Particle sources, profiles and transport in neutral beam heated plasmas at Wendelstein 7-X

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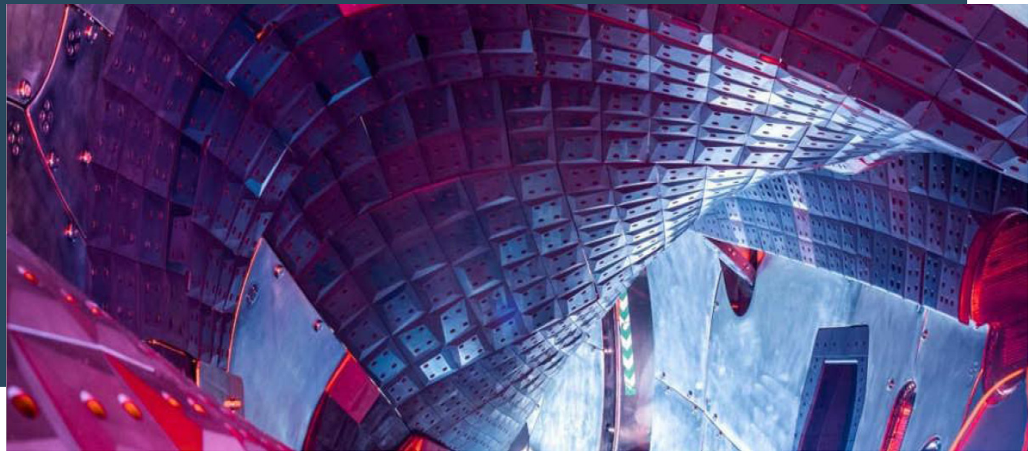

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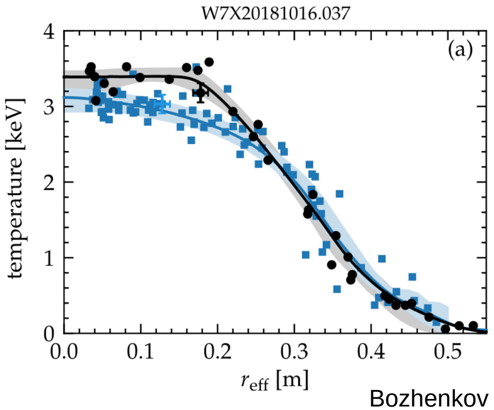
Overview

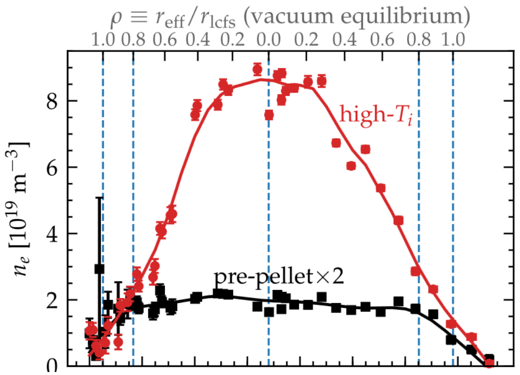
1) Main ion transport in neutral beam heated plasmas at W7-X
2) Neutral beam injection
3) Plasma profiles inversion from beam emission data

Why study particle transport?

High performance discharges (high Ti) at **W7-X** correlated to strong density gradients in plasma core [*Bozhenkov, Beurskens*]



Bozhenkov 2020



Bozhenkov 2020

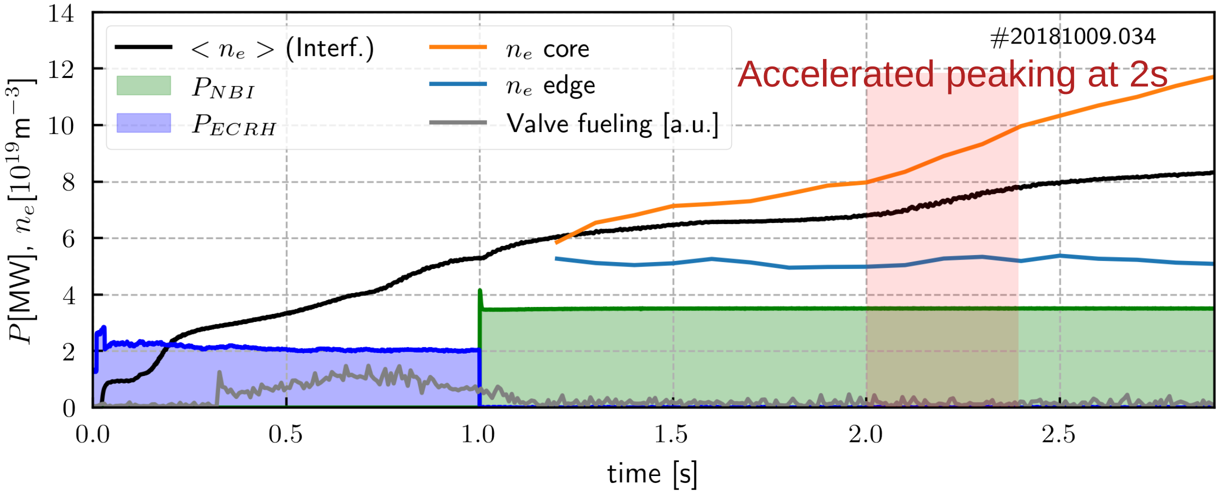
How can density gradients be created?

↓

NBI, pellets or particle pinches (inward convection)

An anomalous pinch lead to peaked density profiles in ECR heated discharges with flat temperature profiles at **W7-AS** [*Stroth, PRL 1999]*

Strong density peaking is seen in purely NBI heated discharges at W7-X:



ECRH discharges at W7-X: Theoretical calculations concluded on an anomalous particle pinch in the plasma core [*Thienpondt, PRR 2023*] → together with the neoclassical outward convective flux explaining the measured flat density profiles

Main ion transport analysis

Experimental flux (valid for electrons and ions)

$$\Gamma(\rho) = \left(\frac{dV}{d\rho}\right)^{-1} \int_0^{\rho} (S_{\mathrm{NBI}} + S_{\mathrm{RCY}} - \partial_t n) \frac{dV}{d\rho'} d\rho'$$

Particle source functions S [m-3s-1]

Change in density profile

Need to measure/model all particle sources and time evolution of density profile along ρ

- Neutral beam injection model
- 1D CX diffusion recycling model
- Density profiles (Thomson/BES)

Split flux:

$$\Gamma = \Gamma_{\mathrm{NC}} + \Gamma_{\mathrm{anom}}$$

Neoclassical Anomalous

Deduce anomalous flux contribution by subtracting the neoclassical flux from total flux

- Neoclassical flux calculated using the code Neotransp

Common parametrization:

$$\Gamma_{\mathrm{anom}} = -D_A \nabla n + V_A n$$

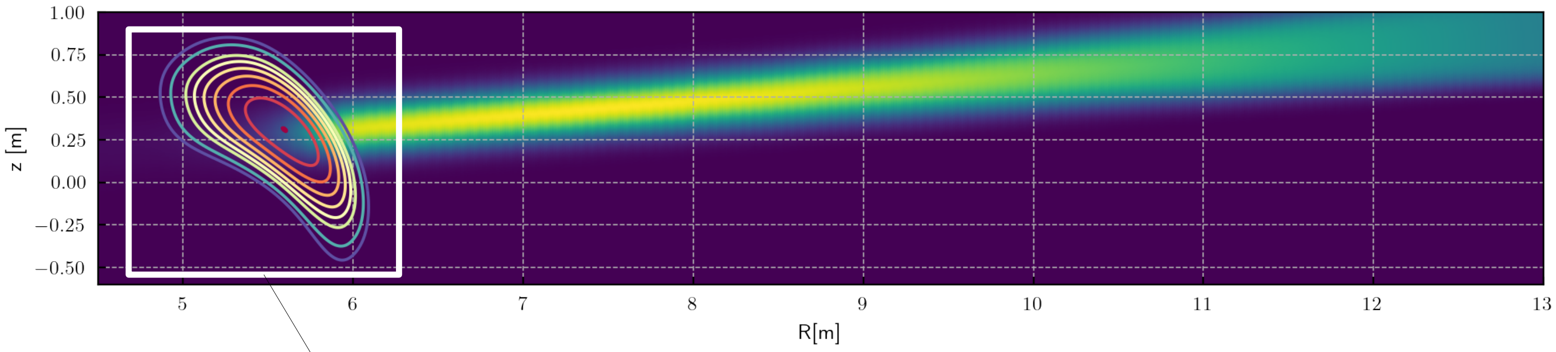
Assume ambipolar diffusive and convective contributions of anomalous flux

