Examining Transport and Integrated Modeling Predictive Capabilities for Negative-Triangularity Scenarios

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High energy confinement (τ_e) is required for a steady-state fusion reactor [1]. High confinement is typically achieved in positive triangularity (δ) H-mode plasmas. Positive-δ has long been known to improve both confinement and stability. However, the improvement in confinement from the H-mode pedestal typically is accompanied by edge localized modes, which produce large spikes in energy flux that can erode the divertor. Experiments on TCV [2] and DIII-D [3] have shown that L-mode confinement improves dramatically in a negative-δ shape. Two similar DIII-D discharges with matched values for major radius, minor radius, and elongation, but opposite $\delta = -0.4, 0.4$ were compared. The plasmas were heated with up to 10 MW of neutral beam injection (NBI) power and up to 3 MW of electron cyclotron heating (ECH) power and had high levels of confinement.

The earliest modeling of transport of negative-δ suggested that trapped electron modes (TEM) could be suppressed by negative-δ [4]. Gyrokinetic simulations of TCV discharges suggested that trapped electron modes were suppressed in negative-δ compared to the positive-δ counterpart [5]. Exploration of negative-δ showed that negative-δ has reduced transport compared to positive-δ [6], and suggested negative-δ may increase the critical gradient leading to improved transport [7].

The predictive capabilities of TGYRO [8] find that predicted profiles of electron temperature (T_e), ion temperature (T_i), electron density (n_e), and $E \times B$ shear (ω) agree reasonably well in both negative-δ and positive-δ at low auxiliary powers (< 5 MW). TGYRO is analyzed for a positive-δ and a negative-δ plasma heated with $P_\mathrm{EC} = 2$ MW and $P_\mathrm{NBI} = 2$ MW with a fixed boundary condition for the kinetic profiles in these simulations is set to the experimental values at $\rho = 0.8$. Figure 1 shows the experimental profile fits and the TGYRO predicted profiles of T_i, T_e, n_e, and ω in positive-δ and negative-δ. Experiments and TGYRO predictions both

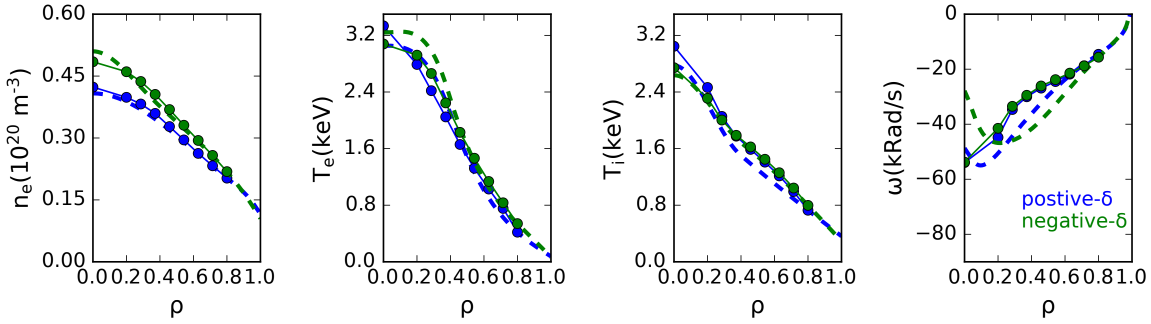

Figure 1: *TGYRO prediction (solid) of* n_e*,* T_e*,* T_i*, and* ω *and experimental profile fits (dashed) in NBI+ECH heated plasmas in positive-*δ *(blue) and in negative-*δ *(green).*

have higher values for n_e and T_e are observed in negative-δ compared to positive-δ. The T_e profile is slightly underpredicted for both positive-δ and negative-δ. The T_i profile is slightly overpredicted ($\sim$10%) for positive-δ, while it is almost perfectly predicted in negative-δ.

Analysis of the turbulent transport using the quasilinear gyro-Landau fluid code TGLF [9] is performed. TGLF predicts a large difference in particle flux (Γ) between positive-δ and negative-δ as a function of temperature gradient scale length a/L_{T_e}, as shown in Figure 2. Here, a is the minor radius, $1/L_{T_e} = \partial T_e/\partial r/T_e$. As a/L_{T_e} is increased, the predicted Γ for the negative-δ scenario becomes negative. This is opposite to the predicted flux in the positive-δ scenario where Γ increases as a/L_{Te} moves away from the experimental gradient. This difference in particle transport behavior could possibly lead to better confinement for negative-δ with negative-δ having better higher experimental n_e and T_e in Figure 2.

