

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

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High energy confinement ( $\tau_e$ ) is required for a steady-state fusion reactor [1]. High confinement is typically achieved in positive triangularity ( $\delta$ ) H-mode plasmas. Positive- $\delta$  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- $\delta$  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- $\delta$  suggested that trapped electron modes (TEM) could be suppressed by negative- $\delta$  [4]. Gyrokinetic simulations of TCV discharges suggested that trapped electron modes were suppressed in negative- $\delta$  compared to the positive- $\delta$  counterpart [5]. Exploration of negative- $\delta$  showed that negative- $\delta$  has reduced transport compared to positive- $\delta$  [6], and suggested negative- $\delta$  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 ( $\omega$ ) agree reasonably well in both negative- $\delta$  and positive- $\delta$  at low auxiliary powers ( $< 5$  MW). TGYRO is analyzed for a positive- $\delta$  and a negative- $\delta$  plasma heated with  $P_{EC} = 2$  MW and  $P_{NBI} = 2$  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  $\omega$  in positive- $\delta$  and negative- $\delta$ . Experiments and TGYRO predictions both

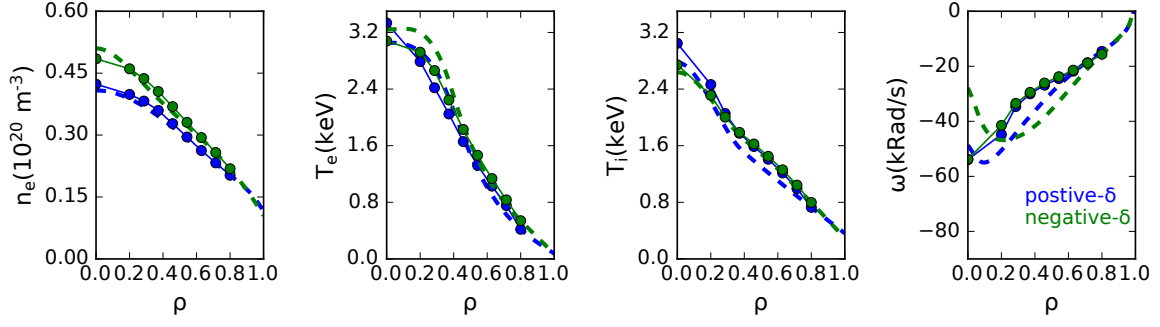


Figure 1: *TGYRO* prediction (solid) of  $n_e$ ,  $T_e$ ,  $T_i$ , and  $\omega$  and experimental profile fits (dashed) in *NBI+ECH* heated plasmas in positive- $\delta$  (blue) and in negative- $\delta$  (green).

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

Analysis of the turbulent transport using the quasilinear gyro-Landau fluid code TGLF [9] is performed. TGLF predicts a large difference in particle flux ( $\Gamma$ ) between positive- $\delta$  and negative- $\delta$  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  $\Gamma$  for the negative- $\delta$  scenario becomes negative. This is opposite to the predicted flux in the positive- $\delta$  scenario where  $\Gamma$  increases as  $a/L_{T_e}$  moves away from the experimental gradient. This difference in particle transport behavior could possibly lead to better confinement for negative- $\delta$  with negative- $\delta$  having better higher experimental  $n_e$  and  $T_e$  in Figure 2.

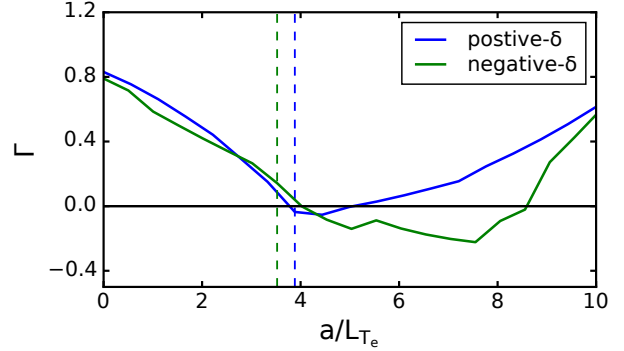


Figure 2: *TGLF-SAT0* predicted  $\Gamma$  ( $10^{20} \text{ m}^{-2} \text{ s}^{-1}$ ) at  $\rho = 0.6$  for a positive- $\delta$  and negative- $\delta$  ECH only plasma plotted vs.  $a/L_{T_e}$ . The vertical dashed lines indicate the experimental scale lengths.

Core-pedestal modeling shows confinement and  $\beta_N$  improve at negative  $\delta$  and at positive  $\delta$ . Similar parameters to the DIII-D experiment of  $\beta_N = 2$ ,  $n_{e,\text{ped}} = 0.35 \times 10^{20} \text{ m}^{-3}$ ,  $\kappa = 1.6$ ,  $B_t = 2 \text{ T}$ , and  $I_p = 0.8 \text{ MA}$  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 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  $\delta$ . While H-mode has rarely been observed experimentally for strong negative- $\delta$  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- $\delta$  plasma down to  $\delta = -0.2$  [16]. Using EPED below  $\delta = -0.2$  gives a reduction in edge confinement at negative- $\delta$  without needing different edge models for negative- $\delta$  and positive- $\delta$ . 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- $\delta$  is predicted to be stronger at high power densities and with strong electron heating sources. Figure 3 shows STEP predicted  $\beta_N$  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  $\beta_N$  are predicted with simulations when  $\delta$  is decreased from  $\delta = -0.2$  to  $\delta = -0.6$ . For the 50/50 mix of NBI+ECH heating, the STEP prediction of  $\beta_N$  becomes U-shaped at  $P_{aux} = 20$  MW with positive- $\delta$  with  $\beta_{N,\delta=-0.6} \sim \beta_{N,\delta=0.6}$ . The increase in  $\beta_N$  at negative- $\delta$  compared to positive- $\delta$  is stronger for NBI+ECH than with NBI only. However, all values of  $\beta_N$  are lower than the NBI only prediction.

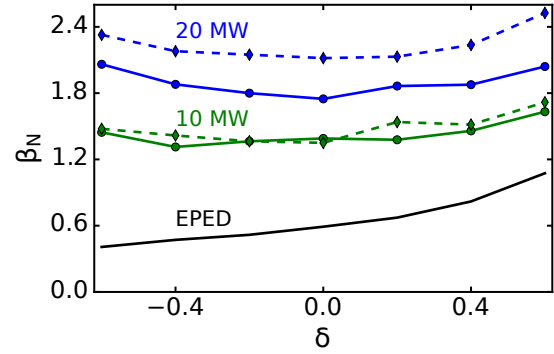


Figure 3: STEP predicted  $\beta_N$  NBI only (dashed) and NBI+ECH (solid) heating  $P_{aux} = 10$  MW (blue) and  $P_{aux} = 20$  MW (green) with EPED boundary (black).

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

power electron heated plasmas.

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## Acknowledgements

Work supported in part by the US Department of Energy, Office of Science, Office of Fusion Energy Sciences DE-FG02-95ER54309, DE-FC02-04ER54698, and DE-SC0017992. Part of the data analysis was performed using the OMFIT integrated modeling framework.

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