Confinement Modelling Of Enhanced Plasma Performance After Multiple Pellet Injections In The TJ-II Stellarator

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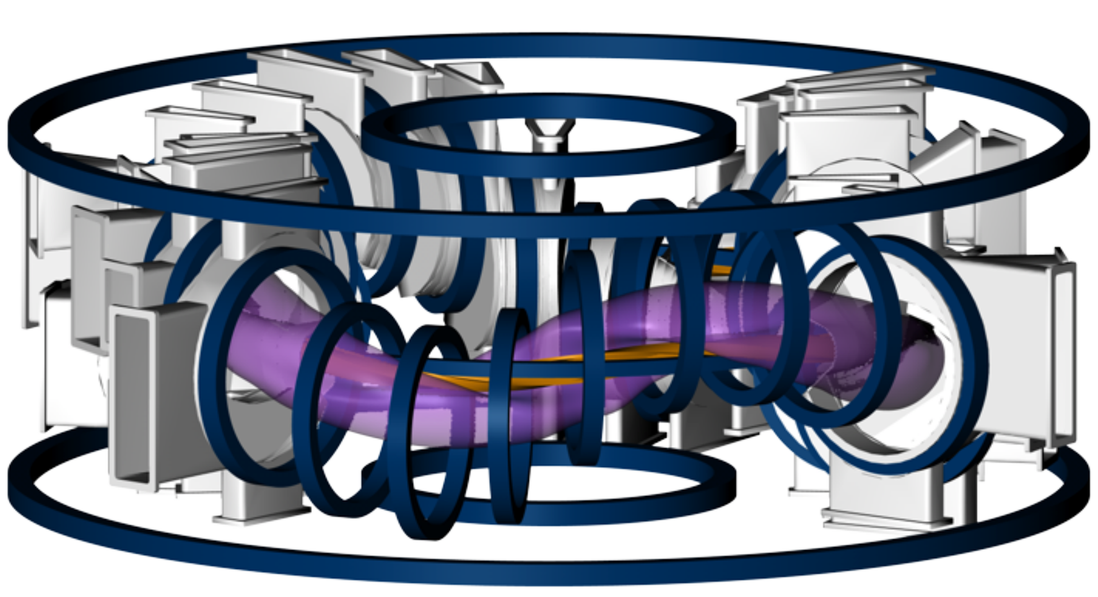
1 Experimental Facts

Recent experimental campaigns on the TJ-II stellarator have investigated the effects of multiple cryogenic hydrogen pellet injections into neutral beam injection (NBI)-heated plasmas [1,2], expanding on earlier studies focused on ablation, deposition, and fueling efficiency. The plasmas generated through multiple pellet injections exhibit sustained record central densities, ion temperatures and diamagnetic energy confinement times exceeding ISS04 [3]. While a significant decrease in density and electrostatic potential fluctuations in the outer plasma region indicates a turbulent transport contribution [4], the more negative values of the radial electric field also point toward a neoclassical transport channel.

