Laboratorio Nacional de Fusión

Ciemat

TRANSPORT IN HIGH-PERFORMANCE PLASMAS OF THE TJ-II STELLARATOR

FROM FIRST-PRINCIPLES SIMULATIONS TO EXPERIMENTAL VALIDATION

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Abstract

We present an overview of TJ-II activities on **first-principles transport and power balance studies**, including gyrokinetic (**stella**, **EUTERPE**), neoclassical (**SFINCS**), particle deposition (**HPI2**), and heat source (**ASCOT5**) simulations. These efforts address mechanisms in plasmas with improved confinement via pellet injection, resembling pellet-fueled high-performance scenarios observed in W7-X.

Addressing pellet-induced enhanced confinement in TJ-II plasmas from a numerical viewpoint

- The discharges and the time slice to be modeled exhibit a 25% higher τ_E and W_{dia}, and a 45% higher T_{i0} , in favor of the pellet-fueled discharge.

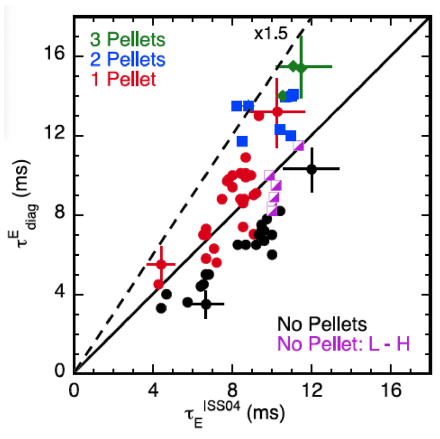

Figure 1: Comparison of τ_E between discharges with and without pellet injection (figure from [McCarthy NF´24])

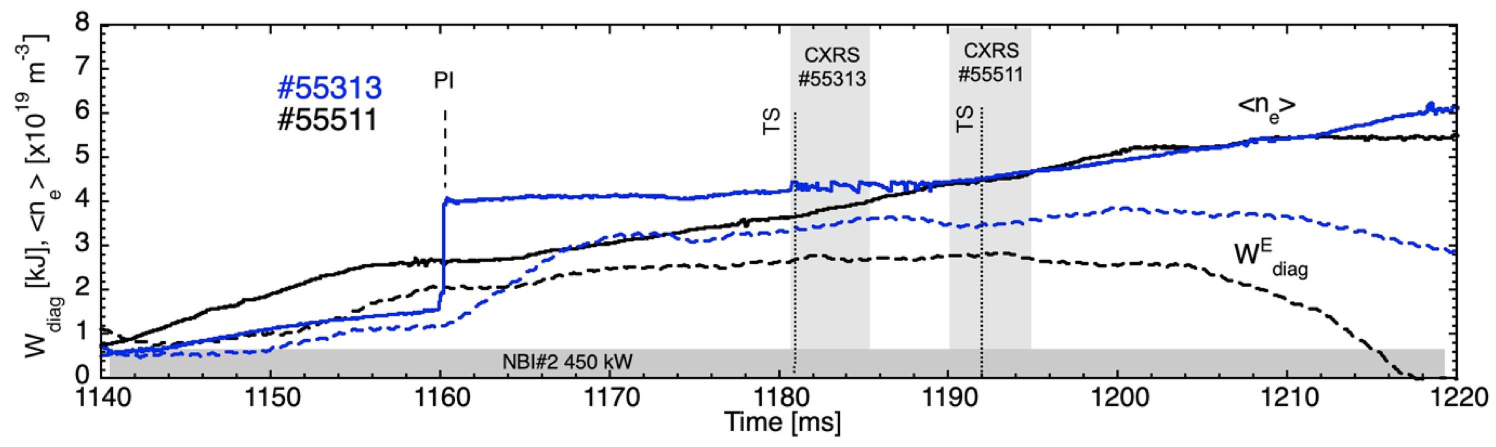

Figure 2: Line-averaged density (solid lines) and stored diamagnetic energy (dashed lines) for TJ-II discharges **#55511** (**without pellet** injection, black) and **#55313** (**with pellet** injection applied at 1160 ms, blue).