- Phases with constant transport coeff. should evolve along line:

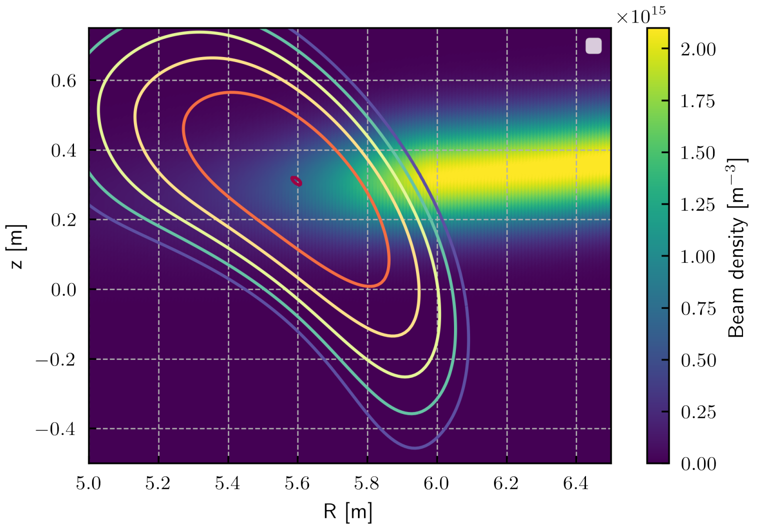
$$\frac{\Gamma}{n} = -D\frac{\nabla n}{n} + V$$

Neutral beam injection

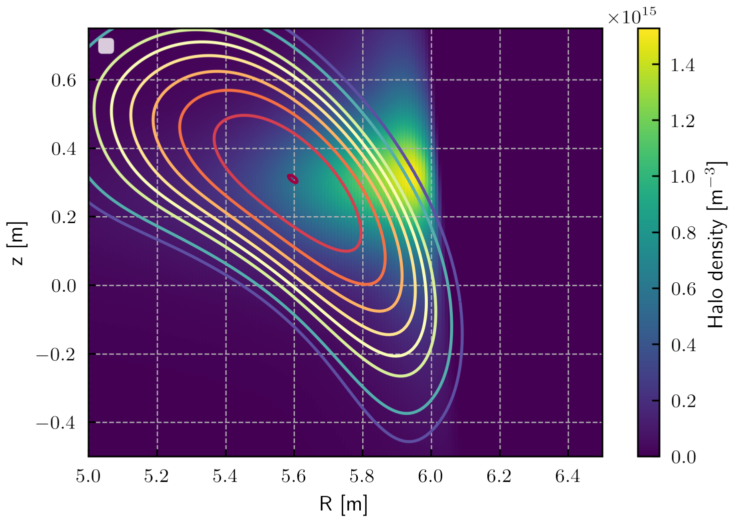
Neutral beam modeling W7-X



Beam attenuation in plasma



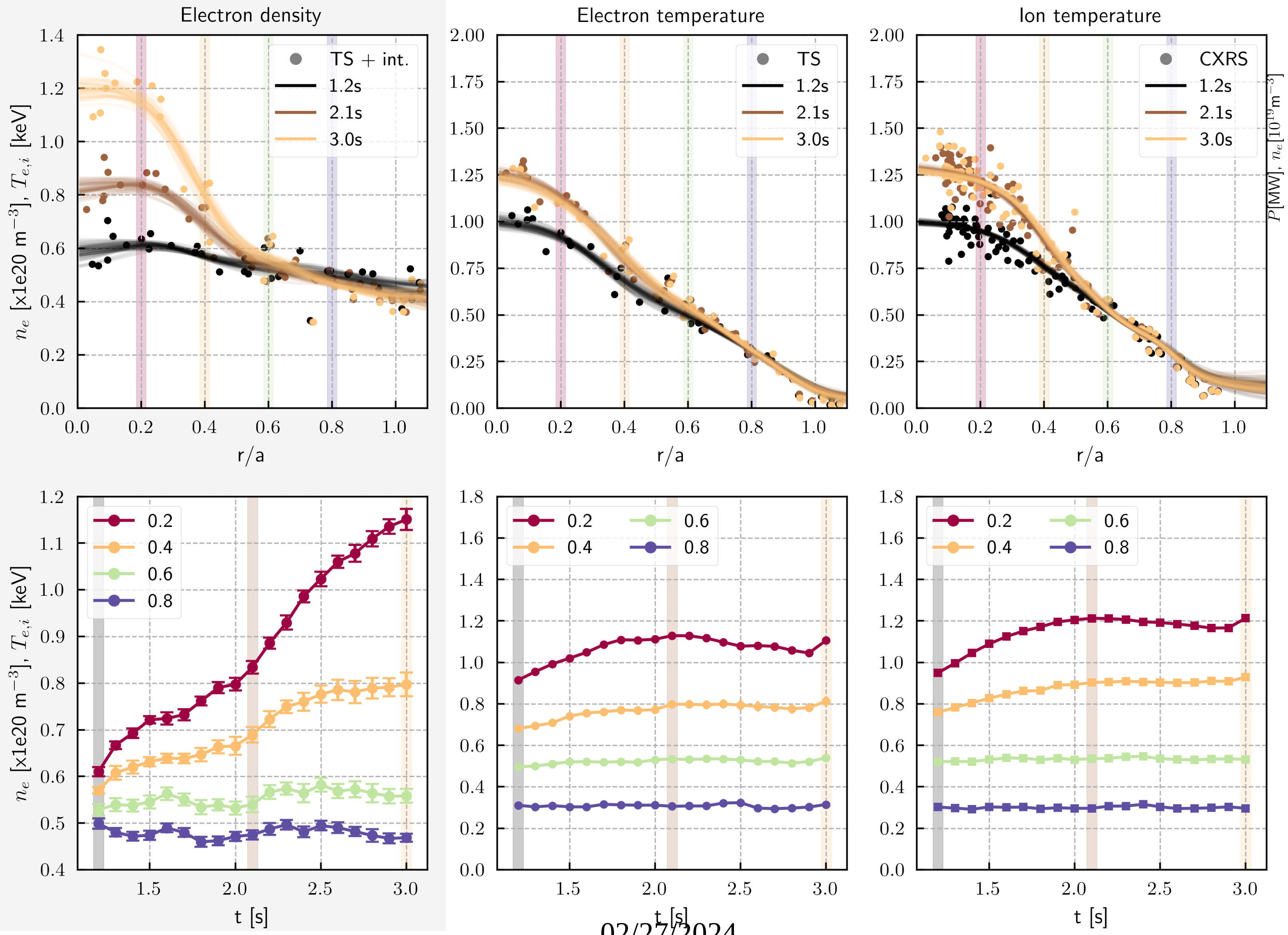
Halo formation due to CX

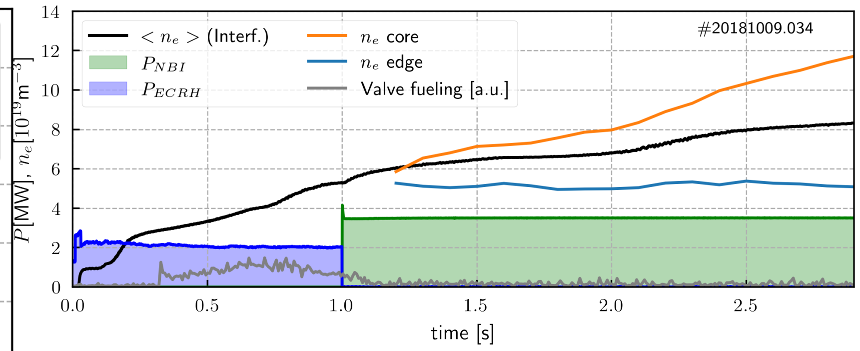


- Hydrogen ions (H^+, H_2^+, H_3^+) are accelerated up to 55 keV
- Beam particles are neutralized on way to plasma
- On way through plasma beam is ionized (electron and ion impact collisions, charge exchange)
- Charge exchange reactions create new thermal, neutral species the “halo”
- Plasma is heated and fueled by NBI
- Neutral beam particles can radiate due to excitation from plasma particle collisions
- NBI system at W7-X (OP1.2b): two active sources (S7, S8) each injecting ~1.7 MW into the plasma

To model neutral beam attenuation, deposition and emission need full collisional-radiative and geometry model!