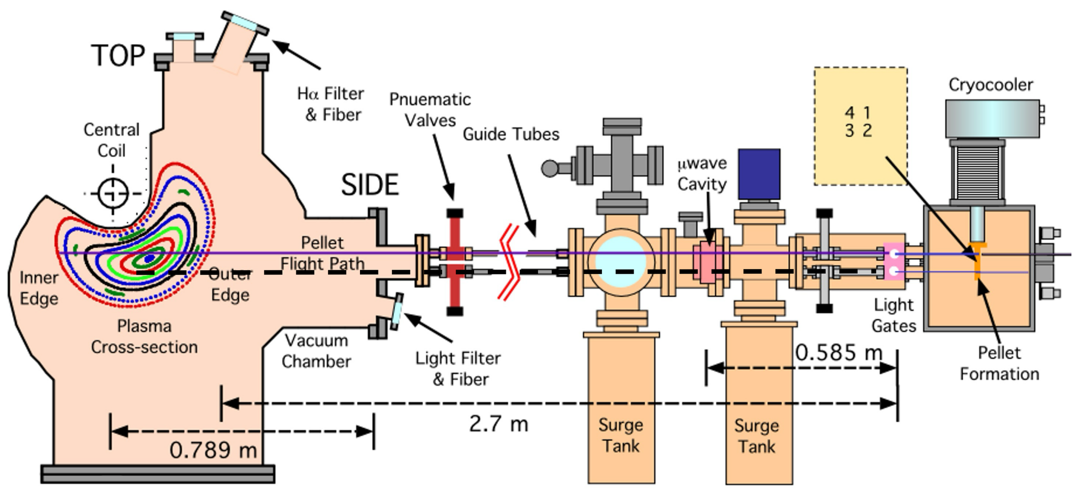


R [m]	a [m]	V [m^3]	B [T]	$\iota/2\pi$
1.5	0.2	1	1	0.9 − 2.5

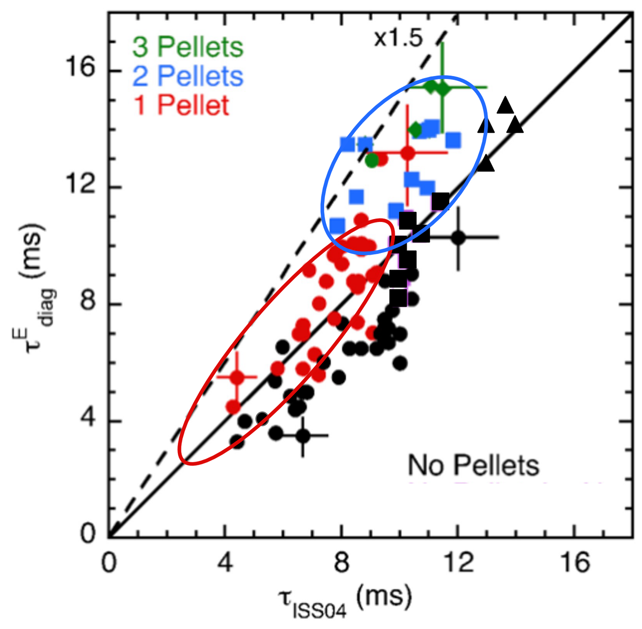
ECRH 2×500 kW @ 53.2 GHz
$n(0) \leq 1.75 \times 10^{19}\mathrm{m}^{-3}$
$T_e(0) \leq 1.5\,\mathrm{keV}$

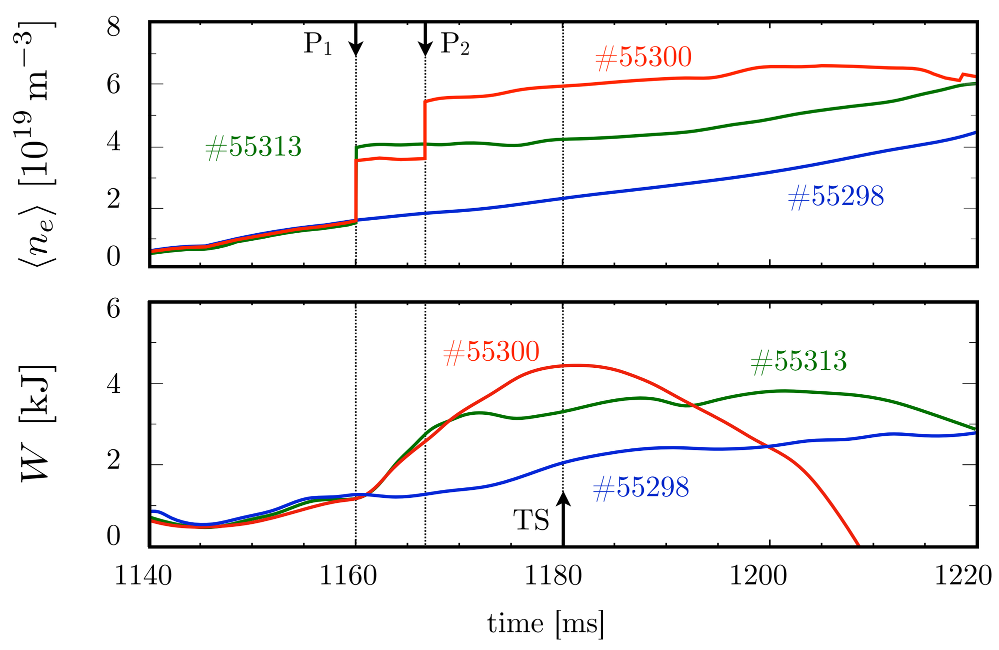
NBI 2×500 kW @ 30 kV
$n(0) \leq 9 \times 10^{19}\mathrm{m}^{-3}$
$T_e(0) \leq 400\,\mathrm{eV}$
$T_i(0) \leq 200\,\mathrm{eV}$