Simulated transport

Simulations with stella, EUTERPE and SFINCS

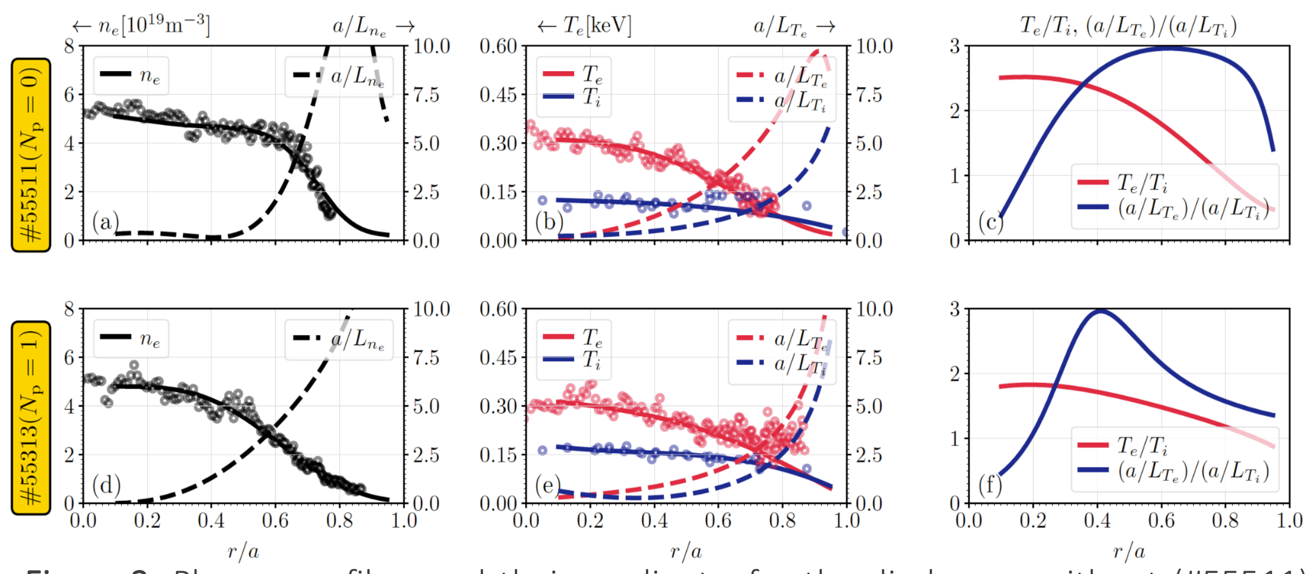

Figure 3: Plasma profiles, and their gradients, for the discharges without (#55511) and with (#55313) pellet injection.

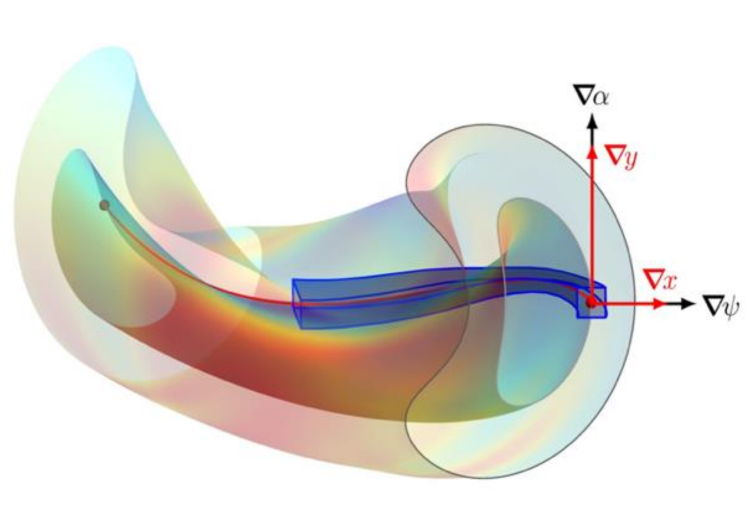

Figure 4: Segment of the flux tube used for the stella simulations at $r/a = 0.5$ of the standard TJ-II configuration.

