’Importance of opacity for physics understanding of density pedestal formation’ – highlights from 47th ITPEA PEP TG meeting (Spring-2026)

C. Perez von Thun

On behalf of the EU PEP TG members

M. Agostini, N. Chaudhari, B. Labit, P. Maget, S. Saarelma,

E. Viezzer, M. Willensdorfer

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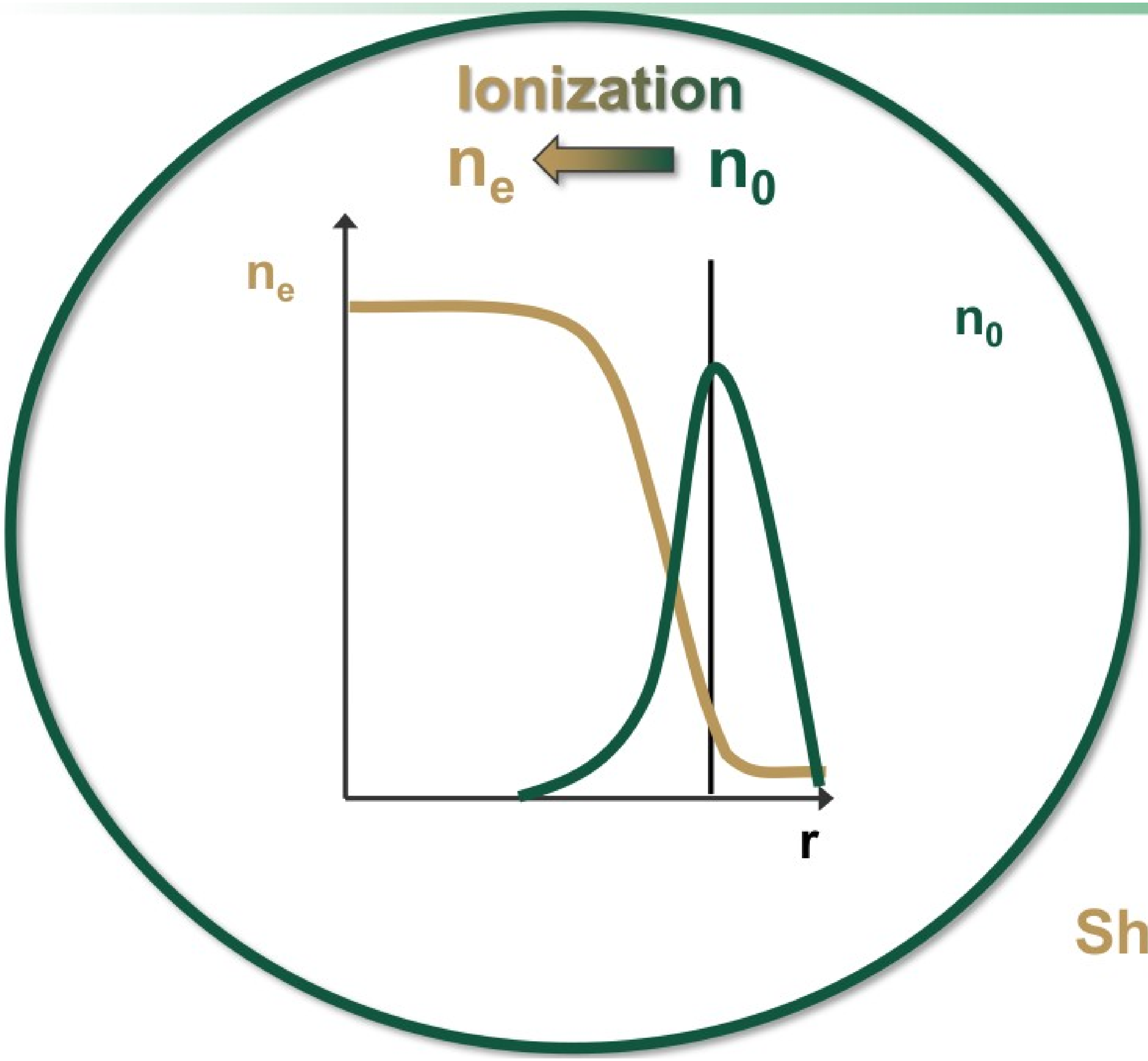
47th PEP TG meeting

- Meeting held at **KTH Royal Institute of Technology (Stockholm, Sweden)**, 02-05 March 2026
- Large focus of this meeting: **pedestal density prediction**
  - **Importance of opacity** for physics understanding of density pedestal formation (4 sessions, chair: S. Mordijck)

shows who presented

In the following will show a selection of key points discussed at this meeting...

Intro: What sets the pedestal density profile?



$$\nabla\Gamma = S$$

$$\Gamma = \int S\,dV$$

Diffusive flux > 0 — Convective flux

$$-D\nabla n + vn = \int S\,dV$$

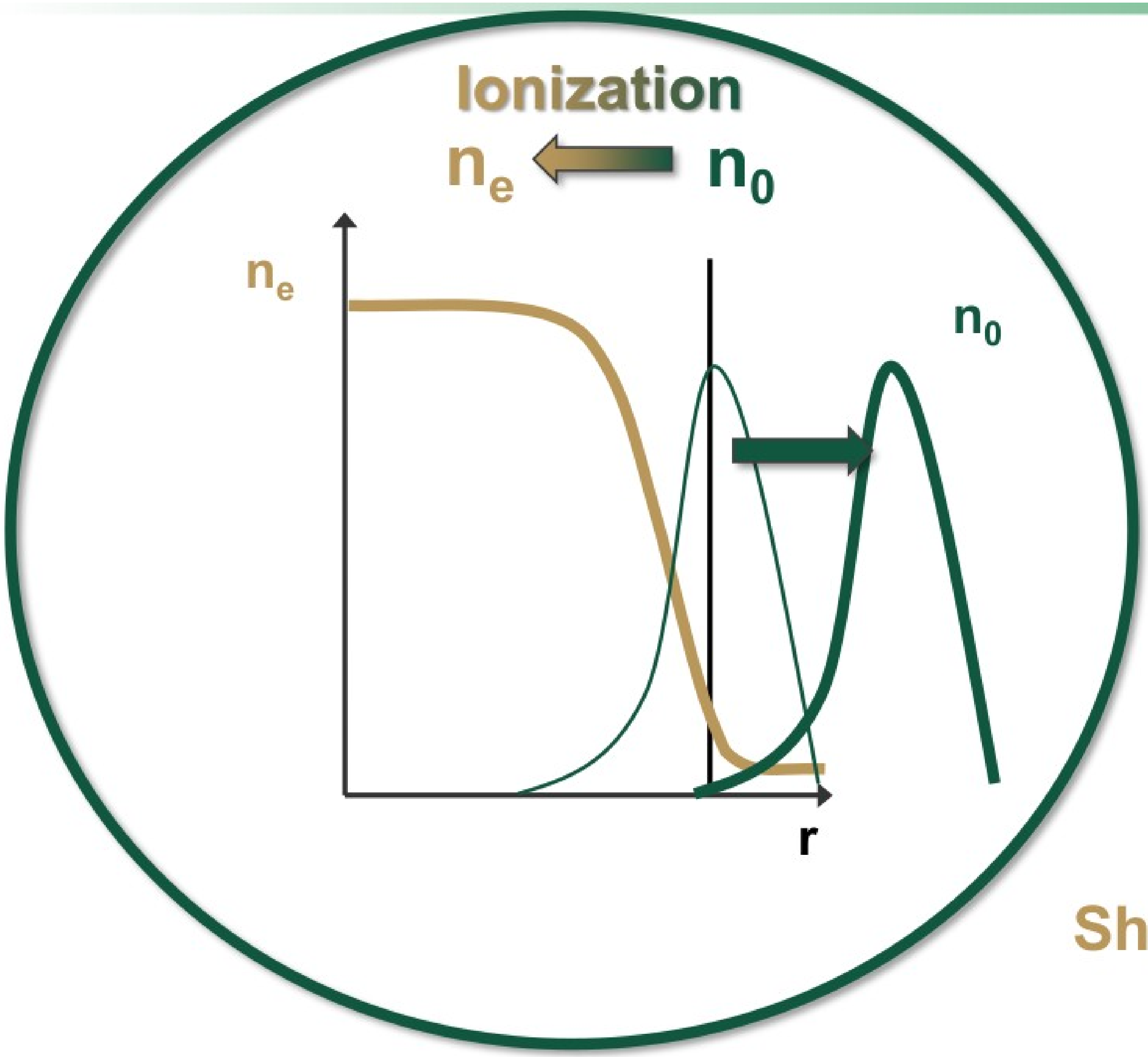
$$\frac{\nabla n}{n} = \frac{v}{D} - \frac{\int S\,dV}{Dn}$$

Shape profile — Transport — Fueling

S. Morjdick

Intro: With opaque SOL the role of transport becomes dominant

(in the absence of pellet fuelling)



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Shape profile

Transport

S. Morjdick

PEP-41: What will the ITER pedestal density gradient look like?

To determine the size and role of the inward pinch at the plasma edge in plasmas with an opaque edge in the build-up of the density profile.

S. Morjdick

Intro: key questions that were addressed in this meeting

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$$\frac{\nabla n}{n} = \frac{v}{D} - \frac{\int S\, dV}{Dn}$$

Shape profile — Transport — Fueling

How accurately must neutral distributions be known...

- to determine source S/particle flux?
- to validate pedestal density models?

How can particle transport coefficients in the pedestal be measured and extracted reliably?

- limitations of a modulated source approach?

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Shape profile

Transport

Fueling

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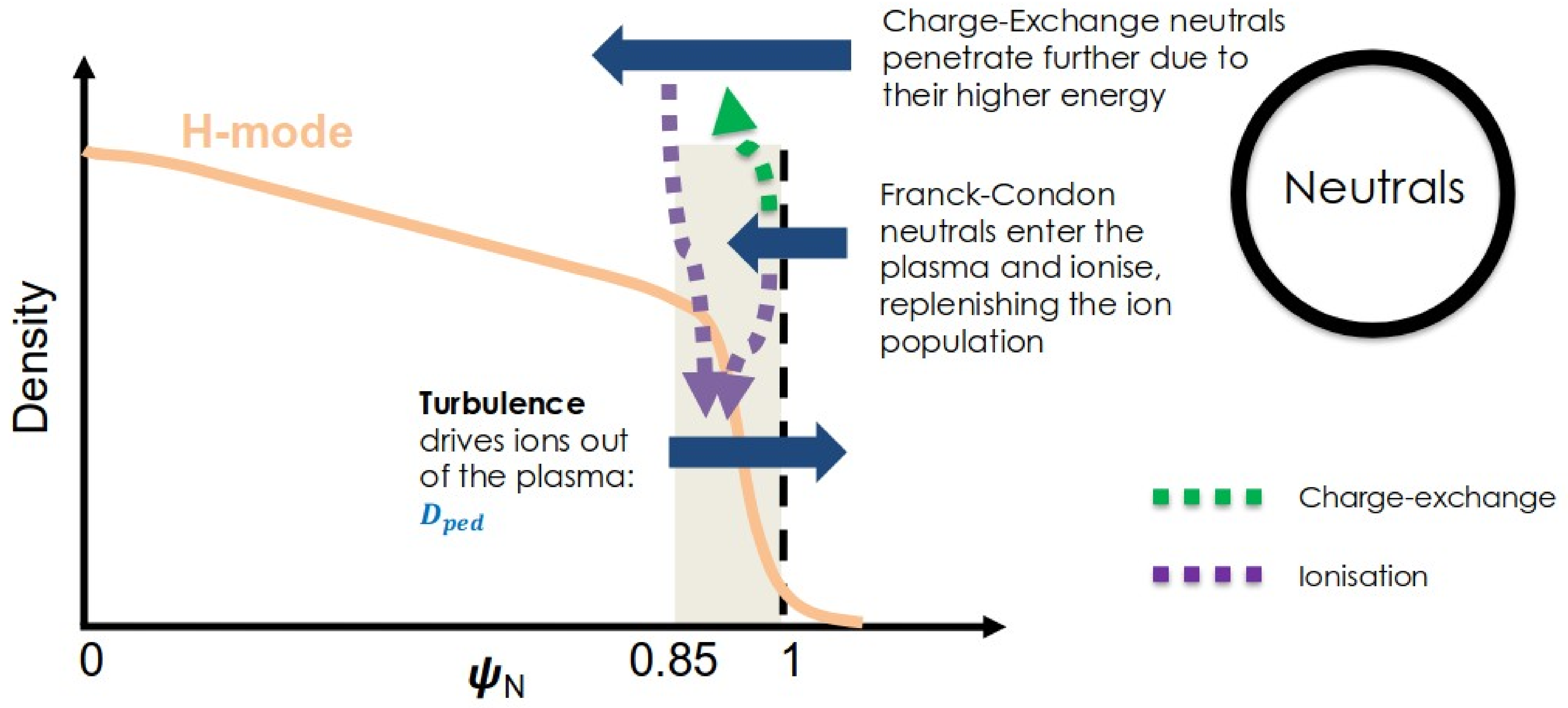
S. Morjdick