Plasma profiles

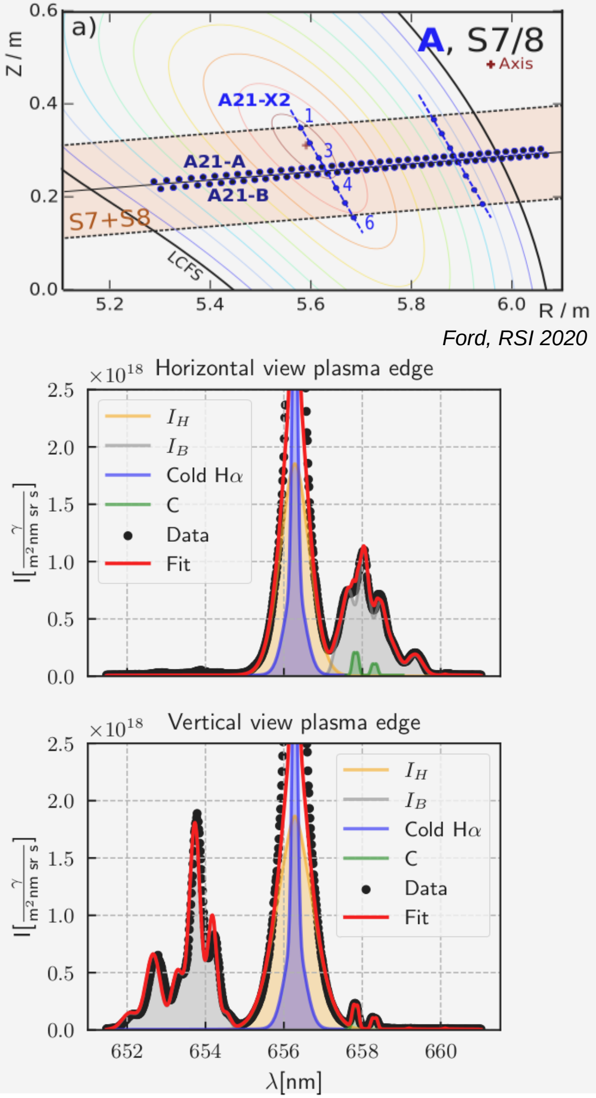




- Fast change of core density around 2s
- Ion and electron temperature “roll over” at 2s
- High density gradient region from r/a=0.2 to 0.5

Plasma profiles II: Inference from beam emission

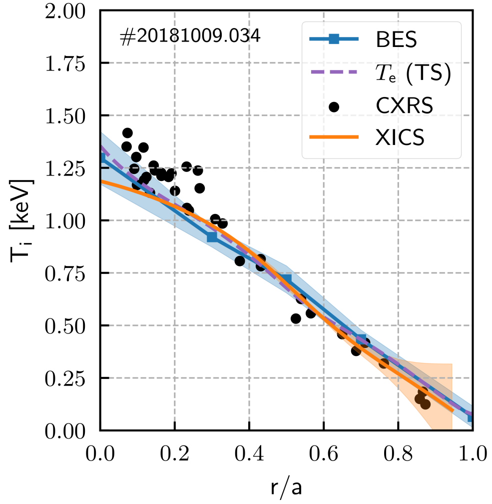
BES system and data



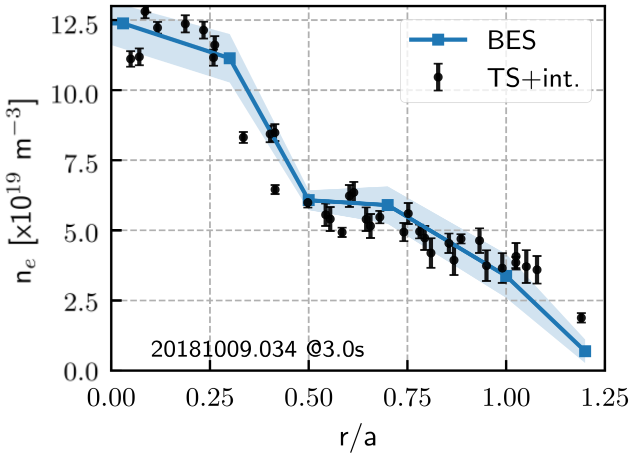
- CXRS system at W7-X: measures Balmer-α spectra with up to 54 lines of sight from several optical heads viewing the neutral beams across the whole plasma radius
- Minerva model: full forward model from the neutral beam injection to the measured spectra at the detector

Inversion of BES data

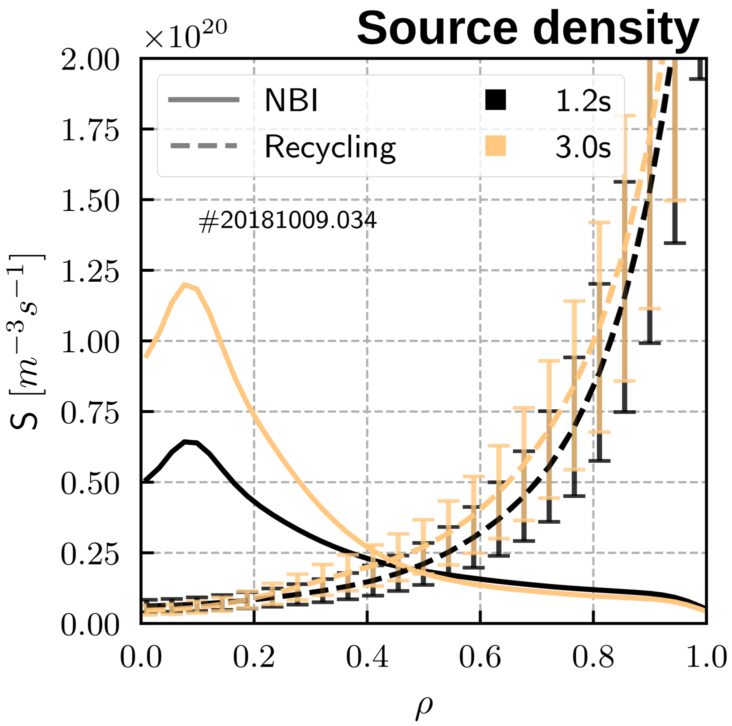
Ion temperature profile inference

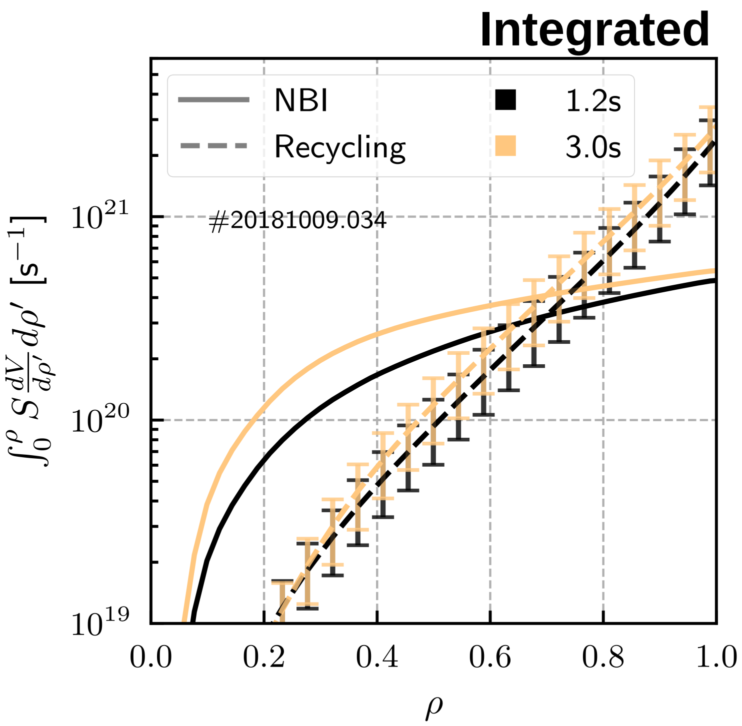


Electron density profile inference



Particle sources



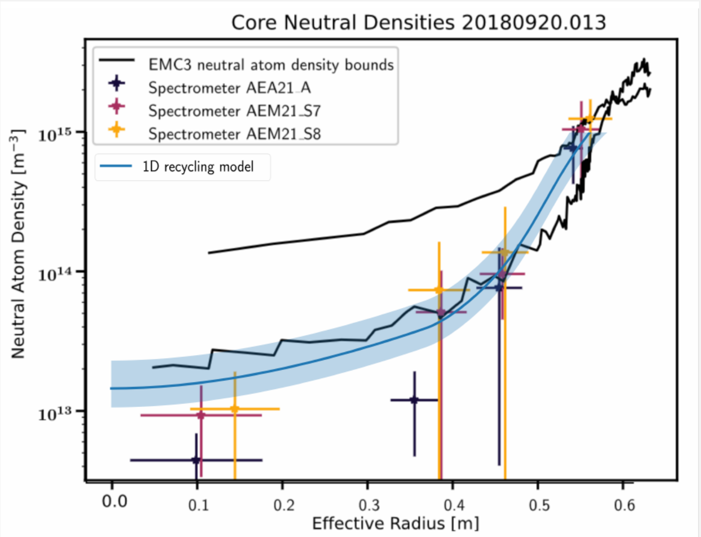


Recycling model:

- 1D CX diffusion model with edge source determined from particle confinement time

Influx: $\Phi_{\mathrm{RCY}} = \frac{\int n_e dV}{\tau_p}$

Diffusion model $-\mathbf{D}\Delta_r \odot \mathbf{n} = \mathbf{T}_{\mathrm{CR}} \cdot \mathbf{n} + \mathbf{S}$

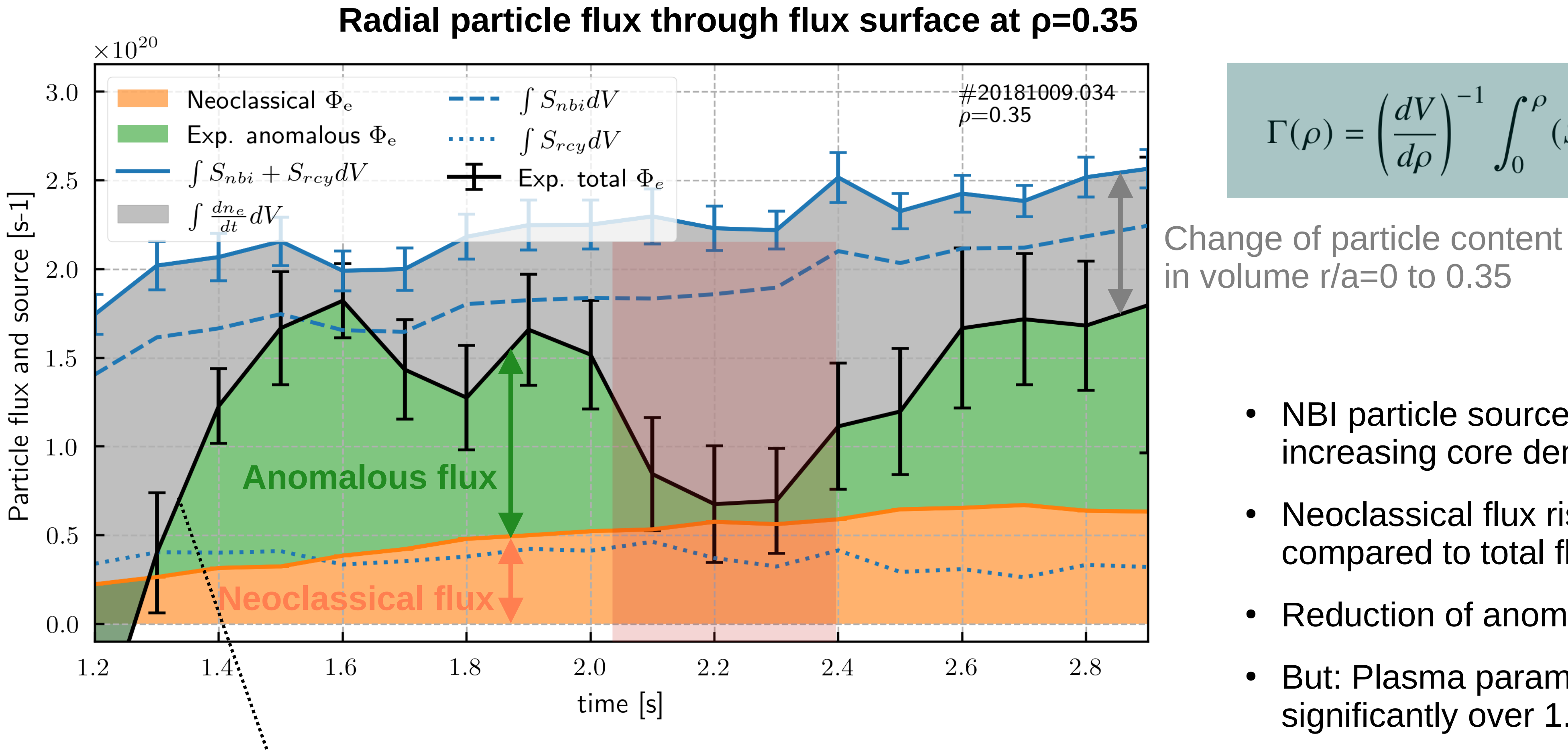


τ=0.27s

Comparison to EMC3-Eirene. *Orig. plot from V. Winters (PPCF 2021)*

- Particle fueling in core (r/a < 0.5) dominated by NBI
- NBI deposition increases with increasing density
- Plasma edge dominated by recycling source
- Note: CX diffusion of recycling particles strongly dependent on edge density! Lower edge density → higher core fueling from recycling

Particle fluxes



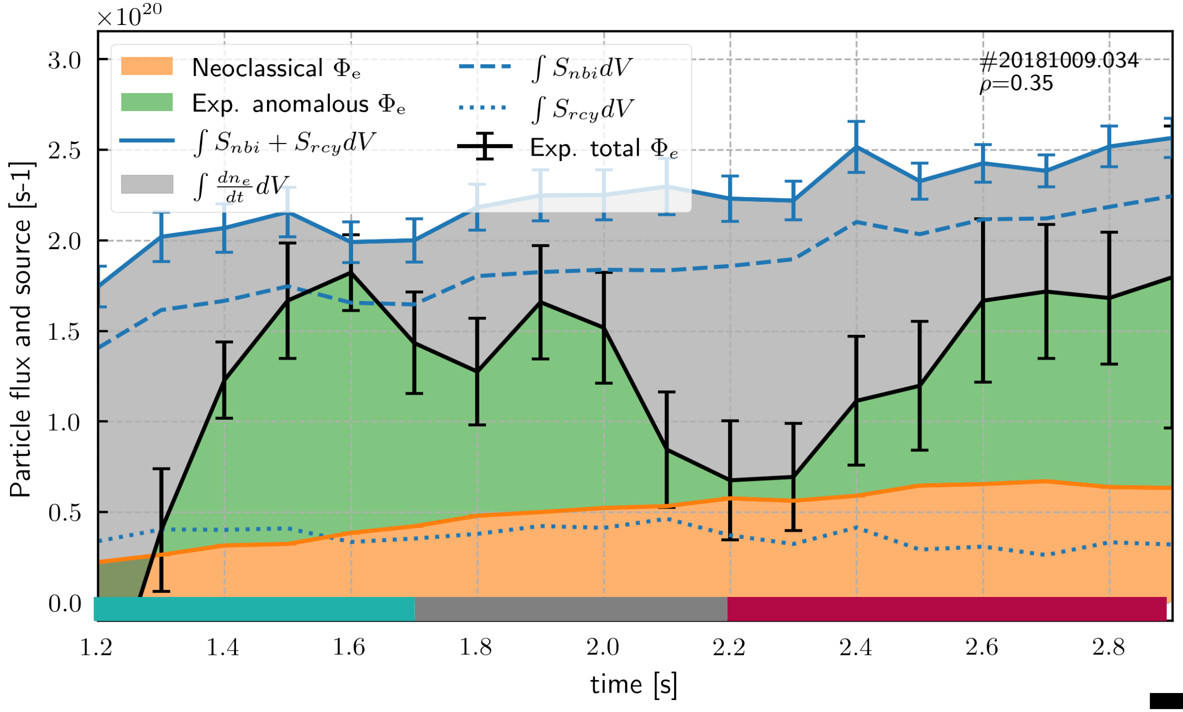
$$\Gamma(\rho) = \left(\frac{dV}{d\rho}\right)^{-1} \int_0^{\rho} (S_{\mathrm{NBI}} + S_{\mathrm{RCY}} - \partial_t n) \frac{dV}{d\rho'} d\rho'$$

- NBI particle source slowly rising due to increasing core density
- Neoclassical flux rising but variation small compared to total flux dynamics
- Reduction of anomalous flux is transient
- But: Plasma parameters changed significantly over 1.5s

