Transport at High $\beta_p$ and Development of Candidate Steady State Scenarios for ITER

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Abstract
Shafranov shift stabilizes turbulence and creates a bifurcation in transport that enables high performance ITB plasmas to be sustained at ITER relevant $q_{95} \sim 6$. On DIII-D, the internal transport barrier (ITB), high $\beta_N \sim 3$, and very high normalized confinement $H_{98,y2} \sim 1.6$ of the high $\beta_p$ scenario has been achieved at $q_{95} \sim 6$. This is projected to meet the ITER steady-state goal of $Q=5$. The ITB is maintained at lower $\beta_p$ with a strong reverse shear, confirming predictions that negative central shear can lower the $\beta_p$ threshold for the ITB. There are two observed confinement states in the high $\beta_p$ scenario: H-mode confinement state with a high edge pedestal, and an enhanced confinement state with a low pedestal and an ITB. At large radius ($\rho \sim 0.8$), the enhanced ITB confinement state has a much lower predicted turbulent ion energy transport than the H-mode confinement state. Simulating intermediate states, a large electromagnetic “mountain” of increased transport is found due to a KBM. Transient perturbations such as edge localized modes (ELMs) may trigger the transition between states by temporarily reducing the KBM drive. It has been observed in a scan of external perturbation amplitude that when there are no large type-I ELMs, there is no transition to enhanced confinement. Quasilinear gyro-Landau fluid predictive modeling of ITER suggests that only a modest reverse shear is required to achieve the ITB formation necessary for $Q=5$ when electromagnetic physics including the KBM is incorporated.

1. Introduction
To achieve the ITER steady-state goal of a fusion gain of $Q = 5$ with the 73 MW of the “day one” heating, ITER must have high normalized confinement $H_{98,y2} \sim 1.5$ while operating at high normalized beta ($\beta_N > 2.6$) and high Greenwald fraction $f_{gw} \sim 1.0$ [1, 2]. Candidate scenarios operating with a mid-radius localized steepening of the temperature and density gradients called internal transport barriers (ITB) are promising for achieving the necessary confinement for $Q = 5$. Understanding the physics governing internal transport barrier formation and sustainment is critical to understanding and extrapolating the improved confinement of ITB scenarios to ITER. The two physical mechanisms which are thought to lead to ITB formation are ExB shear and magnetic shear. The ExB shear flow driven by the torque from neutral beam injection in ITER is expected to be small due to the large moment of inertia [3]. Thus, ITB formation in ITER will likely need to be provided through magnetic shear in the form of Shafranov shift or negative central shear (NCS) [4].

The high poloidal beta ($\beta_p$) scenario on DIII-D [5] has many of the desired properties of ITER steady-state operation. One of the key characteristics of the high $\beta_p$ scenario is the large radius ITB in all transport channels, which is due to the large Shafranov shift ($\propto \beta_p$). The scenario has typical operation at $\beta_N \sim 3$ with enhanced confinement $H_{98,y2} \sim 1.6$, and a Greenwald fraction near unity. However,
the high $\beta_p$ scenario on DIII-D typically operates fully non-inductive at high $q_{95} \sim 10$. Similar fully non-inductive operation on ITER will be at lower $q_{95}$ and $\beta_p$ for two reasons. Firstly, ITER will operate at lower collisionality, which increases the current drive from the bootstrap effect. Secondly, DIII-D typically operates with a larger fast ion fraction than planned ITER operation, and the fast ion pressure does not contribute significantly to the bootstrap current. Because of these reasons, the same bootstrap fraction as DIII-D can be achieved in ITER at lower $\beta_p$ and $q_{95}$ values. Recent experiments extended the high $\beta_p$ scenario to ITER relevant $q_{95} \sim 6$ via a second inductive current ramp. The extended scenario maintained the ITB and high normalized confinement down to $q_{95} \sim 7$, and suggested a $\beta_p = 1.9$ threshold for ITB formation [6].