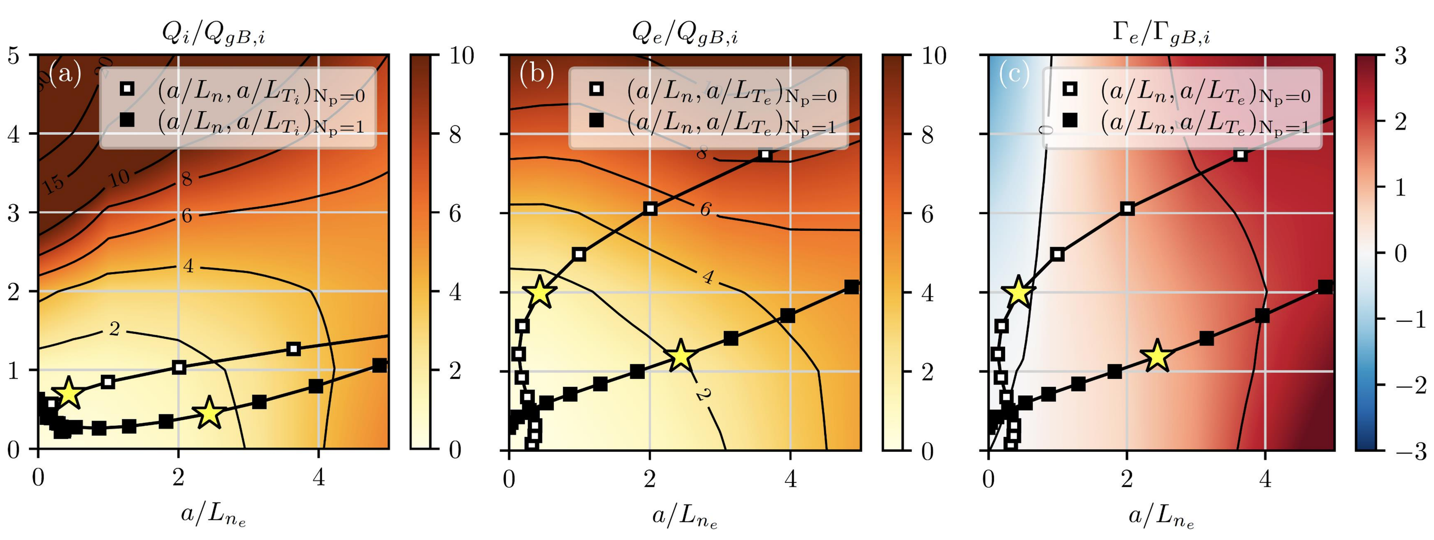

Figure 5: Turbulent fluxes as functions of the density and temperature gradients for the radial position $r/a = 0.5$. Lines represent pairs of normalized gradients of the analyzed discharges. The stars highlight the gradient values at the position r/a=0.5.

- In the case with pellet injection, profiles (Fig. 3) tend to flatten toward the edge. a/L_{T_i} weakly changes, while a/L_{T_e} increases significantly.
- At the gradient map (Fig. 4), the impact on transport qualitatively agrees with the stella [Barnes JCP´19] simulations. Cases with (or without) pellets explore regions of higher (or lower) heat flux.
- For stella simulations that take into account the experimental profiles, together with neoclassical simulations from SFINCS [Landreman PoP´14] (Fig. 5), the following is observed:
  - Turbulent transport dominates over neoclassical transport from $\rho \approx 0.4 - 0.5$ outward.
  - Turbulent transport reaches higher values in the case without pellet at peripheral positions.
  - Total heat transport results in approximately 20% lower turbulent flux in the discharge with pellet.
- Additional simulations with EUTERPE [Kleiber CPC´24] including kinetic electrons (with $m_e/m_i = 1/200$) show similar relative changes, more pronounced for Q_i than for Q_e (Fig 7).

