Report on ITER-relevant Scenario Experiments on DIII-D

Presented by
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What’s Here, What’s Not

• Talk tries to cover DIII-D experiments of interest to ITER and potential future joint experiments from the last run (May-Sept.)
  – Steady-state scenario with off-axis NBI
  – Advanced inductive with low or no external torque input
  – QH mode with no external torque source
  – Divertor characterization
  – Closed-loop demonstration of current profile control with a physics-based model

• Plans for Oct. run will be shown
  – Plans for 2012 very uncertain at this point

• Most, if not all, of the results directly in support of joint experiments will be reported through the joint experiment spokespersons
Steady State Scenario Work Focused on $\min(q)>2$ with Off-axis NBI

- Previous attempts to probe the $\beta$ limit with $\min(q)>2$ found central co-NBI overdrove the central current at the powers needed
  - Insufficient power at higher $B$

- Theoretical and experimental studies indicated higher $\beta$ limits when the pressure and current profiles were broader

- Both considerations motivated modifying 1 beamline in DIII-D to tilt vertically to give off-axis NBI
With On-Axis NBI, it is Difficult to Maintain \( \min(q) > 2 \) and Achieve High \( \beta_N \)

2009 Shot

\( \beta_N \) at ideal wall \( n=1 \) limit

Target \( q_{\text{min}} = 2 \) not maintained

\( B_T = 2 \) T, \( H_{89} = 2 \) require all available co-NBI power
Modeling Indicates Only Modest Gain In $\beta$ Limit by Broadening Only the Pressure Profile

- Changed $P$ at fixed $I_p$
- DCON results

<table>
<thead>
<tr>
<th>$P_0/&lt;P&gt;$</th>
<th>3.1</th>
<th>2.74</th>
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<tbody>
<tr>
<td>$\beta N$ n=1 nw</td>
<td>2.59</td>
<td>2.84</td>
</tr>
<tr>
<td>$\beta N$ n=2 nw</td>
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<td>3.41</td>
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<tr>
<td>$\beta N$ n=3 nw</td>
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<td>3.61</td>
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<tr>
<td>$\beta N$ n=1 iw</td>
<td>3.34</td>
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<td>$\beta N$ n=2 iw</td>
<td>3.66</td>
<td>3.93</td>
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<tr>
<td>$\beta N$ n=3 iw</td>
<td>3.8</td>
<td>3.86</td>
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</table>
Modest Improvement in the Calculated $\beta$ Limit by Increasing $\min(q)$ While Holding $\rho_{\min}$ Fixed

- Scaled $q_{\min}$ at fixed Ip
- DCON results

<table>
<thead>
<tr>
<th>$q_{\min}$</th>
<th>1.495</th>
<th>1.95</th>
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<tbody>
<tr>
<td>Ip</td>
<td>1</td>
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<td>0.6</td>
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<td>$\beta_N$ n=1 no-w</td>
<td>3.56</td>
<td>2.59</td>
<td>2.48</td>
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<tr>
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<td>3.64</td>
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<td>$\beta_N$ n=1 ideal</td>
<td>4.35</td>
<td>3.34</td>
<td>3.87</td>
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<tr>
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<td>3.97</td>
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<tr>
<td>$\beta_N$ n=3 ideal</td>
<td>3.90</td>
<td>3.80</td>
<td>4.12</td>
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Broadening J Increases the Calculated $\beta_N$ Limit Significantly

- $\Delta J_{||}$ derived from difference between simulations of NB on-axis and NB off-axis
- Fixed $I_p$

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Experimental Pressure and Current Profiles Are Broader With Off-Axis NBI and More ECCD Power

\[ B_T = 2 \text{T}, \quad q_{95} = 6.8, \quad \text{Matched} \quad \beta_N \approx 2.8 \text{ of 2009 Reference Shot} \]

\[ \beta_N \]

\[ q_0 \quad \& \quad q_{\text{min}} \]

\[ \rho_{q_{\text{min}}} \]

\[ l_i \]

Pressure Peaking
\[ P_0 / \langle P \rangle \]

(Kinetic EFITs)

Time Averaged Profiles in $\beta_N$ flattop:
With central NBI, with off-axis NBI

\[ q \quad \text{and} \quad p \text{ (Pascal/1.5E4)} \]
Density and Electron Temperature Profiles Are Broader With Off-axis NBI

Time Averaged Profiles in $\beta_N$ flattop

Not clear why the density profile is different
Stability Analysis Indicates the Ideal-Wall $n=1 \beta_N$ Limit is Typically Over 4 With Off-axis NBI

- Min($q$)$>2$ easily sustained
- Confinement limits $\beta$ with the available power for this $B$

