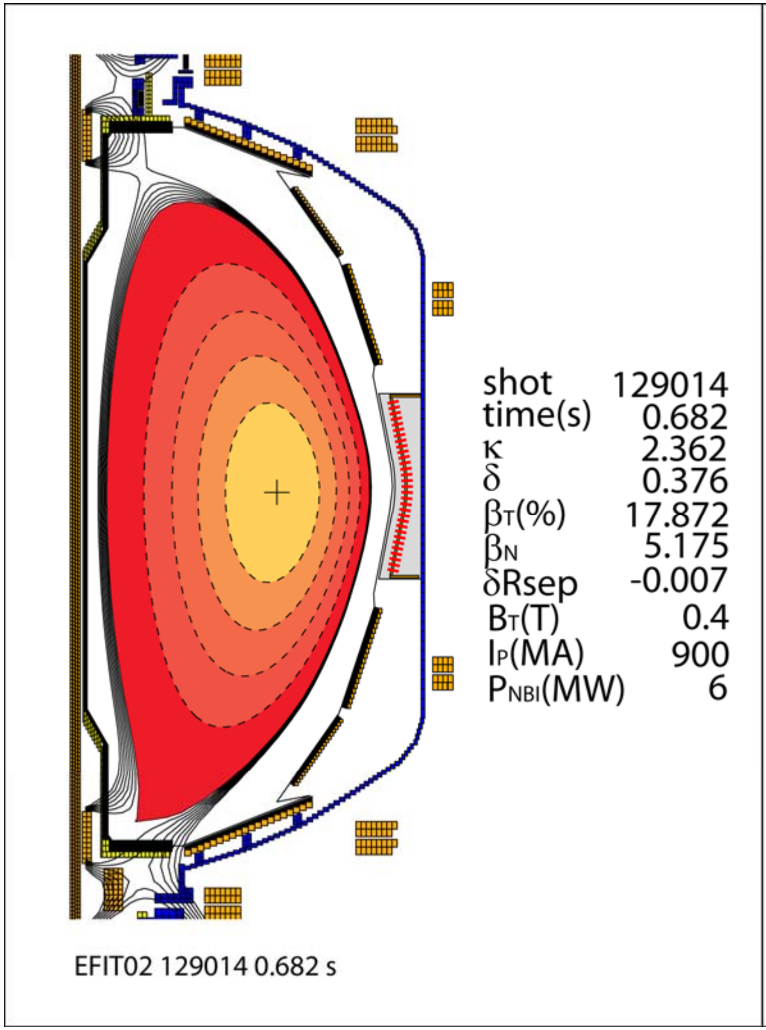
- The reduced recycling strongly modifies the divertor plasma:
  - Reduction/disappearing of high-n Balmer lines
  - Reduced Stark broadening of Balmer lines
  - Reduced neutral pressure
- This suggests that recombination is strongly reduced and inner divertor leg re-attaches in Li-assisted discharges.
- Fluid and spectroscopic modeling can be useful to understand the physics of these divertor regimes.

