Experiment and Modeling of ITER Demonstration Discharges in the DIII-D Tokamak

by
J.M. Park


1) Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee, USA
2) University of California, Los Angeles, California, USA
3) General Atomics, P.O. Box 85608, San Diego, California, USA
4) Lawrence Livermore National Laboratory, Livermore, California

Presented at the
Twenty-Third IAEA Fusion Energy Conference
Daejeon, Republic of Korea

October 11–16, 2010
• Recent progress on the ITER demonstration experiment made since 2008 IAEA and integrated theory-based modeling for ITER projection

• Baseline scenario:
  – Improved match to the expected ITER parameters including:
    • Edge pedestal collisionality and rotation
  – Modeling implication for ITER:
    • Change in confinement, transport, and ELM characteristics in ITER regime of low collisionality and rotation

• Steady state scenario:
  – Demonstration of fully noninductive operation in ITER shape
    • Strong dependence of confinement, stability, and noninductive fraction on $q_{95}$
  – Modeling implication for ITER:
    • Optimizing $q$ profile crucial to simultaneously achieving the fully noninductive ($f_{NI}=1$) and $Q=5$ goal
DIII-D Is Providing Suitably Scaled Experimental Evaluations of the Four Primary ITER Operational Scenarios

- With size reduced by factor of 3.7, the DIII-D discharges match the ITER design values for
  - Plasma cross-section
  - Aspect ratio
  - Normalized current I/aB

- DIII-D demonstration discharges meet ITER normalized performance target
  - Target values for $\beta_N$ and $H_{98}$ were matched or exceeded

$G \equiv \beta_N H_{89}/q_{95}^2$ is a measure of fusion performance

[E. Doyle, IAEA 2008 (NF2010)]
Lower Density Baseline DIII-D Discharge Developed to Match Edge Pedestal Collisionality

- Density reduced by more than factor 2 and temperature raised by:
  - Lowering \( I_p \) (keeping \( I/a_B=1.415 \))
  - Application of ECH

- Target values for \( \beta_N \) and \( H_{98} \) maintained with lower collisionality/density operation
  - No loss in fusion performance

- Significant change observed in ELM characteristics
  - More frequent smaller ELMs

- ECH is multi-purpose
  - Suppressing 2/1 NTM by EC current drive
  - Electron dominant heating

- Improved density control and stationarity
Transport Mechanism Changes Dramatically in ITER Regime of Low Collisionality and Localized Electron-Dominant Heating

- Same normalized global energy confinement ($H_{98} \sim 1$), but significant change in local transport characteristics
  - Collisionality plays a key role in transport
- Localized electron-dominant heating increases energy transport significantly

\[
\langle n_e \rangle = 3.8 \quad 7.2 \quad 8.9 \quad (10^{19} \text{m}^{-3})
\]

\[
\nu_e^* = 0.1 \quad 0.4 \quad 0.6
\]

Power balance analysis (ONETWO)

Density (Collisionality) scan

Linear growth rate (TGLF)

Low density:
- ITG/TEM dominant
High density:
- ETG dominant
TGLF Transport Simulation Reproduces Change in Transport Processes As Observed in Experiment

- **TGLF modeling of $T_e$ and $T_i$**
  - Used experimental density and pedestal
  - Profiles from 80-100 % of ELM cycles
  - Boundary condition at $\rho = 0.84$
  - Miller geometry, electrostatic
  - $E \times B$ shearing rate from CER measurement of rotation
  - FASTRAN transport solver

- **Low density**
  - ITG/TEM dominant (low $k$ mode)
  - Good agreement only when the $E \times B$ shear stabilization included

- **High density**
  - ETG dominant (high $k$ mode)
  - Relative small effects of $E \times B$ shear stabilization
Plasma Rotation Reduced by Adding Counter-NBI in Low Collisionality Discharge

- Initiated study on effect of reduced plasma rotation on confinement
- Modest 1/4 counter-beam changes rotation substantially
- Confinement factor $H_{98}$ reduced by ~15 %, but remains ITER target $H_{98} \approx 1$
Initial Data Indicates that Reduced Plasma Rotation Reduces Confinement in Baseline Scenario

- $\gamma_E \sim 0$ over $0.3 < \rho < 0.6$
- Thermal diffusivity increases with reduced rotation
- Indicate need for performance margin in projection to ITER
Density Profile Is Substantially Peaked for the Baseline Discharge while Insensitive to Collisionality

- Less sensitive to the collisionality than recent AUG and JET observation, which do not use ECH at low density

- Density peaking affected by:
  - NBI core fueling
  - ECH particle pumping
  - ELM characteristics

- Particle balance analysis indicates inward particle flux
  - Consistent with TGLF modeling
Lower Density Results in Smaller and More Frequent ELMs

- Significant change in ELM characteristics
  - More frequent smaller ELMs for low density discharges

- The change in $P_L/P_{TH}$ is likely to affect the ELM characteristics
  - Empirical scaling for L-H power threshold (Y. Martin, et. al., 2008)
    \[ P_{TH} = 0.049 \times n^{0.72} B^{0.8} S^{0.9} \]

- Reduction of energy loss at lower collisionality is counter to scaling obtained in ITPA database

- Fractional energy loss at ELMs substantially exceeds ITER limit
**Magnitude of ELM Energy Loss Correlated With the Shape of Unstable Peeling-Ballooning Modes**

- **High density**
  - Coupled peeling-ballooning mode
  - ELM-affected region extends deep into the plasma