![Graph showing n=1 ideal stability over time](chart.png)
Recent Experiments Are Pushing Advanced Inductive Regime toward Zero External Torque Input

- Previous results with a co-NBI startup followed by a transition toward more balanced injection showed:
  - Significant degradation of confinement as external torque was reduced
  - Lower limit on external torque set by locked mode

- New approach taken this year to start with zero-torque or low-torque from the beginning
Significant Reduction in Confinement Observed as Torque Is Reduced

- 2/1 NTM invariably encountered at low torque
- Power demand increase ~70% for fixed $\beta_N$ (before 2/1 onset)
- $H_{98}$ reduced from $>1.5$ to approx $1.0$
- Similar to previous results [Politzer NF 2008]
H-mode Startup with ECCD (2 Gyrotrons) Resulted in Stable Al Discharge with Zero Net torque Throughout

- Modest ECH power allowed 2/1 to be reduced sufficiently to allow stable operation at $\beta_N \sim 2.5$
  - Unknown whether additional sources would have suppressed mode completely
  - Unknown whether plasma remains stable if remove ECCD later in discharge
- Sustained for max duration of 210RT beam
- Note, no obvious 3/2 or 4/3 mode present
  - Is this a 2/1 Al plasma?
    - In which case, what happens if actually stabilize 2/1?
Reproduced Low Torque Reference, and with All 6 Gyrotrons, NTM Completely Suppressed

- Slight increase in performance without 2/1 NTM, but largely offset by increased use of EC power
  - Similar $\beta_N$ for similar combined NBI+ECH
\( \beta_N \approx 3.2 \), Approaching ITER \( Q=10 \) Equivalent Achieved with Torque \( \approx 1 \) Nm, \( H_{98} \approx 1.1 \), \( G \approx 0.38 \)

- 1 Nm in DIII-D drives approximately the same rotation as ITER beams (30+ Nm)
  - Scaling for moment of inertia and confinement
- \( H_{98} > \approx 1 \)
- Normalized fusion performance, \( G \approx 0.38 \)
  - \( G \approx 0.4 \) is ITER \( Q=10 \) equivalent
Also Achieved Higher Fusion Performance with Net Torque ~0 Nm at Higher Current, $q_{95} \sim 4$

- Torque stepped down from 1 Nm in startup phase back to 0
- $\beta_N \sim 2.7$, $H_{98} \sim 1$, $G \sim 0.32$
High $\beta_N \sim 3$, Torque~1 Nm, H98~1 Achieved Using Central ECH (no q=2 ECCD)

- Previous results needed ECCD at $q=2$ to operate at high beta and low torque
- Most recent results still required EC power, but insensitive to deposition location or heating vs current drive
  - Here, $\rho_{ECH} \sim 0.3$ and configured for heating
QH Mode May Be an ITER-relevant ELM Avoidance Scheme

- QH mode has a saturated (or stationary) edge mode instead of ELMs
  - Observed on all 4 large divertor tokamaks
  - Traditionally observed with ctr-NBI

- Recent results have used the plasma response to non-axisymmetric ($n=3$) magnetic fields to supply the edge rotation in the counter direction believed necessary for QH mode in the absence of external torque input
Neoclassical Torque from 3D Fields Can Replace NBI Torque for QH-mode Access

- Previously, QH-mode required significant NBI torque
  - Minimum pedestal velocity shear necessary for QH-mode, consistent with theory predictions [Burrell et al., PRL (2009)]
- Counter-Ip torque from nonresonant magnetic fields (NRMFs) enables QH-mode in plasmas with zero-net NBI torque [Garofalo et al., NF (2011)]

Path toward QH-mode in self-heated burning regime
Recent Experiments Aimed at Testing ITER-like NBI Torque and External Coils for 3D fields

- C-coil only maintains QH-mode with zero-net NBI torque
- Confinement improves at low NBI torque
- Large counter-rotation obtained with zero-net NBI torque
Divertor Experiments Seek to Validate Basic Scalings and Look for Impact on Pedestal and Core Performance

- For fixed midplane temperature (fixed power flow?), one expects:
  - Divertor target temperature to scale with $1/[R_{\text{target}}]^2$ from basic geometry
  - Divertor target temperature to scale with $1/[L_{||}]^{0.57}$, where $L_{||}$ is the parallel path length from the midplane to the divertor

- BUT, one can turn the argument around and assume fixed divertor temperature and look for the impact on the pedestal and core parameters
Three Basic Shapes used in the Divertor Shaping Experiment