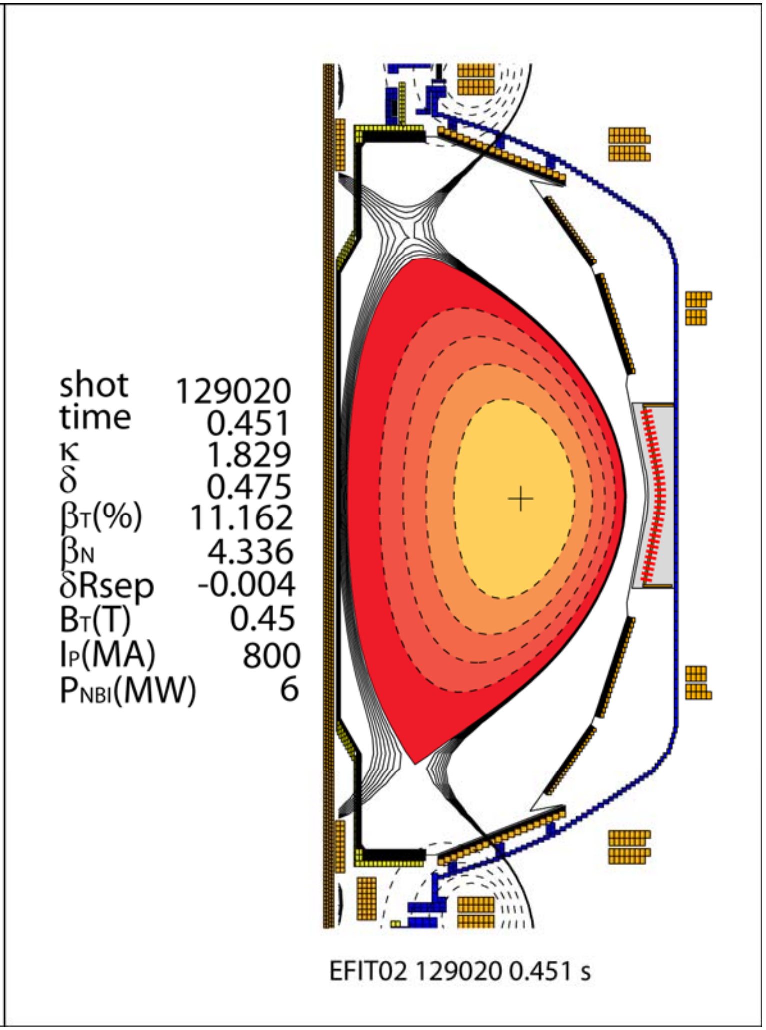




NSTX Reference Discharges

High elongation/ triangularity | Low elongation/ triangularity

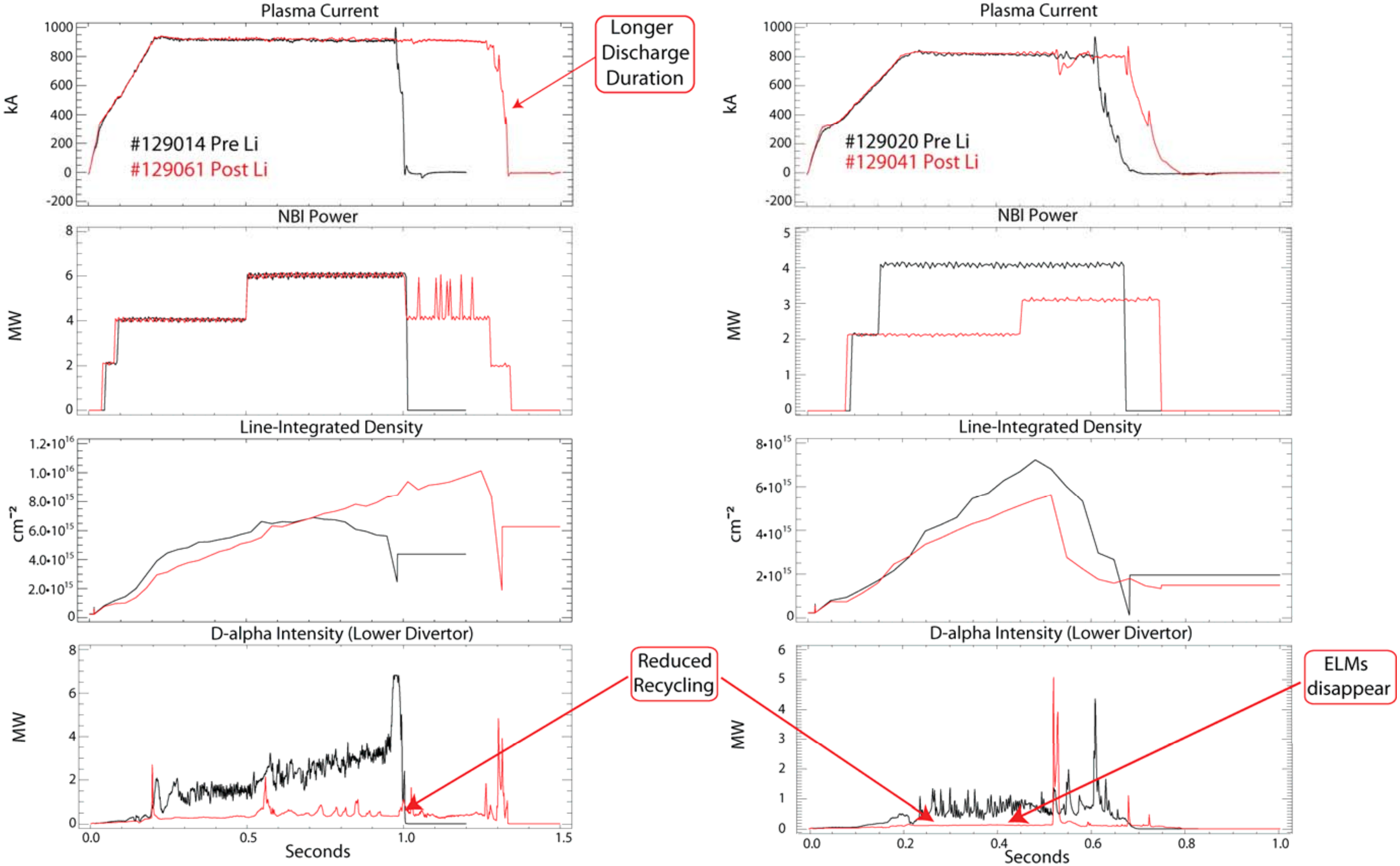




Lithium Coating Increases Discharge Duration, Reduces Recycling and Suppresses ELMs

High elongation/ triangularity

Low elongation/ triangularity



SOL/Divertor Modeling

- SOL plasma transport can be described by the Braginskii equations.
- A simpler set of equations can be used to describe the transport parallel to the magnetic field.

- Continuity Equation

$$\frac{\partial (nv)}{\partial x} = n\left(n_n \langle \sigma v \rangle_i - n \langle \sigma v \rangle_{rec}\right) + S_\perp$$

- Momentum Equation

$$\frac{\partial (mnv^2 + 2nT)}{\partial x} = -mnv\left(n_n \langle \sigma v \rangle_{cx+el} + n \langle \sigma v \rangle_{rec}\right)$$

- Power Balance Equation

$$\frac{\partial}{\partial x}\left(-\kappa_0 T^{\frac{5}{2}} + \frac{1}{2} mnv^3 + 5nTv\right) = -n^2 f_Z L_Z - \frac{3}{2} T n n_n \langle \sigma v \rangle_{cx+el} - nE_{ion} \langle \sigma v \rangle_i + Q_\perp$$

Five point model of the SOL plasma

• Simplified 2-point/1-D models useful to understand divertor detachment.

• In this work a five point model based on [R. Goswami, *Phys. Plasmas*, **8**,3 (2001).], was used.

• Simplified continuity, momentum and power equations are solved for the electrons in five different regions from the midplane to the divertor target.

• Radiation, ionization, momentum loss and volume recombination effects are included in the model assuming constant rates.

• Analytical solution in the five regions provides a pseudo 1-D profile of plasma parameters, n, T, v and pressure.

Five point model of the SOL plasma

- Region 1: volumetric SOL heat $Q_\perp$ and particle sources $S_\perp$, from midplane (x=0) to X-point ($x=x_x$).

$$\frac{d}{dx}(nv) = S_\perp, \qquad \frac{dp}{dx} = 0, \qquad \frac{d}{dx}\left(\kappa_0 T^{\frac{5}{2}}\frac{dT}{dx}\right) = -Q_\perp$$

- Region 2: Conduction region, until start of energy loss zone ($x=x_L$,$T(x_L)$=10eV).

$$\frac{d}{dx}(nv) = 0, \qquad \frac{dp}{dx} = 0, \qquad \frac{d}{dx}\left(\kappa_0 T^{\frac{5}{2}}\frac{dT}{dx}\right) = 0$$

- Region 3: Radiation front region (max. C radiation eff.) until start of the neutral zone ($x=x_C$,$T(x_C)$=4eV).

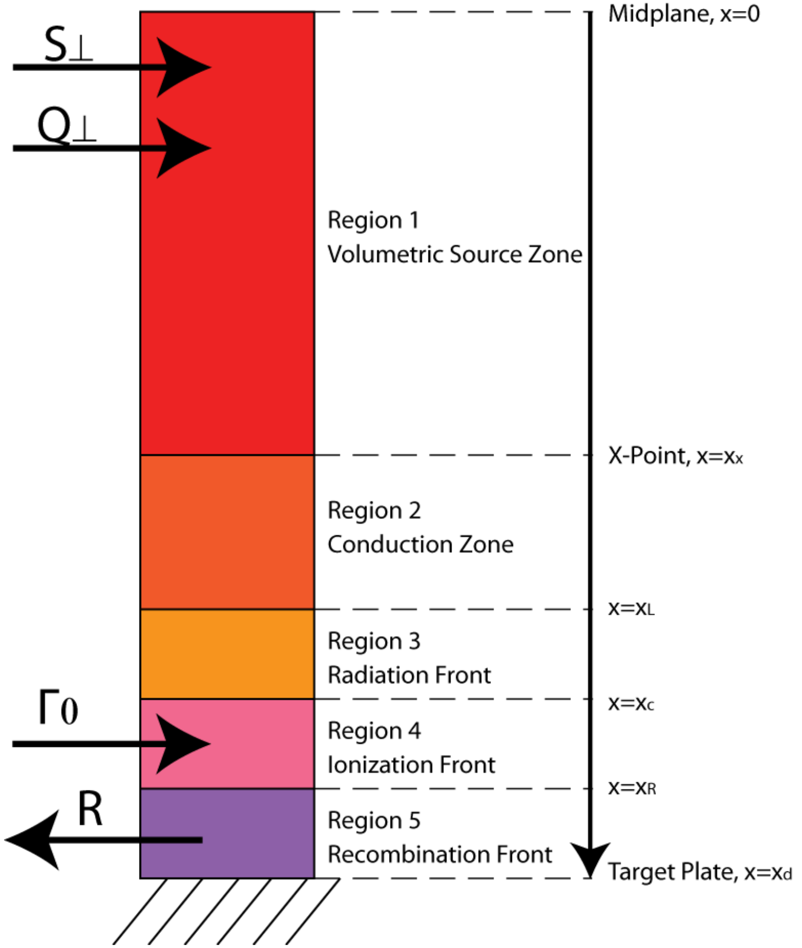
$$\frac{d}{dx}(nv) = 0, \qquad \frac{dp}{dx} = 0, \qquad \frac{d}{dx}\left(\kappa_0 T^{\frac{5}{2}}\frac{dT}{dx}\right) = L$$

- Region 4: Ionization front region (most neutrals are ionized) until onset of recombination region ($x=x_R$,$T(x_R)$=1.6eV).

$$\frac{d}{dx}(nv) = \Gamma_0\delta(x - x_C), \qquad \frac{dp}{dx} = -m_i v_x n v, \qquad \frac{d}{dx}\left(\kappa_0 T^{\frac{5}{2}}\frac{dT}{dx}\right) = 0$$

- Region 5: Recombination front region (recombination exceeds ionization), until divertor plate.

$$\frac{d}{dx}(nv) = -R, \qquad \frac{dp}{dx} = -m_i v_x n v, \qquad \frac{d}{dx}\left(\kappa_0 T^{\frac{5}{2}}\frac{dT}{dx}\right) = 0$$



Modeling Reduced Recycling in Lithium-assisted Discharges

- Volumetric heat source $Q_\perp$ obtained from estimates of the power to the SOL
- Ionization fluxes to the center stack Langmuir probes were used to estimate the scaling of the volumetric particle source $S_\perp$
- Reduced recycling is modeled decreasing the amplification factor Γ of the ionization flux in the divertor region due to the reduced neutral pressure
- The charge exchange frequencies ν are also modified accordingly.