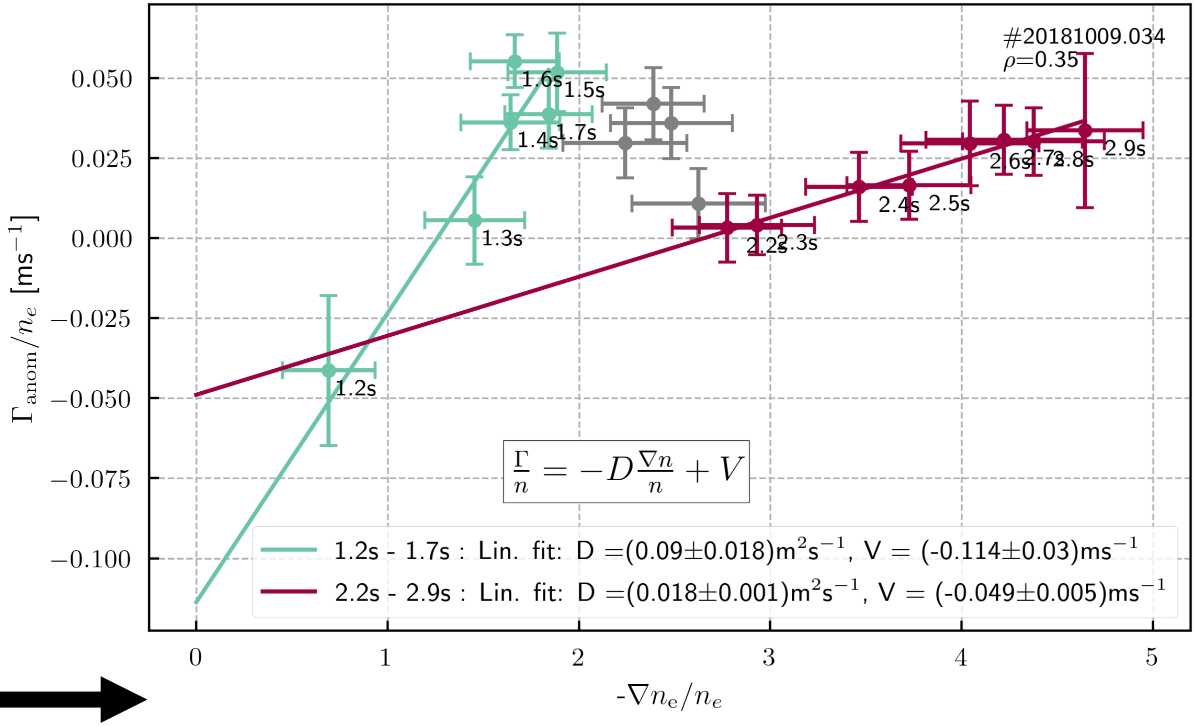
Total experimental particle flux: positive sign → outward directed flux

Strong reduction of anomalous particle flux at 2.2s!

