Physics Advances in the ITER Hybrid Scenario on DIII-D

by
P.A. Politzer*

for
C.C. Petty,* R.J. Jayakumar,† T.C. Luce,* M.R. Wade,*
M.E. Austin,‡ D.P. Brennan,† T.A. Casper,† M.S. Chu,*
J.C. DeBoo,* E.J. Doyle,§ M.E. Fenstermacher,† J.R. Ferron,*
P. Gohil,* C.M. Greenfield,* C.T. Holcomb,† A.W. Hyatt,*
R.J. La Haye,* C. Kim,# G.R. McKee,# M.A. Makowski,†
M. Murakami,Δ T.W. Petrie,* R. Prater,* T.L. Rhodes,
G. Wang,§ and A.S. Welander*

*General Atomics, San Diego, California.
†Lawrence Livermore National Laboratory, Livermore, California.
‡University of Texas-Austin, Austin Texas.
¶University of Tulsa, Tulsa Oklahoma.
§University of California-Los Angeles, Los Angeles, California.
#University of Wisconsin-Madison, Madison, Wisconsin.
ΔOak Ridge National Laboratory, Oak Ridge, Tennessee.

Presented at the
21st IAEA Fusion Energy Conference
Chengdu, China

October 16–21, 2006
Outline and Summary

This paper discusses advances in understanding of the hybrid scenario in three areas:

– Rotation Effects

• The new counter-NBI capability on DIII-D has enabled initial experiments on the dependence of hybrid scenario performance on toroidal rotation.

• The toroidal velocity has been reduced by up to a factor of 6 while maintaining stationary conditions, to a central Mach number $M = v\phi/c_s = 0.075$. [$v/v_A = M[(\beta_e/Z)^{1/2} \approx 0.1 M$]

• At the lowest rotation, the fusion performance parameter $G = \beta_N H_{89}/q_{95}^2$ is reduced by 10-30%, but remains above ITER requirements.

• Energy confinement improves with increasing rotation (and torque).

• We show here details of the changes that occur in a single discharge when the torque is reduced, and some preliminary results for a range of conditions.

– Improved Confinement in Hybrid Plasmas Dominated by an $m/n = 4/3$ NTM

• Occasionally we observe a hybrid plasma with a 4/3 NTM instead of a 3/2 NTM.

• With either NTM, both the electron and ion thermal diffusivities are small, but the electron channel consistently dominates the conduction loss. $\chi_i$ is within a factor of two of the neoclassical value, and $\chi_e$ is typically $\sim 4\chi_i$.

• With a dominant $m/n = 4/3$ NTM both $\chi_e$ and $\chi_i$ are further reduced by a factor of 2, with $\chi_i$ approaching $\chi_{ineo}$. The 4/3 NTM dominated plasmas also have a higher core rotation velocity.

• The effect of the $m/n = 3/2$ NTM on the bootstrap current profile has been seen explicitly for the first time, using direct analysis of MSE data.

– The Effect of the $m/n = 3/2$ NTM on the Current Profile

• The beneficial broadening of the current profile in hybrid plasmas has been shown to be associated with the presence of the 3/2 NTM. We are exploring the physical mechanism(s) involved.

• One possibility is that the modulation of the 3/2 mode by ELMs leads to a poloidal flux pumping process (akin to the sawtooth mechanism) which raises $q_0$.

• Another possibility is that the effect is associated with the growth in the $m/n = 2/2$ component of the 3/2 mode as $q_0$ approaches 1.

• We are also exploring the role of fast ion profile modification in the broadening of the overall current profile.
A Brief Introduction to Hybrid Scenario Plasmas

Definitions

– A high performance scenario for ITER operation.
– Stationary, inductive operation with bootstrap fraction $\approx 0.3-0.5$ enables long pulse ($\geq 3000$ s) ITER operation.
– High beta ($\beta_N \geq 2.5$) gives high neutron fluence in ITER.
– High fusion performance parameter ($G = \beta_N H_{89}/q_{95}^2 > 0.25$) projects to $Q_{\text{fus}} \geq 10$ in ITER.

