Internal Transport Barriers in the DIII-D Tokamak

by

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For the DIII-D Research Team

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**MOTIVATION — IMPORTANCE OF ITB RESEARCH**

- Obtaining ITBs with large radius and barrier width leads to:
  - Higher fusion performance
  - Improved MHD stability limits
  - Improved bootstrap current alignment

**Schematic ITB \( T_i \) profiles**

**MHD modeling of \( \beta_N \) limit**

**ARIES-AT Modeling**

- Assisted in obtaining significant fusion gain (\( Q \sim 10 \)) in Next Step burning plasmas
- More compact and/or economic powerplants
- Assist in achieving steady-state tokamak operation

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**ITB Radius, \( \rho_{ITB} \)**

- Optimal ITB profile
- Non-optimal ITB profile

**ITB half width**

**\( \beta_N \) (%-m-T/MA)**

- Stable
- Unstable

**\( T_i \) (keV)**

- Desired current profile

**\( r/a \)**

- ITB
OVERVIEW

• Significant progress on DIII-D in addressing critical issues for ITB research:

  — Improved understanding of physical mechanisms responsible for ITB formation
    ★ Evidence for a range of turbulence/transport reduction mechanisms

  — New Quiescent Double Barrier (QDB) regime provides sustained, high quality ITB operation with an ELM-free H-mode edge, allowing us to examine:
    ★ Edge-core integration issues, e.g. effect of ELMs
    ★ ITB sustainment
    ★ Impurity accumulation

  — MHD stability will determine ultimate performance limit of ITB plasmas
    ★ Stabilization of resistive wall modes (RWM) and neoclassical tearing modes (NTM) demonstrated on DIII-D. Invited talk by M. Okabayashi, Wednesday
### UNDERSTANDING OF ITB FORMATION CONDITIONS FLOWS
### FROM UNDERSTANDING OF TRANSPORT DRIVE AND SUPPRESSION MECHANISMS

<table>
<thead>
<tr>
<th>Indicative turbulence scales</th>
<th>$0.1$</th>
<th>$k_\theta \rho_s$</th>
<th>$1.$</th>
<th>$10$</th>
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<tr>
<td></td>
<td>$1.$</td>
<td>$k_\theta (cm^{-1})$</td>
<td>$10$</td>
<td>$100$</td>
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<tr>
<th>Turbulence/transport mechanisms</th>
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<tr>
<td>ITG</td>
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<td>TEM</td>
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<td>ETG</td>
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<th>Affected transport channels</th>
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<tr>
<td>Ion thermal</td>
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<tr>
<td>Momentum</td>
</tr>
<tr>
<td>Electron particle</td>
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<tr>
<td>Electron thermal</td>
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<td>ExB shear</td>
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<th>Stabilization mechanisms</th>
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<td>Reversed magnetic shear (NCS)</td>
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<td>$\alpha$-stabilization (Shafranov shift)</td>
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<td>Impurity injection</td>
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- Theory-based modeling predictions for turbulence and transport drive and control mechanisms are compared to experiment
- DIII-D results indicate following turbulence control mechanisms can be effective:
  - $\alpha$-stabilization/Shafranov shift
  - $q$ profile
  - Growth rate reduction via impurity injection
  - Sheared ExB flows (rotation)
- Direct evidence for ETG modes is lacking
\(\alpha\)-STABILIZATION AND NEGATIVE MAGNETIC SHEAR ARE PREDICTED TO REDUCE TURBULENCE GROWTH RATES

- Theory calculations, e.g. Waltz et al, Phys Plasmas 1997, indicate that turbulence growth rates can be reduced by negative magnetic shear and \(\alpha\)-stabilization (Shafranov shift)
  - Where \(\alpha\) is the normalized pressure gradient (ballooning parameter)

- In comparisons to theory, extensive use is made of the GLF23 transport model
  - Drift-wave based model (ITG, TEM, ETG), providing quasilinear estimates of transport
  - Includes ExB shear, \(\alpha\)-stabilization, magnetic shear and dilution effects

- ExB shear predicted to suppress turbulence when the shearing rate \(\omega_{\text{ExB}}\) exceeds the turbulence linear growth rate \(\gamma\)
EVIDENCE FOR ROLE OF $\alpha$-STABILIZATION PROVIDED BY ELECTRON THERMAL ITBs OBTAINED WITH LOCALIZED ECH

- E-ITB develops rapidly following ECH onset
- Electron transport reduced
SIMULATIONS INDICATE $\alpha$-STABILIZATION IS CRITICAL IN FORMATION OF ELECTRON ITB

- Dynamical simulations using GLF23 model maintain E-ITB only if $\alpha$ is sufficiently large
  - GLF23 also reproduces dynamics of barrier evolution

- Results also provide indirect evidence for ETG modes:
  - $T_e$ gradient at location of E-ITBs consistently observed to be at marginal stability to ETG mode

![Graph showing experimental and simulated $T_e$ profiles with $\alpha=0$ comparison.](image-url)

![Graph showing calculated ETG critical gradient.](image-url)
SUBSTANTIAL EVIDENCE FROM MANY EXPERIMENTS FOR ROLE OF $q$-PROFILE IN FACILITATING ITB FORMATION

- On DIII-D, use of strong negative shear, plus high heating power results in ITBs in all four transport channels.