Saarelma-Connor density pedestal prediction model (SCM)



Saarelma et al., *Nuclear Fusion* (2023)

J. Dunsmore

Saarelma-Connor-Model: full set of equations

note SC Model uses purely diffusive term for electrons

- $\nabla \cdot \left(D_{\text{ped}} \nabla n_e\right) = -n_e(n_{\text{FC}} + n_{\text{CX}})S_i$ — Plasma density (1)
- $\nabla \cdot (V_{\text{FC}} n_{\text{FC}}) = -n_e(n_{\text{FC}} S_i + n_{\text{FC}} S_{\text{CX}})$ — Franck-Condon (cold) neutrals (2)
- $\nabla \cdot (V_{\text{CX}} n_{\text{CX}}) = -n_e\left(n_{\text{CX}} S_i - \frac{1}{2} n_{\text{FC}} S_{\text{CX}}\right)$ — Charge exchange (hot) neutrals (3)
- $S_i(T_e), S_{CX}(T_e)$ are the ionization and charge exchange rates.

- **Neutral transport:**
- $|V_{\text{FC},r}| = \sqrt{8E_{\text{FC}}/\pi^2 m_i}$
- $|V_{\text{CX},r}| = \sqrt{2T_i/\pi m_i}$

Boundary conditions:

$n_{e,sep}, n_{FC,sep}, n_{CX,sep}, \nabla n_{e,core}$

Plasma transport:

$$D_{\text{ped}} = D_{\text{NC}} + D_{\text{KBM}} + D_{\text{TG}}$$

$$D_{\text{NC}} = \frac{\chi_{e,\text{NC}}}{2} = 0.05\left(\frac{\rho_s^2 c_s}{a}\right)$$

$$D_{\text{KBM}} = \begin{cases} C_{\text{KBM}}(\alpha - \alpha_{\text{crit}}), & \alpha > \alpha_{\text{crit}} \\ 0, & \alpha < \alpha_{\text{crit}} \end{cases} \quad \alpha = -\frac{2\partial_\psi V}{(2\pi)^2}\left(\frac{V}{2\pi^2 R_0}\right)^{\frac{1}{2}} \mu_0 \partial_\psi p$$

$$D_{\text{TG}} = \left(\frac{D}{\chi}\right)_{\text{TG}} \frac{P_{\text{tot},e}}{S n_e \nabla T_e}$$

Full derivation in S. Saarelma NF 2023

Three contributions to pedestal transport considered in SC Model...

$$D_{ped} = D_{NC} + D_{KBM} + D_{ETG}$$

$$D_{NC} = 0.05\left(\frac{\rho_s^2\, c_s}{a}\right)$$

$$D_{KBM} = \begin{cases} C_{KBM}(\alpha - \alpha_{crit}) \cdot \left(\frac{\rho_s^2\, c_s}{a}\right), & \alpha > \alpha_{crit} \\ 0, & \alpha < \alpha_{crit} \end{cases}$$

$$D_{ETG} = \left(\frac{D_e}{\chi_e}\right)_{ETG} \frac{P_{tot,e}}{S\, n_e\, \nabla T}$$

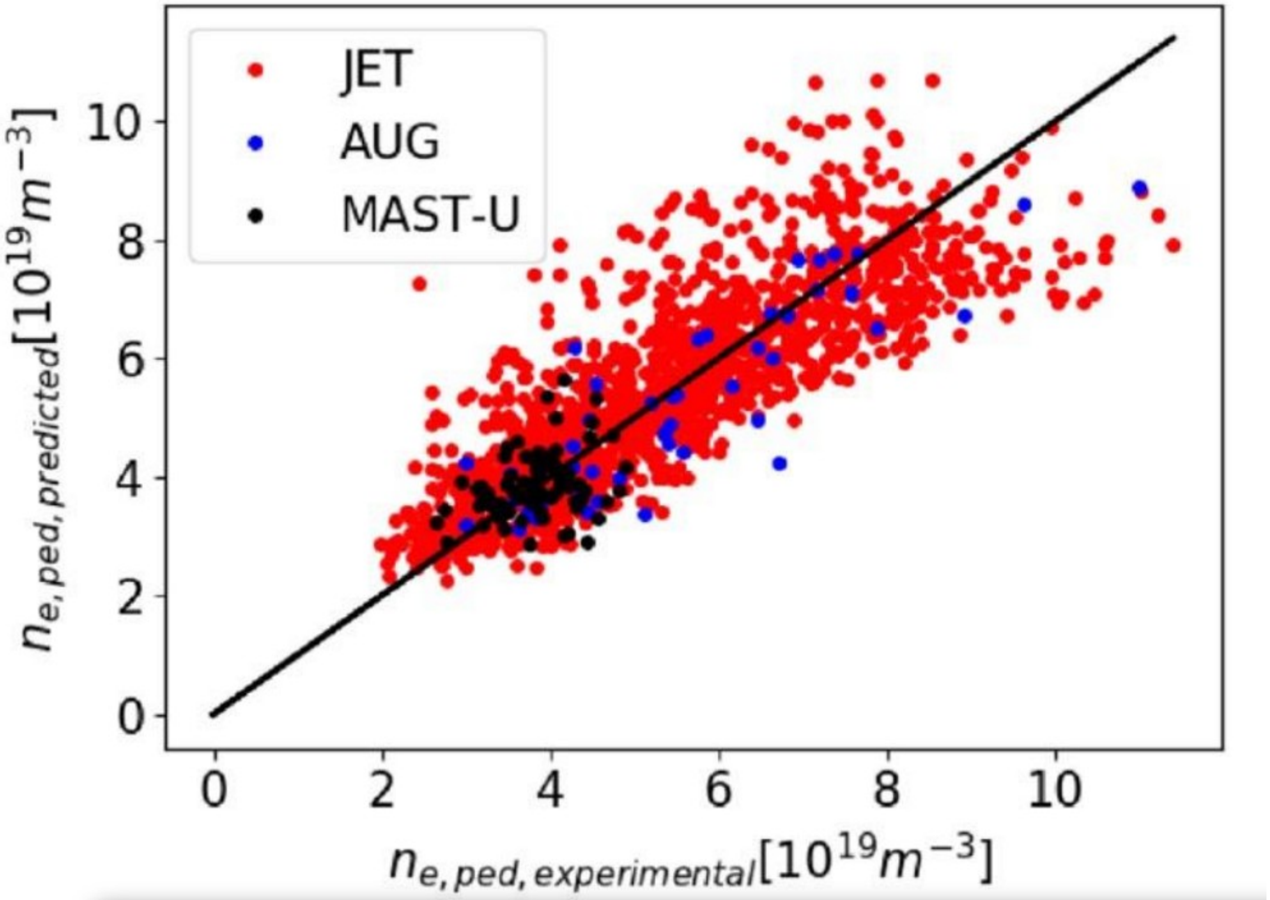
$$\alpha = \frac{2\mu_0}{(2\pi)^2}\frac{\partial V}{\partial \varphi}\left(\frac{V}{2\pi^2 R_0}\right)^{1/2}\frac{dp}{dr}$$

Saarelma et al., *Nuclear Fusion* (2023)

J. Dunsmore

Status as of NF-2024: SCM tested on three devices

Saarelma et al., *Nuclear Fusion* (2024)



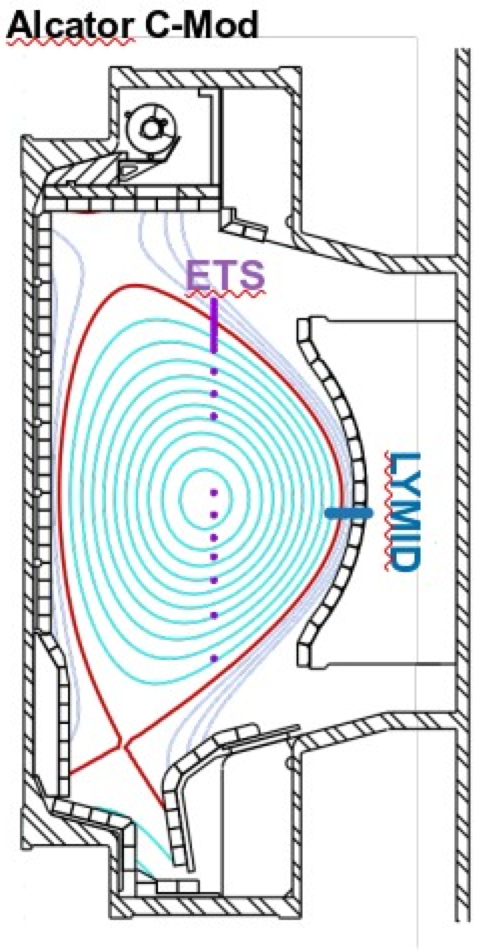
RMSE: JET 22%, AUG: 17%, MAST-U: 14%

Assumptions:

- $n_{e,sep}$ and ∇n_{core} from experiment
- fixed $\langle n_{0,sep} \rangle = 10^{15} m^{-3}$
- D_{ped}: fit C_{KBM} and $(D_e/\chi_e)_{ETG}$ for JET and use the same value for all devices

can do better?...