• For $q_{95} < 4$, “Hybrid” $\Rightarrow$ “Advanced Inductive”

General Characteristics

– The hybrid mode is a variant of ELMy H-mode. It has an H-mode edge/pedestal structure and behavior.
– Hybrid plasmas are stationary, lasting several current redistribution times.
– Compared to standard H-mode, a hybrid plasma has a broader current profile ($0.75 < \ell_i < 0.95$). The current profile broadening is associated with the presence of MHD activity – in DIII-D usually an $m/n = 3/2$ neoclassical tearing mode (NTM).
– As a consequence of the broader current profile,
  • the hybrid is more stable to the deleterious $m/n = 2/1$ NTM, allowing higher $\beta$ operation;
  • sawteeth are weaker (for $q_{95} < 4$) or absent (for $q_{95} \geq 4$), improving confinement and removing a trigger for the 2/1 NTM, and
  • growth rates for drift wave turbulence are reduced, allowing higher confinement.
Some Other Papers related to Hybrid Plasmas in DIII-D at this Conference


– EX/1-5: Chu, M.S., et al., “Maintaining the Quasi-Steady State Central Current Density Profile in Hybrid Discharges”

Changing Toroidal Rotation by Adding Counter-NBI Affects Most Aspects of Hybrid Plasma Behavior

A detailed example: \( \beta_n = 2.58 \, (2.45), \, n_e = 4.3 \, (4.4) \times 10^{19} \, \text{m}^{-3}, \)
\( q_{95} = 4.6, \, B_T = 1.92 \, \text{T}, \, I_p = 1.20 \, \text{MA}. \)
[() indicates values at low rotation.]

\[
\begin{align*}
t \leq 3.5 \, \text{s}: & \quad P_{co} = 6.4 \, \text{MW} & t \geq 3.5 \, \text{s}: & \quad P_{co} = 5.2 \, \text{MW} \\
& \quad T_{co} = 4.9 \, \text{N-m} & & \quad T_{co} = 4.2 \, \text{N-m} \\
& & & & \quad P_{ctr} = 4.2 \, \text{MW} \\
& & & & \quad T_{ctr} = -3.2 \, \text{N-m} \\
& & & & \quad P_{net} = 9.4 \, \text{MW} \\
& & & & \quad T_{net} = 1.0 \, \text{N-m}
\end{align*}
\]

\( \beta \) is held constant, power needed increases.

\( \beta \) is held constant, confinement decreases.

3/2 NTM island width increases (\( q = 3/2 \) surface does not move)

NTM frequency decreases
Even with a significant reduction in rotation, there are only small changes in the kinetic profiles. (In part this is because $\beta_N$ and $n_e$ are under feedback control.) (profiles averaged 2.99-3.48 s and 4.05-5.72 s)

The changes in the $J$ and $q$ profiles are also small, consistent with the broader deposition profile of the counter-NBI.

The relative change in the NBCD profile is large. The profile is much flatter (broader) and the total NBCD is reduced. However this affects only a small fraction of the total current.
The large change in torque leads to a reduction in rotation (which becomes negative near the edge), and in the shearing rate of the ExB velocity.

Electron and ion thermal diffusivities increase (by about a factor of 2), as does the momentum diffusivity.
The low rotation hybrids still meet ITER requirements, even with somewhat reduced performance.

- Compare similar discharges with $\beta_N = 2.7$, $q_{95} = 3.2$.
- A factor of 3 reduction in central Mach number results in a 20% reduction in $G$.
- $G = 0.46$, exceeding the ITER requirement of 0.42.

Preliminary scaling analysis indicates that $\tau_E \propto \text{torque}^{\sim 1/4}$ best fits both high and low $q_{95}$ data.
GLF23 accurately predicts the ion and electron temperature profiles at both high and low rotation. At high rotation, GLF23 requires inclusion of ExB flow shear at high rotation. At low rotation, the ExB flow shear makes little difference.

The dependence of confinement parameters on NB torque is consistent over the range $4.0 \leq q_{95} \leq 4.6$.

As the torque is reduced, the amplitude of the 3/2 NTM increases, more rapidly at lower $q_{95}$. 
Our database of DIII-D hybrid plasmas (2000-06) illustrates the systematic dependence of confinement on toroidal rotation.

(The database has 417 discharges with stationary conditions for >1 s; with parameters averages over the stationary period.)