- Different simulation scenarios:

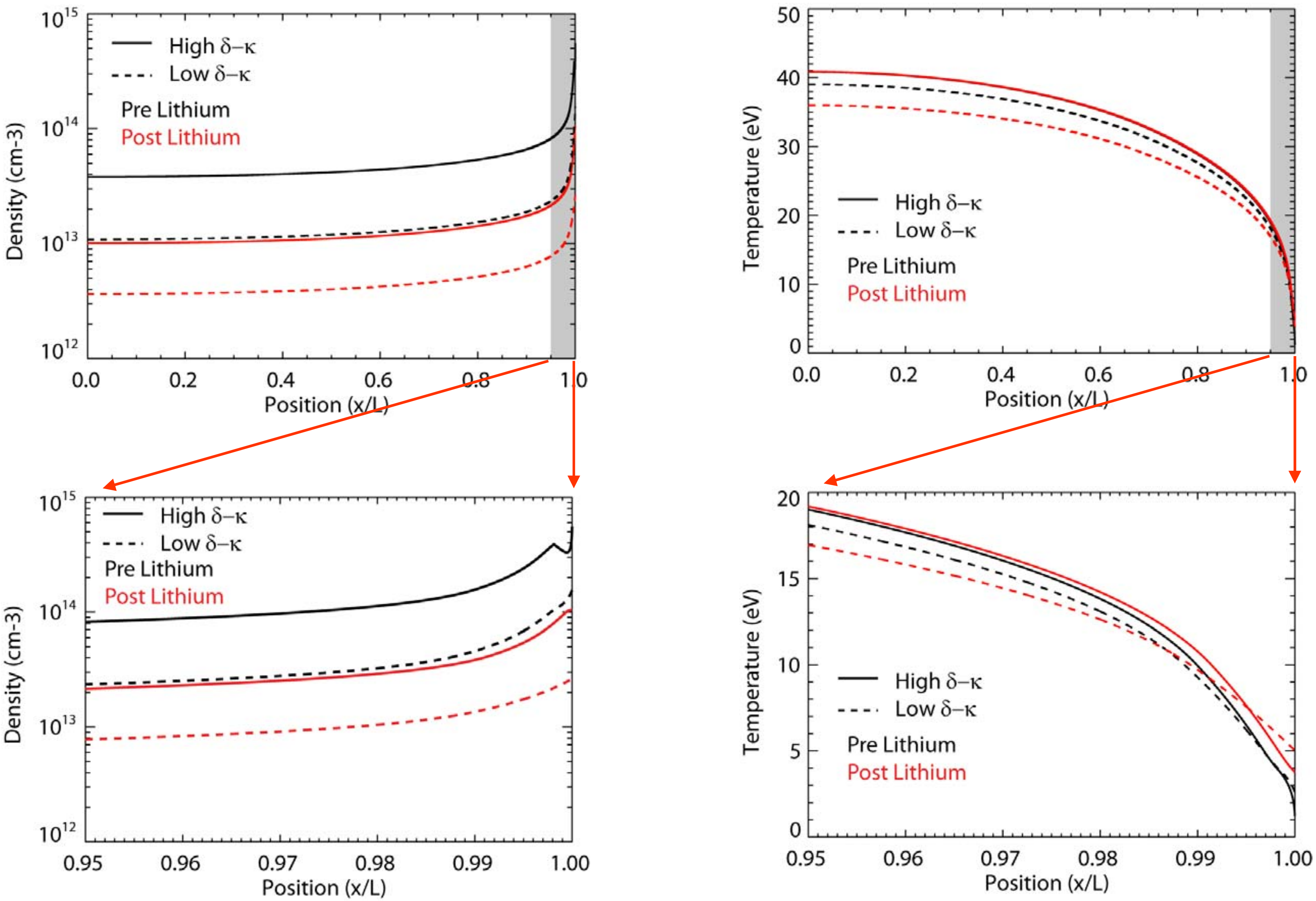
  - In Scenario-1 $f_{RAD} = \dfrac{L \cdot \delta_L}{q_{\|}}$ is kept constant for Pre/Post Li discharges
  - In Scenario-2 f_{RAD} is increased for Pre-Li discharges and decreased for Post-Li discharges

Five Point Model: 1st Scenario

	High δ-κ, Pre-Li	High δ -κ, Post-Li	Low δ-κ, Pre-Li	Low δ-κ, Post-Li
$Q_\perp$ (MWm^{-3})	3.28	3.28	2.8	2.1
$S_\perp$ ($10^{23}\ s^{-1}m^{-3}$)	2.5	1.2	1.8	0.8
Γ_0 ($10^{23}\ s^{-1}m^{-2}$)	20	3.2	1.1	0.05
v_0 ($10^5\ S^{-1}$)	4	1.33	0.26	0.026
R ($10^{23}\ s^{-1}m^{-3}$)	1	1*	1	1*

- Midplane-target connection length L=13m, Xpoint-Target L_x=4m
- Radiated power fraction was kept constant in the 4 different simulations.
- *In Lithium discharges the higher T_e at the target places the divertor in a regime of low radiation and no recombination.

Simulation Results (1st Scenario)
Re-attachment of Inner Divertor in Lithium Discharges

