

Gyrokinetic calculations of pedestal transport in neon-seeded JET-ITER baseline plasmas

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This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

The effect of neon seeding is particularly relevant in the pedestal of JET-ITER baseline plasmas

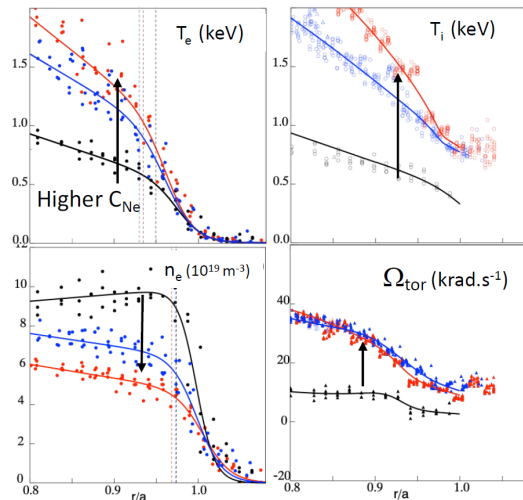
An example is given by three D pulses with similar input power and same gas: $P_{\text{in}} \simeq 27 - 33$ MW, $\Gamma_e \simeq 3.6 \times 10^{22}$ e/s

but different Ne-seeding:

#	C_{Ne}	Z_{eff}
97481 (S0)	0	1.20
97482 (S1)	1.39	2.25
97490 (S2)	2.07	2.86

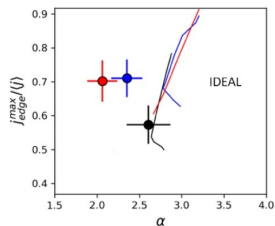
For $C_{\text{Ne}} \uparrow$ the plasma profiles are clearly affected:

$T_{i/e} \uparrow, n \downarrow, \Omega_{\text{tor}} \uparrow$



[Giroud, submitted to Nucl. Fus.]

The ELM dynamics is strongly affected as well [Nyström, Nucl. Fus. 2026].

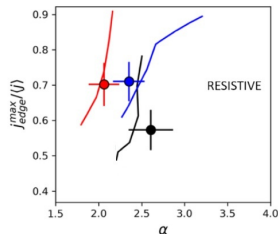


Type-I ELMs in the unseeded case disappear with high seeding

In the stability diagram the seeded pulses are pushed leftwards

MHD stability investigated with ELITE/CASTOR:

- Ideal MHD: unseeded case at the ballooning boundary, seeded cases are stable
- Resistive MHD: all pulses are close to the boundary



Transport is likely to play a role in limiting the pedestal pressure.

Aim of this work: analysis of transport in the pedestal with GENE

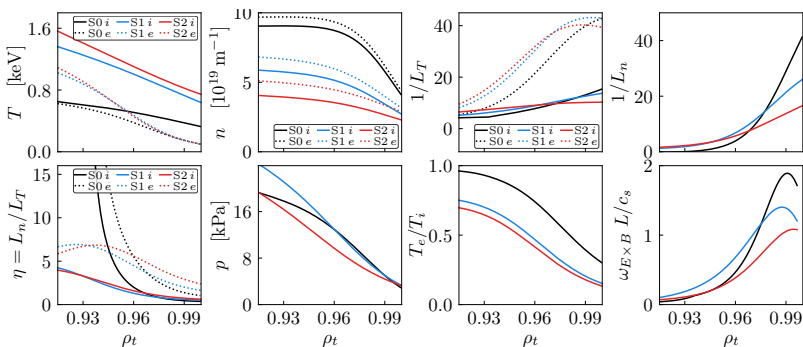
- 3 species simulations: D, e^- and a single impurity: 97481 Be ($C_{\text{Ne}} = 0$), 97482 Ne, 97490 Ne
- the whole impurity content is assumed to be in a fully ionized state: Be^{4+} , Ne^{10+} , Ne^{10+}
- realistic equilibria, β , $T_i \neq T_e$, ν , $E \times B$ shear only due to pressure gradient
- simulations covering the whole pedestal, $0.92 \lesssim \rho_t \lesssim 0.995$

In the following we will discuss:

- ▶ neoclassical transport
- ▶ stability/turbulence, with scale separation $\left\{ \begin{array}{ll} \text{electron-scale} & \rightarrow \text{local approach} \\ \text{ion-scale} & \rightarrow \text{global approach} \end{array} \right.$
- ▶ comparison with power balance

Approximately the same plasma shape and similar q and $\hat{s}$ profiles for the 3 pulses.

Profiles/equilibria self-consistently calculated with Helena.



