Carbon content and transport investigations on W7-X with Charge Exchange Recombination Spectroscopy

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Fusion on Earth

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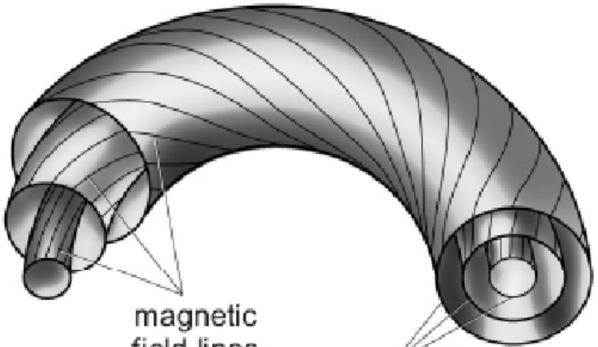
- Most viable reaction for fusion reactors:

$$D + T \rightarrow {}^{4}He\,(3.52\,MeV) + n\,(14.1\,MeV)$$



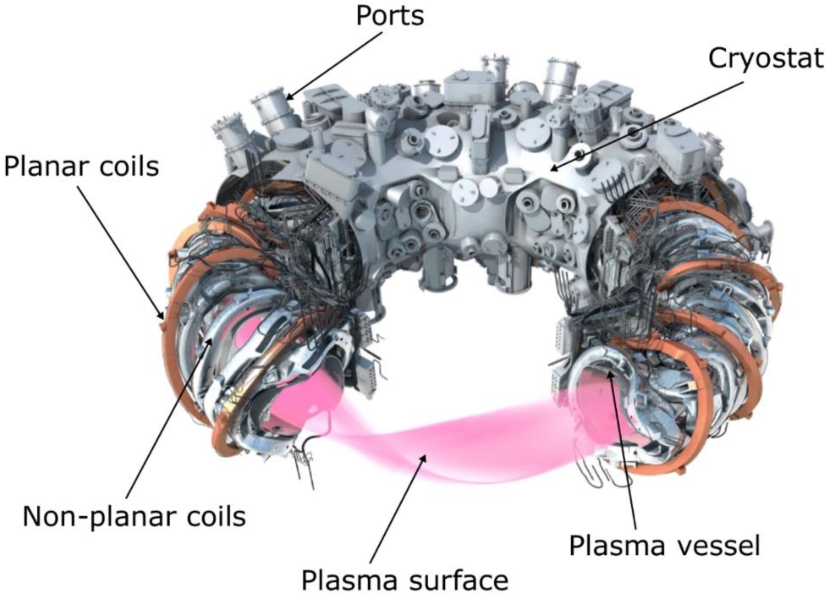
- For energy producing $n_i T_i \tau_E$ needs to be above a certain limit.

→ Magnetic confinement: torus shaped plasma, twisted magnetic lines

$$n_i \propto 10^{19} - 10^{20}\,m^{-3}$$
$$T_i \propto 10\,keV \propto 100\,million\,°C$$

Wendelstein 7-X stellarator

- Twisted plasma shape
- Changing plasma cross section
- Carbon plasma facing components



Impurities in the plasma:

- Entering the plasma from wall components.
- Performance losses by dilution and radiation. Need for control.
- Understanding of behavior is crucial.

Impurity transport

- **Neoclassical transport**: collisional transport in toroidal geometry
- **Anomalous transport**: additional transport effects (e.g. turbulence)
- Neoclassical models predict impurity accumulation in the core plasma for W7-X, which can affect the performance through power losses.

[Burhenn, Nucl. Fusion (2009) 065005]

Is impurity accumulation observed during specific plasma settings?
What dominates the impurity transport during different configurations?

Impurity transport

- $\frac{\partial \, n_{imp}}{\partial \, t} = -\nabla \, \Gamma_{imp} + Q_{sources} + Q_{sinks}$

- Impurity transport flux: $\Gamma_{imp} = -D \frac{\partial n_{imp}}{\partial r} + v \, n_{imp}$

- Transport coefficients: diffusion (D) and convection velocity (v)

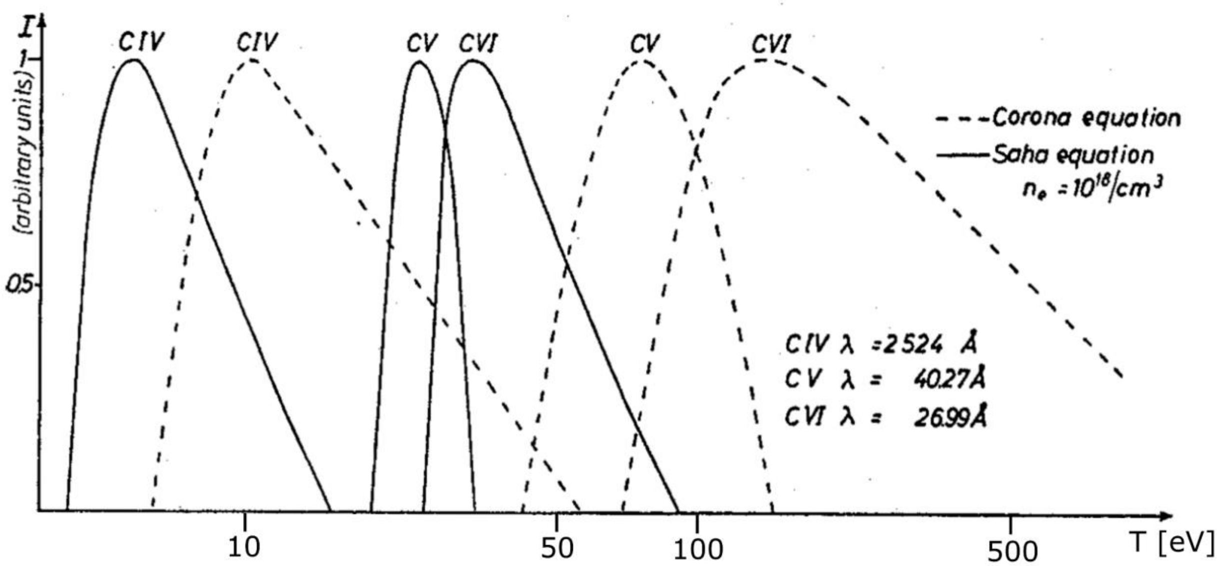
- In steady state scenario in the core: $\Gamma_{imp} = 0 \rightarrow \frac{v}{D} = \frac{1}{n_{imp}} \frac{\partial n_{imp}}{\partial \, r}$

Tool: [B. Geiger, C. Swee]

1 dimensional impurity transport code pySTRAHL. Changing the input diffusion (D) and convection velocity (v) to match the output carbon density with the experimental profiles.