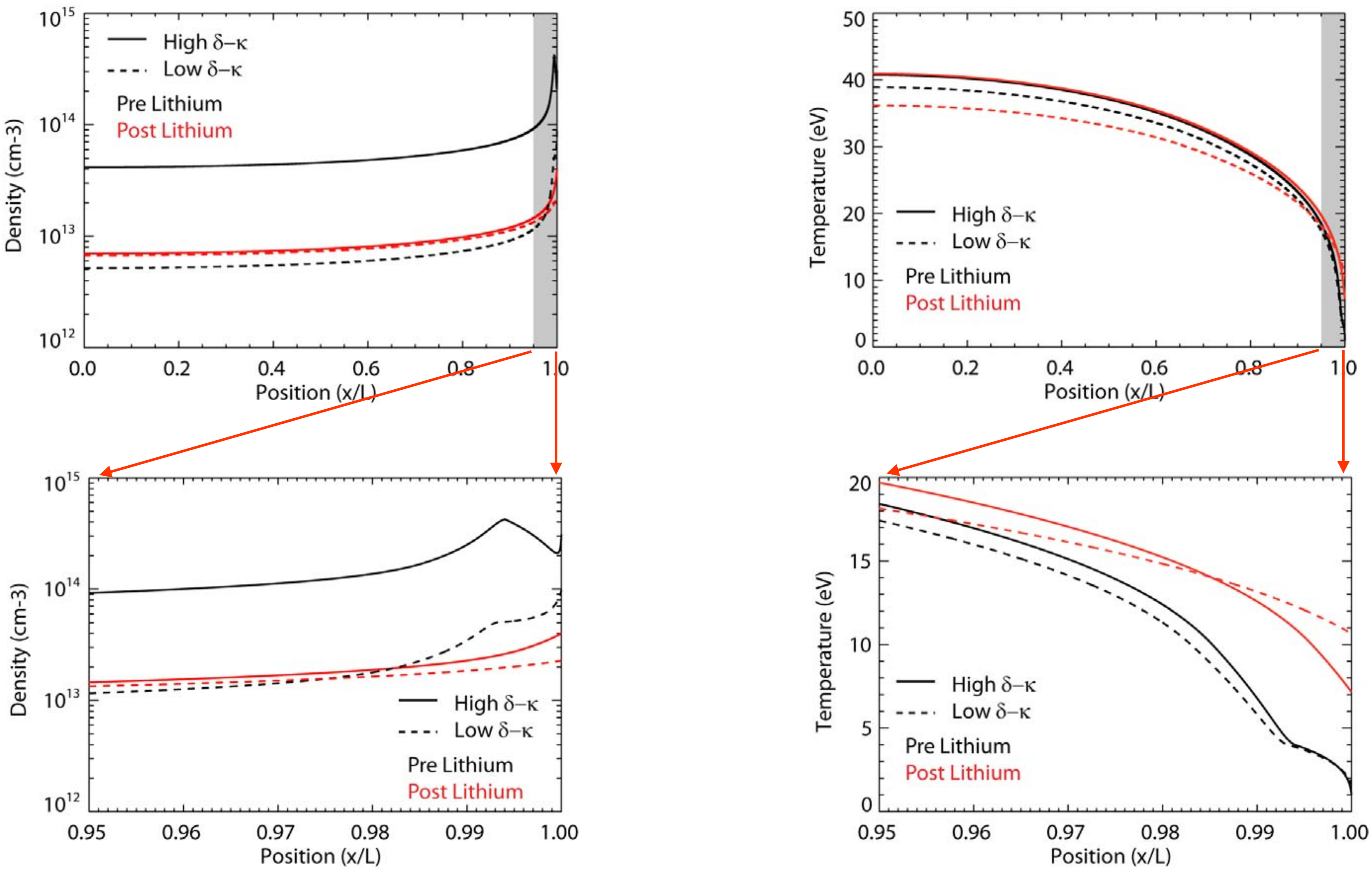


Five Point Model: 2nd Scenario Varying f_{RAD}

	High δ-κ, Pre-Li	High δ -κ, Post-Li	Low δ-κ, Pre-Li	Low δ-κ, Post-Li
$Q_{\perp}$ (MWm^{-3})	3.28	3.28	2.8	2.1
$S_{\perp}$ (10^{23} $s^{-1}m^{-3}$)	1.25	1.2	0.9	0.8
Γ_0 (10^{23} $s^{-1}m^{-2}$)	10	3.2	0.55	0.05
v_0 (10^5 S^{-1})	4	1.33	0.26	0.026
R (10^{23} $s^{-1}m^{-3}$)	1	1*	1	1*

- A 5-10% increase in the radiated power for the pre lithium discharges allowed the accessibility of the detached regime for lower ionization fluxes (50% in this simulation).
- The recombining, low temperature region expands towards the X-point.
- A reduction of the radiated power fraction for the post Li case increases T_e at the divertor target (even 50% higher fluxes would still allow an attached solution).

Simulation Results (2nd Scenario) Te at Target Increases for Reduced f_{RAD}



CRETIN Code: Atomic Model

• **CRETIN** is a non-local thermodynamic equilibrium (NLTE) radiation transport code, [H. A. Scott, *J. Quant. Spectrosc. and Radiat. Trasfer*, **71** (2001)].

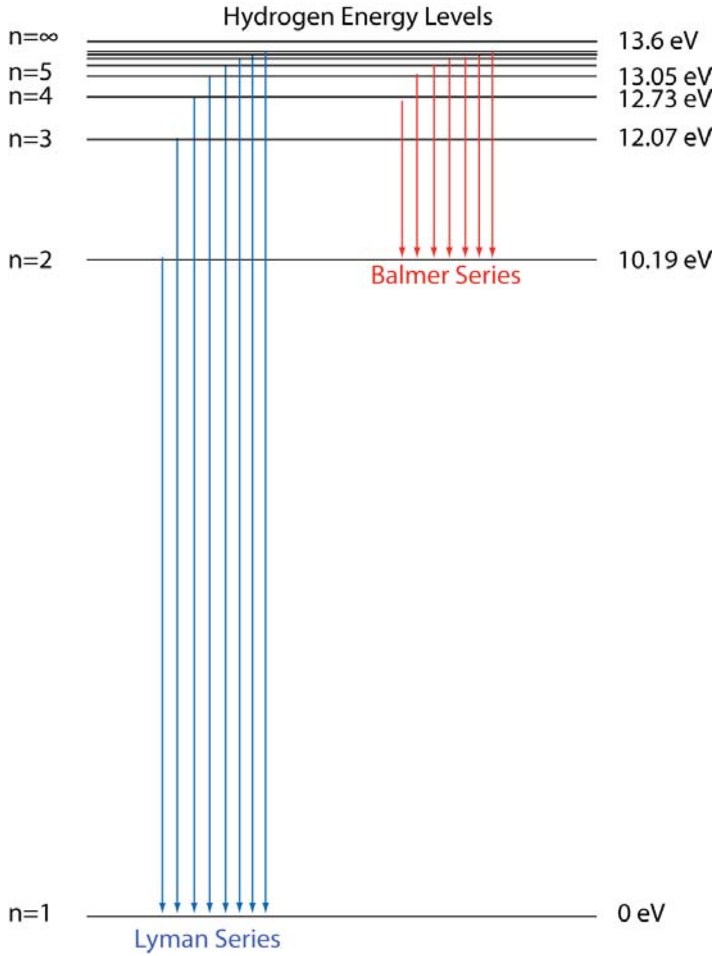
• A simple Hydrogenic model for Deuterium (D) levels was used to generate the atomic structure.

-Principal quantum numbers up to *n=30* and orbital quantum numbers up to *l=14* were included.

-No molecular species/transitions are included.

• **CRETIN** can be run as postprocessor to external data (plasma parameters, e.g. n, T) or it can generate its own time-space dependent profiles.

-1-D steady state plasma models were used in this work.