- Without strong negative shear, ITBs on DIII-D often limited to ion thermal and angular momentum channels.

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**Graphs:**

- **Ion Temperature**
  - $T_i$ (keV)
  - Steep gradient zone
  - 1.2 s, 1.4 s, 1.5 s

- **Electron Density**
  - $n_e$ ($\times 10^{19} \text{ m}^{-3}$)

- **Carbon Rotation**
  - Toroidal rotation (kHz)
  - Inset: q-profile

- **Electron Temperature**
  - $T_e$ (keV)

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**DIII-D**

NATIONAL FUSION FACILITY
SAN DIEGO
IMPURITY DILUTION CAN REDUCE TURBULENT TRANSPORT BY REDUCING GROWTH RATES AND INCREASING ExB SHEAR

- Results from neon injection into co-NBI plasma with L-mode edge, no prior ITB
- Results explain physics of RI-mode:
  - Linear growth rates reduced and ExB shearing rate increased
  - Density fluctuations dramatically reduced
  - Core temperatures rise, energy confinement and neutron rate double, profiles broaden

![Graphs showing growth rates and shearing rates](attachment:image.png)

- Turbulence growth and shearing rates
- BES spectra of $\tilde{n}/n$ at $\rho=0.7, 1.1-1.2$ s

EJD Toki 2001 12/14/2001 9
ExB SHEAR FLOW IS MOST STUDIED TRANSPORT BARRIER FORMATION MECHANISM (EDGE AND CORE)

- Self-consistent dynamical modeling using GLF23 can explain details of step-wise formation of ITBs on DIII-D
  - Steps are generated by a competition between the $\nabla P$ and $v_\phi B_\theta$ contributions to $E_r$ and the ExB shearing rate in co-NBI discharges

$$E_r = \frac{\nabla P_i}{en_i Z_i} - v_\theta B_\phi + v_\phi B_\theta$$

- Occurrence of steps sometimes correlates with presence of rational q values
INTERPLAY OF TERMS IN ExB SHEARING RATE

$\omega_{ExB}$ IS DIFFERENT FOR CO- AND COUNTER-NBI

- Main ion shearing rate $\omega_{ExB}$ can be separated into pressure and rotation terms

$$\omega_{ExB} = \omega_{ExB}^{\nabla p} + \omega_{ExB}^{\text{rotation}}$$

- With counter-NBI, increasing the pressure gradient component increases $\omega_{ExB}$, rather than reducing it, as with co-injection
  - Counter-NBI favorable for ITB expansion with L-mode edge
  - Counter-NBI experiments led to discovery of Quiescent Double Barrier (QDB) regime
QUIESCENT DOUBLE-BARRIER (QDB) OPERATION

Will examine:

- Performance obtained in QDB regime
- Significance of QDB results
- Transport and fluctuation analysis and modeling
- Impurity issues

Some new acronyms:

- QH-mode: Quiescent H-mode
  - An ELM-free H-mode with density and radiated power control
- QDB: Quiescent Double Barrier
  - Operation with an internal transport barrier (ITB) inside a QH-mode edge
QDB REGIME OBTAINED USING COUNTER-NBI —
COMBINES ITBs WITH ELM-FREE QUIESCENT H-MODE EDGE

- Edge pedestal elevates central temperatures, improving fusion performance
COMBINATION OF CORE ITB AND QH-MODE EDGE RESULTS IN SUSTAINED HIGH PERFORMANCE PLASMAS

- $\beta_n H_{89} = 7$ for $10 \tau_E$ (1.6 s)
- Duration limited by NBI sources
- Have maintained QH-mode for $>3.5$ s, $\sim 25 \tau_E$
- Feature of QH-mode is ELM-free operation with density and radiated power control
  - Density controlled using divertor pumping

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**Graphs**

- Plasma Current (MA) vs Time (s)
- Central Density ($10^{19}$ m$^{-3}$) vs Time (s)
- NBI Power (MW) vs Time (s)
- Radiated Power (MW) vs Time (s)
- Line Average Density ($10^{19}$ m$^{-3}$) vs Time (s)
- $\beta_n H_{89}$ vs Time (s)
- Neutron rate ($10^{15}$ s$^{-1}$) vs Time (s)

**Data**

- Duration limited by NBI sources
- Feature of QH-mode is ELM-free operation with density and radiated power control
- Density controlled using divertor pumping
WHAT IS THE SIGNIFICANCE OF QDB OPERATION?