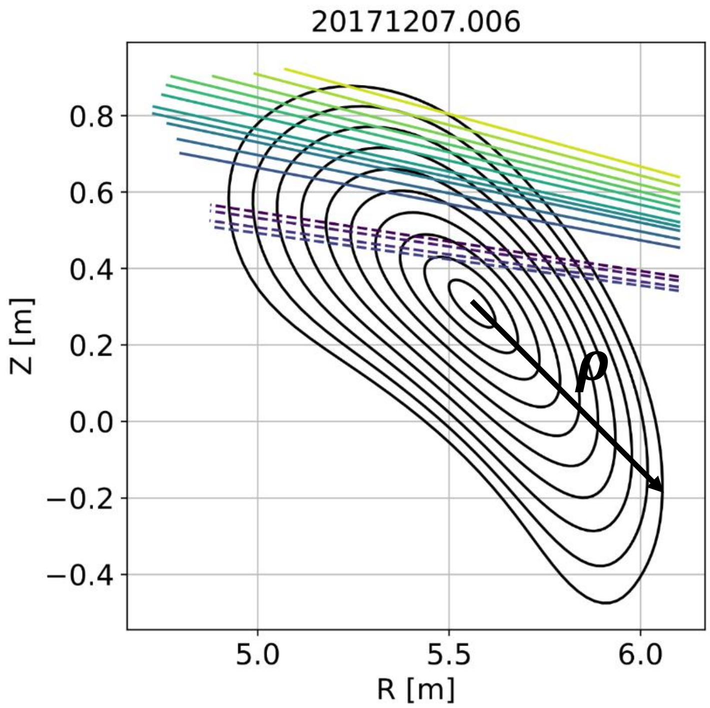
Impurity observation

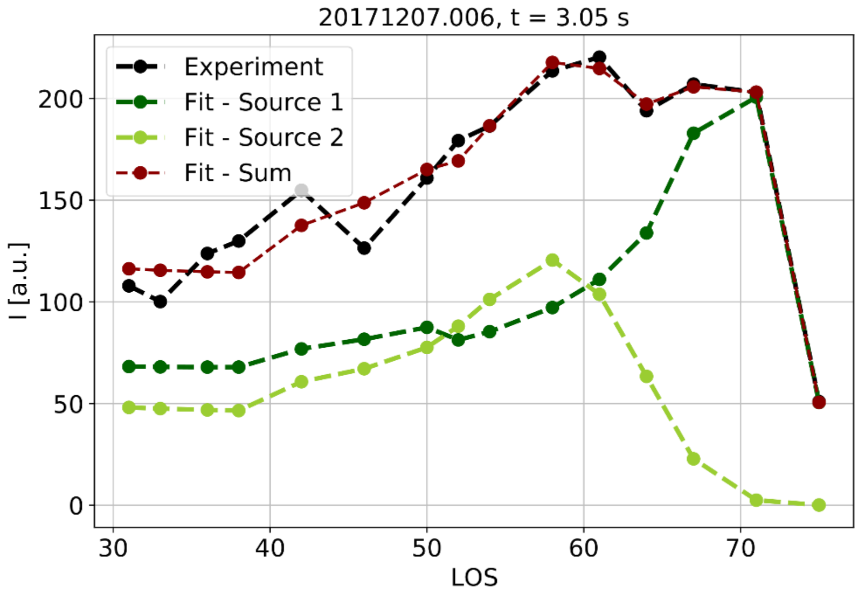
- Impurity properties obtained from measured spectral line.
- Coronal Equilibrium: models the temperature dependence of the ionisation stages.



Passive Spectroscopy - Measurement

- Measures the line integrated intensity of C^{5+} $(529.07\ nm)$ with multichannel mirror spectrometer.
- Inversion (Forward modelling) to assess radial distribution of emission intensity that gives comparable line integrated intensity.



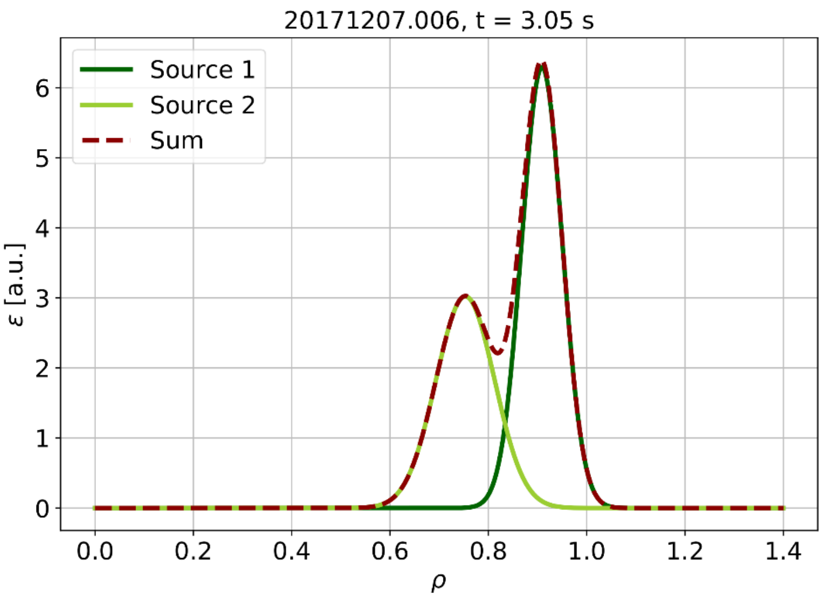


Passive Spectroscopy - Inversion

- Every flux surface is represented by a value of ρ. Array of ρ determined for each LOS given the flux surfaces the LOS looks through.
- The modelled emissivity is parametrised to be a double Gaussian shape
- Atomic processes leading to C^{5+}:

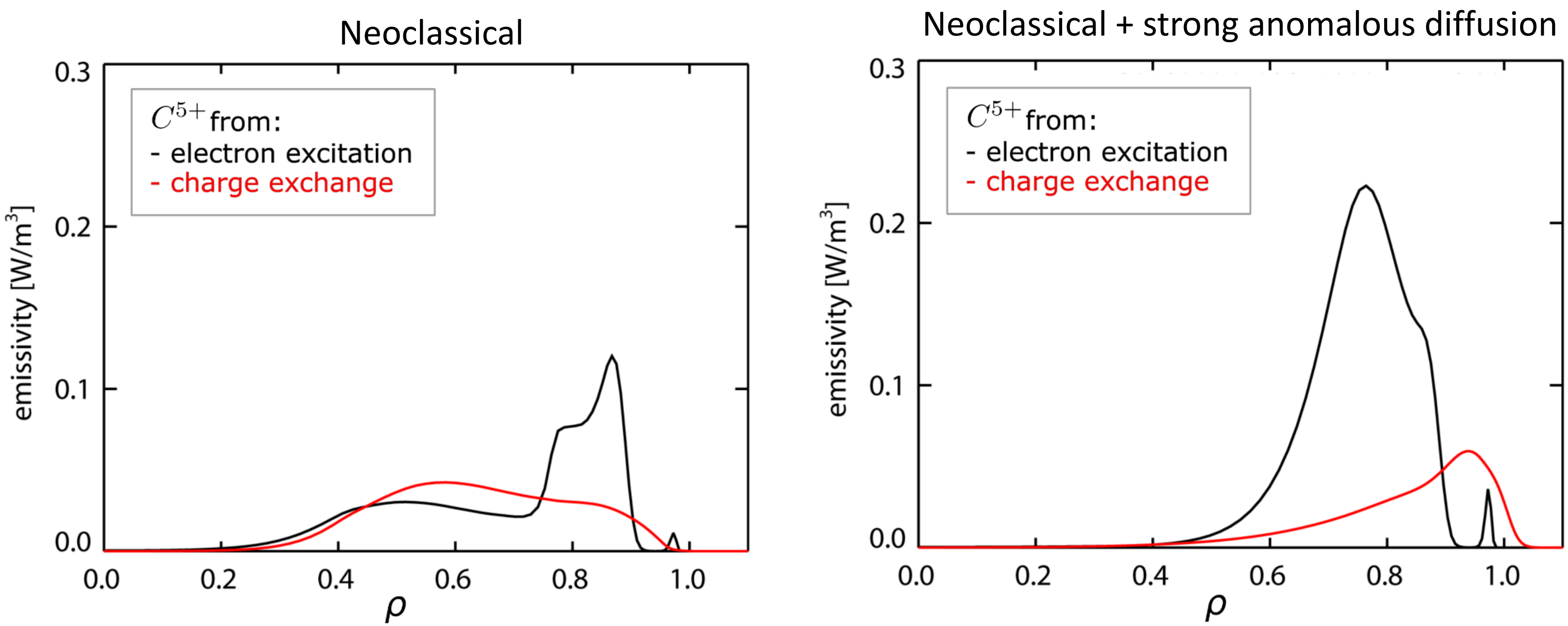
Electron impact excitation: $C^{5+} + e^{-} \rightarrow [C^{5+}]^{*} + e^{-}$

Charge exchange: $C^{6+} + H^{0} \rightarrow [C^{5+}]^{*} + H^{+}$



Passive Spectroscopy – Calculation

- Inner peak is radially deeper than either of the source particles is expected.
- Strong radial anomalous transport could carry the C^{5+} ions further in before they are ionised.
- Preliminary radiation calculation supports this.