NEW: Exploit neutral edge profile measurements to inform right choice of n0,sep for SCM

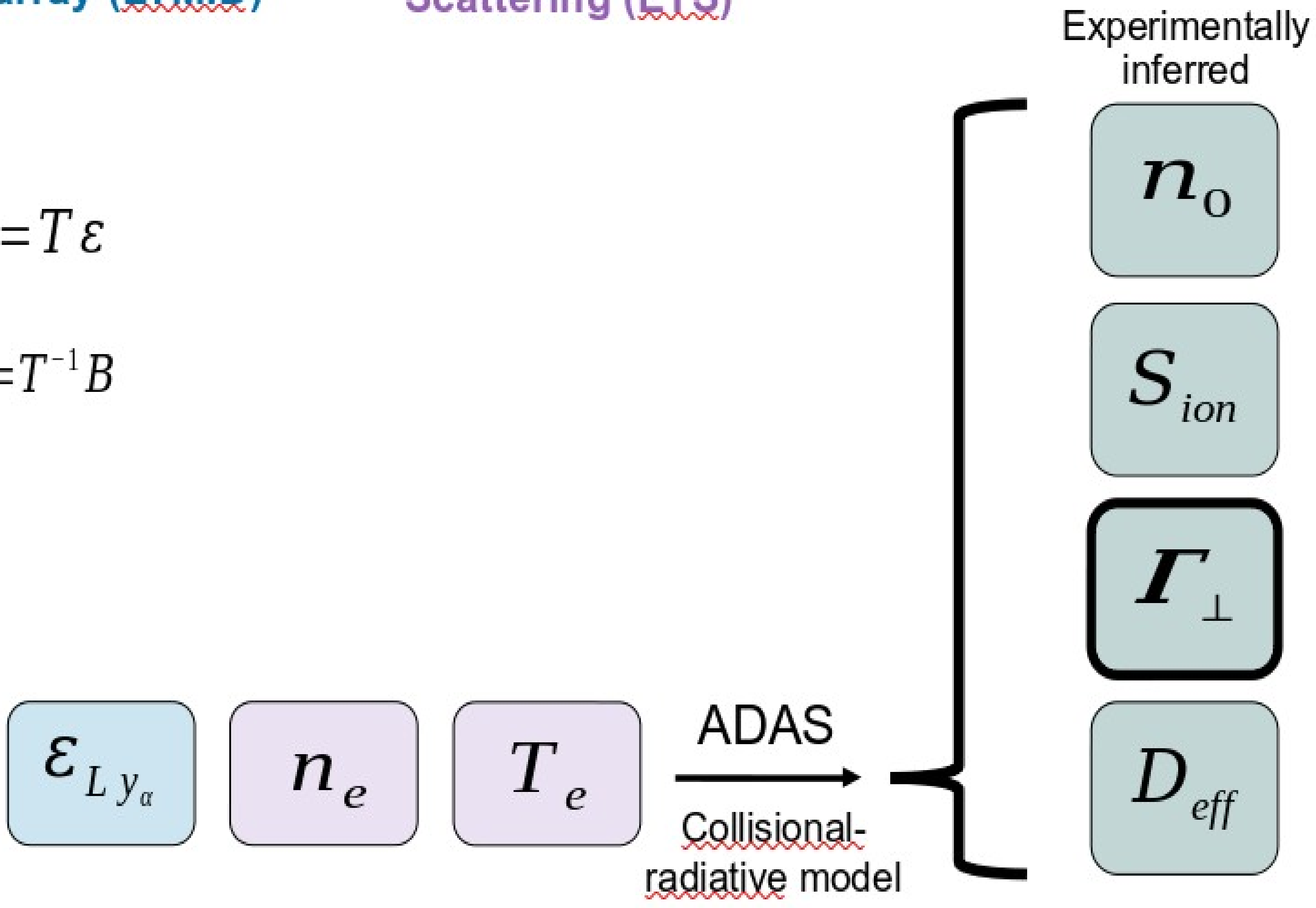


Ly_α array (LYMID)

Edge Thomson Scattering (ETS)

$$B = T\varepsilon$$

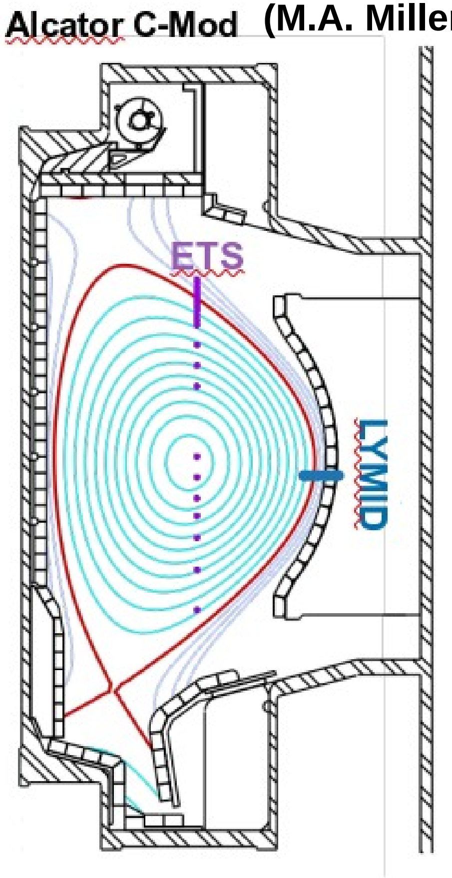
$$\varepsilon = T^{-1}B$$



M.A. Miller

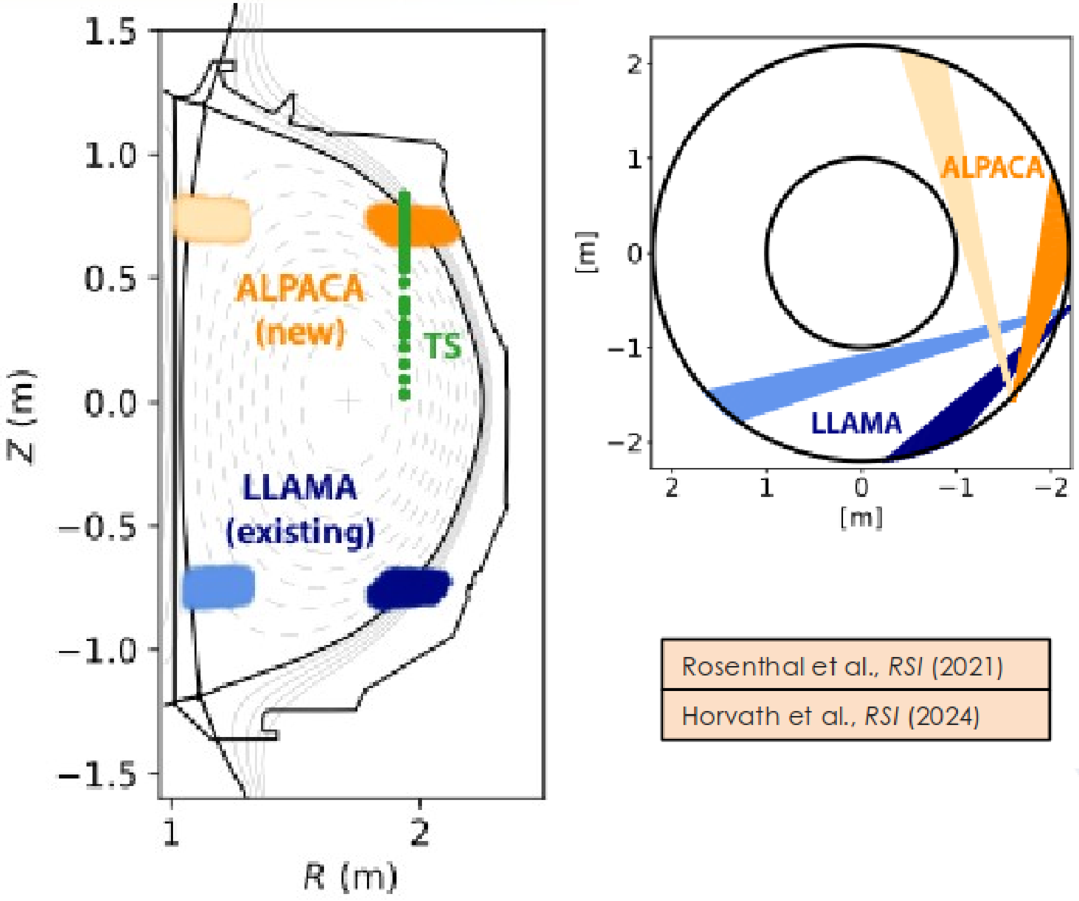
Neutral profile measurements capabilities for C-Mod, DIII-D, MAST-U

(M.A. Miller)



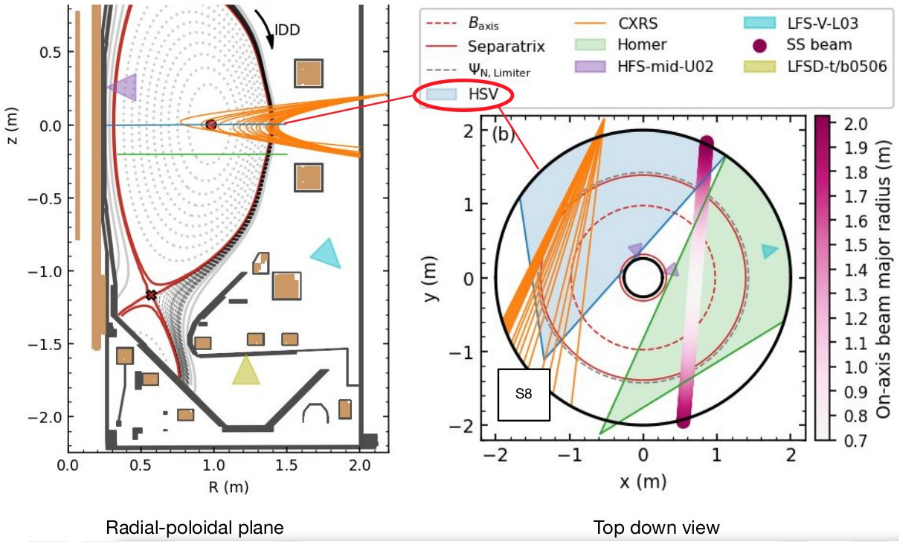
Ly$_{alpha}$-based

DIII-D (J. Dunsmore)



Ly$_{alpha}$-based

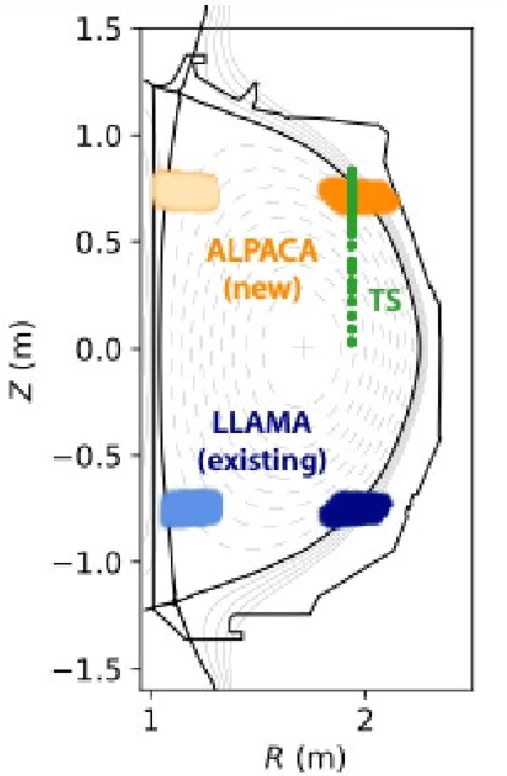
MAST-U (S. Thomas)