There have been many transport studies that examined steady-state scenarios for ITER. It has been suggested that ITB scenarios would be difficult to sustain without additional current drive off-axis beyond the “day one” heating [7]. Many transport studies that evaluated the addition of lower hybrid current drive to produce an off-axis current to generate an NCS were found to predict an ITB [8, 9]. By operating at lower overall plasma current, the high $\beta_p$ scenario provides a larger percentage of off-axis current via the ITB driven bootstrap. Previous TGYRO [10] transport simulations of ITER suggested that a high $\beta_p \sim 2$ scenario could achieve $Q = 5$ only with a strong NCS with on-axis $q_0 = 7$, which was likely incompatible with the near axis current drive from the neutral beam injection planned for ITER. [11]

Since that work, improvements to the quasilinear gyro-Landau fluid code that is used by TGYRO to predict turbulent fluxes have been made [12]. These improvements increase the fidelity of electromagnetic simulation, allowing prediction of the KBM instability, and are found to be important in ITB plasmas.

In this paper, it is shown that Shafranov shift stabilizes turbulence and creates a transport bifurcation that enables high performance ITB plasmas to be sustained at ITER relevant $q_{95} \sim 6$. On DIII-D, the internal transport barrier and very high normalized confinement $H_{98,5,2} \sim 1.6$ of the high $\beta_p$ scenario has been achieved at $q_{95} \sim 6$ at low rotation. By simple $H_{98,5,2}$ scaling of confinement, this scenario is projected to meet the ITER steady-state goal of $Q = 5$. The ITB is maintained at lower $\beta_p$ with a reverse shear. Quasilinear gyro-Landau fluid predictive modeling of ITER suggests that only a modest reverse shear is required to achieve the ITB formation necessary for $Q=5$ when electromagnetic physics including the KBM is incorporated.

2. THE HIGH $\beta_p$ SCENARIO ON DIII-D

An enhanced energy confinement quality in the high $\beta_p$ scenario ($H_{98,5,2} \sim 1.6$) has been achieved at low $q_{95} \sim 6$ for multiple energy confinement times with low toroidal rotation near zero at $\rho = 0.5$. Fig. 1 shows the discharge which achieved the enhanced confinement (172461), along with another extended high $\beta_p$ discharge where the confinement was reduced from enhanced ($H_{98,5,2} \sim 1.6$) to H-mode confinement ($H_{98,5,2} \sim 1.3$) when the $q_{95}$ was reduced beyond 7 (164510). These discharges were extended to lower $q_{95}$ via a second inductive $I_p$ ramp after 1 s $I_p$ flattop. The delay between the second and first current ramp allows for the scenario to form to near ITB conditions in density and $\beta_p$ at high $q_{95} \sim 10$ near non-inductive conditions before $q_{95}$ is lowered. Previous measurements suggested that there is a minimum amount of Shafranov shift needed to lead to ITB formation, with a threshold of $\beta_p = 1.9$. At low $q_{95} \sim 6$ and $\beta_p = 1.9$, the enhanced confinement is achieved in discharge 172461 even though it is at the $\beta_p$ threshold. This suggests that there is an additional mechanism for turbulence suppression other than the Shafranov shift. The mid-radius toroidal rotation near zero at $\rho = 0.5$ suggests that ExB shear is likely not the additional turbulence suppression mechanism.

A comparison of the pressure and $q$ profiles is shown in Fig. 2 to better understand what causes the enhanced confinement. The enhanced confinement state has a lower pedestal and an ITB, while the H-mode confinement state has a higher pedestal and no ITB. This result is the opposite of the typical stiff profile assumption, where the energy confinement is simply a multiple of the pedestal height. The high
confinement state has a reverse shear at mid-radius. Since the rotation is low at mid-radius, the difference in q-profiles is likely the cause of the enhanced confinement. This result supports the predictive ITER simulations which suggested that a reverse shear could lower the $\beta_p$ threshold required for ITB formation [11].