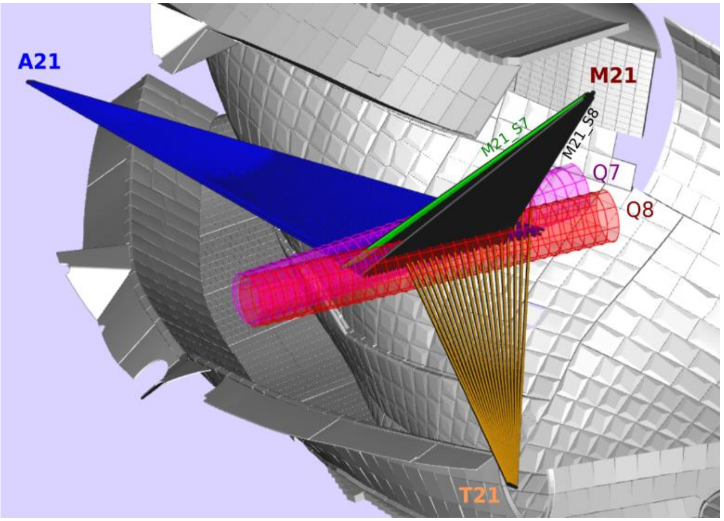


Charge eXchange Recombination Spectroscopy

- In the plasma core: only fully-ionized ions, no radiation to be detected
- Neutral Beam Injection (NBI): controllable external neutral source to the charge exchange process.

$$H^0 + C^{6+} \rightarrow H^+ + [C^{5+}]^*$$

- Spatially localised data available.
- Separation of the active and passive component is needed.



- Main spectrometer: ILS (C^{5+}, H^{α})
- This work focuses on carbon density calculated from the measured C^{5+} intensity.

Carbon density calculation

- Calculation of the carbon density is possible using the H^{α} and C^{5+} intensities measured by the ILS.

$$I^{CX} \propto \int_{LOS} n_C \sum_{E=E,E/2,E/3} Q_E^{CX}\, n_E^{beam}\, dl \qquad I_E^{BES} \propto \int_{LOS} n_e\, Q_E^{BES}\, n_E^{beam}\, dl$$

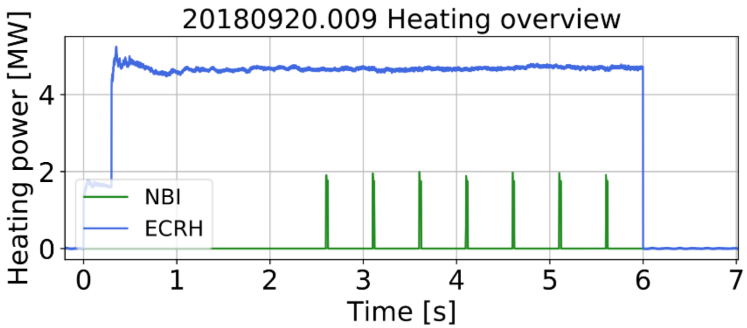
- Intersection integral between the NBI and the LOS can be eliminated, as the two detectors share the same LOS-s.

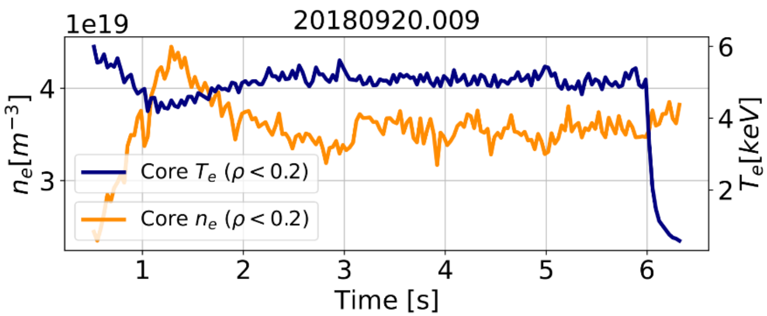
$$n_C = \frac{I^{CX}}{\sum_{E=E,E/2,E/3} \frac{I_E^{BES} Q_E^{CX}}{Q_E^{BES}}}\, n_e$$

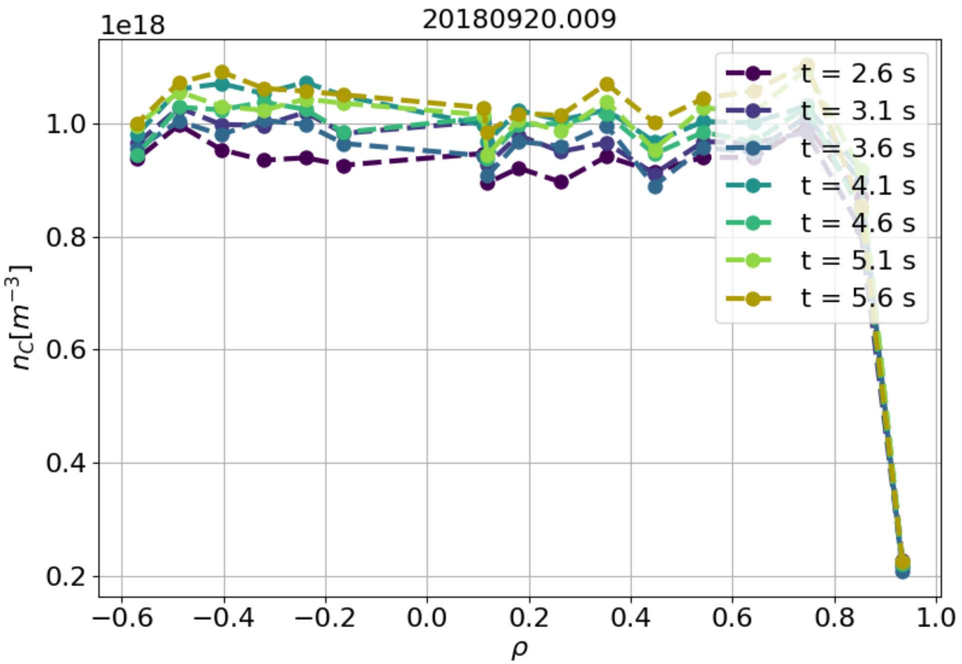
Outline of results

- ECRH dominated plasma scenarios
- NBI dominated plasma scenarios
- Mixed heating plasma scenarios
- High performance plasmas