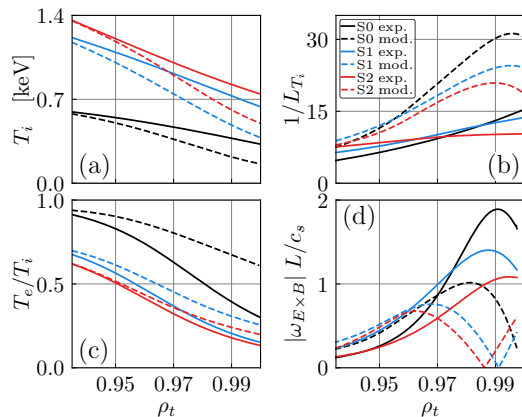
Remarks, based on the reconstructed profiles:

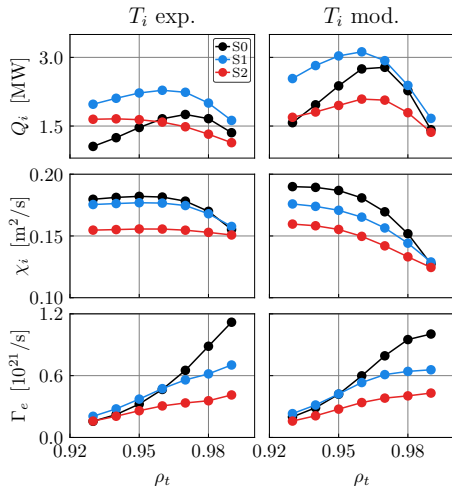
- $T_e/T_i \downarrow$ and $\eta_e \uparrow$ as $C_{Ne} \uparrow$, particularly in the outer pedestal, cause $\gamma_{ETG} \uparrow$.
- $T_e/T_i \downarrow$ as $C_{Ne} \uparrow$ and low η_i , particularly in the outer pedestal, cause $\gamma_{ITG} \downarrow$ (ITG modes could be important at the pedestal).

We have selected another set of (lower) T_i profiles, due to

- experimental uncertainties, and T_D potentially lower than impurity temperature,
- lower $T_{i,\text{ped}}$ resulting from SOL modelling.

Here we match the neoclassical χ_i at the lcms with Soledge modelling in the SOL.





Mainly ion heat transport

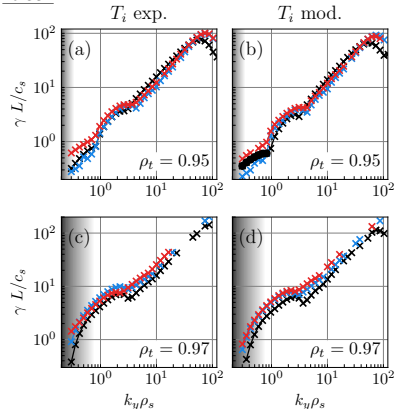
- $\langle Q_i \rangle \simeq 1.5 - 2.5$ MW: not negligible
- $\chi_i / \chi_e \simeq 20 - 30$
- $\chi_i \downarrow$ as S0 $\rightarrow$ S1 $\rightarrow$ S2 (increasing seeding)

Effect of C_{Ne} : artificially increasing the impurity concentration causes higher fluxes and transport coefficients $\Rightarrow$ NC transport determined by the profiles rather than by n_z/n_e alone

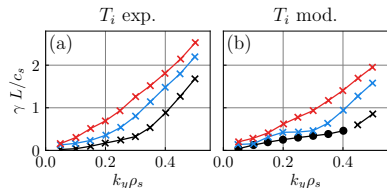
Local/global linear analysis
(global for $k_y \rho_s \ll 1$ with large gradients)

- rich spectrum of e.s. instabilities from low to high wavenumbers
- ETG modes always present (both toroidal/slab branches)
- in the outer pedestal ($\rho_t \geq 0.97$), ETG modes dominate, starting from very low wavenumbers
- close to pedestal top ($\rho_t \sim 0.95$), at $k_y \rho_s < 1$:
 S0: dominant TEMs ($T_{i,\text{exp}}$) and ITG modes ($T_{i,\text{mod}}$)
 S1/S2: dominant modes with mixed TEM/ETG nature

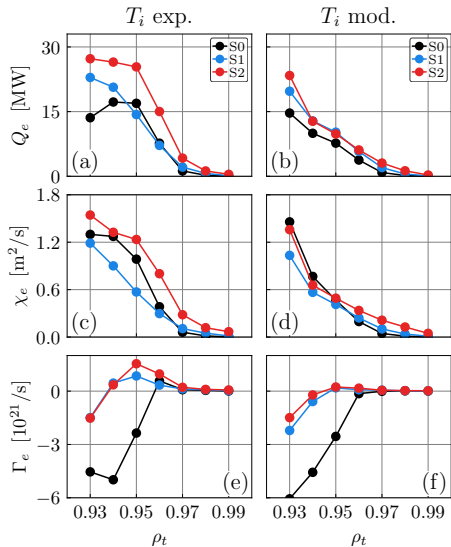
local



global



Local GENE simulations, $\rho_t \in [0.93, 0.99]$, $\Delta k_y \rho_s \simeq 1.5 - 2.5$ at ped. top, and $2.5 - 4.5$ at ped. foot