A similar relationship between pressure profiles and normalized confinement has been observed at high $q_{95} \sim 10$ with two confinement states: an H-mode confinement state with a high edge pedestal; and an enhanced confinement state with a low pedestal and an ITB. The high $\beta_p$ scenario exhibits a bifurcation in mid-radius transport based on the pressure gradient. Fig. 3 shows experimental evidence of this bifurcation, when the injected power by neutral beams ($P_{aux}$) is fed back to maintain constant $\beta_N$. At low pressure gradient $|dp/d\rho|$, $P_{aux}$ increases as $|dp/d\rho|$ increases. However, as $|dp/d\rho|$ exceeds 80, the trend reverses with $P_{aux}$ decreasing as $|dp/d\rho|$ is increased further creating a bifurcation. This is consistent with the Shafranov or $\alpha \propto |dp/d\rho|$ stabilization where turbulence is suppressed with increasing pressure gradient. The decreased injected power at high mid-radius pressure gradient results in a state with enhanced confinement even when the pedestal is significantly lower. The bottom panel of Figure 3
shows two bands of pedestal pressure when plotted against mid-radius pressure gradient, suggesting that the two confinement states are distinct. There is a high \( p_{e,\text{ped}} \) low \( dp/d\rho \) band, and a low \( p_{e,\text{ped}} \) high \( dp/d\rho \) band.

\[ \text{Figure 3: Experimental bifurcation is shown in the high } \beta_p \text{ scenario: injected power } P_{\text{aux}} \text{ (Top) and pedestal pressure (bottom) vs. pressure gradient } dp/d\rho. \]

3. **The pedestal of the high } \beta_p \text{ scenario**}

The pedestals of the two confinement states are examined to better understand why the two states have different pedestal height and width. Pedestal analysis on the H-mode confinement high pedestal state suggests that the state is limited by the peeling mode, while it is unclear what limits the stability of the low pedestal state. Fig. 4 shows stability analysis of the pedestal using the ELITE code. The pink-red region on the top of the plots represents the current gradient peeling stability limit. The pink region on the right of the plots represents the pressure gradient ideal ballooning mode limit. The ELITE analysis shows a gap between the ballooning stability and the peeling stability limits. The high pedestal state is inside the gap and near the peeling stability limit suggesting that the state is limited by the current gradient. The low pedestal enhanced confinement ITB state is lower in both pressure gradient and current gradient than the high pedestal state, and far away from both the peeling and ballooning limit. This suggests that the ITB and high pedestal are not incompatible.

Since it is unclear what limits the lower pedestal from the ELITE analysis, the quasilinear gyro-Landau fluid code TGLF is used to better understand the stability and transport at \( \rho = 0.8 \). Shown in Fig. 5, the electromagnetic prediction of turbulent transport is consistent with the experiment, with energy being lost faster for the H-mode confinement state than the enhanced confinement ITB state. Simulating intermediate states, the predicted turbulent ion energy flux increases significantly. This large flux suggests that there is a stability boundary separating the two states at this radius. The large increase in flux for the intermediate states disappears when electromagnetic effects are turned off by setting \( \beta_e = 0 \), suggesting that the two states are separated by the electromagnetic KBM. This barrier in the ballooning stability limit separating the two states at \( \rho = 0.8 \) could have been missed by the ELITE analysis, since the equilibria in that analysis were only perturbed at the pedestal to scan the current and pressure. Note that while ELITE only calculates the ideal peeling ballooning modes, the instability threshold for KBM and ideal modes are similar [13].
It has been proposed that large transient perturbations such as type-I edge localized modes (ELMs) may trigger the transition between pedestal states. A large ELM can lower the electron temperature ($T_e$) to near zero from the plasma edge inward up to $\rho = 0.75$. This temporarily makes electromagnetic effects insignificant reducing the KBM drive and lowering the KBM mountain at large radius (red dashed line in Fig. 5). At the same time, the $T_e$ profile change increases the pressure gradient at $\rho = 0.6$. This increases the Shafranov shift stabilization at mid-radius both by the increase in pressure gradient and by the reduction of local shear because of the increased bootstrap current. The plasma can then transition to the enhanced confinement ITB state without going over the large mountain of transport at the edge.