ECRH dominated plasma scenario

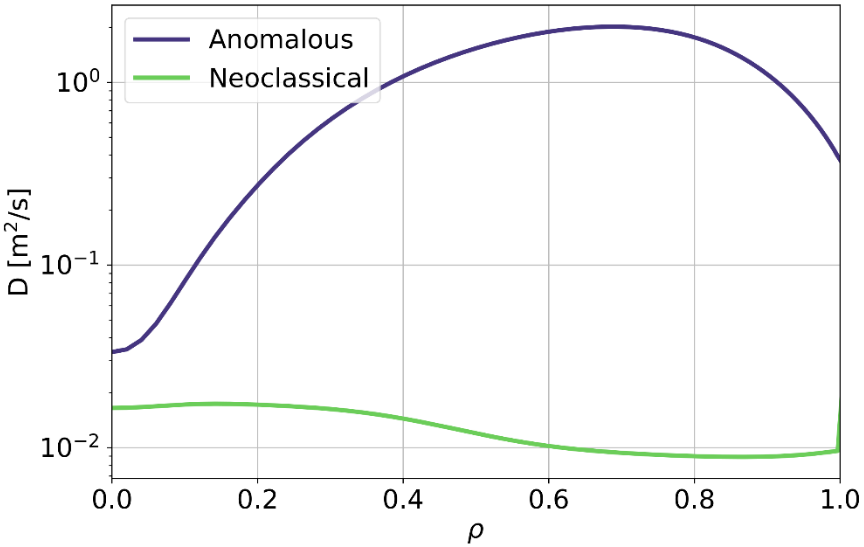


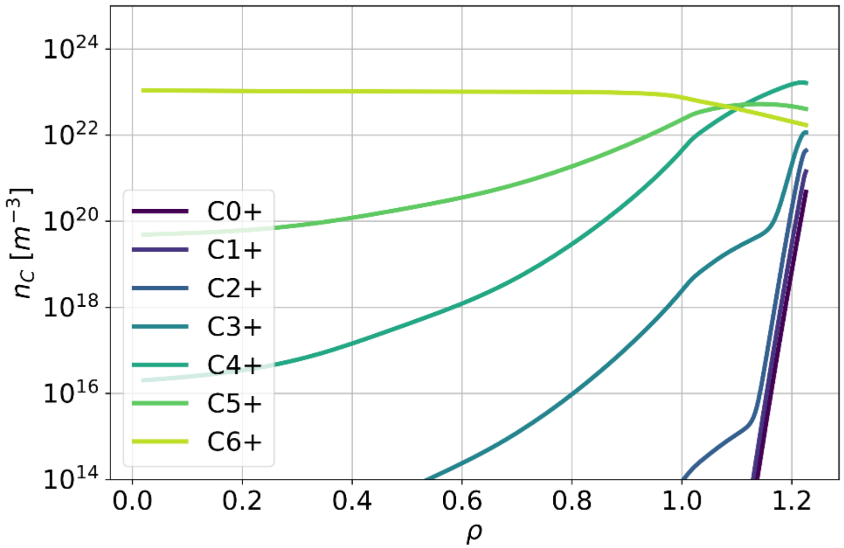




Flat carbon profile throughout the radius, no impurity accumulation.

ECRH dominated plasma scenario

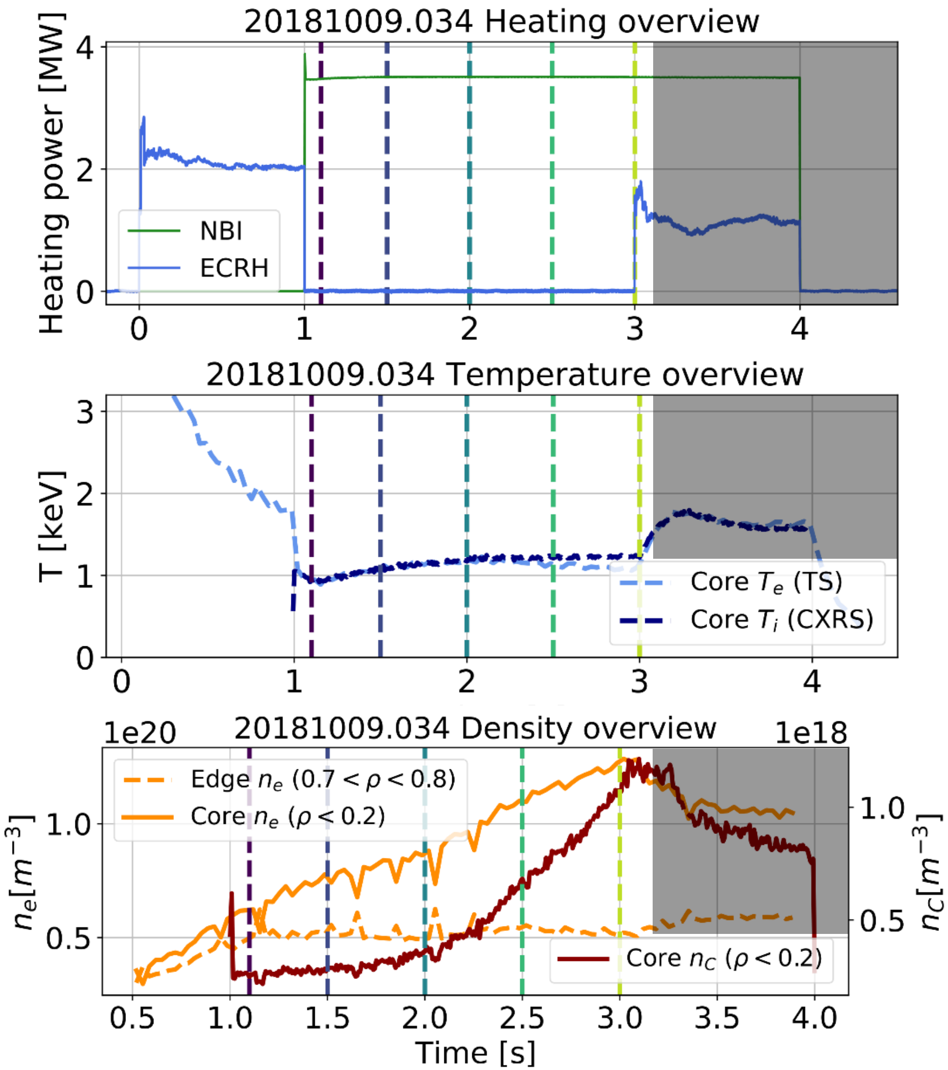




- Strong anomalous diffusion was found in these plasmas based on pySTRAHL simulations. [Geiger, Nucl. Fusion (2019) 59 047009]