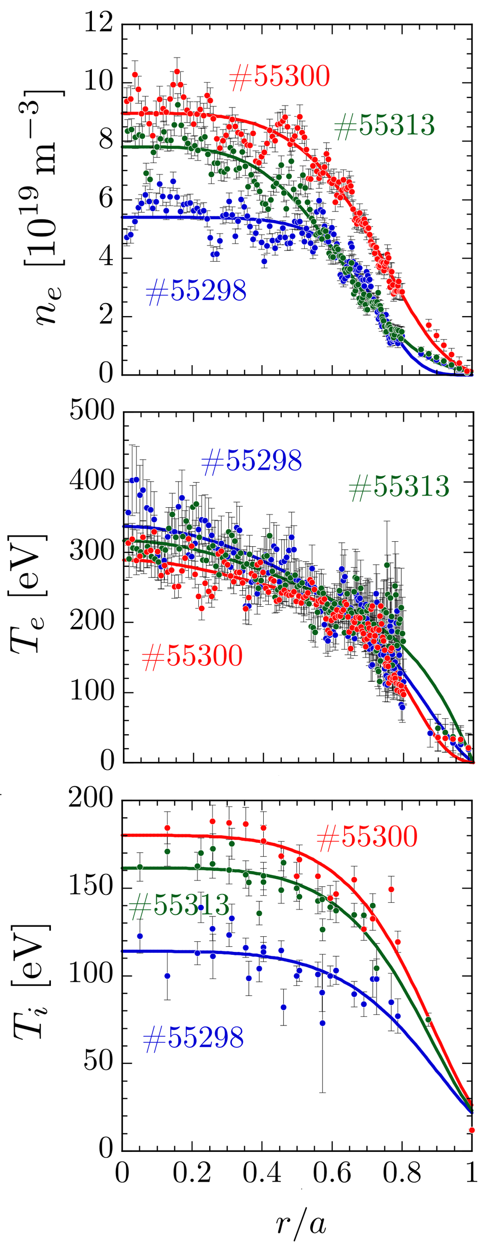
$$\tau^E_{\mathrm{ISS04}} = 0.5 \times 0.134\, a^{2.28} R^{0.64} P_{\mathrm{abs}}^{-0.61} \langle n_e \rangle^{0.54} B^{0.84} \iota_{2/3}^{0.41}$$