CRETIN Code
Reaction Rates

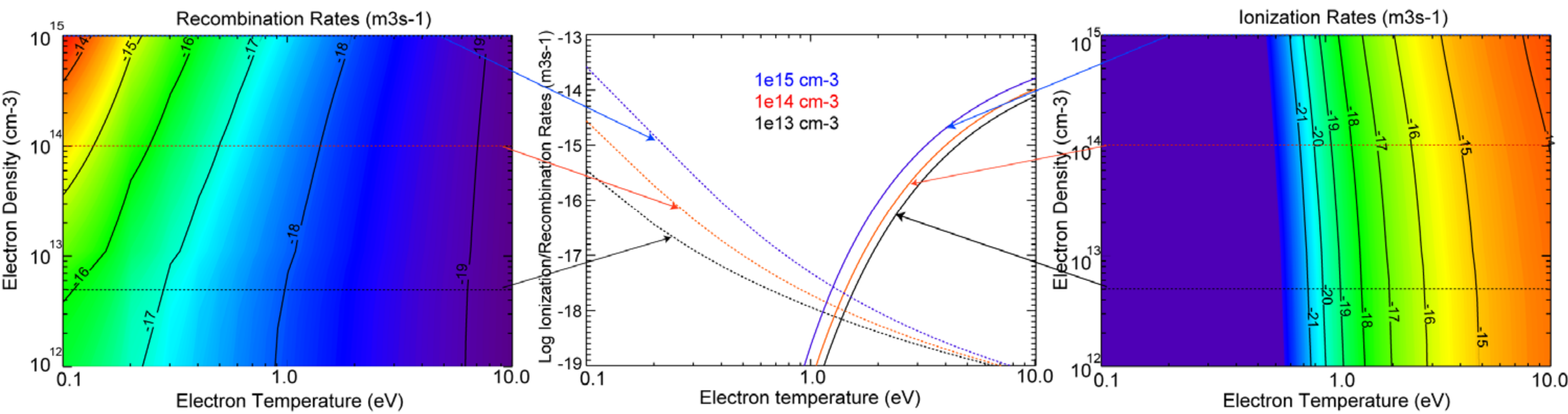
• **CRETIN** calculates rates for ionization, excitation and recombination (collisional and radiative) based on local parameters.

-The spatial coupling occurs through radiation transport.

-Atomic populations are then derived.

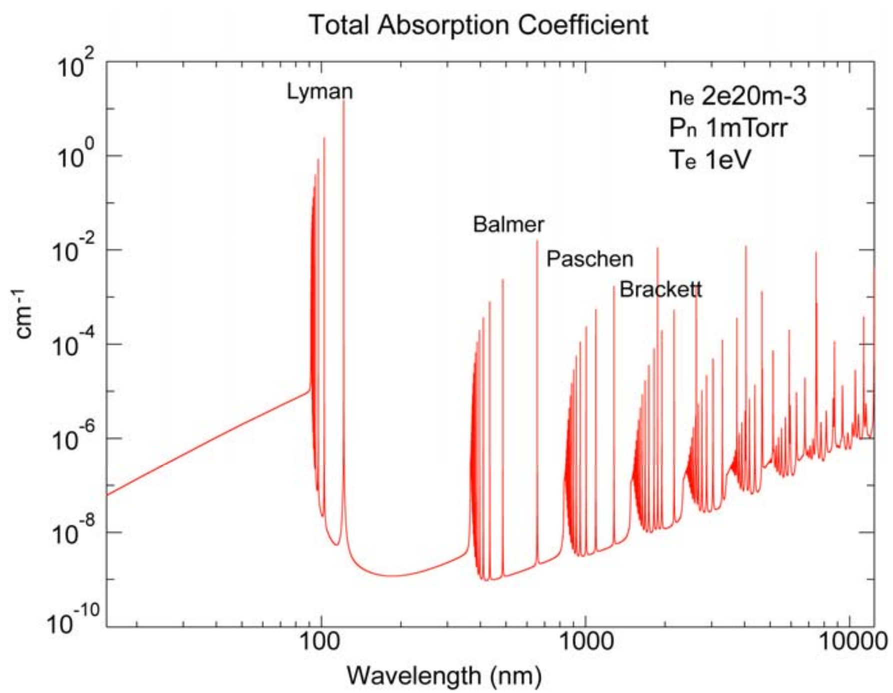
-Continuum and line radiation are treated separately and coupled to the atomic kinetics.

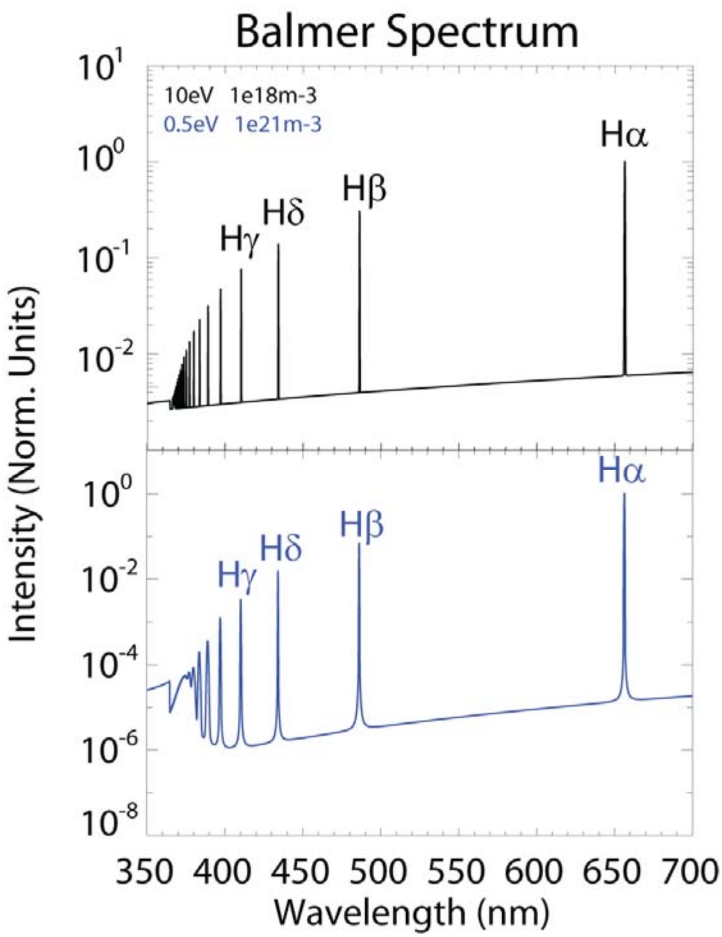
• Rates calculated by **CRETIN** based on an Hydrogenic model for Deuterium, show that for low Te (<1.5 eV) and high ne (>1e13cm-3), recombination dominates over ionization processes.



Recombination Processes in the Divertor Region

- Due to recombination processes high-n excited states are efficiently populated. Their relaxation results in the appearance of the high-*n* UV Balmer lines spectra.
- In high n_e low T_e plasmas, radiation trapping could modify the excited states level populations. Balmer series lines radiation can be assumed optically thin.





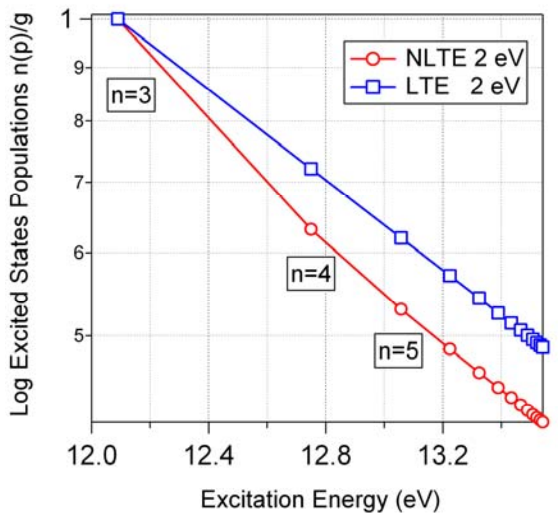
High-n Balmer transitions as plasma diagnostics

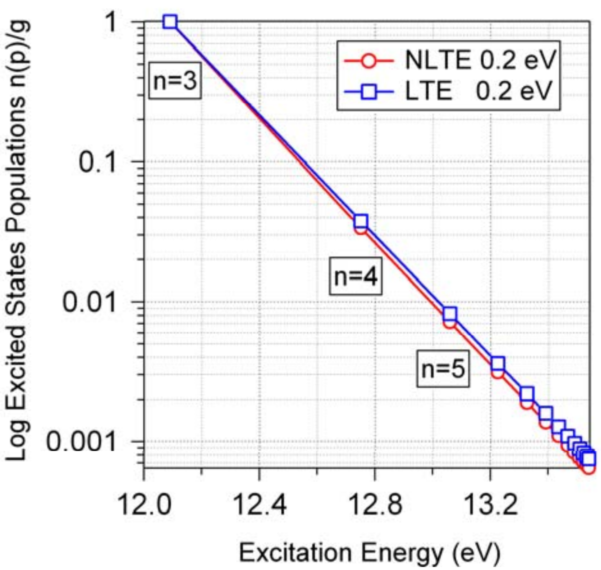
- Signature of recombination.
- For T_e < 1.5 eV, T_e diagnostics:

  -From the slope of the excited states population against the level energy (need assumptions of Saha-Boltzmann equilibrium).