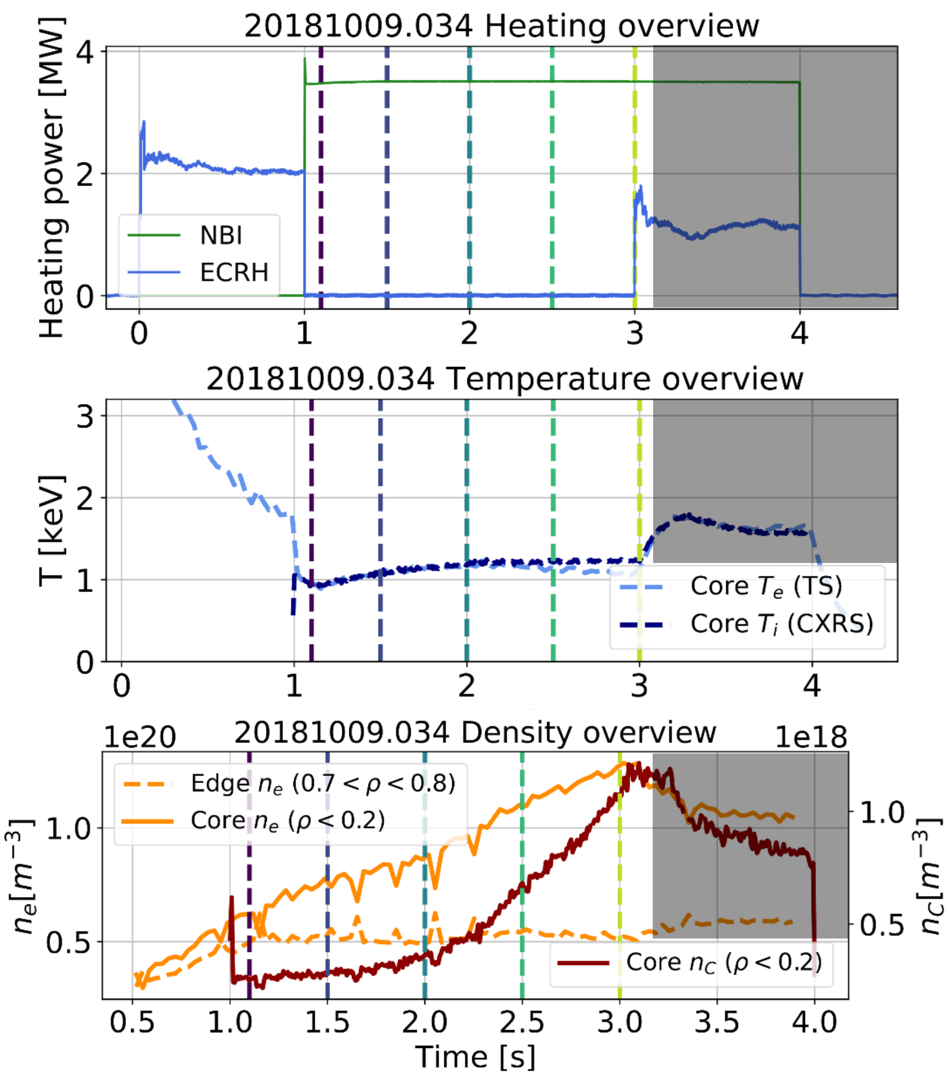
- This outward diffusion keeps the profiles flat against the neoclassical convection.

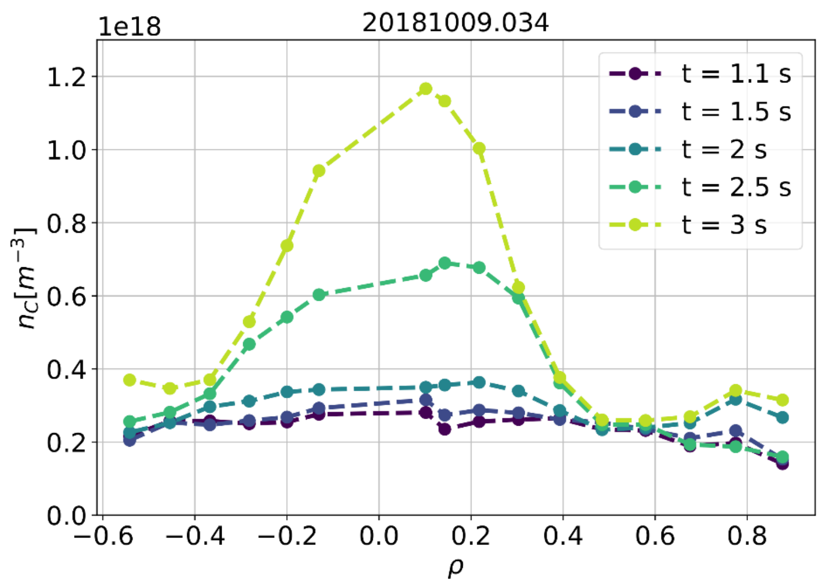
NBI dominated plasma scenario



- Heating switch at $t \approx 1s$
- ECRH turned back on at $t \approx 3s$
- n_e starts peaking in the core continuously.
- n_C peaking takes off around $1s$ into the pure NBI phase.

NBI dominated plasma scenario





- Flat n_C profiles in ECRH phase
- n_C peaking starts slowly after heating switch at $1s$

Carbon transport in NBI dominated plasma

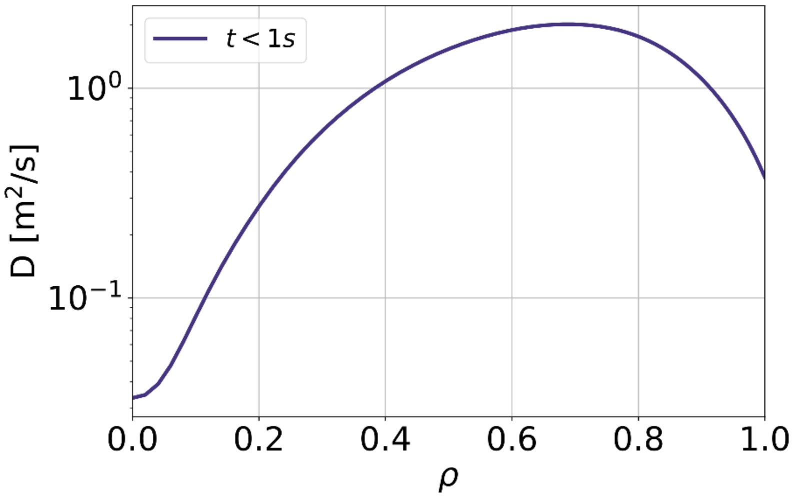
pySTRAHL simulation:

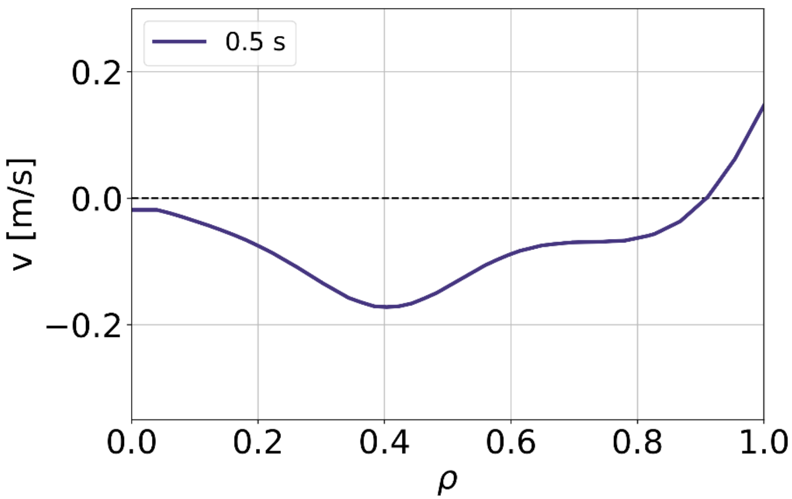
- One simulation for the whole discharge

- Background kinetic profiles every $100ms$ (from experiment)
- Neoclassical D and v profiles corresponding to the given kinetic profiles (calculated from Neotransp)
- Anomalous D profile from ECRH plasma studies