An experimental scan of non-axisymmetric ($n=3$) perturbation applied to mitigate ELMs is consistent with this picture, shown in Fig. 6. With the largest perturbation (green), there are no large type-I ELMs, and there is no transition to enhanced confinement otherwise observed with lower amplitude perturbations. This is consistent with the hypothesis that a large edge perturbation may be needed to trigger the transition to the ITB state.
4. Transport modeling of ITB scenarios in ITER

Here, results of two types of transport simulations are presented: one with a fixed q-profile (i.e. TGYRO), and one where the q-profile is evolved self consistently with temperature and density using the expected day-one current drive systems in ITER. TGYRO modeling was found to predict DIII-D high $\beta_p$ scenario temperature and density profiles well when $q_{95} \sim 6$ [11]. The density is slightly above the Greenwald fraction with $f_{gw} = 1.2$. Modeling of a weak reversed-shear q-profile similar to that in Fig. 2 is performed to better understand if an enhanced confinement ITB scenario can exist in ITER. With a fixed weak reversed-shear q-profile, electromagnetic TGYRO transport modeling predicts density and temperature profiles that would correspond to $Q \sim 5$ in ITER (Fig. 7); i.e. the target Q of the steady-state mission. This type of q-profile has the positive transport properties of NCS, and allows current to be applied on-axis. The predicted temperature profiles are flat at $\rho = 0.8$, suggesting that the KBM is likely limiting the pressure gradient in that region. Prediction of an ITB with only a modest reverse shear is significantly more optimistic than the previous results, which suggested ITB formation would only occur at large NCS.

TGYRO analysis which only evolves the temperature and density profiles can only make predictions on
whether ITB formation can occur for a given q-profile. To test whether the ITB can be sustained, self-consistent modeling of the current profile and kinetic profiles is performed. Self-consistent modeling suggests that this type of operation could be possible to sustain using only the day heating and current drive. Modeling is done iteratively using the new STEP module in OMFIT [14]. The STEP module uses TGYRO to evolve the densities and temperatures, ONETWO [15] to relax the current profile to steady-state and update the heating profiles, and EFIT [16] to ensure the new pressure and current profiles satisfy the grad-Shafranov equation. Starting from the q-profile in Fig 7, after ten iterations, a strong ITB and reverse shear is predicted by this workflow. Shown in Fig. 8, the scenario has a stronger reverse shear than the extrapolated q-profile from a DIII-D high $\beta_p$ scenario shown in Fig. 7. This is due to TGYRO predicting a steeper ITB for ITER than in DIII-D. This q-profile has similar properties to that of DIII-D experiment, having a mid-radius reverse shear, and lower on-axis q-profile. Note that the strong reverse shear that forms is due to the strong off-axis current for the bootstrap current of the ITB, and is not necessary for ITB formation as suggested by Fig. 7. However, the stronger reverse shear does lead to prediction of a stronger ITB, and higher peak $T_i \sim 27$ keV.

![Figure 8: $T_e$, $T_i$, and q predicted after 10 iterations of STEP modeling show an ITB in temperatures and reverse shear in the q-profile in ITER.](image)

5. CONCLUSION

A high bootstrap fraction ITB scenario is a promising candidate to meet the necessary confinement in order to achieve the ITER steady-state goal of $Q = 5$. The high $\beta_p$ scenario in DIII-D has been extended inductively to $q_{95} \sim 6$ at low rotation while maintaining the ITB and normalized confinement well above $H_{98,2} = 1$. Shafranov shift stabilizes turbulence and creates a bifurcation in transport that enables high performance ITB plasmas. From peeling-ballooning analysis of the pedestal, it is unclear what limits the pedestal in the ITB plasmas. Nevertheless, the stability of the KBM is shown to be important at $\rho = 0.8$, and likely plays an important role in dynamics of the ITB and the pedestal. Due to the bifurcation of transport of the KBM predicted at $\rho = 0.8$, a large perturbation like a type-I ELM may be necessary to transition from a non-ITB state to an ITB state. TGYRO transport modeling suggests that an ITB scenario exists, and could achieve $Q = 5$ with only a modest reverse magnetic shear. Self-consistent modeling converged to an ITB and reverse shear solution, suggesting that the scenario could be sustained on ITER.

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