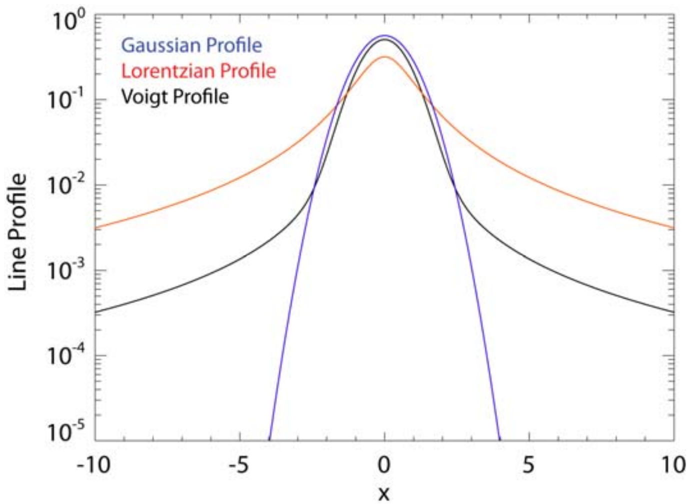
  -From the relative intensity of line and continuum background. (neglect molecular pseudo-continuum background).

  -From the slope of photo-recombination continuum.
- Stark broadening of Balmer lines as an electron density diagnostics.





Stark Broadening and Line Shape Calculations



- Broadening mechanisms:

  -Natural broadening (Lorentzian)

  -Doppler broadening (Gaussian) → Voigt Profile

  -Stark broadening (Lorentzian)

- Stark effect generated by the action on the neutral emitter of the electric microfield created by the perturber particles at scales where quasi neutrality is not fulfilled.
- **CRETIN** includes a code for line shape calculations, **TOTAL** [Calisti, PRA 1990].
- **TOTAL**: line shapes from binary electron impact model and quasistatic ion microfield.
- Electrons: binary (one perturber /collision) and instantaneous impact approximations.
- Ion quasistatic approx: collisions as an almost constant perturbation. Requires line width much larger than typical fluctuation frequency of ion microfield.

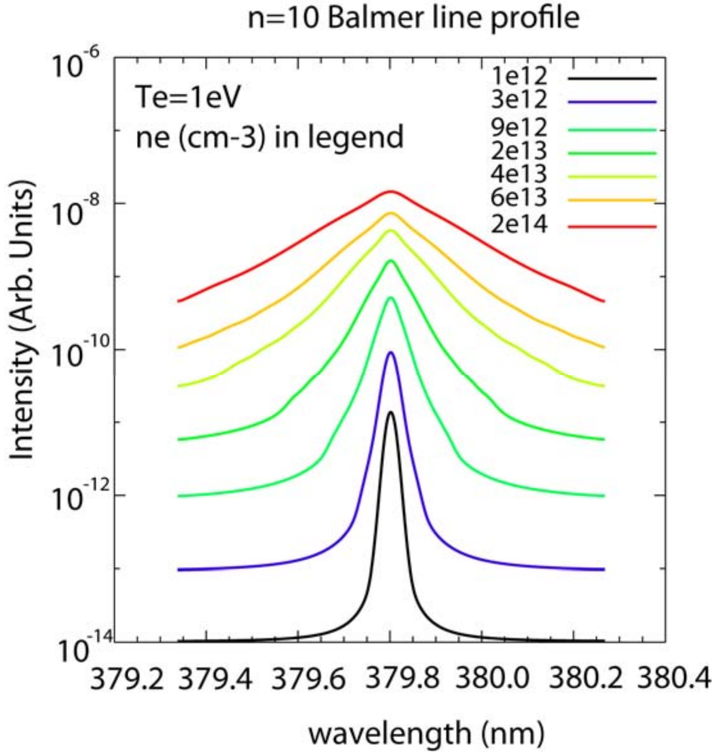
Stark Broadening and Line Shape Calculations

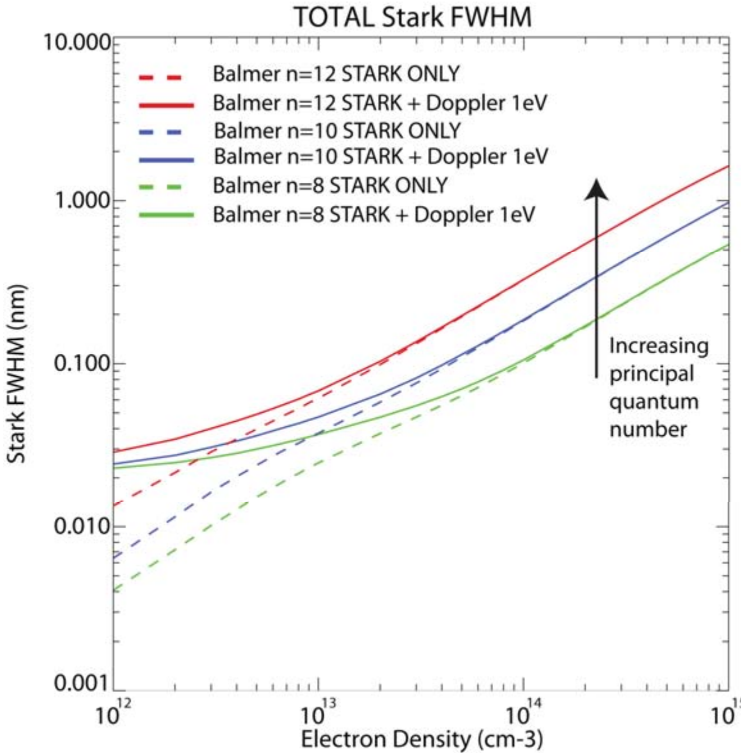
• Stark broadening increases with n_e due to the higher microfields.

• High-n level transitions show larger broadening. More suitable as n_e diagnostics.

• In the present work, Deuterium UV Balmer series lines with n_{max} up to 15 were treated with **TOTAL** to take into account for Stark effect and Doppler broadening.