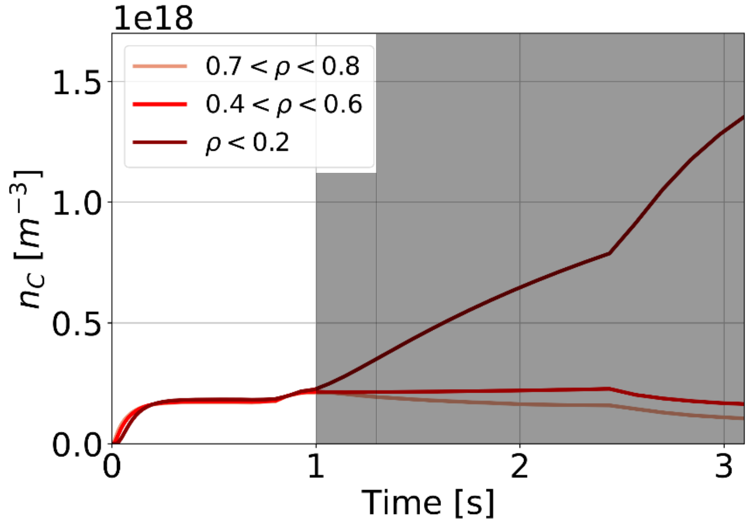
- Edge and source parameters set to match n_C level at the edge of the confined plasma at the beginning of the experiment.

Simulation for ECRH phase



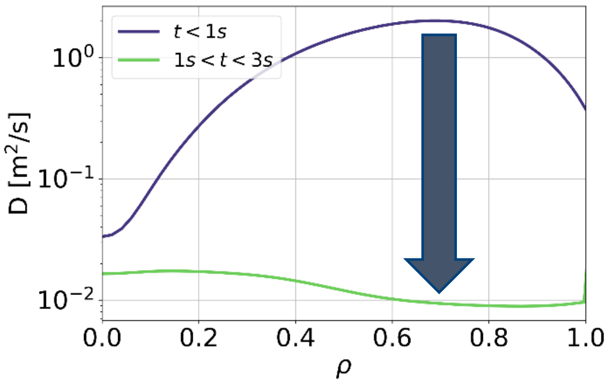


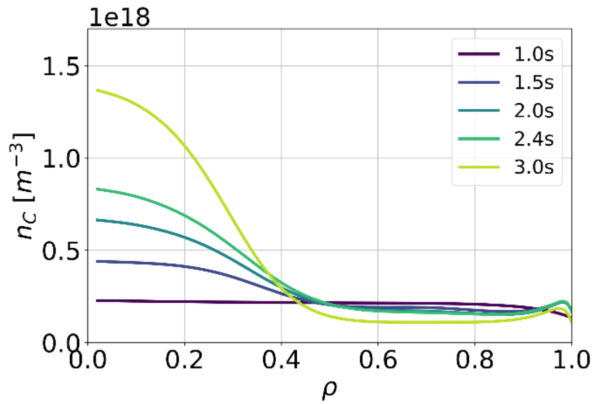
- High turbulent D [Geiger, Nucl. Fusion (2019) 102654]
- Keeps n_C profile flat as expected.
- v is assumed to be neoclassical, high D is dominating the transport

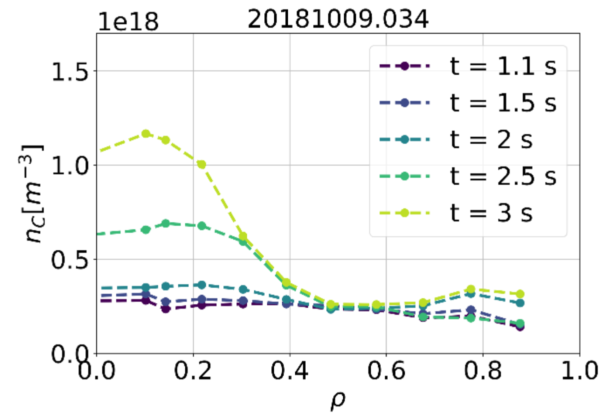


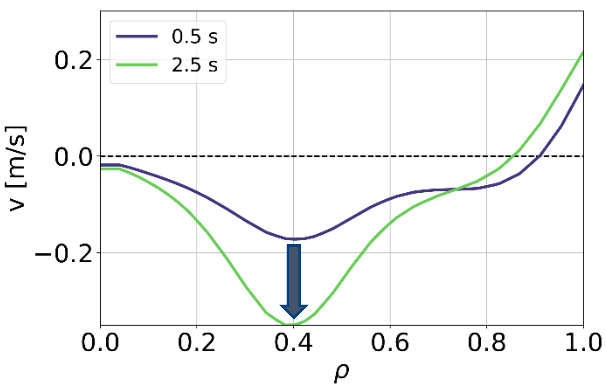
Simulation for NBI phase with neoclassical D

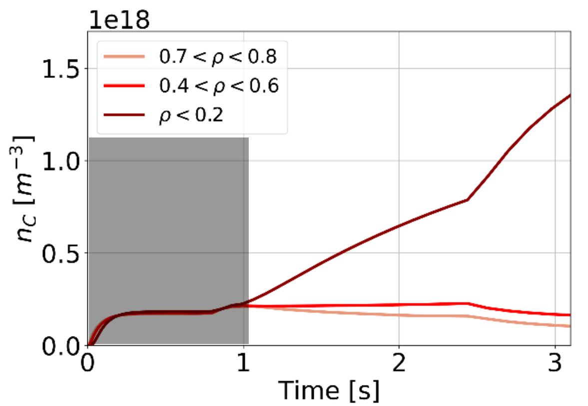
Transport coefficients | Simulation | Experiment