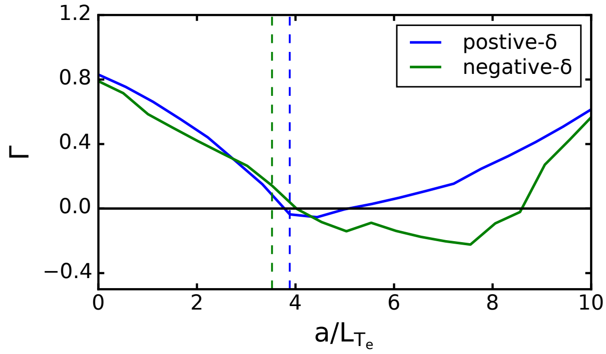

Figure 2: *TGLF-SAT0 predicted* Γ *(*10^{20} m^{-2} s^{-1}*) at* $\rho = 0.6$ *for a positive-*δ *and negative-*δ *ECH only plasma plotted vs.* a/L_{Te}*. The vertical dashed lines indicate the experimental scale lengths.*

Core-pedestal modeling shows confinement and β_N improve at negative δ and at positive δ. Similar parameters to the DIII-D experiment of $\beta_N = 2$, $n_{e,ped} = 0.35 \times 10^{20}$ m^{-3}, $\kappa = 1.6$, $B_t = 2$ T, and $I_p = 0.8$ MA are used. Modeling is done using the STEP [10] module in OMFIT [11], which iterates between TGYRO[8], ONETWO [12], and CHEASE [13]. TGYRO is used to predict kinetic profiles. ONETWO is used to predict the current evolution. CHEASE is used to to ensure Grad-Shafranov is satisfied with a Miller geometry The current is evolved assuming the current fully penetrates to steady-state from neoclassical resistivity. An additional radially constant current diffusion is applied where $q < 1$ to raise the on-axis q just above unity. A radially uniform $Z_{eff} = 1.7$ is used. Fixed Gaussian sources of electron heating are used, one located at $\rho = 0.6$ and the other at $\rho = 0.0$ to represent electron cyclotron heating. The pedestal boundary condition is taken to be the EPED [14] prediction with $\beta_N = 2$ shown in Figure 3. The pedestal height increases monotonically with increasing δ. While H-mode has rarely been observed experimentally for strong negative-δ potentially prevented due to ballooning modes [15], we still use EPED to set the edge conditions for negative triangularity as EPED has been shown to accurately predict negative-δ plasma down to $\delta = -0.2$ [16]. Using EPED below $\delta = -0.2$ gives a reduction in edge confinement at negative-δ without needing different edge models for negative-δ and positive-δ. TGLF-SAT0 is used in TGYRO with settings for electrostatic and using the $E \times B$ quench rule.

The STEP predicted confinement improvement at negative-δ is predicted to be stronger at high power densities and with strong electron heating sources. Figure 3 shows STEP predicted β_N vs triangularity for two injected powers: 10 MW and 20 MW, and NBI only and a 50/50 mix of NBI+ECH. At $P_{aux} =$ 10 MW for both heating types, modest improvements in β_N are predicted with simulations when δ is decreased from $\delta = -0.2$ to $\delta = -0.6$. For the 50/50 mix of NBI+ECH heating, the STEP prediction of β_N becomes U-shaped at $P_{aux} = 20$ MW with positive-δ with $\beta_{N,\delta=-0.6} \sim \beta_{N,\delta=0.6}$. The increase in β_N at negative-δ compared to positive-δ is stronger for NBI+ECH than with NBI only. However, all values of β_N are lower than the NBI only prediction.

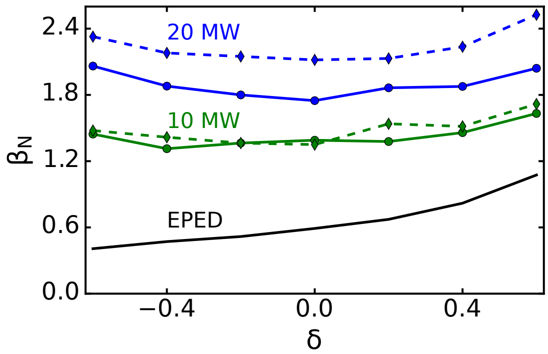

Figure 3: *STEP predicted β_N NBI only (dashed) and NBI+ECH (solid) heating $P_{aux} = 10$ MW (blue) and $P_{aux} = 20$ MW (green) with EPED boundary (black).*

The transport and integrated modeling predictive capabilities of the negative-δ scenario are examined in which TGYRO predicts stronger n_e and T_e gradients in negative-δ compared to positive-δ, consistent with the experiment. TGLF predicts that increasing electron temperature gradient scale length reduces the particle transport in negative-δ. This suggests that electron heating may not degrade core plasma particle confinement the way positive-δ does. The predicted confinement improvement at negative-δ from core-pedestal modeling is stronger in high power electron heated plasmas.

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