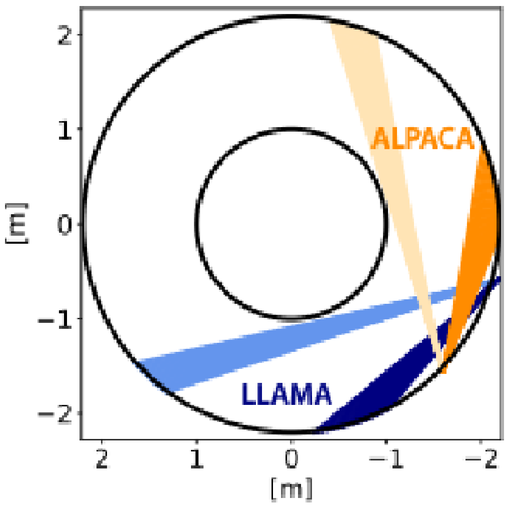


D$_{alpha}$-based

Ly$_{alpha}$ diagnostic on KSTAR: in progress

NEW: SCM tests incl. neutrals extended to DIII-D





Rosenthal et al., *RSI* (2021)
Horvath et al., *RSI* (2024)

KN1D Factsheet

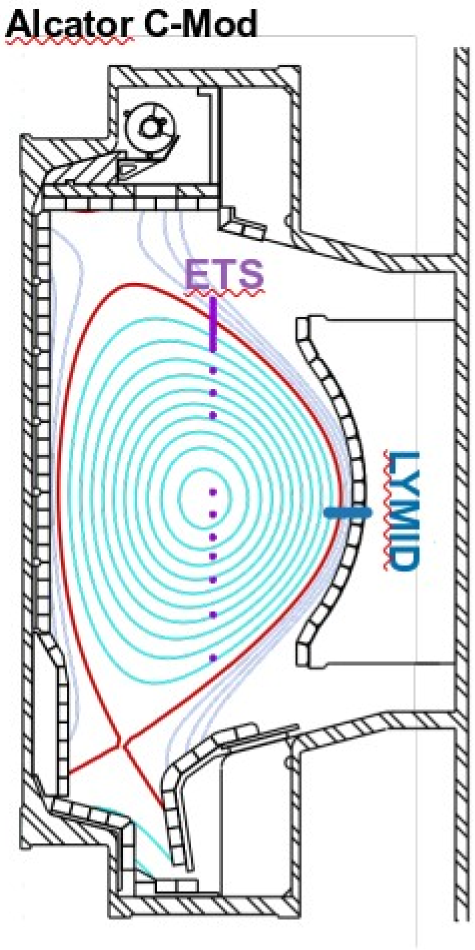
	KN1D	Saarelma-Connor
1D?	✓	✓
Charge exchange?	✓	✓
Higher generation charge exchange?	✓	✗
Elastic scattering?	✓	✗
Includes outwardly propagating neutrals?	✓	✗
Neutral distribution representation?	Full distribution function	Two-jet model

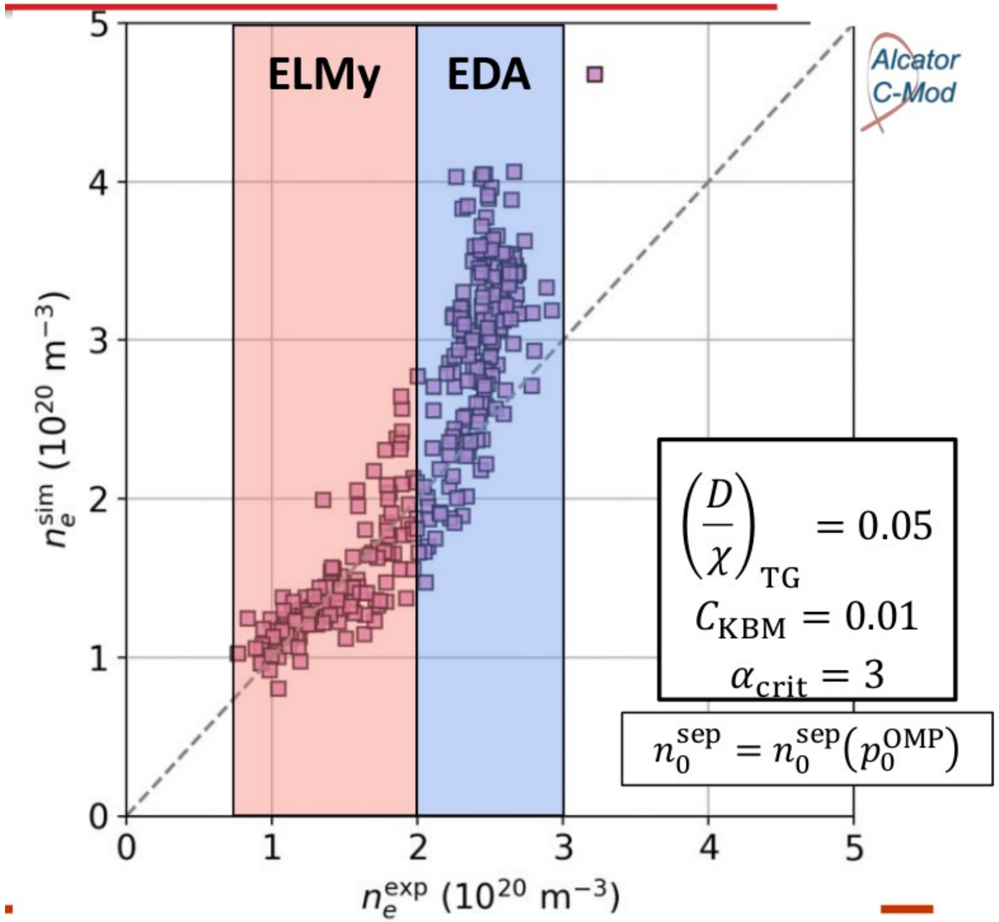
Standard SCM density pedestal prediction on DIII-D improved ‘step-by-step’ by:

- using experimental n0,sep measurements (LLAMA) instead of fixed $n_{0,sep}$=1E15m-3
- using KN1D’s neutrals model instead of SCMs two monoenergetic jets
- using Bernard’s alpha_crit (instead of constant alpha_crit = 2)

J. Dunsmore

NEW: SCM tests incl. neutrals extended to Alcator C-Mod



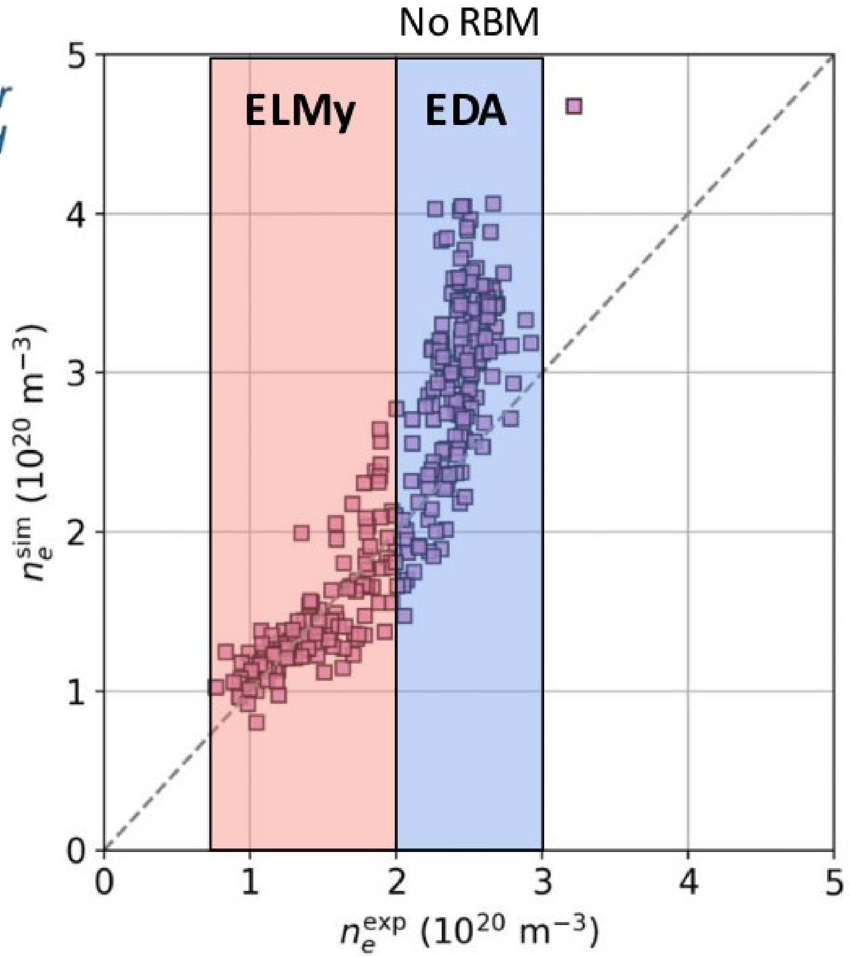


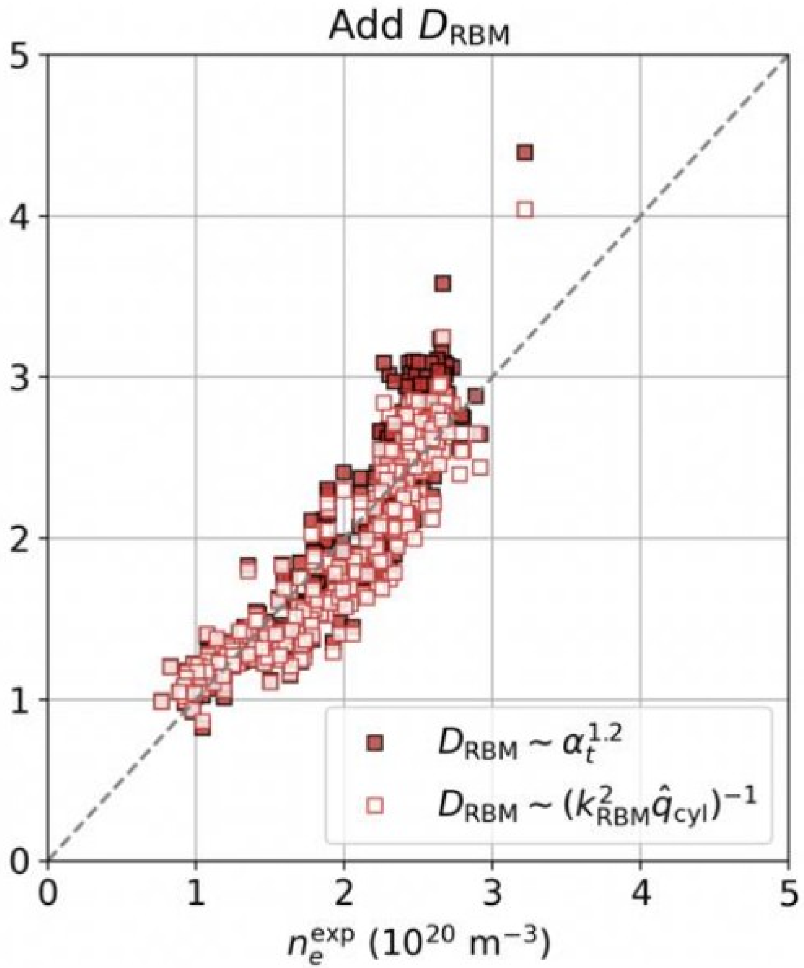
- depending on choice of transport parameters, agreement on C-Mod not as good as for JET/AUG/MAST-U
- systematic deviation especially for EDA H-modes...