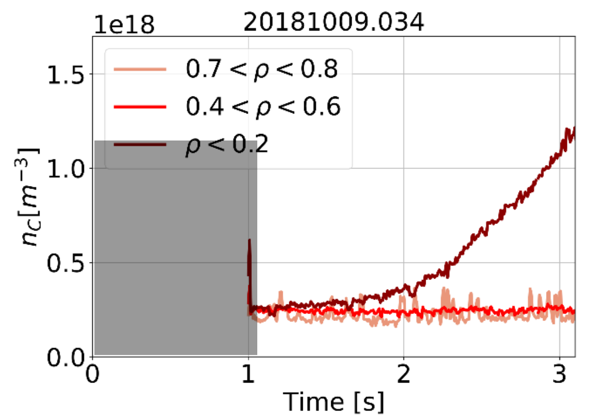








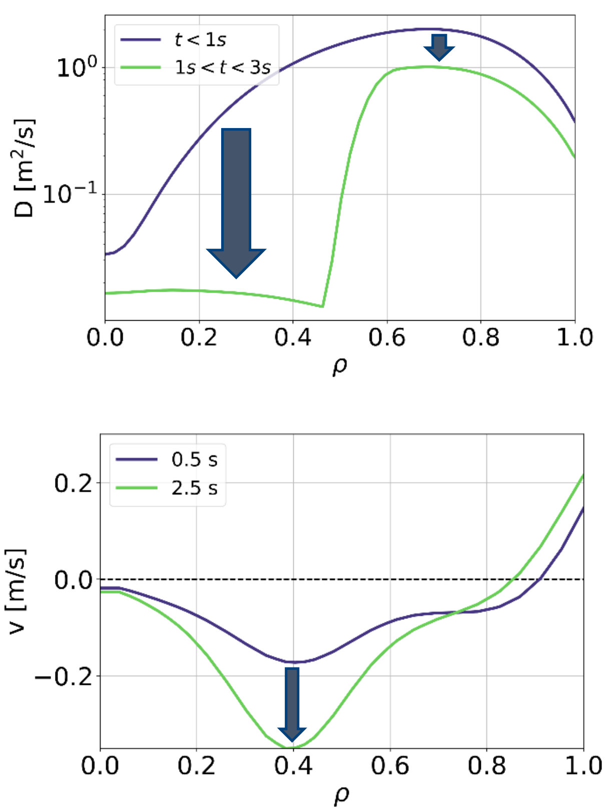




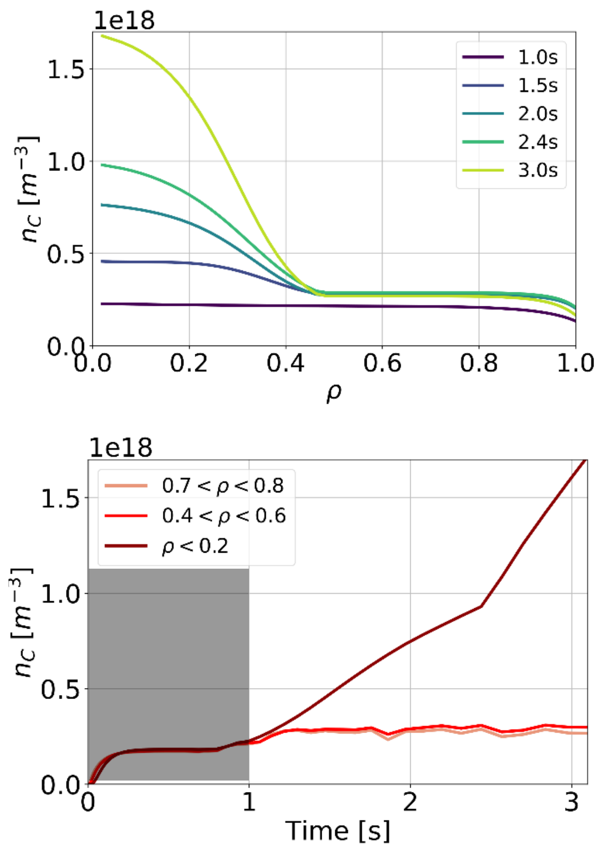
Gives carbon peaking for $\rho < 0.5$ with similar quantitative increase in time as experiment.