- $R_{TAR} = 1.20$ m, $L_{||} (mid) \approx 40$ m
- $R_{TAR} = 1.21$ m, $L_{||} (mid) \approx 32$ m
- $R_{TAR} = 1.64$ m, $L_{||} (mid) \approx 36$ m
The Base Case for the $R_{\text{TAR}}$ Comparison
Have Similar Plasma Properties

$R_{\text{TAR}} = 1.20\ m$
$f_{\text{EXP}} \approx 3.2$

$R_{\text{TAR}} = 1.67\ m$
$f_{\text{EXP}} \approx 1.8$

IP (MA)
Pinj (MW)
$H_L89$
nped ($10^{20}$)
Tped (eV)

Time (ms)
The Time-averaged Emissivity Along the Outer Divertor Leg is Markedly Different in These Attached Plasmas

\[ \bar{n}_e/n_G \approx 0.35 \]
\[ P_{RAD}/P_{IN} \approx 0.38 \]

\[ \bar{n}_e/n_G \approx 0.38 \]
\[ P_{RAD}/P_{IN} \approx 0.43 \]
Electron Density and Temperature at the Outer Target During H-mode Do Not Show the Expected Behaviors

$$T_{\text{TAR}} \propto \frac{1}{R_{\text{TAR}}^2} \quad n_{\text{TAR}} \propto R_{\text{TAR}}^2$$

Expect $\approx 2\times$ differences
Current Profile Control Has Demonstrated Impressive Closed-Loop Results

- **Primary motivations are:**
  - Feedback control to explore suitability of target current profiles for advanced scenario operation
  - Provide reproducible target conditions to clearly distinguish effects of variations in the high performance phase

- **Two approaches were successfully demonstrated on DIII-D this year**
  - System identification approach will be discussed by Moreau in IOS-6.1 talk
  - Model-based control results discussed here
First-principles Model-based Current Profile Control

• Why Current Profile Control?
  – Effect on steady-state operation, MHD stability and confinement.

• Why Model-based Control?
  – The high dimensionality and nonlinearity of the system dynamics, and the strong coupling between magnetic and kinetic variables, motivate the design of a model-based, multi-variable controller that takes into account the dynamic responses of both magnetic and kinetic profiles to the different actuators.

• Why First-principles Control?
  – The model can be expanded/modified as our system understanding improves. New physics can be easily incorporated into the model.
  – No need for a system identification experiment for each scenario of interest. Model can be more easily adapted to different scenarios.
  – The high dimensionality and nonlinearity of the system can be preserved in the model, overcoming limitations of linearized models.
First-principles Model-based Current Profile Control

- **Our Approach to Control-oriented Modeling:**
  - A first-principle model of current profile evolution in response to auxiliary heating and current drive systems (NBI, ECH, ECCD), line-averaged density and electric field due to induction was developed for an L-mode plasma.

\[
\frac{\partial \psi}{\partial t} = \frac{\eta(T_e)}{\mu_0 \rho_b^2 \hat{F}^2} \frac{1}{\hat{\rho}} \frac{\partial}{\partial \hat{\rho}} \left( \hat{\rho} \hat{F} \hat{G} \hat{H} \frac{\partial \psi}{\partial \hat{\rho}} \right) + R_o \hat{H} \eta(T_e) \left( \hat{J}_{NI} \cdot \frac{\hat{B}}{B_{\phi,o}} \right)
\]

Magnetic diffusion equation

\[
\frac{\partial \psi}{\partial \hat{\rho}} \bigg|_{\hat{\rho}=0} = 0
\]

\[
\frac{\partial \psi}{\partial \hat{\rho}} \bigg|_{\hat{\rho}=1} = -\frac{\mu_o}{2\pi} \frac{R_o}{\hat{G} \bigg|_{\rho=1} \hat{H} \bigg|_{\rho=1}} I(t)
\]

- **Boundary Control**
- **Interior Control**
- **Diffusivity Control**
- **Fueling**
- **Radio Frequency H&CD**
- **Induction**
- **Neutral Beam Injection**

First-principles Model-based Current Profile Control

FBK ON: $1 < t < 1.2$
FBK ON: $1.6 < t < 1.8$
FBK ON: $2.2 < t < 2.7$
FBK ON: $3.2 < t$

Disturbance is artificially introduced at $t=2.2$ sec.
Plans for “October” run period

• DIII-D management identified 3 areas of focus for this 3 week run
  – ITER baseline scenario (especially n=1 tearing stability)
  – QH mode (focus on fusion performance metric and co-NBI startup)
  – Performance extension in steady state scenario with off-axis NBI

• Additional experiments will be done in the following areas
  – Correction of TBM fields with coils
  – Pellet pacing of ELMs
  – Runaway channel control