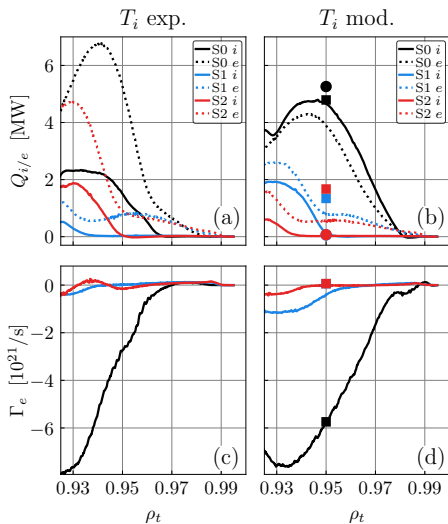


- overall $Q_e \uparrow$ with seeding
- transport with $T_{i,\text{mod}}$ lower than with $T_{i,\text{exp}}$
- transport is large at pedestal top, negligible in the edge
- ion scales are partially captured at the pedestal top, where

relatively low- k_y ITG/TEMs modes provide part of the heat fluxes and a large $\Gamma_e < 0$ in the unseeded pulse (to be confirmed in global simulations!)

Effect of C_{Ne} : artificially increasing C_{Ne} causes lower fluxes and transport coefficients, but with a rather weak dependence on $n_z/n_e \implies$ e-scale turbulent transport determined by the profiles rather than by n_z/n_e alone

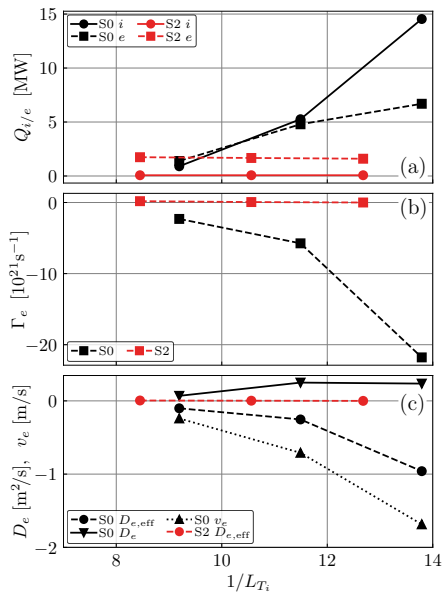
Global GENE simulations in the radial domain $\rho_t \in [0.92, 0.995]$ for $k_y \rho_s \lesssim 1.5$, $n_x = 512$, $n_{k_y} = 32$, 10% left/right buffer zone with Krook-type operators.

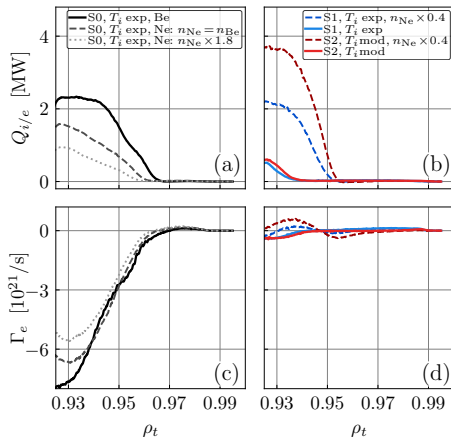


- ion-scale turbulent transport more important in the unseeded case at the pedestal top, where $T_i \sim T_e$
(especially with $T_{i,\text{mod}}$, where $T_i \rightarrow T_e$, $1/L_{T_i} \uparrow$ and ITG modes are more relevant)
- clear trend with the seeding only with $T_{i,\text{mod}}$
- confirmed large $\Gamma_e < 0$ in the unseeded case, radially more extended with $T_{i,\text{mod}}$
- local ion-scale simulation at the pedestal top (dots/squares) in line with the global results

Local GENE simulations at the pedestal top to quantify the particle flux composition and the dependence on $1/L_{T_i}$ ($1/L_{T_i,exp} \pm 20\%$).

- unseeded (S0): the scan vs $1/L_{T_i}$ shows a clear increase of the fluxes due to ITG-TEM turbulence, leading to an ITG dominated regime.
- seeded (S2): no dependence on $1/L_{T_i}$, $Q_i \sim 0 \sim \Gamma_e$, according to the lack of unstable ITG/TEMs.
- a passive electron species is added to the simulations to calculate D_e and v_e . The coefficients increase with $1/L_{T_i}$ for S0, they vanish for S2.