M.A. Miller PhD MIT 2025, NF in preparation

S-C model modified with RBM term has improved agreement with C-Mod EDA H-modes

$$\mathrm{D_{ped} = D_{neo} + D_{KBM} + D_{TG} + \mathbf{D_{RBM}}}$$





- Propose a collisionality-dependent RBM term to provide additional particle transport
- Apply to SPARC for high α_t scenarios?

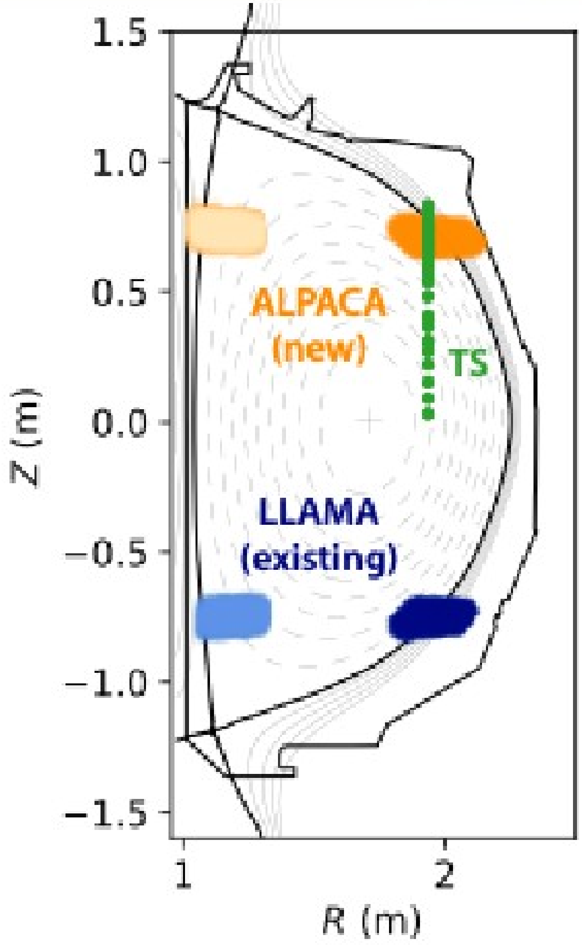
$$\alpha_t \equiv C\omega_B \sim \hat{q}_{cyl}\nu^*$$

Eich *et al. Nuclear Fusion* (2020)

M.A. Miller, MIT PhD 2025

J.W. Hughes

Main chamber neutral fuelling poloidal asymmetries also important → 2D problem!



On DIII-D see strong asymmetry in pedestal fueling (LFS/HFS) upon reversal of toroidal magnetic field

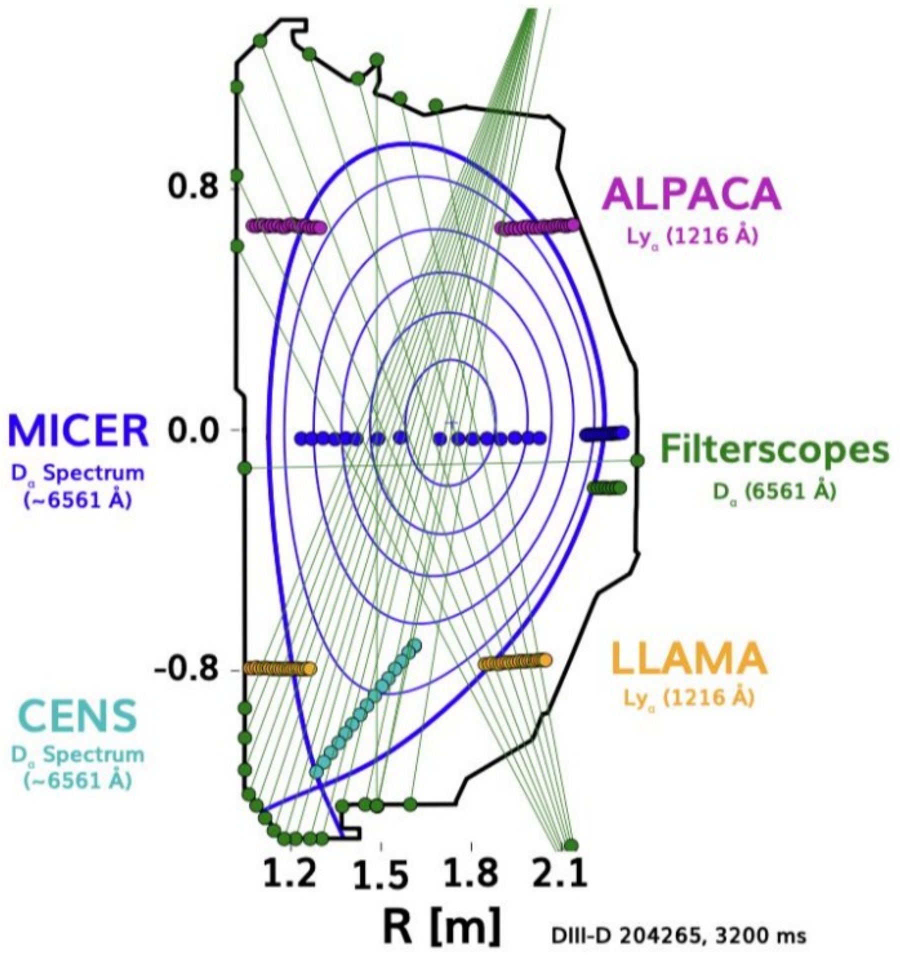
Div.detachment, PFR, and main SOL flows also found important in setting recycling and main chamber LFS/HFS asymmetries on DIII-D

→ Measurements at multiple poloidal locations are needed

How many viewing geometries (poloidal, toroidal, radial) are required to adequately constrain neutral distributions?

L. Horvath

Main chamber neutral fuelling poloidal asymmetries also important → 2D problem!



[1]L. Horvath *et al.* Rev. Sci. Instrum. 95 (2024)
[2]J. Herfindal *et al.* Rev. Sci. Instrum. 95 (2024)
[3]S. Haskey *et al.* Rev. Sci. Instrum. 95 (2024)
[4]S. Haskey *et al.* Rev. Sci. Instrum. 93, (2022)

Workflow demonstrated on DIII-D for obtaining the flux-surface averaged <S_{D+}> profile inside the confined region

- involves neutral MonteCarlo DEGAS2 calculations with 1D plasma background plus neutrals info experimentally constrained in 2D using multiple diagnostics
- in addition, spectral neutral diagnostics provide a means to separate ‘thermal’ (~pedestal Ti) from ‘cold’ (=SOL) emission

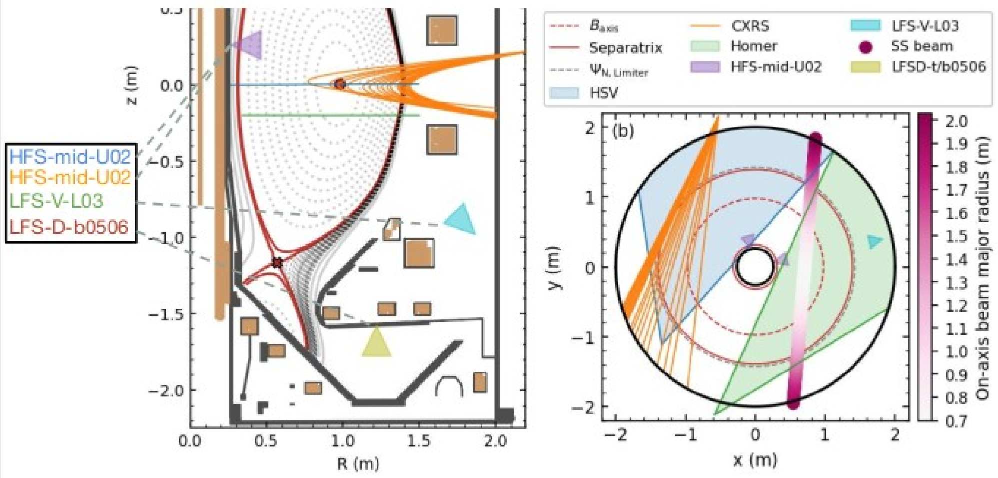
Good agreement along most poloidal plane except near lower inner target → must be due to presence of a HFSHDF

For DIII-D case analysed: Both sources of neutrals (divertor and main chamber) contribute to pedestal fuelling on DIII-D (rel. contrib. psiN-dependent), and dominate over NBI source.

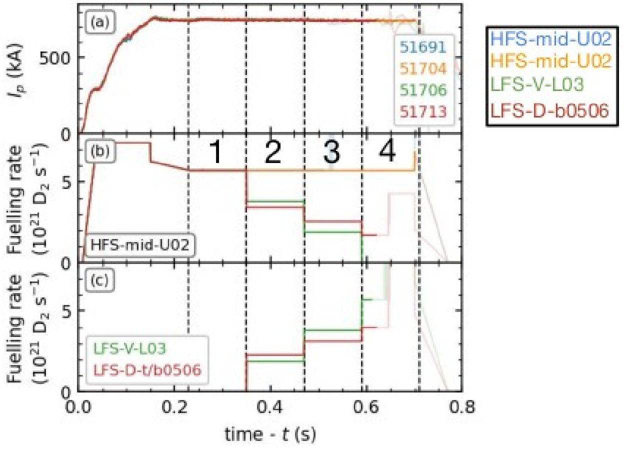
Q. Pratt

Main chamber neutral fuelling poloidal asymmetries also important → 2D problem!

Poloidal fuelling experiment MAST-U (MU04)



Radial-poloidal plane, and top-down view



Neutrals-wise, LFS fuelling location on MAST-U found to behave differently to other fuelling locations (HFS, divertor):

- $n_{e,ped}$ and $n_{0,sep}$ resilient to poloidal fuelling location
- Larger S_0 for LFS – but countered through transport increase
- Diffusive-convective model infers presence of inward particle pinch

S. Thomas

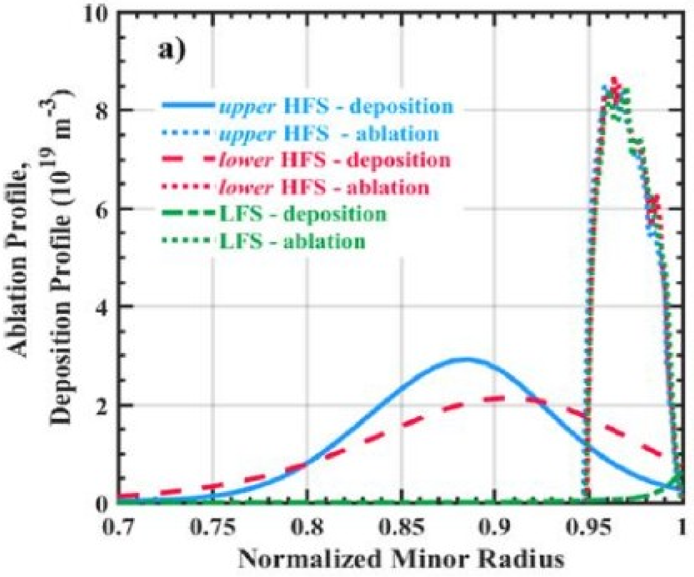
Neutral diagnostics: Can we apply lessons learned to JT60SA?

