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

by
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with
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High $\beta_p \sim 2$ ITB scenario is a promising candidate for ITER steady-state

- Shafranov shift causes bifurcation in turbulent transport at high $q_{95} \sim 10$

- ITB and enhanced normalized confinement ($H_{98,y2} \sim 1.8$) maintained at $q_{95} \sim 6$ on DIII-D with help of reverse magnetic shear

- Modeling suggests only modest reverse shear is needed for ITB prediction in ITER
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The high $q_{95}$ high $\beta_p$ scenario transitions to high confinement at fixed $\beta$.

- **High performance typical operation:**
  - $\beta_p \sim \beta_N \sim 3$, $f_{gw} \sim 1$, $f_{bs} \sim 0.8$, $q_{95} \sim 10-12$
  - $H_{98} > 1.5$ even at low torque

- **Multiple confinement states**
  - H-mode ($H_{98} = 1.3$)
  - Enhanced ($H_{98} = 1.8$)

- **What is the difference between confinement states?**
H-mode and enhanced confinement states have very different pressure profiles

- Enhanced confinement state has lower pedestal height
- Large radius transport barrier improves confinement
Simple model predicts Shafranov shift and magnetic shear creates bifurcation in transport

- For circular flux surface large aspect ratio limit, the drift frequency is:

\[
\overline{k}_\perp \cdot \overline{v}_{da} \equiv k_\theta \frac{m_a \left( 2v_\parallel^2 + v_\perp^2 \right)}{2 e_a R_0} \left[ 1 + \left( -\frac{1}{2} + \hat{S} - \alpha \right) \theta^2 \right] + \ldots
\]

Magnetic shear \( \hat{S} = \frac{r}{q} \frac{dq}{dr} \)

Shafranov shift \( \alpha = -R_0 q^2 \frac{d\beta}{dr} \)

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Bifurcation of transport with mid-radius pressure gradient observed when plasma is in $\beta_N$ feedback

- $\beta_N$ feedback
  - $P_{\text{aux}}$ is dependent on $\rho$

$\beta_N > 1$, $I_p > 550$ kA

$P_{\text{aux}}$ (MW) vs $-\frac{dp}{d\rho}$ (kPa) at $\rho = 0.6$
Bifurcation of transport with mid-radius pressure gradient observed when plasma is in $\beta_N$ feedback

- **$\beta_N$ feedback**
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- **Small $dp/d\rho$**
  - Increasing pressure gradient increases required $P_{aux}$

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$164527-164542$
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- High pedestal, low mid-radius pressure gradient state
- Low pedestal, high mid-radius pressure gradient state
- Transition between states is usually triggered by ELM
• Quasilinear gyro-Landau fluid code fit to non-linear gyrokinetic turbulence simulations

• Recent correction to Ampere’s Law leads to prediction of KBM mountain, which is important in predicting high $\beta_p$ ITB plasmas

TGLF transport code used to analyze core transport

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TGLF predicts transport at $\rho=0.6$ decreases as ITB forms

- Predicted flux greater for H-mode state
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- Predicted flux greater for H-mode state
- TGLF input linear interpolated for intermediate state
- At $\rho=0.6$, turbulence is stabilized as $\alpha$-s increases
Large electromagnetic transport in between two states at large radius $\rho=0.8$

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- Predicted flux greater for H-mode confinement state
- When $\beta_e=0$ (i.e. electrostatic), increasing $\alpha$-s is stabilizing
- How does plasma cross the KBM mountain?
Large ELM could help plasma across KBM mountain

- Large ELM that occurs 50 ms before ITB begins to form
- Allows transition from H-mode to ITB state
  - ELM lowers edge $T_e$ and increases mid-radius $\rho'$
  - Transiently lowers $\beta_e$ at edge
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q dependence of Shafranov shift makes sustainment of ITB at lower $q_{95}$ more difficult

Local measure of Shafranov shift:

$$\alpha = -R_0 q^2 \frac{d \beta}{dr}$$
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- Plasma extended to lower \( q_{95} \approx 6 \) via second current ramp
  - Allows plasma to get to near ITB conditions before going to lower \( q_{95} \)
- Threshold \( \beta_p \approx 1.9 \)
Enhanced confinement at $q_{95} \sim 6$ has been achieved with reverse shear.

Simple model: $\alpha_s$

Reverse shear produced with use of off-axis beams.

$H_{98,\gamma_2} = 1.3$

$H_{98,\gamma_2} = 1.8$

Graphs showing $q_95$, $\beta_p$, and $H_{98}$ over time.
Lower pedestal observed with ITB (same as high $q_{95}$!)

$$H_{98,\gamma^2} = 1.3 \quad H_{98,\gamma^2} = 1.8$$

**Diagram:**

- $P(10^4 \text{ Pa})$ vs. $\rho$
- $q$ vs. $\rho$

**Simple model:** $\alpha, s$
Rotation ITB does not align with temperature ITB, suggests that $ExB$ shear not important for energy confinement.
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- TGYRO predictive simulation suggests ITB exists w/o ExB shear.
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High confinement required to achieve ITER steady-state goal of $Q=5$ with day one heating

- 0D modeling using GA Systems Code

- Constraints include:
  - $f_{gw} = 1$, $H_{98y2}$, $f_{Ni} = 1$, $Q=5$

- $H_{98} \sim 1.5$ is required to achieve $Q=5$ with $P_{aux} = 73$ MW

Each point is $Q=5$ solution

ITER day one heating

$P_{aux}$ vs $H_{98}$
Iterative loop for integrated modeling is used to find self-consistent steady-state solution

- **Self-consistent modeling loop**
  - Iterate between kinetic evolution (TGYRO) current evolution (ONETWO), and magnetic equilibrium solver (EFIT)
- **$T_i$, $T_e$, $n_e$, $q$ are evolved**
  - Day 1 heating: 33MW NNBI, 20MW ECCD, 20MW ICRF
  - $\text{ExB}=0$, $T_{e,\text{ped}}=3.25\text{ keV}$, $I_p=8\text{ MA}$, $f_{gw}\sim1.2$
Self-consistent modeling suggests that ITER ITB could be sustained with day one actuators

- Converged prediction shows $Q \sim 6$ solution with ITB and reverse shear
  - However, $Q$ is very sensitive to height of ITB

- Predicted $n=1$ no-wall stable by GATO at $\beta_N \sim 3.2$
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Recent correction to EM effects predicts ITB without need for large NCS

• Prediction of $T_i$ is roughly what is needed for $Q=5$

• $q$-profile not consistent with evolved kinetic profiles.

ExB=0

evolve $T_i, te, ne$ profiles
fixed $q$ profile
Previous TGYRO predictive modeling suggested large NCS required for ITB formation

- TGYRO predict $n_e$, $T_e$, $T_i$ profiles by matching predicted flux from TGLF, NEO to power balance
- $n_e$, $T_e$, $T_i$ profiles needed for $Q=5$ approximately $q_0=7$

Fixed $I_p=7.4$ MA

ITB formation
When there are no large type-I ELMs, and there is no ITB formation, consistent with ELM hypothesis

- Three extended high $\beta_p$ discharges with varied RMP I-coil perturbations
  - Largest I-coil perturbation (green) has no Type-I ELMs and no ITB
Low pedestal state stability not near instability threshold

- Stability analysis performed using the ELITE code
- Gap in right corner
High pedestal state is inside the right corner gap

- State current gradient peeling limited