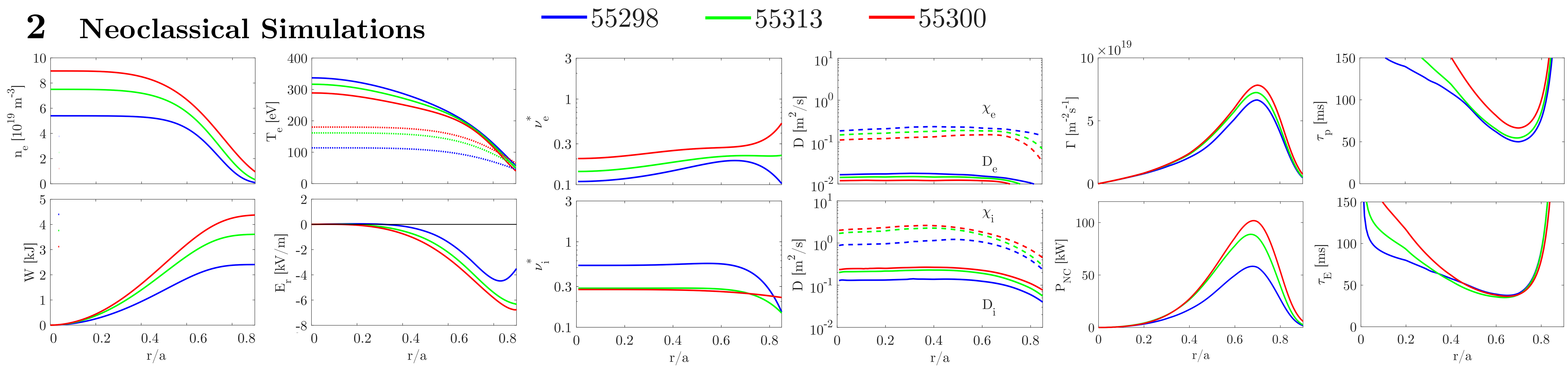
Pellet sizes 2.4×10^{19}, 1.4×10^{19}, 8×10^{18}, 5×10^{18} H atoms $v_p = 710\,\mathrm{m/s}$







2 Neoclassical Simulations



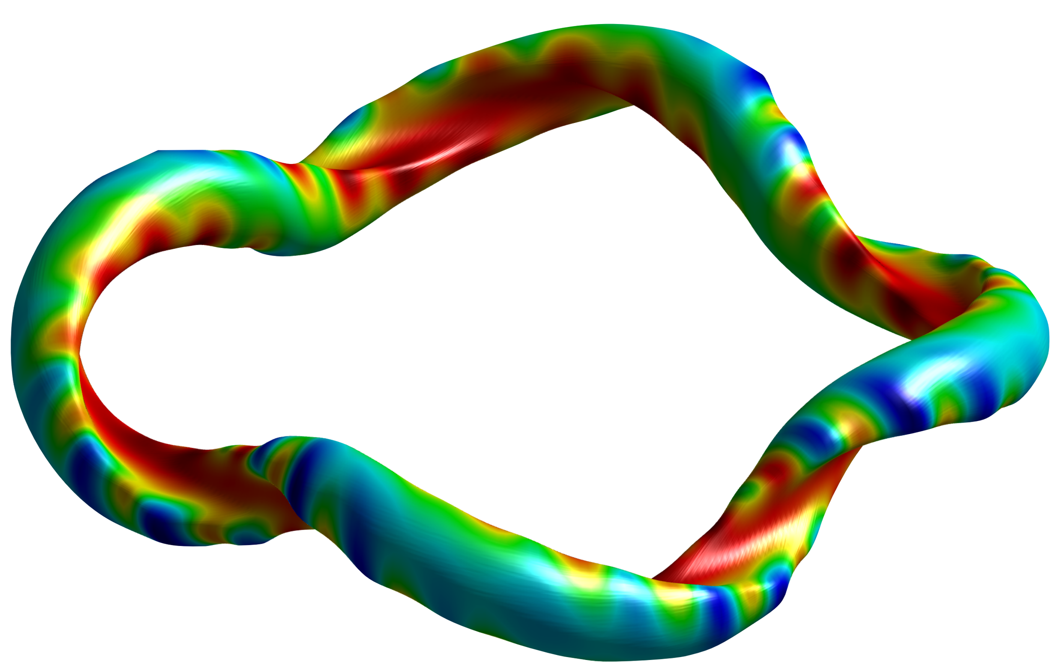
Unfortunately, radial electric field measurements employing CXRS are not available for these discharges. However, measurements conducted for similar discharges reveal profiles characterized by a minimum in the same region, approximately $r/a \sim 0.8$, with values ranging from -5 to -10 kV/m. These profiles exhibit a consistent dependence on pellet injection, with more negative values observed for higher densities and ion temperatures.