- **Low density**
  - More peeling-like mode
  - Narrow mode structure
  - Smaller and more frequent ELM

- Eigenmode structure calculated by ELITE stability code
STEADY STATE SCENARIO
Fully Noninductive Operation Demonstrated in ITER Shape

- Fully noninductive operation obtained in 8.5 MA equivalent discharge with $\beta_N = 3.1$
  - $q_{95} = 6.3$
  - High bootstrap fraction (~70%)
  - Relatively low fusion performance
  - Not stationary

- Standard DIII-D prescription

- Steady-state discharges utilize off-axis ECCD to maintain stable q-profile with $q_{\text{min}} \geq 1.5$

- $G = \frac{\beta_N H_{89}}{q_{95}^2}$
  - Measure of fusion performance
Measurement and Simulation Show that Inductive Current Density is Small Everywhere

- Measurement of inductive current density - loop voltage analysis
- Transport code simulation

Kinetic EFIT $\langle J_{||} \rangle_{\text{tot}}$ (MA/m²)

$\langle J_{||} \rangle_{\text{inductive}}$

Radius, $\rho$

134372, $t=3600$ ms

Transport simulation (TRANSPI) $D_B = 1.0$ m²/s

134372, $t=3610$ ms

J.M. Park et. al., 23rd IAEA Fusion Energy Conference, Daejeon, Korea, 2010, EXC/P2-05
Noninductive Fraction Increases while Fusion Performance Decreases with $q_{95}$

- Thermal energy confinement time decreases with $q_{95}$
  - Generally follow the scaling of $H_{98}$
- $f_{NI}$ and $f_{BS}$ increase with $\beta_N q_{95}$
- Edge pedestal provides typically ~40% of the total bootstrap current
  - Pedestal height and width depend on $q_{95}$
- Theory-base (GLF23) projection using the scaled edge profiles shows the same trade-off between $f_{NI}$ and $Q$ with variation of $q_{95}$ [M. Murakami: ITR P1-35]
- Indicate need for optimizing $q_{95}$ in projection to ITER
Electron and Ion Thermal Diffusivities Correlated Mainly with Magnetic Shear

- Electron and ion thermal diffusivities correlated mainly with magnetic shear both in the power balance analysis by TRANSP and in the TGLF modeling.
- TGLF transport simulation reproduces the transport dependency on $q_{95}$.
- Predictive simulation suggests that a larger radius of minimum $q$ with weak magnetic shear can reduce turbulent transport significantly.
Calculated ideal $\beta_N$ limit using experimental profiles and equilibria
- $n=1$ no-wall $\sim 2.8$
- $n=1$ ideal-wall $\sim 3.7$

Predictive modeling indicates:
- $\beta_N$ Limit decrease (increase) with $q_{\text{min}}$ at $q_{95} = 4.5$ (6.5)
- Tradeoff between stability and confinement to achieve higher $\beta_N$ at lower $q_{95}$

Edge pedestal provides typically $\sim 40\%$ of the total bootstrap current
- Key role in optimizing steady-state scenario

Pedestal height and width decrease with $q_{95}$
- Consistent with EPED prediction
**Optimum Scenario Studied by Integrated Theory-based Modeling to Achieve the \( f_{NI} = 1 \) and \( Q = 5 \) Goals Simultaneously**

- Newly developed iterative steady-state solution procedure:
  - Iterative numerical method to find a steady state solution (\( \frac{d}{dt} = 0 \)) of core transport (TGLF) using FASTRAN with self-consistent calculation of equilibrium (EFIT) and heating/CD sources (NUBEAM, TORAY, CURRAY)

- Predictive simulations suggest:
  - A larger radius for \( q_{\text{min}} \) helps to increase both the fusion performance and \( f_{NI} \) at \( \beta_N \) limit calculated from ideal wall stability

- Maximally utilize the benefits of low magnetic shear and higher pedestal pressure from the increased \( \beta_P \)
Low $q_{95}$ (High $I_p$) Operation is Important to Reach the $f_{NI}=1$ and $Q=5$ Goals Simultaneously

- Optimum q profile scan starting from the experimental condition:
  - Modest improvement of fusion performance for $4.5 < q_{95} < 6.5$

- Higher $q_{95}$ (lower $I_p$)
  - Maximum improvement of plasma confinement factor is not sufficient to reach $G=0.3$ for the $Q=5$ goal

- Lower $q_{95}$ (higher $I_p$)
  - Significant increase of $f_{BS}$ with a larger radius of $q_{min}$
  - At $q_{95}=5.0$ ($q_{min} \sim 2.5$), reach $f_{BS}=0.72$ with $G=0.3$ at the calculated ideal wall stability limit
SUMMARY AND FUTURE WORK

• **Baseline scenario:**
  – Substantial progress made in improving the match to the expected ITER parameters including edge pedestal collisionality and rotation
  – Significant change in confinement and ELM characteristics in ITER regime of low collisionality and rotation indicates need for performance margin in ITER projection

• **Steady state scenario:**
  – Noninductive operation demonstrated but with relatively low fusion performance, indicating need for \( q_{95} \) optimization in ITER projections
  – Optimization of current profile is crucial to simultaneously achieving the fully noninductive (\( f_{NI}=1 \)) and \( Q=5 \) goals

• **Future work:**
  – Apply new tools for better match to the ITER parameters (off-axis NBI, higher power EC, and FW current drive)
  – Develop steady state scenario with higher fusion performance and bootstrap fraction
  – Theory-based ITER projection using validated models against the DIII-D ITER demonstration discharges