Thus far we have not maintained stationary hybrid performance at zero rotation. Instead, braking due to the residual error field and to the interaction between the 3/2 NTM and the wall leads to locking and the appearance of a static $n = 1$ perturbation.
**Hybrid Discharges Can Have a Dominant m/n = 4/3 NTM Rather Than a 3/2 NTM**

- All hybrid plasmas have some MHD activity. In DIII-D this is usually an m/n = 3/2 NTM. Occasionally we see a hybrid plasma dominated by an m/n = 4/3 mode.
- The 4/3 dominated hybrid plasmas have better confinement than the 3/2 dominated plasmas, and meet or exceed the ITER requirement for $G = \beta_N H_{99}/q_{95}^2$.
- Compared to the 3/2 NTM dominated cases, the 4/3 NTM has a weaker effect on plasma profiles.
- This would be the preferred operating mode except for the observation that, as $\beta_N$ is increased the 4/3

- 3/2 and 4/3 modes coexist only transiently.
- Discharges with a 4/3 NTM have an ~25% higher $H_{99}$ factor.
- They also have $q_{\text{min}} < 1$ and sawteeth, indicating a weaker modification of the current profile.

- Direct analysis of MSE data yields the pressure and pressure-driven current profiles. 
- Flattening of $p(\rho)$ by the 3/2 mode reduces confinement. The Chang-Callen belt model gives an ~8% reduction.
- Little or no flattening is seen in the 4/3 mode dominated case.
- This analysis shows the “missing” bootstrap current associated with the pressure profile flattening.

With the 4/3 NTM, thermal diffusivities are 
~1/2 the diffusivities obtained with 3/2 NTM, and $\chi_i$ is close to $\chi_{\text{neoclassical}}$.

Raising $\beta_N$ above 2.8 leads to a 4/3 $\Rightarrow$ 3/2 NTM transition.
The $m/n = 3/2$ NTM Has Been Shown to Modify the Current Profile in Hybrid Plasmas – What Is The Mechanism?

- Experiments using ECCD to stabilize the 3/2 NTM have shown that the NTM is responsible for broadening the current profile in hybrid plasmas. This is also clear from the differences between 3/2 and 4/3 NTM dominated plasmas.
- This effect leads to much of the improved performance of the hybrid. The cost to confinement of the presence of an island structure is more than compensated by the improved stability to $n=1$ modes and by improved confinement in the rest of the plasma.
- While there is as yet no clear answer as to the details of the physical mechanism causing the change in the current profile, we are continuing to examine several possibilities.

- The sum of the calculated current components matches the measured $J_\parallel$, except in the core (inside the $q=3/2$ surface).
- The difference (integrated to the $q=3/2$ surface) is small, ~50 kA.
- The 25-30% decrease in $J(0)$ increases $q_0$ by an equal amount.

- The $3/2$ NTM amplitude is modulated by ELMs.
- This can lead to a poloidal magnetic flux pumping effect (similar to the process whereby sawteeth maintain $q_0 \sim 1$).
- At an ELM, $q$ increases inside the $q=3/2$ surface.

The redistribution of current by the NTM occurs when $q_0$ approaches 1. One explanation for this is related to the global structure of the mode.

- The BES ($\delta n_e$) and ECE ($\delta T_e$) diagnostics shows the signature of an island structure as expected.
- $\delta T_e \neq 0$ near the axis, but is ~30% of the maximum near the island. Also there is a phase shift of $\sim 2\pi/3$ between the axis and the island.
- This may indicate the presence of the 2/2 component of the 3/2 NTM.

- The sum of the calculated current components matches the measured $J_\parallel$, except in the core (inside the $q=3/2$ surface).
- The difference (integrated to the $q=3/2$ surface) is small, ~50 kA.
- The 25-30% decrease in $J(0)$ increases $q_0$ by an equal amount.

- The 3/2 NTM amplitude is modulated by ELMs.
- This can lead to a poloidal magnetic flux pumping effect (similar to the process whereby sawteeth maintain $q_0 \sim 1$).
- At an ELM, $q$ increases inside the $q=3/2$ surface.

Finally, spatial redistribution of the fast ion population may also play a role in the modification of the current profile in hybrids, through changes in the NBCD profile.

Very recent experiments have been done to address this directly, and we are presently analyzing data from the new FIDA (fast ion D $\alpha$) diagnostic to determine whether such changes occur.