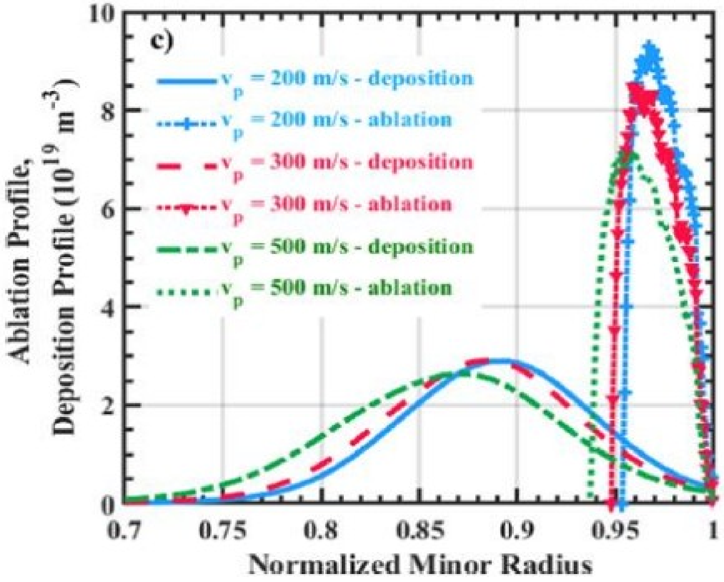
- High-opacity operation will be achieved in JT-60SA (and SPARC)
- Neutral diagnostics will play a key role in improving our physics understanding of opacity
- Lesson learned: Neutral distribution poloidal asymmetries are important to measure → recommend 2D spectroscopic measurements on JT60SA
- 2D fast camera spectroscopic measurements identified as most promising diagnostic technique to measure neutrals
  - likely should be complemented with 1D 'LLAMA-like' measurements, e.g. to cross-calibrate or test for consistency
- Aim to prepare list of diagnostics available for neutral studies on JT60SA (next PEP meeting?)
- **MANTIS-like diagnostic for JT-60SA will be provided by EUROfusion (TCV/DIFFER) and has the potential to provide key information for pedestal studies, including high opacity plasmas (details? filters? right geometry? are we still on time to adapt?)**
- Before fall TG meeting, it will be useful to identify what support we need from DSOL colleagues so that discussions can be productive.

Outcome of discussions

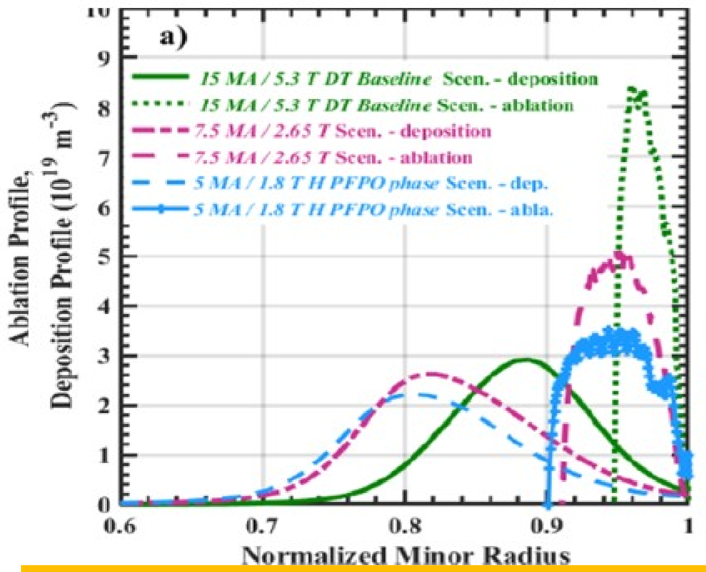
New developments regarding pellet fuelling

❑ Pellet fuelling source impact on pedestal





Pellet deposition expected to occur inside pedestal for HFS injection due to significant plasmoid ExB drift



[Panadero NF 2023]

[Na NF 2019]

Potential caveat:

- Pellet-induced ELM losses
- Pellet rocket acceleration dependence on strong local pedestal gradients (in addition to plasmoid shading) → [Guth PRL 2025]

F. Koechl

Ongoing effort for cross-validation of pellet codes with multi-machine data under IOS-JA13 (N. Panadero)

Intro: key questions that were addressed in this meeting

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Shape profile — Transport — Fueling

How accurately must neutral distributions be known...

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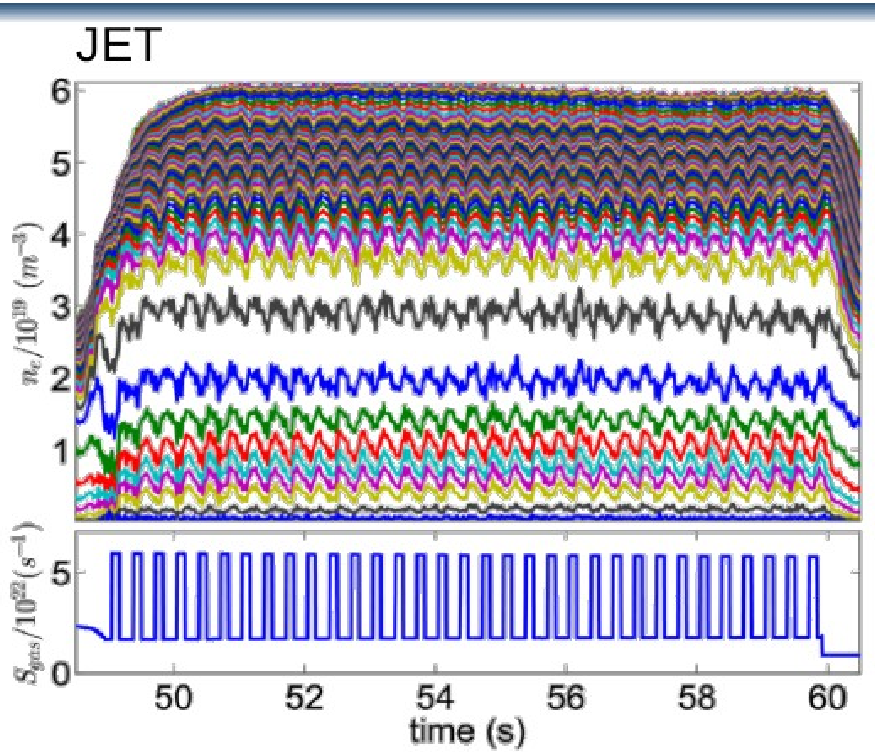
How can particle transport coefficients in the pedestal be measured and extracted reliably?

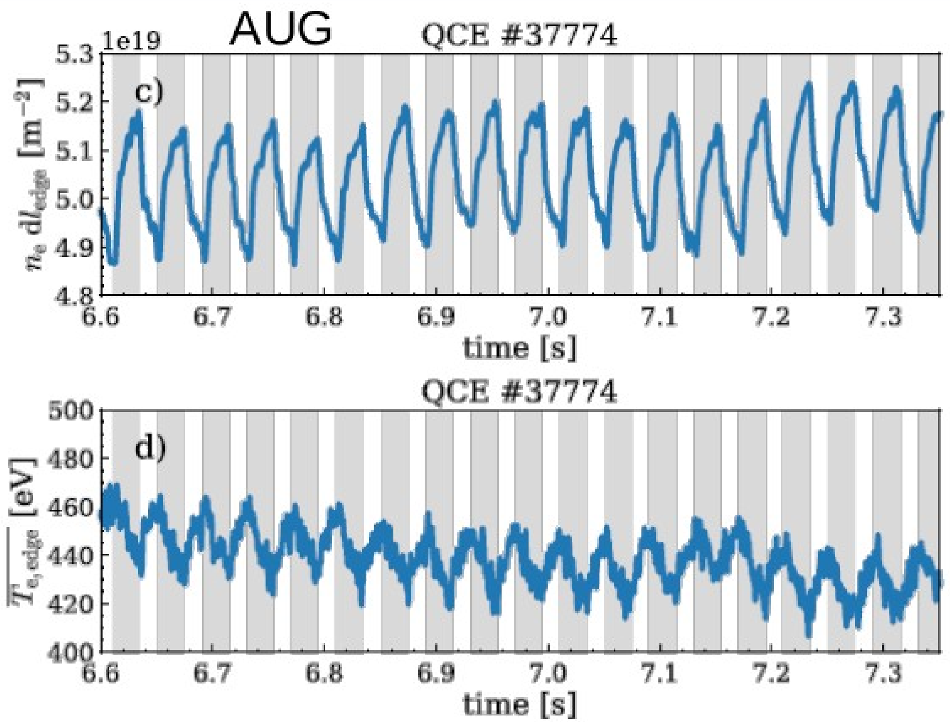
- limitations of a modulated source approach?

S. Morjdick

Particle transport study by gas puffing modulation



T. Tala et al 2019 Nucl. Fusion 59 126030



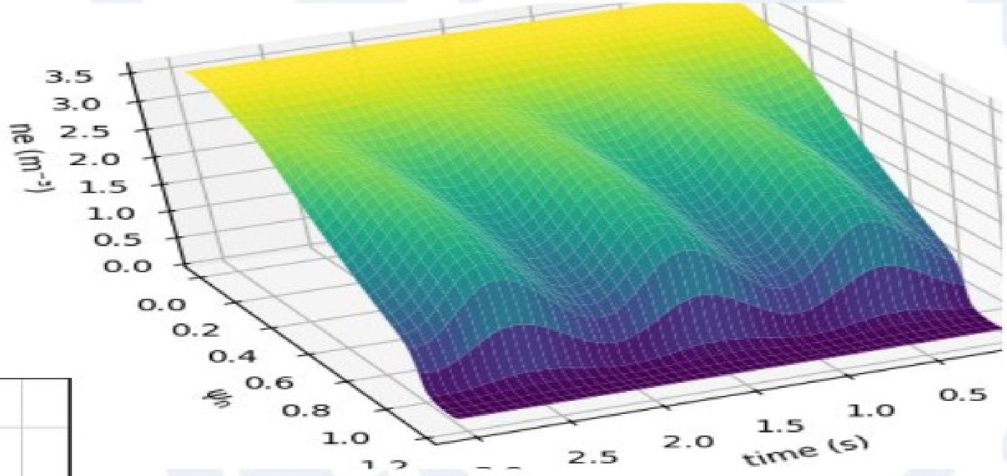
C.U. Schuster et al 2023 Nucl. Fusion 63 092001

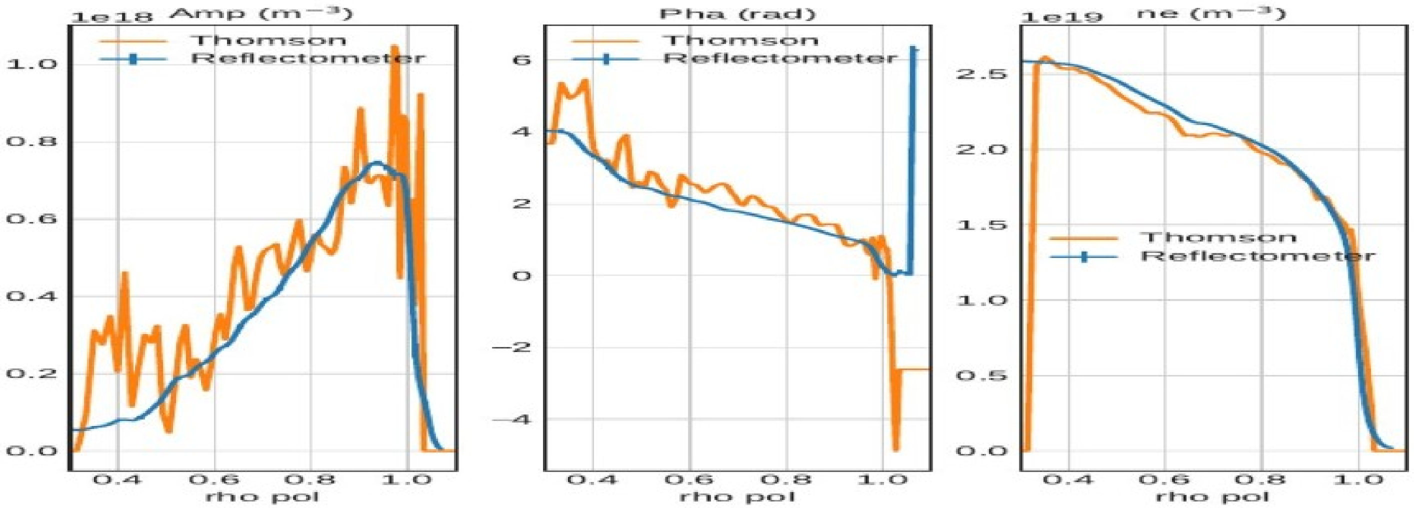
- Gas puffing modulation is frequently used to study the particle transport in both core and edge regions.