- H-mode is the operating regime of choice for next-step devices, but has non-optimal features due to the impact of Edge Localized Modes (ELMs)
  - Pulsed heat loads to the divertor can cause rapid erosion
  - Type I (Giant) ELMs can inhibit or destroy the ITBs desired for advanced tokamak (AT) scenarios
  
  ★ Double barriers have been achieved on JT-60U and JET

- QDB plasmas address critical next-step and ITB issues:
  - Provides high quality ELM-free H-mode, eliminating pulsed divertor heat loads
  - The QH-mode edge is compatible with ITBs
  - Sustained long pulse, high performance capability:
    
    ★ >3.5 s or 25 $\tau_E$ achieved, limited only by beam pulse duration
    
    ★ $\beta_N H_{89} = 7$ for 10 $\tau_E$
  - Long pulse capability provides opportunity to study impurity accumulation issues in detail
Transport analysis confirms presence of double (core and edge) transport barriers.

- Core transport is similar to that in ITB plasmas with an L-mode edge.
  - ITB refers to region of reduced transport relative to L-mode.
- Edge transport is typical of H-mode.
- Core and edge barriers are kept separate by region of low ExB shear.

\[ \chi_i \text{ ITB} \]
\[ \chi^\text{neo} \]
\[ \chi_e \text{ ITB} \]
\[ \text{QDB} \text{ ITB + L-mode} \]
\[ \text{L-mode} \]

\[ \text{QDB} \text{ ITB} \]
\[ \text{L-mode} + \text{ITB} \text{ 998491.12s} \]
\[ \text{L-mode} \text{ 998520.80s} \]
SIMULATIONS USING THE GLF23 MODEL REPRODUCE THE QDB CORE ION BARRIER

- Steady-state simulation reproduces core ion temperature barrier
  - Core $T_e$ profile not accurately reproduced
- GLF23 also predicts core turbulence should not be completely suppressed, as $E_xB$ shearing rate and turbulence growth rate in approximate balance.
CORE BARRIER EXISTS WITHOUT COMPLETE TURBULENCE SUPPRESSION, IN AGREEMENT WITH GLF23 MODELING

- Internal broadband turbulence is not completely suppressed as the QDB core barrier evolves
  - Residual turbulence still significantly above the FIR scattering system detection limit
  - Contrasts with typical ITB in DIII–D, where core turbulence is suppressed to the noise floor

- High frequency coherent core modes are often detected.
  - Reflectometer data indicate these modes are localized to $\rho \sim 0-0.4$.
STEP SIZE FOR CORE TURBULENT TRANSPORT IS REDUCED IN QDB PLASMAS

- In L-mode, correlation lengths are observed to scale approximately as $5 \sim 10 \rho_s$
- In QDB plasmas, core correlation lengths are significantly lower than the scaling observed in L-mode
- Initial modeling using the UCAN global gyrokinetic code tracks core experimental trends and magnitude

- Where $\rho_s$ is the ion gyroradius evaluated using $T_e$

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**L-mode data set**

- Correlation length, $\Delta r$
- $5-10 \rho_s$

**QDB data set**

- Correlation length, $\Delta r$
- $5-10 \rho_s$

**Simulations**

- Correlation length, $\Delta r$
- $5-10 \rho_s$
QDB DISCHARGES ALLOW US TO STUDY IMPURITY ACCUMULATION IN DIII-D ITB PLASMAS

- Nickel content increases with time, but contribution to radiated power is low, < 0.3 MW. Large impact on $Z_{\text{eff}}$
- Low-Z impurities, e.g. carbon, stay approximately constant
NEOCASSICAL MODELING PREDICTS CENTRAL PEAKING OF HIGH-Z IMPURITIES, DUE TO PEAKED $n_e$ PROFILE

- Measured impurity convection and diffusivity is larger than neoclassical from $0.1 < \rho < 0.5$

- Measured neon profile is less peaked than profile calculated using neoclassical transport
CONTROL TOOLS EXIST TO MODIFY
DENSITY PROFILE AND REDUCE DENSITY PEAKING

- Example of use of central ECH to modify density profile
- $n_e(0)/n_{AVE}$ decreases from 2.6 to 1.7
- MIST modeling indicates Ni concentration is reduced
- Reduced density peaking would also improve bootstrap current alignment
CONCLUSIONS

- DIII-D results have improved our understanding of ITB formation conditions
  - Evidence for the effect of $\alpha$-stabilization/Shafrranov shift, magnetic shear, impurity injection, and sheared ExB flows

- QDB results demonstrate that it is possible to have long pulse, high performance ITB operation with an ELM-free H-mode edge, with density and radiated power control
  - $>3.5$ s or $25 \tau_E$ achieved, limited only by beam pulse duration
  - $\beta_{NH89} = 7$ for $10 \tau_E$
  - Pulsed divertor heat loads eliminated
  - Core and edge transport barriers are compatible
  - Turbulence and transport behavior of QDB discharges is reproduced by initial simulations and modeling
  - Issues are increasing the operating density, impurity accumulation and obtaining QDB with balanced or co-NBI (JT-60U has unique capability!)