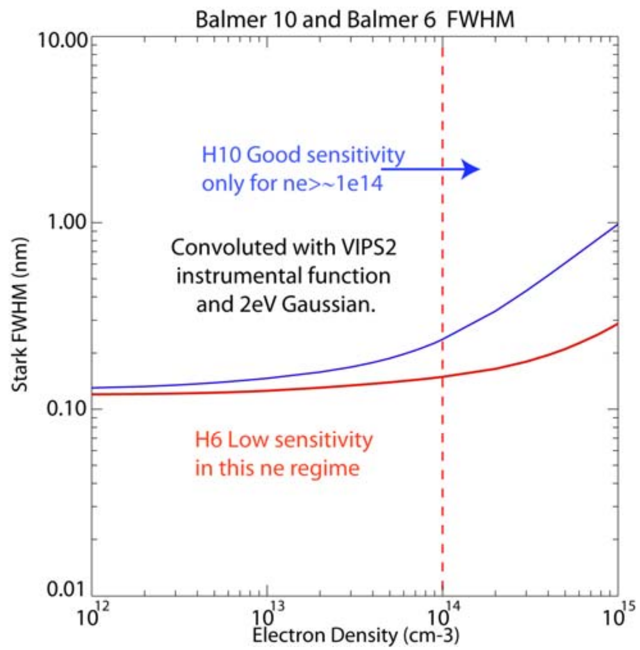
• The Gaussian instrumental response was convolved with the line shape generated by **TOTAL** to obtain the final spectra.

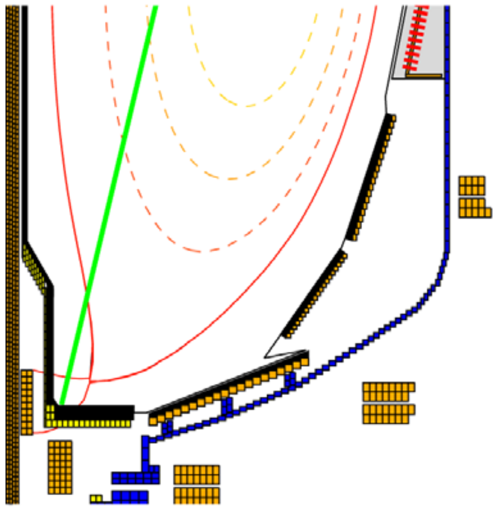




CRETIN Simulation

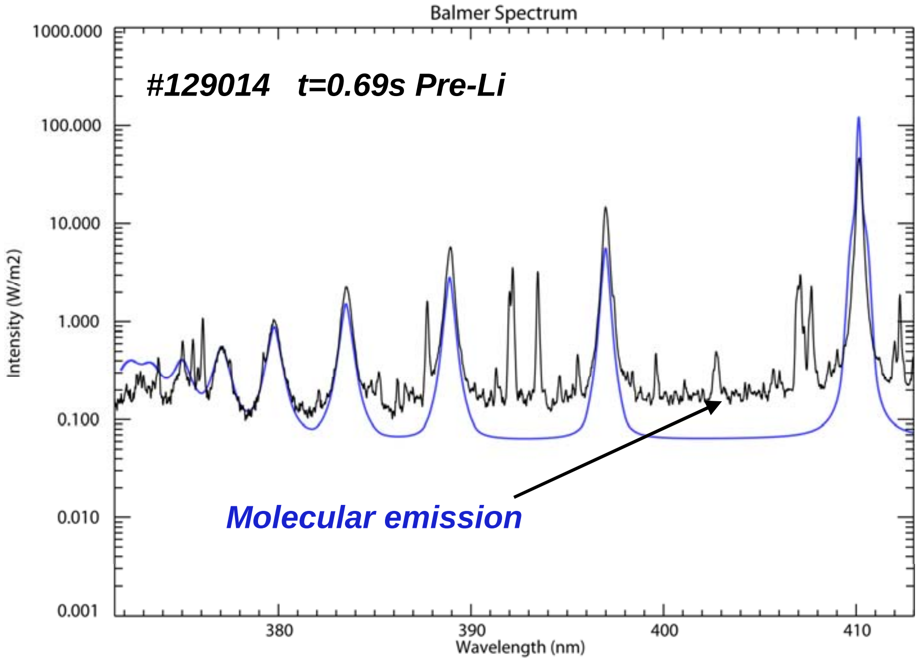
- Data were acquired by the divertor spectrometer VIPS:
  - Viewing chord looking at the inner divertor
  - Instrumental function 1.1 A (1.2 A after convolution with 2eV ions).
- n_e was estimated from Balmer line Stark broadening from n=10.
- 1D CRETIN simulations were used to reproduce spectroscopic data.
- Simulated spectra were scaled by a constant factor in order to reproduce the detector view.