Anomalous transport coefficients



Fit anomalous transport coefficients



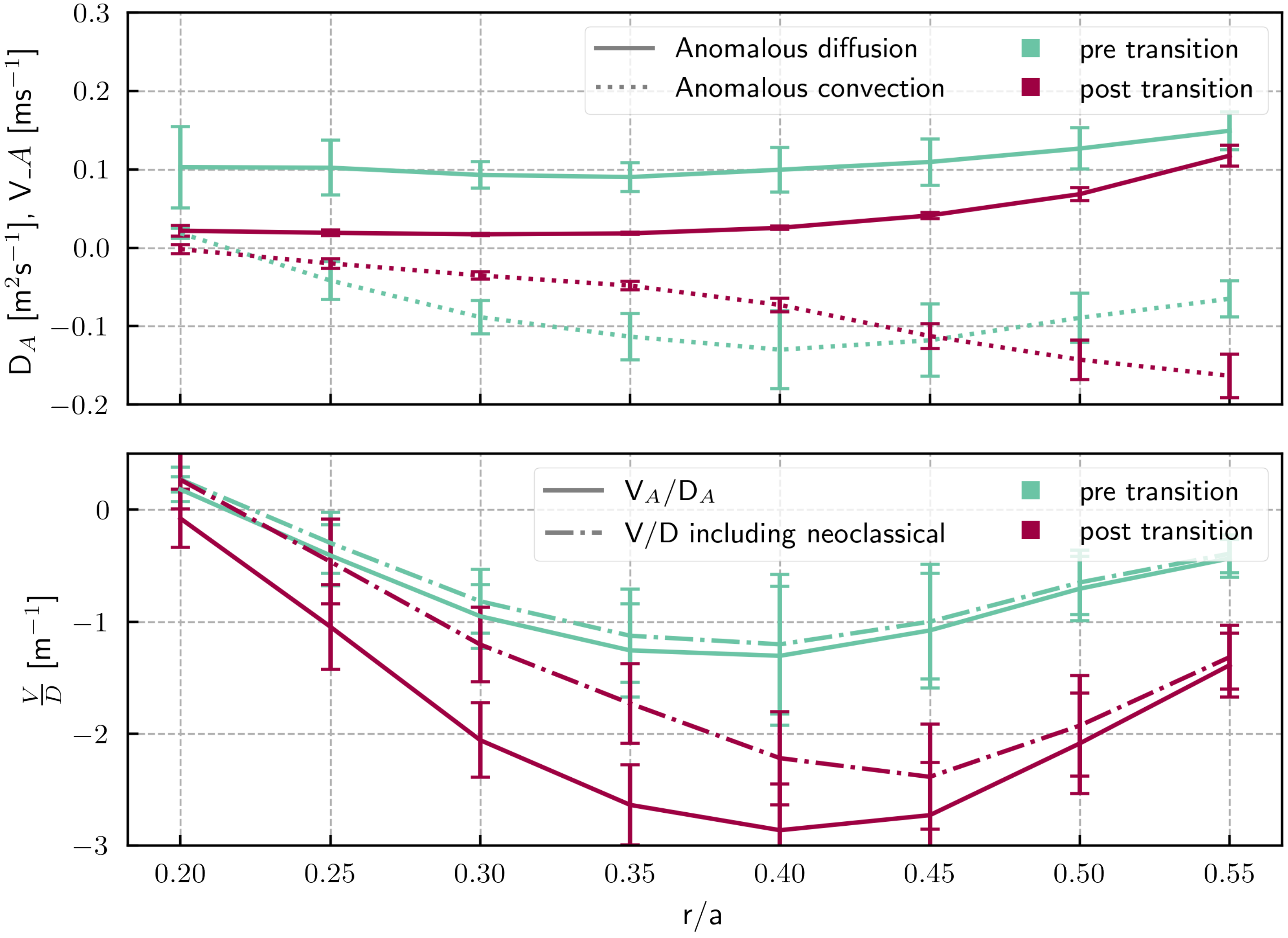
Take anomalous flux of each time point

Phases with constant transport coefficients lie on straight lines

Two distinct phases are clearly visible → transition in between

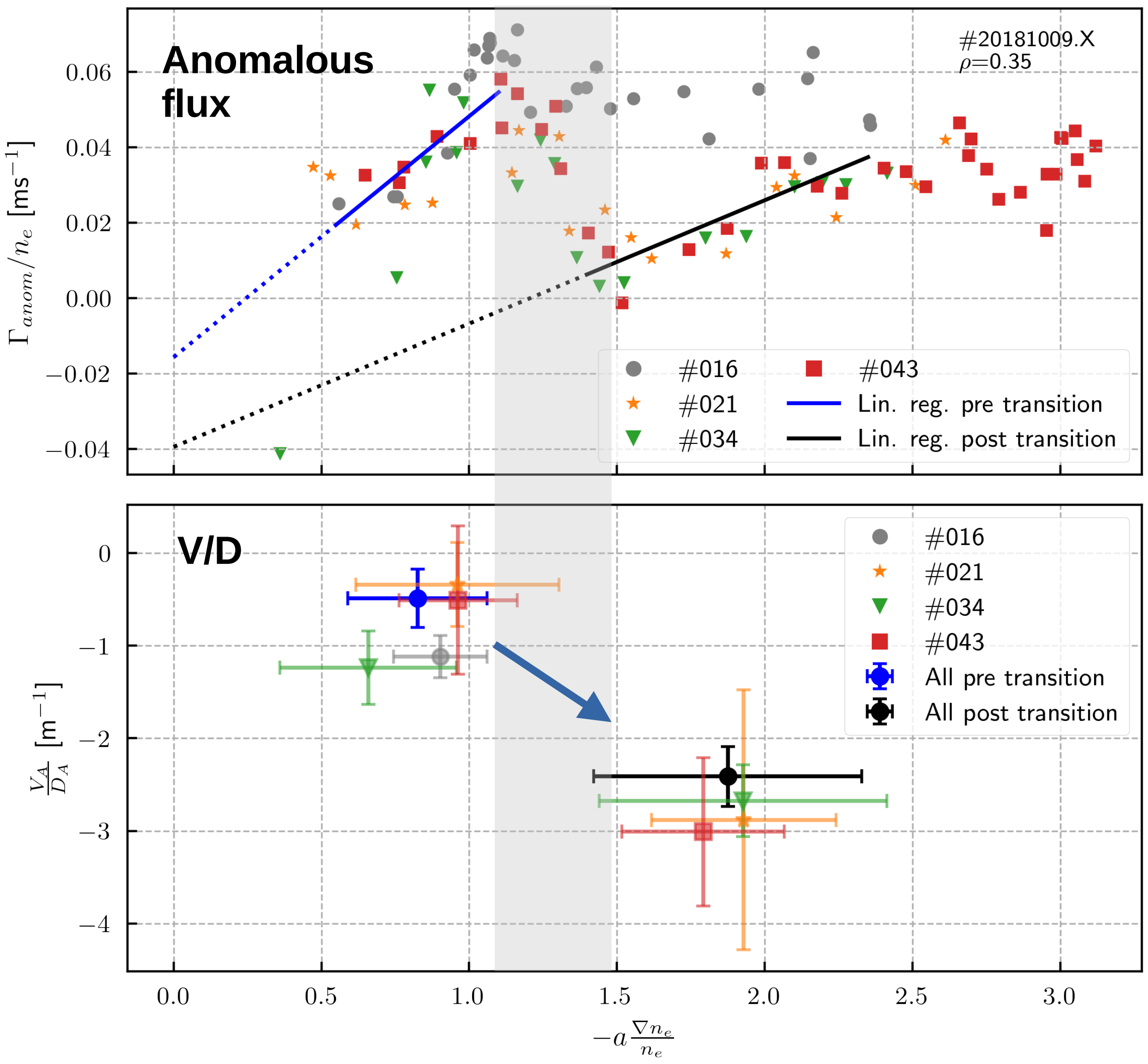
Anomalous transport coefficients

Radial profile of transport coefficients in plasma core



- Fit anomalous transport coefficients at several radii from r/a=0.2 to 0.55 (mid radius)
- Negative convection leads to gradient build up
- Diffusion reduced after transition
- Peaking tendency (V/D) clearly increased after transition → accelerated density peaking
- Neoclassical contribution already included in bottom plot

Transport analysis – multiple discharges



- Repeat analysis for 4 discharges on same day, all with peaking density profiles
- All 4 exhibit a similar behavior in the first second of NBI
- In 3 of them the same transition is seen when crossing normalized density gradient length of ~1.1
- Anomalous V/D shows a significant change consistent with density peaking measured
- In 20181009.016 the ion temperature is higher than in the other discharges + the NBI phase begins at a lower plasma density

Conclusion

- Information on particle fluxes could be accessed experimentally by performing a full particle balance study
- Exploiting the non steady state conditions it was possible to fit anomalous transport coefficients in the high gradient region in the plasma core
- In several discharges a clear transition was seen in the transport coefficients when crossing a certain normalized density gradient
- In all phases there existed an anomalous negative (inward) convection term
- From the used data set it was not possible to clearly determine the driving parameter causing the transition as several plasma parameters are strongly correlated
- The presented study should be used for comparisons to theoretical calculations to draw further conclusions

Appendix: ColRad rates

$$T_{CR} = T_{CR}(T_e, T_i, n_e) = \begin{bmatrix} -L_1 & A_{21} & A_{31} & . & A_{k1} \\ E_{12} & -L_2 & A_{32} & . & A_{k2} \\ E_{13} & E_{23} & -L_3 & . & . \\ . & . & . & . & A_{ki} \\ E_{1k} & E_{2k} & . & E_{jk} & -L_k \end{bmatrix}$$

Matrix containing all ColRad rates

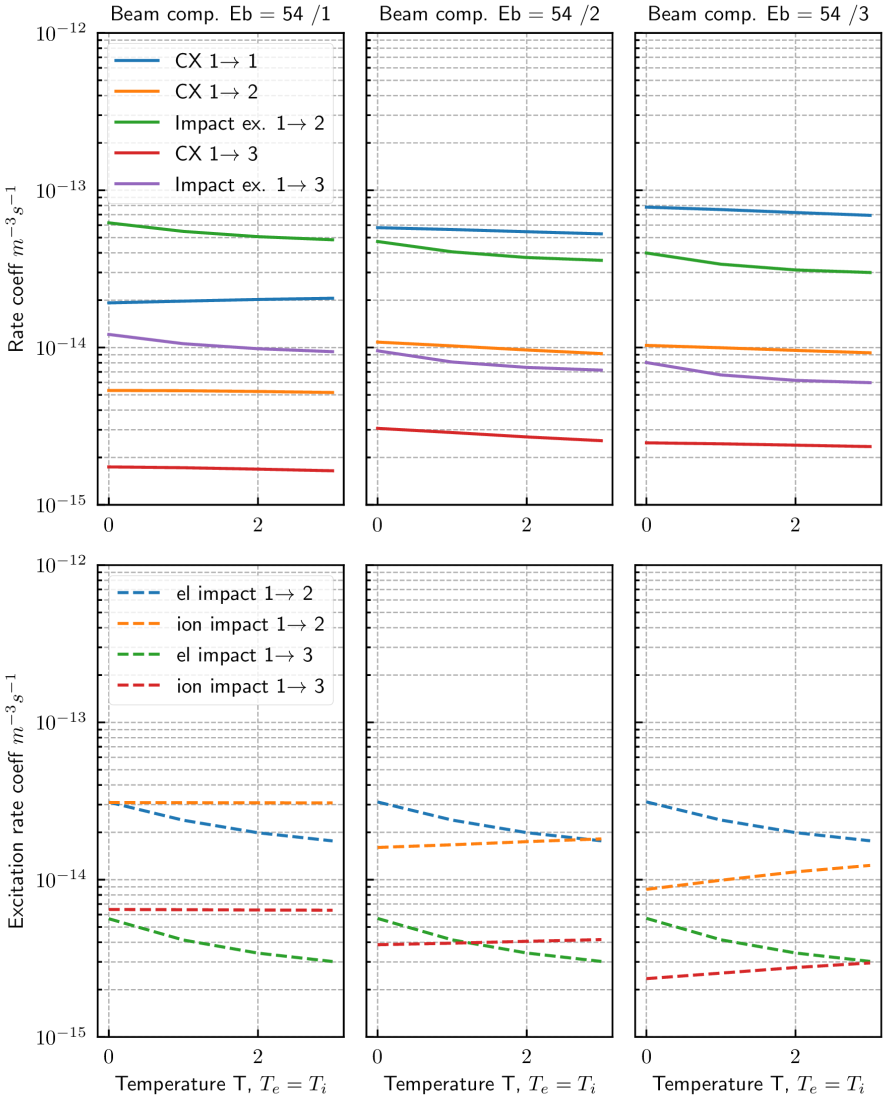
$$E_{ij} = n_e < \sigma_e^{(ij)} v > + n_i < \sigma_p^{(ij)} v >$$

$$I_i = n_e (< \sigma_e^{(iI)} v > + < \sigma_p^{(iI)} v > + \sum_{j=1}^{k} < \sigma_{CX}^{(ij)} v >)$$

$$L_i = I_i + \sum_{m=i+1}^{k} E_{im} + \sum_{m=1}^{i-1} A_{im}$$

Excitation, ionization and loss rates in detail

Collisional-radiative modeling



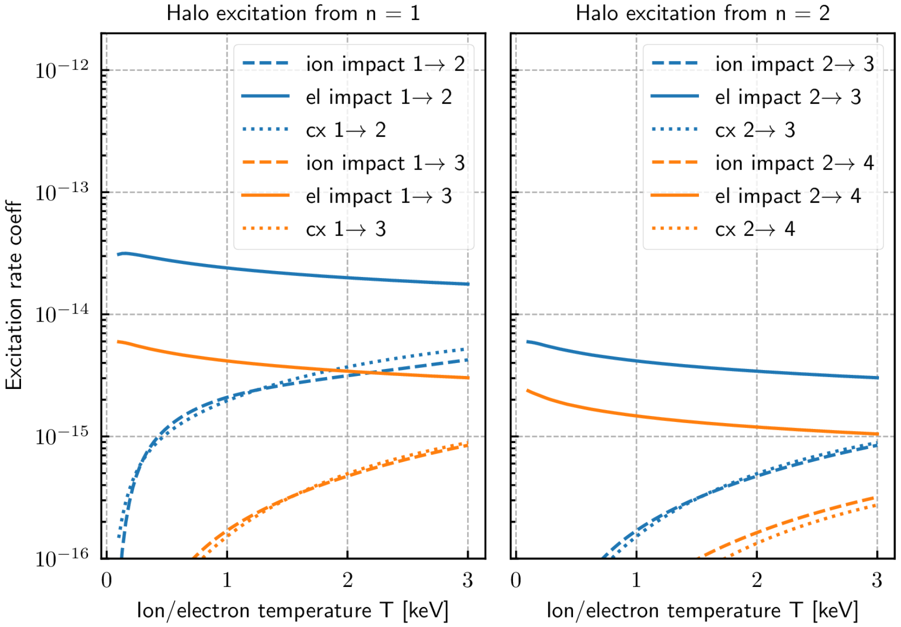
Matrix containing all excitation and deexcitation rates