Simulation for NBI phase with an. D for ρ>0.5

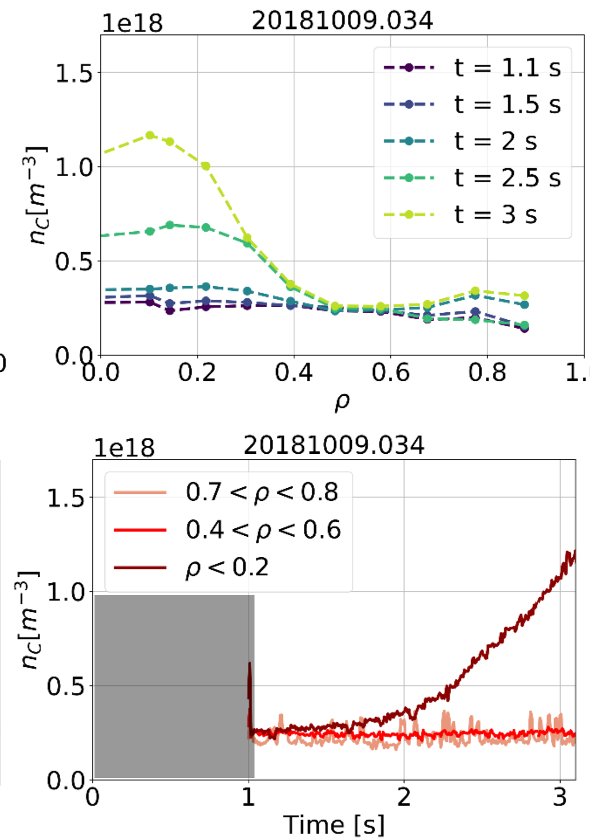
Transport coefficients



Simulation



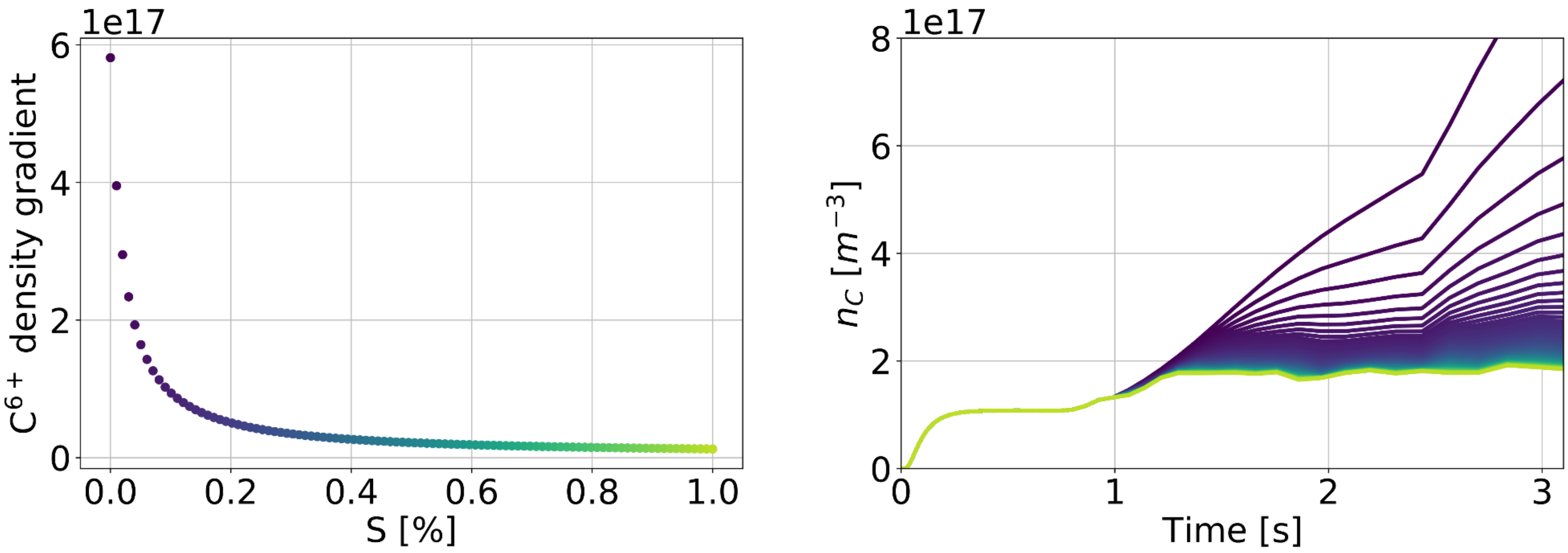
Experiment



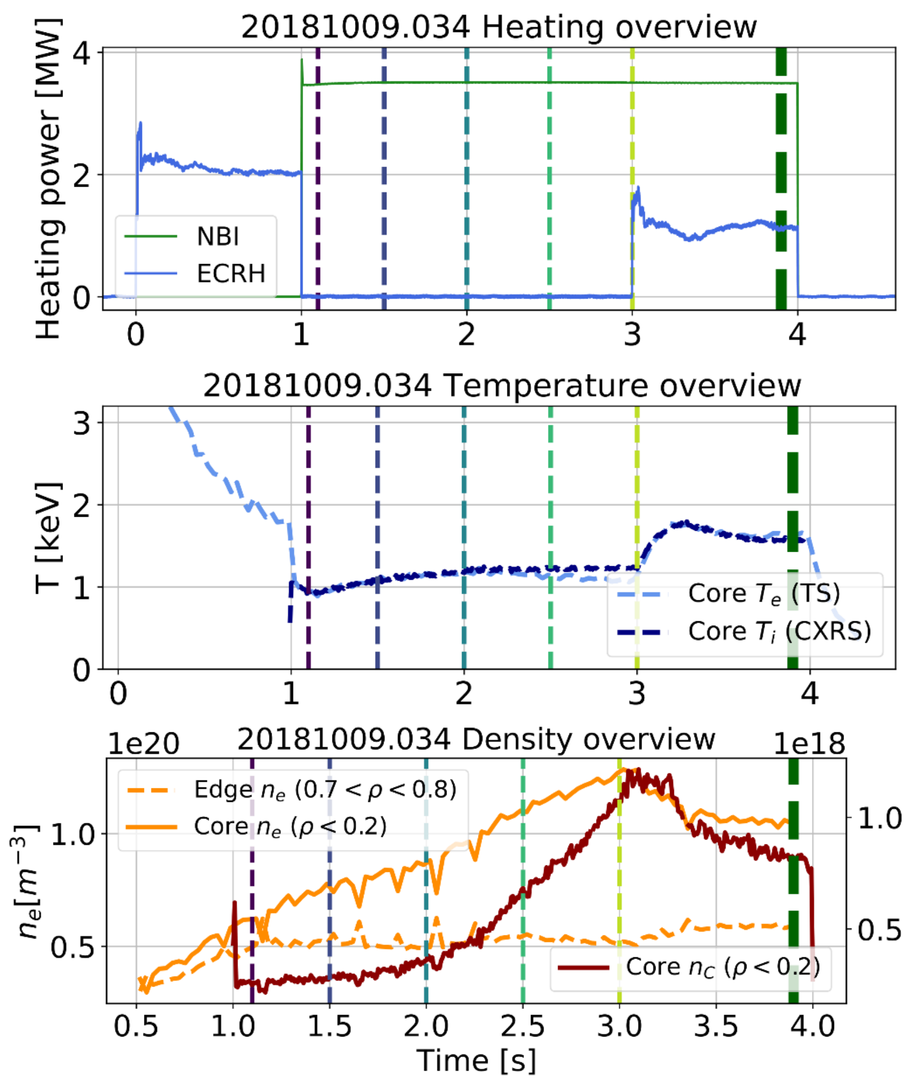
Profile flattens out for $\rho > 0.5$ and stops decreasing in time.

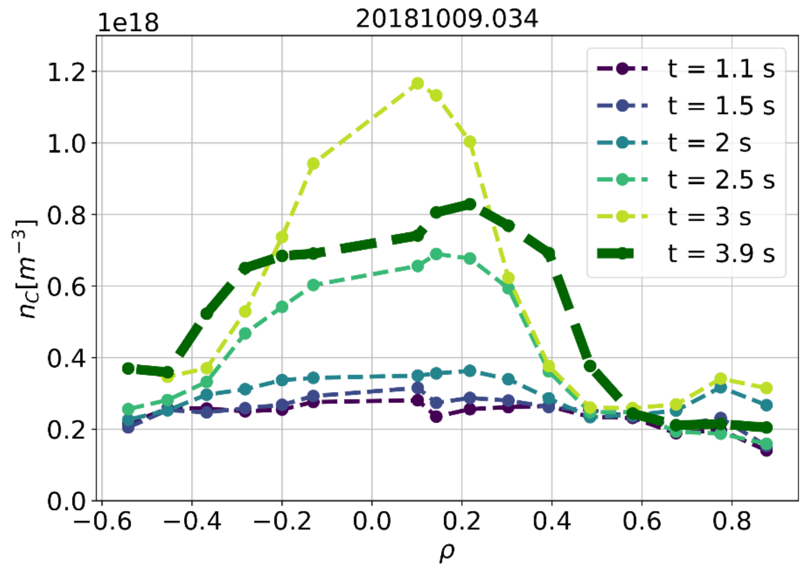
Simulation for NBI phase with an. D for ρ<0.5

- S: ratio of simulated diffusion level and full anomalous diffusion
- No significant peaking observed for S > 5%



Combined ECRH and NBI heating





- Carbon flushed out from the core
- Barrier-like gradient remains at $\rho = 0.4 - 0.5$
- Core turbulence becomes significant again.

High performance plasma scenario

- Achieved with continuous pellet injections.

- Triple product: $n_i T_i \tau_E = \frac{n_i}{n_e} n_e T_i \frac{W_{dia}}{P_{heating}}$

- Comparing the performance of different machines on the way to net energy producing fusion reactors.

- Reported highest triple product for stellarators:

$$n_i T_i \tau_E = 6.46 * 10^{19}\ m^{-3} keV\ s$$

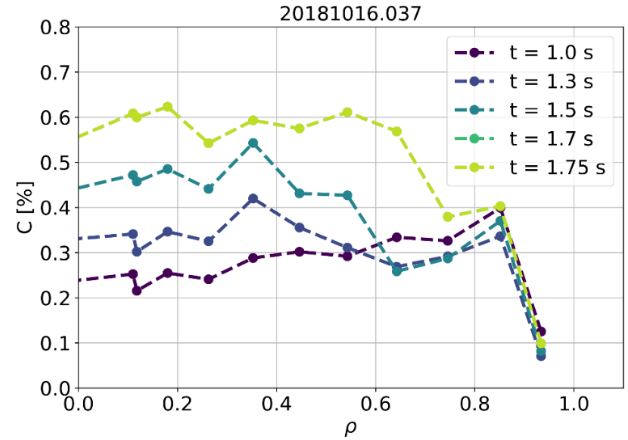
[Pedersen, Plasma Phys. Control. Fusion (2019) 61 014035]

- To measure the amount of impurities: $Z_{eff} = \frac{\sum n_j Z_j^2}{\sum n_j Z_j}$

Triple product with core impurity measurements

Measured global parameters:

$$T_i = 3.08\ keV$$
$$W_{dia} = 1.14\ MJ$$
$$P_{heating} = 4.65\ MW$$
$$n_e = 8.55 * 10^{19}\ m^{-3}$$



With measured carbon concentration:

$$C_C = 0.6\%$$
$$Z_{eff} = 1.17 \longrightarrow n_i T_i \tau_E = 6.26 * 10^{19}\ m^{-3} keV\ s$$

Assuming same oxygen concentration:

$$C_C = 0.6\%,\ C_O = 0.6\%$$
$$Z_{eff} = 1.48 \longrightarrow n_i T_i \tau_E = 6.00 * 10^{19}\ m^{-3} keV\ s$$

Supports the recorded record triple product for stellarators.

Summary

- Impurity transport needs to be understood for their control to achieve reactor like plasma conditions.
- n_C was measured at W7-X by the CXRS diagnostic.
- Carbon transport simulations were done based on the experimental n_C profiles.

- **Passive Spectroscopy**: only measuring carbon at the plasma edge, line integrated
- **CXRS**: measuring carbon in the plasma core, spatially resolved
  - ECRH plasmas: turbulent dominated impurity transport
  - NBI plasmas: neoclassical impurity transport in the core, causes accumulation
  - Mixed heating plasma: turbulent core keeps the accumulation lower
  - High performance plasmas: n_C profiles used for validation