Inferring transport (D,v) from the experimental modulation data

- Optimization approach where unknown parameters D & V are varied until the simulated n_e matches the measurements (profile reflectometer)

$$\frac{dn_e}{dt} + \nabla \cdot (D \nabla n_e - v n_e) = S - \frac{n_e}{\tau_{||}}$$





Possible unwished side-effects of gas modulation to infer particle transport:
- impact on ELMs (type, f_{ELM})
- impact on Te
- ….

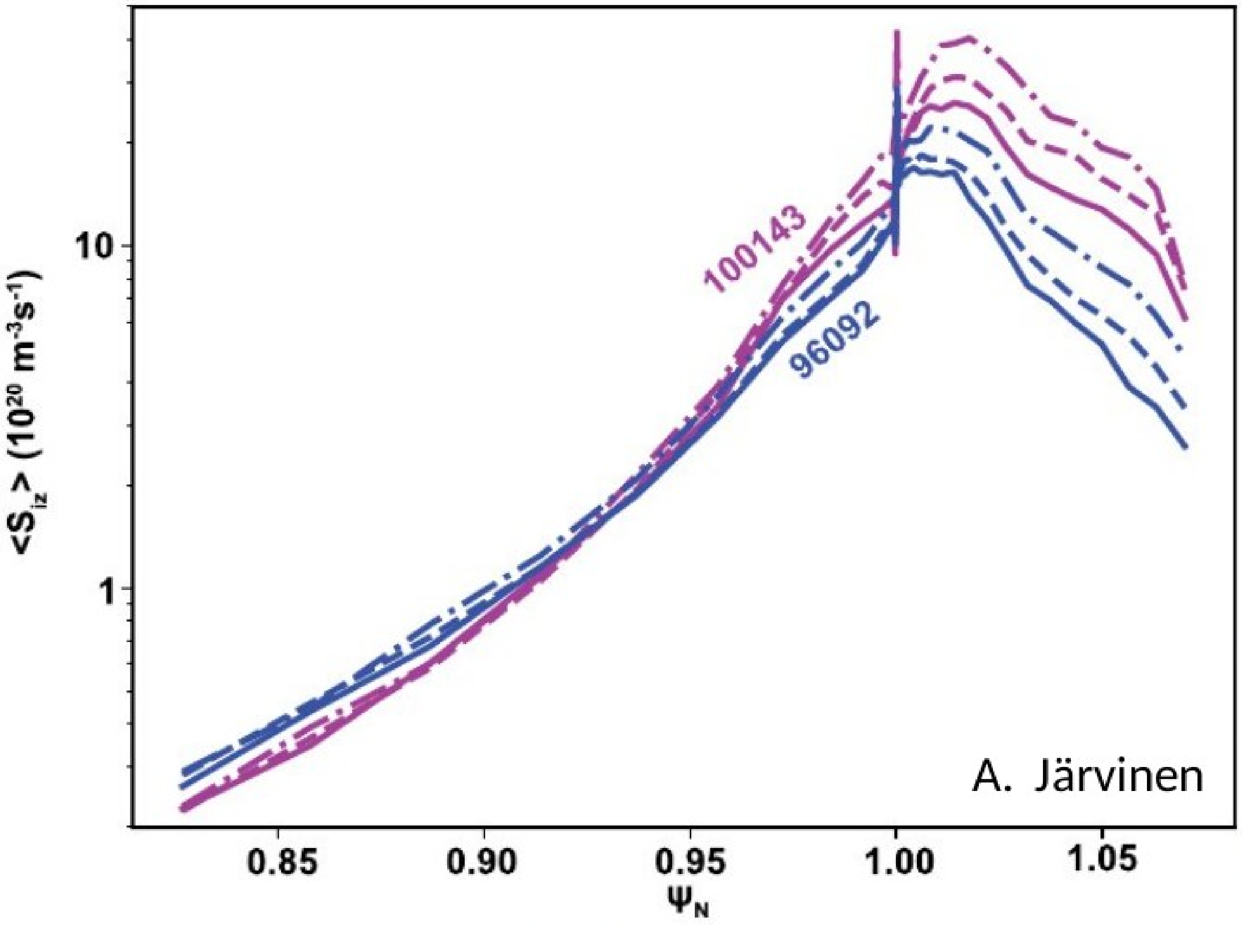
A. Salmi

For source computation on JET relied on EDGE2D-EIRENE

- To constrain the optimisation we assume EDGE2D-EIRENE calculated source profiles are accurate and profile shape remains the same throughout the modulation cycle
  - Could of course use full time dependent source information but due to the strong edge localization it makes no difference for core transport – pedestal studies may need it

!

D-alpha at mid-plane used as constraint

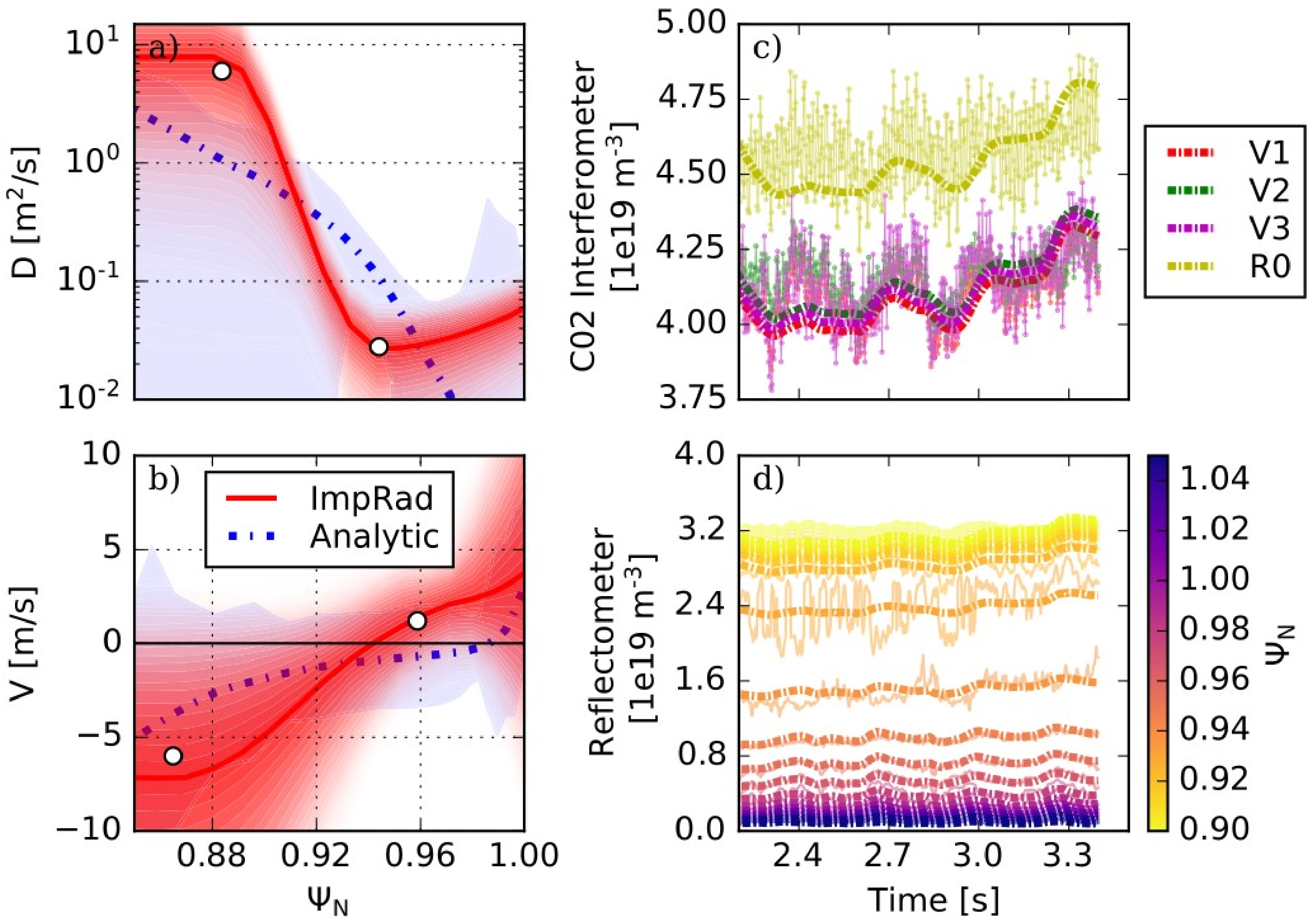


T. Tala Nucl. Fusion 2023

A. Salmi

Gas puff modulation with MEASURED sources (LLAMA, DIII-D)

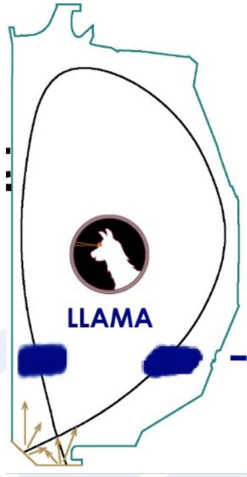
Rosenthal NF 2024



Advantage: Don't have to rely on simulated neutral distributions

Transport coefficients extracted with forward modelling (AURORA)

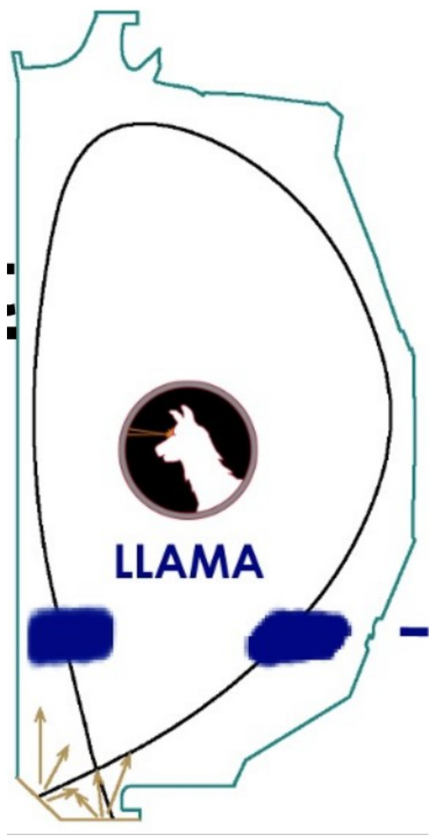
Bayesian inference finds large error bars