$$T_{CR} = T_{CR}(T_e, T_i, n_e) = \begin{bmatrix} -L_1 & A_{21} & A_{31} & . & A_{k1} \\ E_{12} & -L_2 & A_{32} & . & A_{k2} \\ E_{13} & E_{23} & -L_3 & . & . \\ . & . & . & . & A_{ki} \\ E_{1k} & E_{2k} & . & E_{jk} & -L_k \end{bmatrix}$$

L: total losses

A : photonic deexcitation

E: excitation



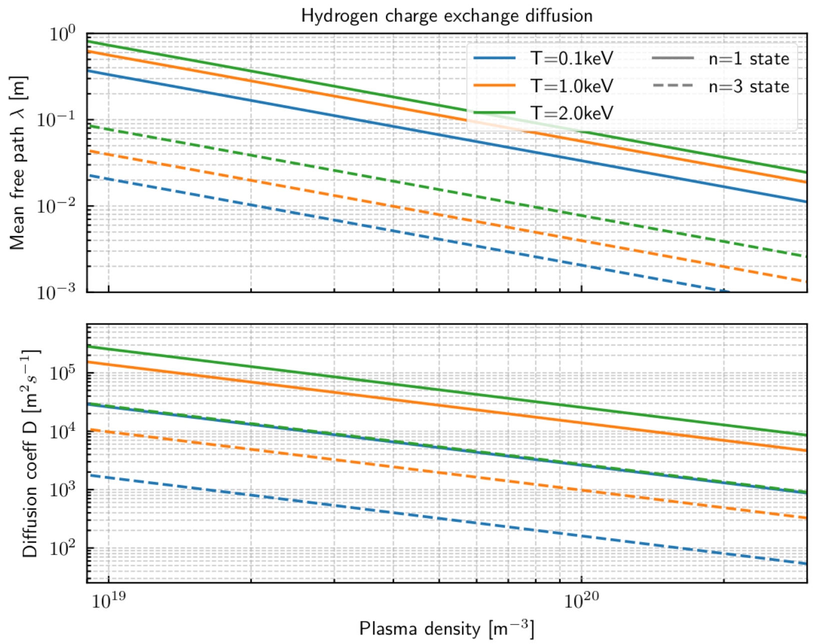
Appendix: CX diffusion coefficient

$$D^{(i)} = \frac{(\Delta x)^2}{2\Delta t} = \frac{\lambda_{\mathrm{CX}}^{(i)} < v >}{2} \quad \text{(A.1)}$$

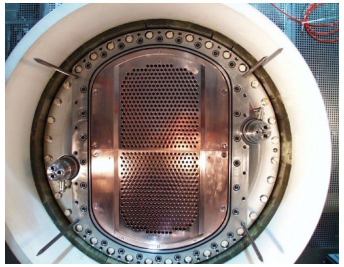
$$< v > = \sqrt{8kT_i/(\pi m_p)} \quad \text{(A.2)}$$

Here $\lambda_{\mathrm{CX}}^{(j)}$ is the mean free path of a neutral in energy state j if only taking CX into account. Maxwell averaged mean free path:

$$\lambda_{CX} = \frac{< v_1 >}{n_{\mathrm{ion}} < \sigma_{CX} v >}$$



Neutral beam injection model



NBI source grid

Geometry

- NBI source grid made up of many pinholes
- All beamlets pointed on horizontal and vertical beam focus

Single Gaussian beam model not sufficient for detailed BES analysis

Collisional-radiative model

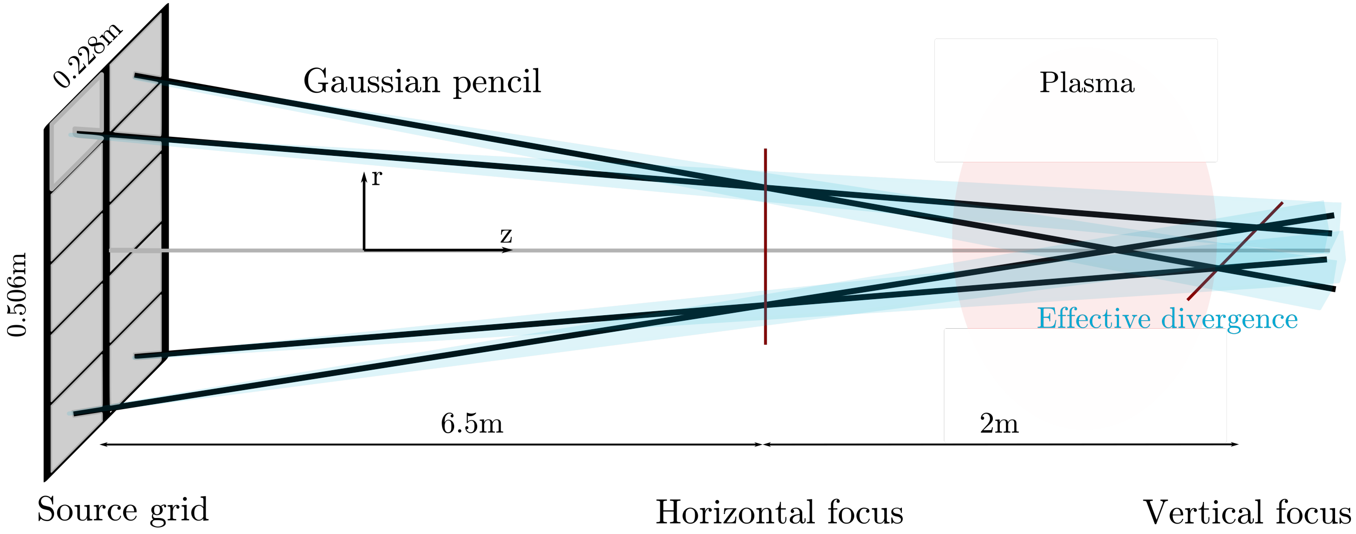
- Necessary to correctly model plasma edge beam emission
- Solved for each Gausscil along its axis
- Track ground state + 5 excited states

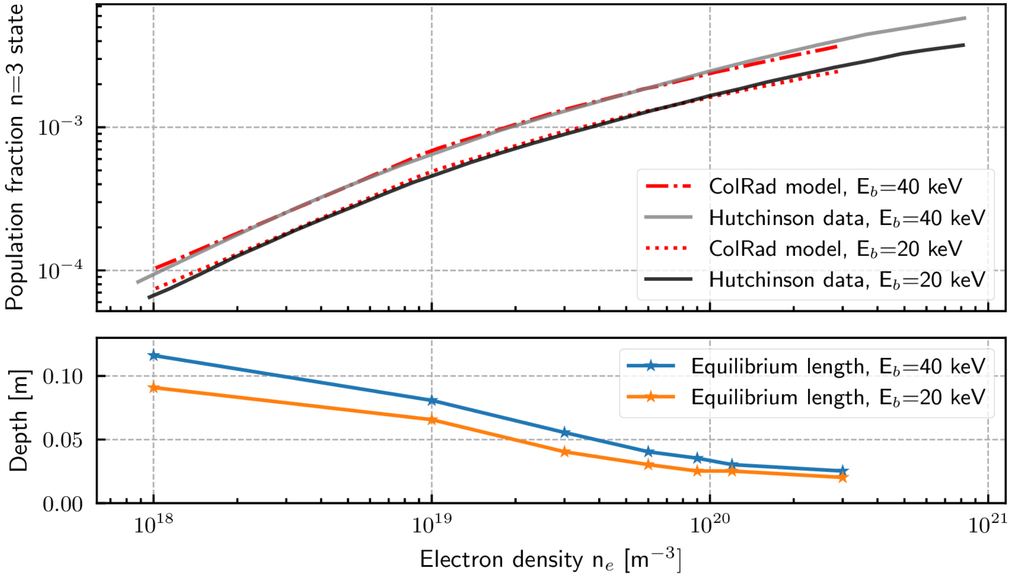
$$\frac{d\mathbf{\Phi}(z)}{dz} = \frac{1}{v_b}\mathbf{T}_{CR}\mathbf{\Phi}(z)$$