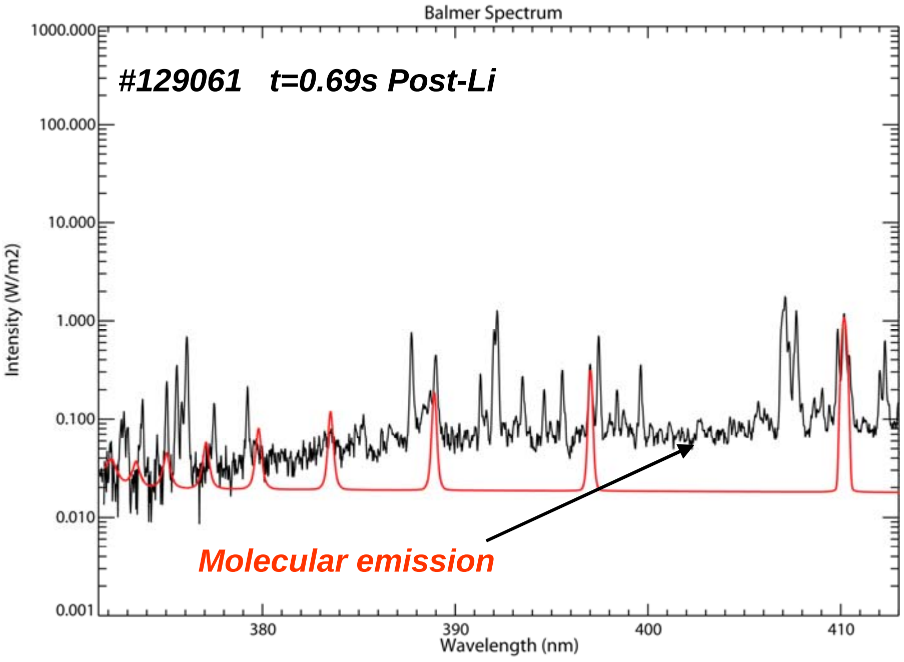




1-D CRETIN Simulation

High elongation/ triangularity





ne~5±0.5e20m-3 from H10 Stark Broadening

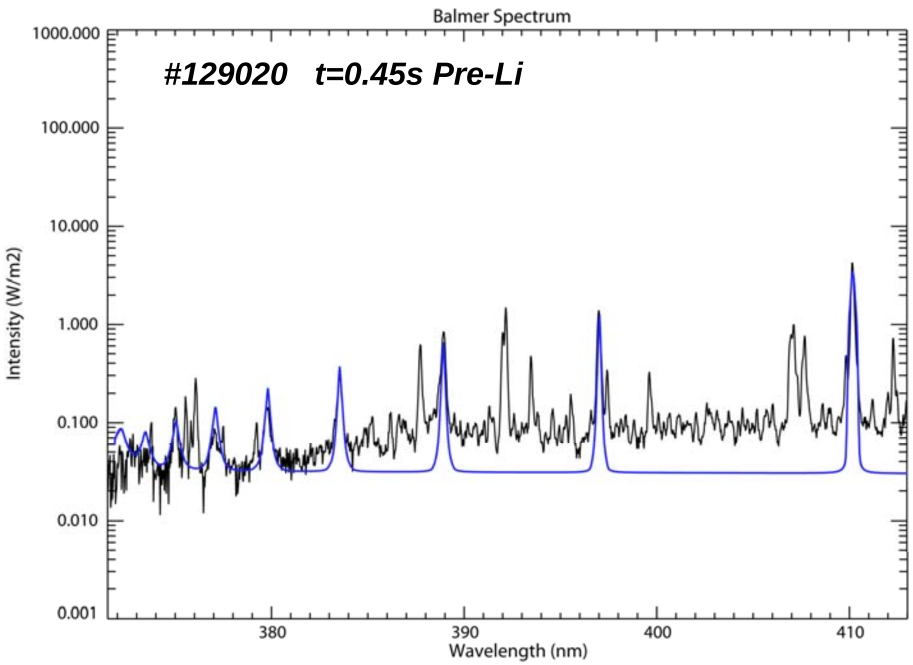
Te~1.1 eV

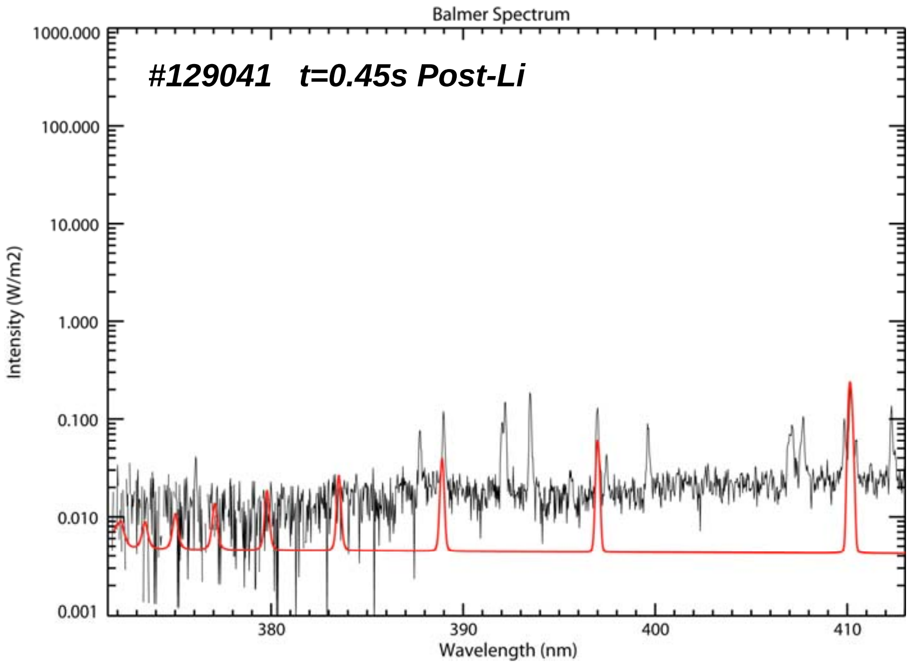
ne=1.1±0.2e20m-3 from H6 Stark Broadening

Example spectrum for Te=5 eV is shown in red

1-D CRETIN Simulation

Low elongation/ triangularity



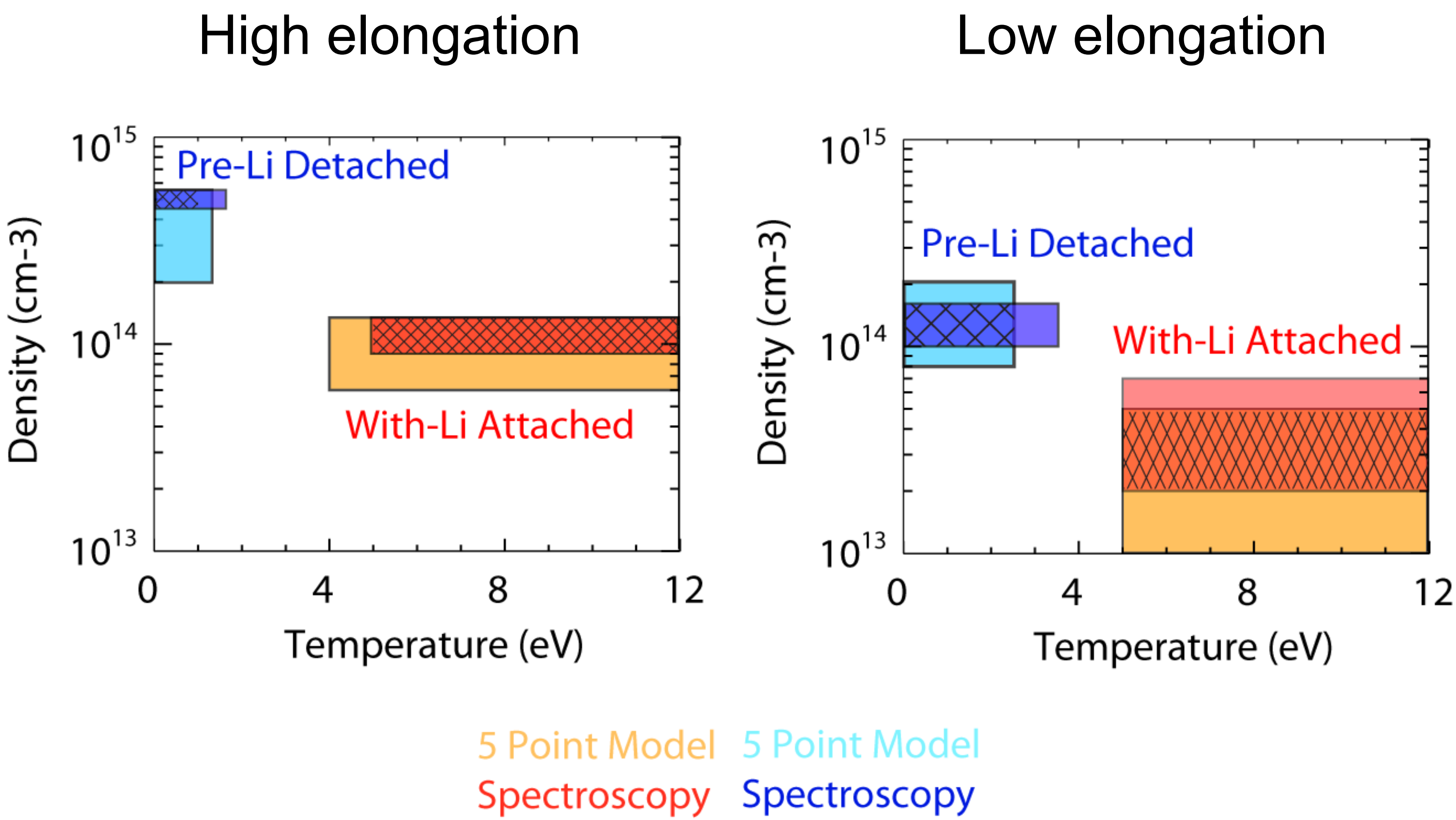


ne~1.3±0.2e20m-3 from H10 Stark Broadening
Te~3 eV

Ne~5±3e19m-3 from H6 Stark broadening

Example spectrum for Te=7 eV is shown in red

Results Comparison



Discussion

- Five Point Model:
  - Helps to qualitatively explain the lower recycling regimes but
  - Constant rates are used for the atomic processes
  - Perpendicular transport effects are ignored in this treatment
  - Radiation losses are overestimated
- Sensitivity
  - H10 Stark broadening is only sensitive to high densities (n>1e14cm-3)
  - Higher-n transitions would be more convenient but intensity is too low (in attached case only H6 is available)
- Contamination issues:
  - Carbon impurity lines make difficult excited state population evaluation especially in the lower density attached regimes.
  - Molecular emission significantly modifies the continuum background