This work used LFS LLAMA source location only
→ expanding source location measurements to 2D could reduce error bars

→ connects to work by Q. Pratt on how can provide poloidally averaged source

Particle transport in the presence of RMPs (DIII-D)



- Density pedestal prediction even harder to predict for RMP ELM-free regimes in future devices and with opaque SOL
- DIII-D experiment applying gas puff modulation to varying levels of RMPs
- Ionisation rates and neutral densities inferred from Ly-alpha spectroscopy (LLAMA)
  Work in progress: add further neutral diagnostics)
- Bayesian inference of transport D,v using AURORA model
- Resulting diffusion and convection profiles indicate substantial differences in resulting particle transport (also well inwards of pedestal)
  → particularly when RMP is sufficient to suppress ELMs

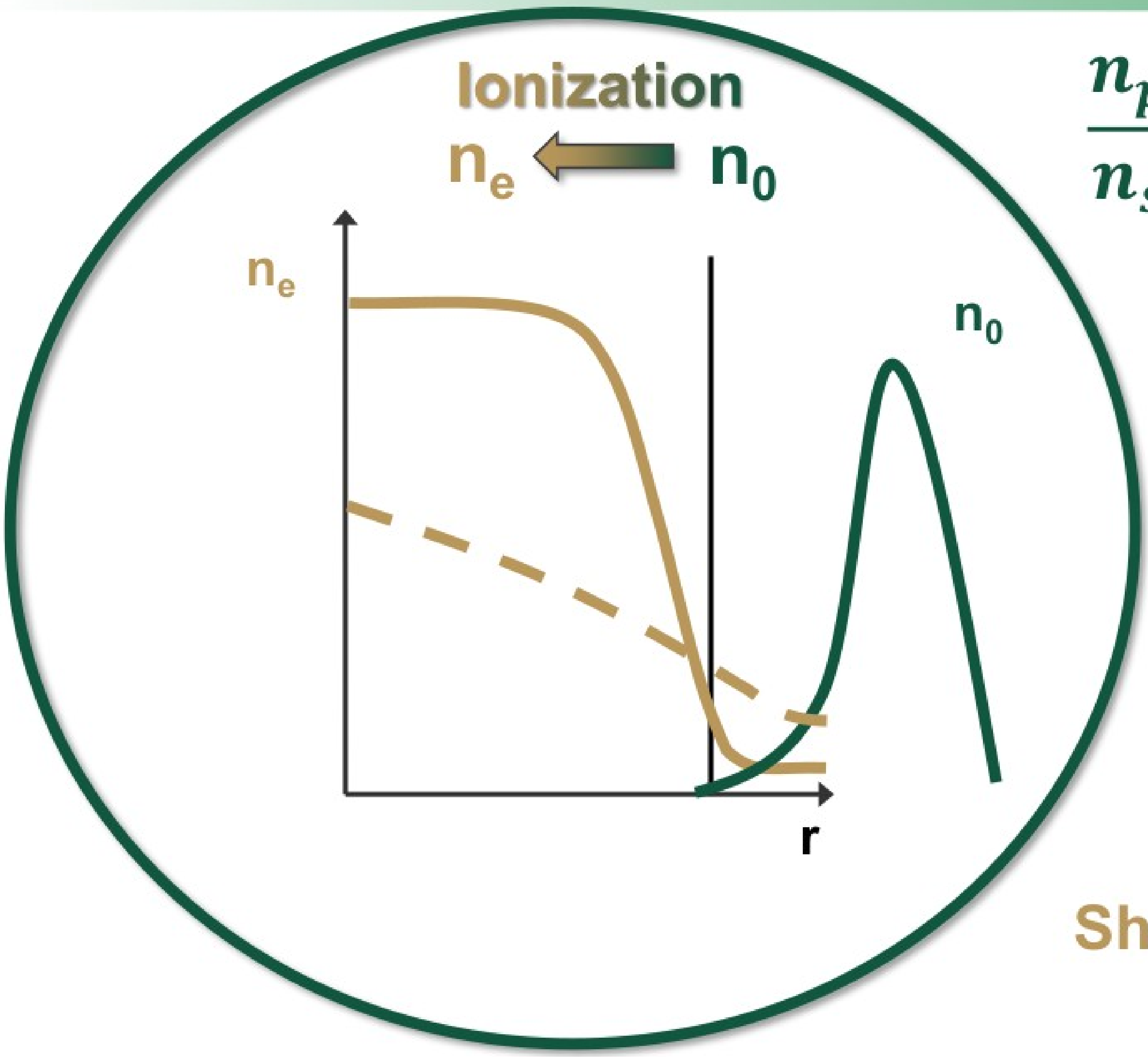
J. Loughran

Key take-away messages

- Measuring (and understanding) relative importance of pedestal transport vs source for future density pedestal predictions at high SOL opacity has proven to be a ‘tough nut to crack’
- In order to validate pedestal transport models on current devices, poloidally distributed neutral diagnostics coverage is essential
- Only few devices can access high SOL opacity conditions
  - ‘Best opportunities’ to explore pedestal physics with high opacity SOL will be JT-60SA and SPARC
  - need to ensure JT-60SA will be equipped with broad enough set of neutral diagnostics to tackle this challenge
    - EUROfusion can play a key role in ensuring this (MANTIS on JT-60SA)

Reserve slides...

Intro: Without a pinch, flat density profiles will be observed at the plasma edge



$$\frac{n_{ped}}{n_{sep}} \sim 1$$

$$\nabla \Gamma = S$$

$$\Gamma = \int S \, dV$$

$$-D\nabla n + vn = \int S \, dV$$

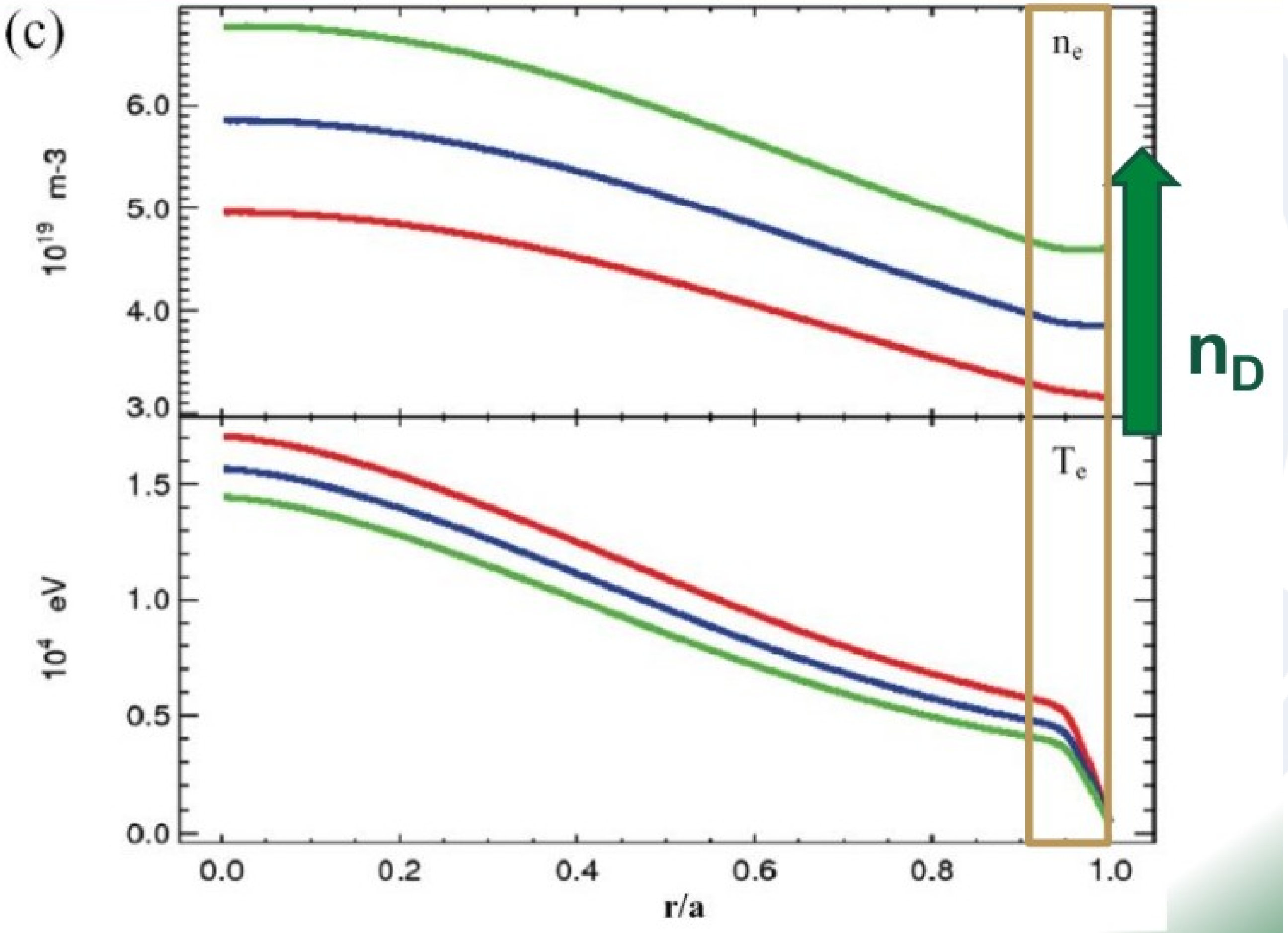
Shape profile

$$\frac{\nabla n}{n} \sim 0 \quad \text{if } v \sim 0$$

S. Morjdick

Integrated predictive modeling for ITER based on understanding of current devices result in disappearance of density pedestal structure

- Integrated modeling using JINTRAC & SOLPS to predict ITER profiles
- The model relies for transport on a diffusion coefficient
- Increases in fueling does not result in a shift, nor an increase of the density gradient
- Need to perform experiments to investigate the role of opaqueness



S. Morjdick

M. Romanelli *et al* 2015 *Nucl. Fusion* **55** 093008

Saarelma-Connor-Model: summary of inputs

General Inputs

Z_{imp} R_{geo}

Z_{eff} r

I_P δ

B_T κ

P_{SOL}

Transport Inputs

- C_{KBM}
- $\boldsymbol{\alpha_{crit}}$
- D/χ

Boundary Inputs

- $n_{e,sep}$
- $\mathbf{n_{0,sep}}$
- CX/FC ratio at separatrix
- **Core n_e gradient**

  (core means ψ=0.85)
- $\tau_{\parallel,sol}$

(+ T_e profile)

either measured or
from selfconsistent prediction (EUROPED)

SCM predictions for future devices (JT60-SA, ITER, STEP)

- Europed coupled self-consistently to SCM-density model

- The predictions for pedestal top density (**ne,ped)** in JT60-SA & ITER show
  - **strongest sensitivity to ne,sep** (= ‘free’ input parameter)
  - relatively insensitive to following global parameters: Bt, Ip, power, plasma size.

- Dependence on neutrals density (n0,sep) in ITER:
  - if the SOL is very opaque (n0,sep < $10^{15}m^{-3}$) very little variation in ne,ped
  - for n0,sep > $10^{15}m^{-3}$ ne,ped increases rapidly and fusion power plummets

For STEP: overall more modest n0,sep dependence

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