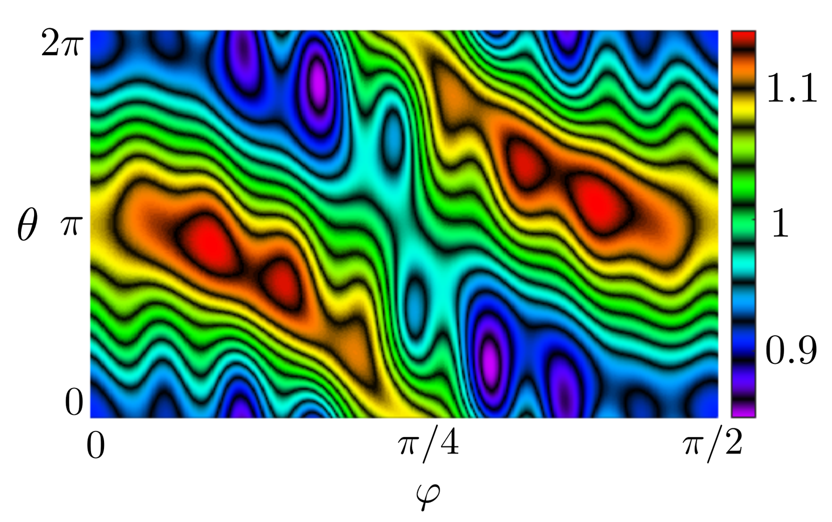
Shot	W_{diag}[kJ]	$\tau_{\mathrm{E}}^{\mathrm{exp}}$[ms]	$\tau_{\mathrm{E}}^{\mathrm{ISS04}}$[ms]	$\tau_{\mathrm{E}}^{\mathrm{NC}}$[ms]	$\tau_{\mathrm{p}}^{\mathrm{NC}}$[ms]	I_b[kA]	I_p[kA]	$I_{NBI}+I_b$[kA]
#55298	2.4	10.2	7.5	38	50	0.6	-1.5	-1.5
#55313	3.6	13.3	11.3	35	54	1.0	-1.2	-1.1
#55300	4.4	13.8	12.6	36	66	1.2	-0.8	-0.9

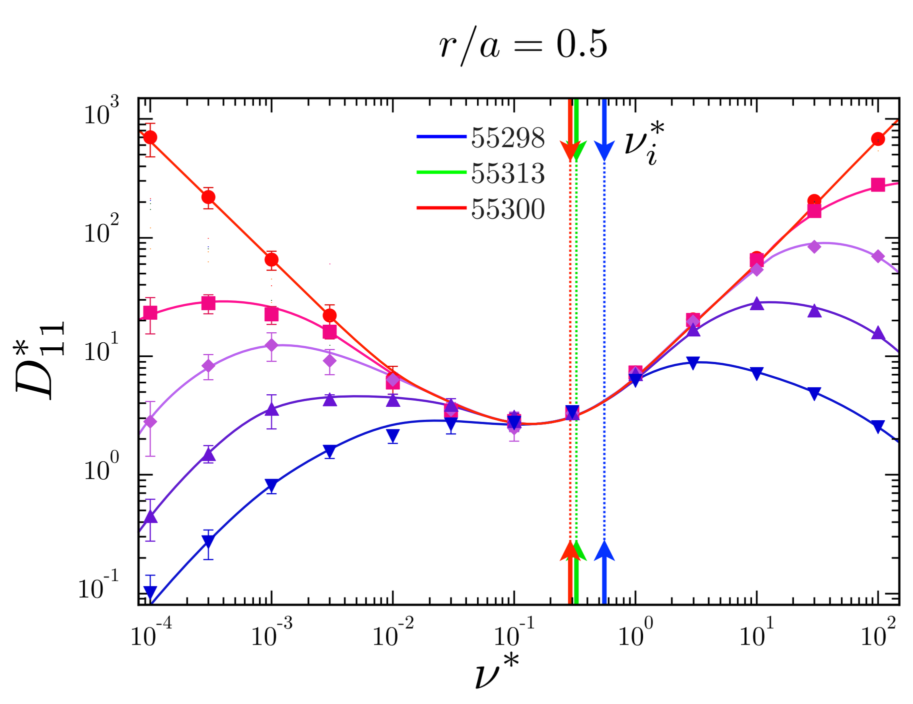
$$\tau_{\mathrm{p}}(r) = \frac{4\pi^2 R \int_0^r n_e(r')r'dr'}{4\pi^2 r R \Gamma(r)} \qquad \tau_{\mathrm{E}}(r) = \frac{4\pi^2 R \int_0^r \frac{3}{2}[n_i(r')T_i(r') + n_e(r')T_e(r')]r'dr'}{4\pi^2 r R[Q_e(r) + Q_i(r)]}$$