To test the dependence on C_{Ne} we consider:

- S0 with two additional cases: with Ne replacing Be (i.e., $n_{Ne} = n_{Be}$, but increased ion dilution), and with $n_{Ne} \times 1.8$.
- **S1** and **S2** with $n_{Ne} \times 0.4$

Effect of the C_{Ne} concentration on the ion-scale transport:

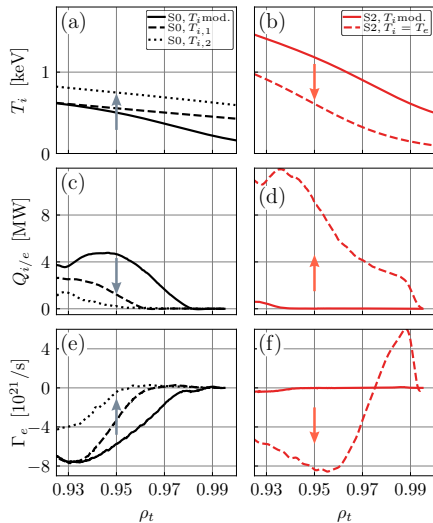
- $Q_{i/e} \downarrow$ as $C_{Ne} \uparrow$
- Γ_e much less affected (remaining inward-directed for S0 and ~ 0 for **S1** and **S2**).

To test the dependence on T_i we build synthetic profiles:

- S0 with a higher $T_{i,\text{sep}}$ and an overall higher T_i
- S2 with a lower T_i : $T_i = T_e$

Different T_i profiles strongly influence the ion-scale transport, mainly through T_e/T_i and $1/L_{T_i}$:

- S0 with $T_i \uparrow \implies Q_{i/e}$ and $|\Gamma_e| \downarrow$
- S2 with $T_i \downarrow \implies Q_{i/e}$ and $|\Gamma_e| \uparrow$

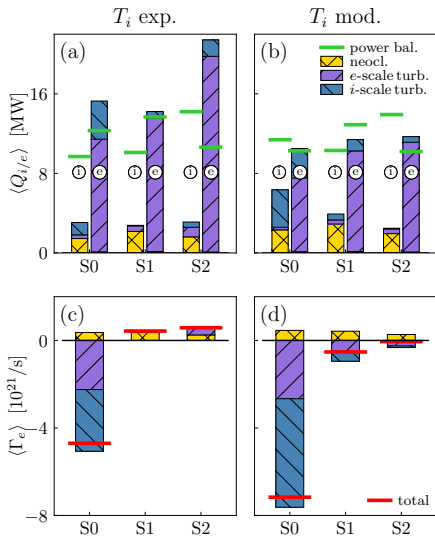


Both $Q_{i/e}$ and Γ_e are strongly affected by changes of the pedestal T_i



A possible picture emerging from the gyrokinetic simulations is the following:

- **without seeding**, the inward particle flux originating from ion-scale turbulence due to $T_i \simeq T_e$ (low $T_{i,\text{sep}}$) is compatible with a slowly growing pedestal density in the inter-ELM phase, bringing the experimental profiles close to the MHD limit (i.e., the ballooning boundary) which guides the ELM cycle
- **with seeding**, the absence of a turbulent inward pinch and the small particle diffusion due to $T_i \gg T_e$ (high $T_{i,\text{sep}}$) imply vanishing particle fluxes, consistently with steady, lower density profiles in MHD-stable conditions



Average values for $\rho_t \in [0.94, 0.98]$

- Q_e dominated by electron-scale ETG turbulence
- Q_i mainly due to NC transport or ion-scale turbulence
- Γ_e mainly determined by turbulent transport

Two different trends of the heat fluxes with the seeding for the different T_i :

- $T_{i,\text{exp}}$: Q_i constant, $Q_e \uparrow$ (S1 out of the trend)
- $T_{i,\text{mod}}$: Q_e constant, $Q_i \downarrow$.

The comparison with interpretative TRANSP runs is not satisfactory:

- unbalanced Q_e across the radius in local simulations: too large at the pedestal top, too low at the pedestal foot
- the simulated Q_i is underestimated with respect to power-balance, especially with seeding



- for particle transport and density, the picture is rather clear: increasing impurity seeding favors the transition from a MHD-limited to a transport-limited pedestal.
- for heat transport, the picture is less clear: no conclusive statements (so far) on the impact of seeding in the pedestal.
- key role of the T_i profile. Based on our gradient driven simulations, the higher $T_{i,sep}$ with seeding cannot be justified by the pedestal transport itself. $T_{i,sep}$ likely determined by the SOL, expected to increase with seeding (SOL modelling: due to ion dilution, a lower n_i provides additional heating of the ion population which tends to raise T_i in the near SOL).
- to be more quantitative: global, multiscale simulations?