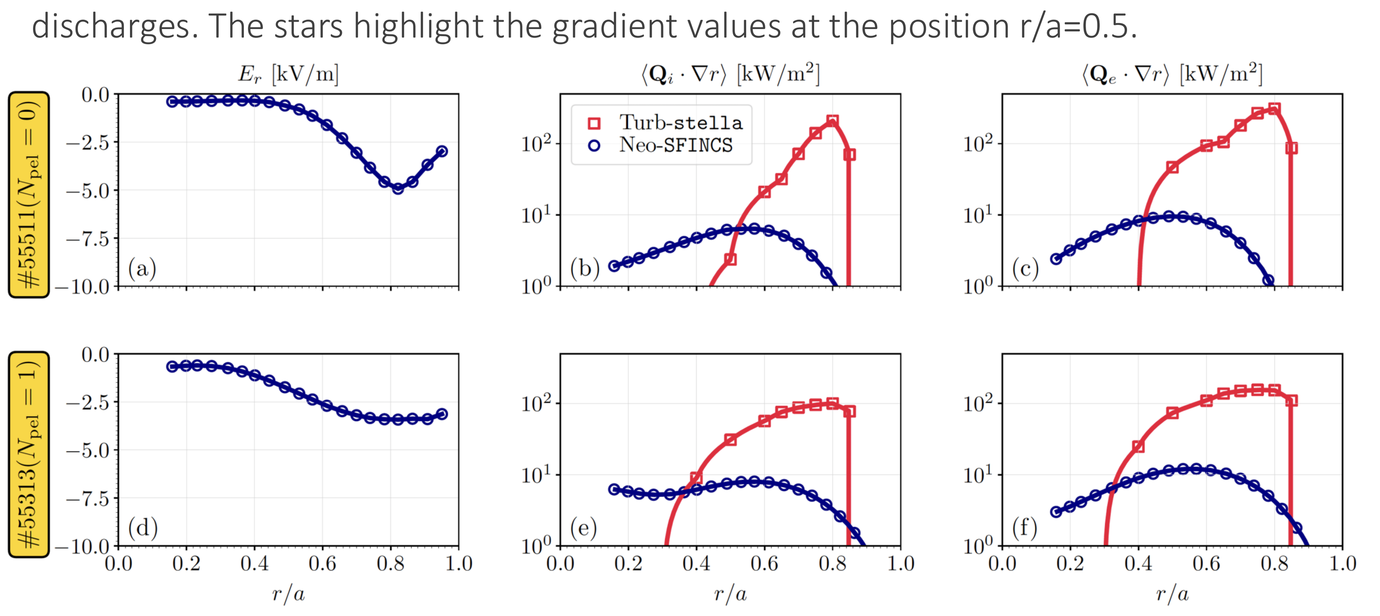

Figure 6: Neoclassical radial electric field and heat fluxes (blue) obtained with SFINCS, and turbulent fluxes obtained with stella for (red) for the two scenarios.

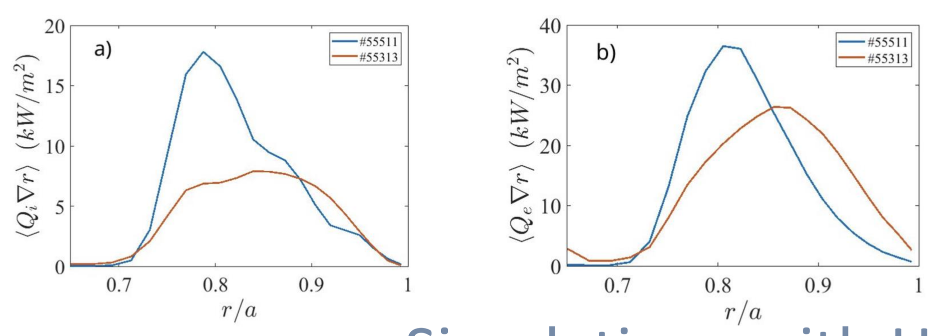

Figure 7: Heat fluxes obtained with EUTERPE as a function of the radial coordinate in the peripheral region for the two scenarios.

Particle and heating sources

Simulations with HPI2 and ASCOT5

- HPI2 [Pégourié PPCF´05] simulations show deep pellet ablation, extending up to near the magnetic axis, with a profile resembling the H_α signal (Fig. 8).
- Immediately after injection ($t = 1160$ ms), the pellet produces a drastic change in the density value and its gradient (Fig. 9).

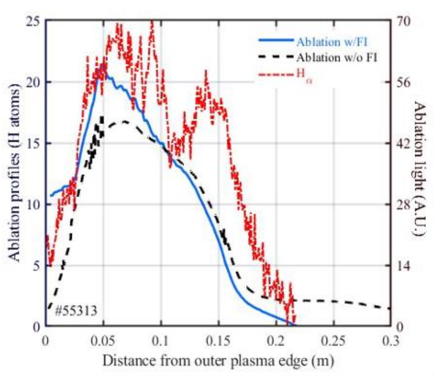

Figure 8: HPI2 simulated ablation profiles compared with the measured H_α light for the discharge with pellet #55313.

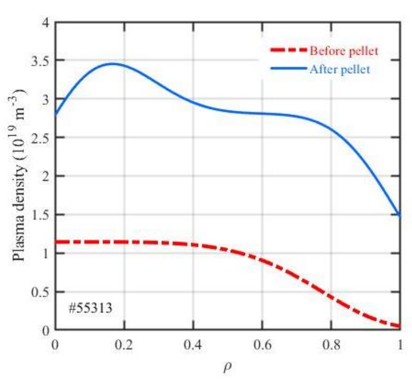

Figure 9: Plasma density before (TS from a similar discharge) and immediately after (from HPI2) the pellet injection in shot #55313.

- ASCOT5 [Hirvijoki CPC´14] simulations of the power deposited by the NBI system show a centrally peaked deposition profile in both discharges, with slight changes in shape and total absorbed power (Fig. 10).
- 75% of the transferred power, slightly higher in case w/o pellet, to electrons (Fig 10 and table).