For counter-NBI heating the measured total plasma current I_p includes both bootstrap and NBI-driven components. By subtracting the neoclassical bootstrap current estimate I_b from the measured I_p of the reference discharge #55298, an NBI current $I_{\mathrm{NBI}}=I_p-I_b$=-2.1 kA was estimated. Assuming I_{NBI} remains constant across all discharges -a significant assumption- this calculation yields results consistent with the experimentally measured current, exhibiting a discrepancy of only 0.1 kA (≈ 10%).

3 Neoclassical Transport in TJ-II







$$D_n^\alpha = \frac{\sqrt{\pi}}{8}\frac{\rho^2 v_\alpha^{th}}{R\iota}\int_0^\infty dK_\alpha\, e^{-K_\alpha}\, K_\alpha^{n-1/2}\, D_{11}^*\left(\frac{r}{a}, \frac{\nu_\alpha}{v_\alpha}, \frac{E_r}{v_\alpha B}\right)$$

$$n = 1,\, 2\,,3$$

$$\Gamma_\alpha = -n_\alpha D_1^\alpha \left\{\left(\frac{n'_\alpha}{n_\alpha} - \frac{Z_\alpha E_r}{T_\alpha}\right) + \left(\frac{D_2^\alpha}{D_1^\alpha} - \frac{3}{2}\right)\frac{T'_\alpha}{T_\alpha}\right\}$$

$$Q_\alpha = -n_\alpha T_\alpha D_2^\alpha \left\{\left(\frac{n'_\alpha}{n_\alpha} - \frac{Z_\alpha E_r}{T_\alpha}\right) + \left(\frac{D_3^\alpha}{D_2^\alpha} - \frac{3}{2}\right)\frac{T'_\alpha}{T_\alpha}\right\} \qquad K_\alpha = \frac{m_\alpha v_\alpha^2}{2T_\alpha}$$

The neoclassical local particle Γ_α and energy Q_α fluxes and the bootstrap current densities J_α are calculated using the monoenergetic approach [5] with a combination of codes [6,7] for the experimental configuration 100_44_64,

In the experimental and neoclassical results the energy confinement time does not vary significantly between discharges, despite the plasma energy nearly doubling and the ion temperature increasing by 50%. In the neoclassical simulations the energy doubles, the energy fluxes double, and consequently, the confinement time must be roughly the same. The transition between the onset of the Pfirsch-Schlüter and the plateau regime is the responsible for the mild dependence..

An enhanced confinement regime is induced by multi-pellet injection in NBI-heated plasmas at TJ-II. A systematic comparison between experimental measurements and simulations, including turbulent, neoclassical and ASTRA [8] models, is currently underway to quantify the contribution of these transport channels.

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