Φ: neutral flux

T: ColRad reaction rates at z

Group beamlets into Gaussican pencil (Gausscil) beams





Halo formation model

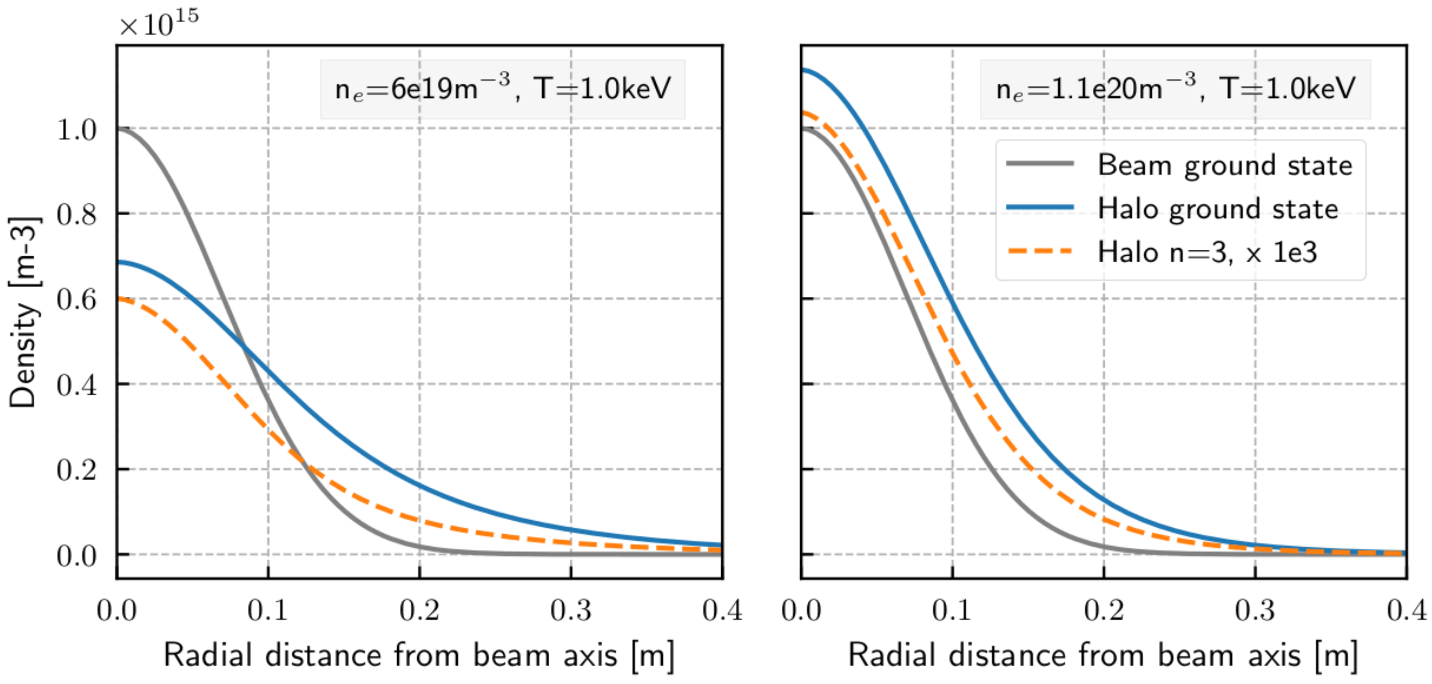


Figure 3. Computed diffusive halo profile as a function of radial distance from the beam axis with shown prescribed beam density as a charge exchange source term and flat plasma profiles. The halo density in the n=3 state is scaled by a factor of 1e3. The halo density shape follows the beam density shape but extends radially due to diffusion.

Diffusion ansatz

$$\mathbf{n} = (n^{(1)}, \dots, n^{(i)}, \dots, n^{(k)})$$

$$\frac{\partial \mathbf{n}}{\partial t} - (\nabla(\mathbf{D}\nabla)) \odot \mathbf{n} = \mathbf{T}_{\mathrm{CR}} \cdot \mathbf{n} + \mathbf{S}_{\mathrm{DCX}}$$

Assumptions

$$\partial_t \mathbf{n} = 0$$

$$\Delta_z = \Delta_\phi << \Delta_r$$

$$\partial_r \mathbf{D} << \frac{D}{r}$$

Simplified radial diffusion equation

$$-\mathbf{D}\Delta_r \odot \mathbf{n} = \mathbf{T}_{\mathrm{CR}} \cdot \mathbf{n} + \mathbf{S}_{\mathrm{DCX}}$$

Beam emission spectroscopy

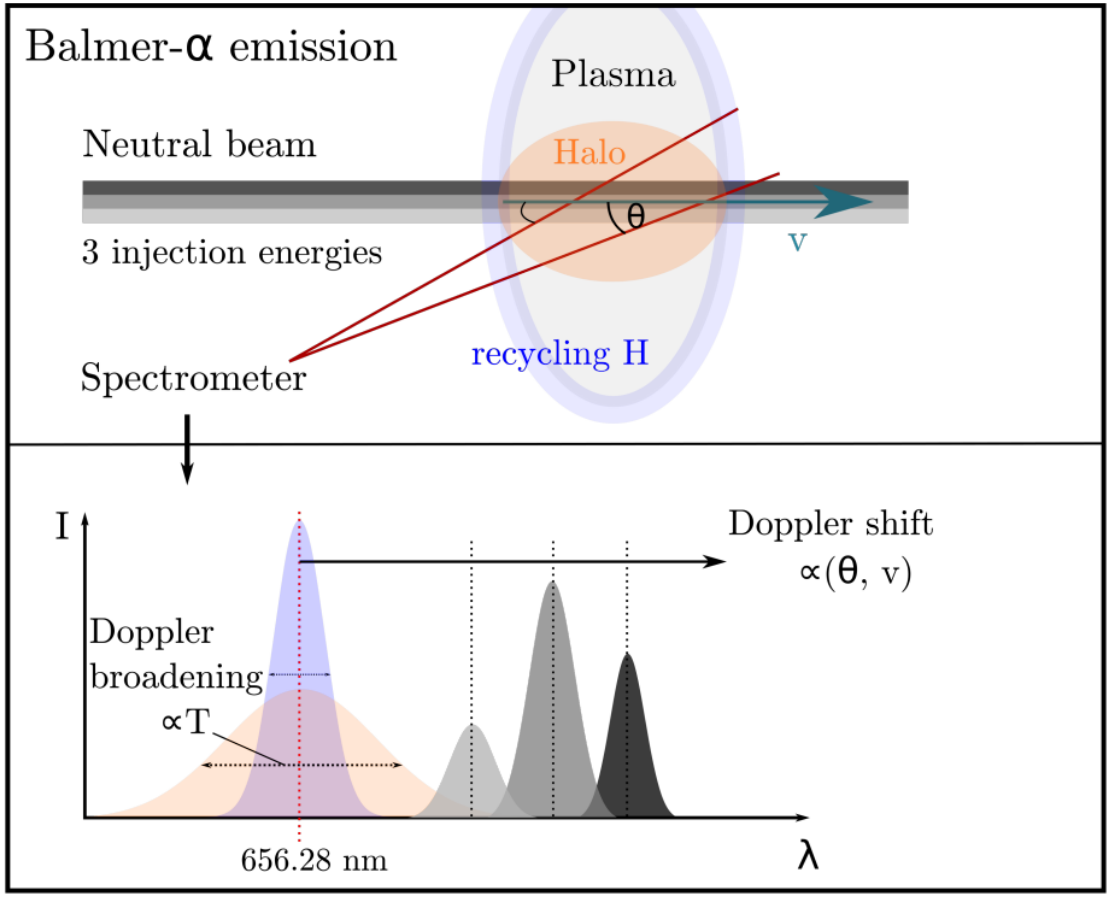


Figure 1. Constituents of a Balmer-α beam emission spectrum (bottom) from different physical and geometrical contributions (top) including Doppler shifted beam emission (black/gray), halo (orange) and cold recycled hydrogen (blue).