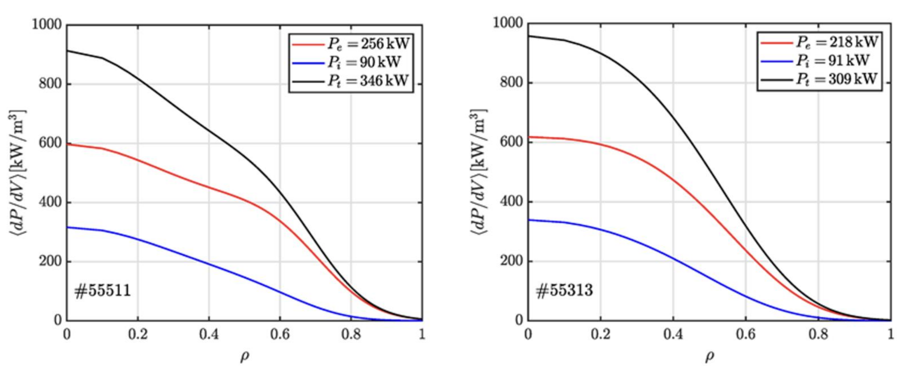

Figure 10: NBI power deposition profiles calculated with ASCOT5 for the discharges without pellet injection (left) and for the discharge with pellet injection (right).

Shot#	P_{in} [kW]	Energy [keV]	P_{st} [%]	P_{av} [%]	P_{abs} [kW]
55511	470	31.5	11.3	88.7	346
55313	450	30.2	15.9	84.1	309

Power balance analysis

- Considering ASCOT5 power deposition, SFINCS neoclassical fluxes, and experimental profiles:
- Pellet-fueled case shows clear reduction of turbulent heat flux for $\rho > 0.55$. Strongest difference ($\sim 30\,\%$) at $\rho \approx 0.75$ (Fig 11).
- Results align with GK predictions and increased τ_E in pellet-fueled discharges.

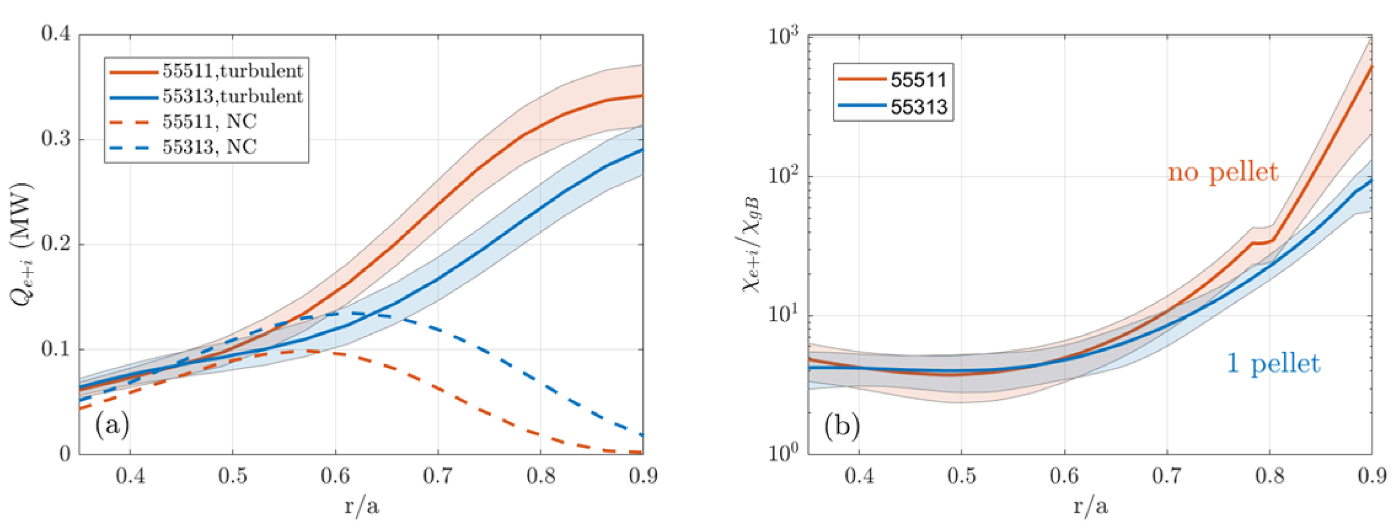

Figure 11: Radial profiles of the neoclassical and total turbulent energy transport (a) and total heat diffusivity (b) obtained by power balance analysis for shots #55511 (no pellet) and #55313 (1 pellet) in red and blue, respectively.

Summary

- First combined numerical (gyrokinetic + neoclassical + sources) and experimental (power balance) analysis, comparing a reference discharge without pellet and one with pellet injection.
- **Key findings**: Pellet modifies density and deposition profiles, leading to reduced turbulent transport in the outer region, with gyrokinetic predictions, power balance and confinement improvement consistent with each other.

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