LONG-PULSE HIGH-PERFORMANCE DISCHARGES IN THE DIII–D TOKAMAK

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The DIII–D team is pursuing research to establish the basis for a high fusion gain steady-state tokamak. This requires simultaneously:

- High fusion power $\propto \beta$
- High bootstrap fraction $\propto \beta_p$
- High fusion gain $\propto \beta \tau_E$

To achieve this on DIII–D at reactor-relevant parameters will require several control tools — density control, pressure control, off-axis non-inductive current drive, and to reach the ultimate performance limits, direct control of MHD instabilities.
OUTLINE — HIGHLIGHTS

- Progress in long-pulse advanced tokamak development since the 1998 IAEA meeting
  - \( \beta_N H_{89} \sim 10 \) for \( 5 \tau_E \)
  - \( \beta_N H_{89} \sim 9 \) for \( 16 \tau_E \)

- Stability
  - Resistive wall modes are the \( \beta \) limiting instability in most discharges with \( q_{\text{min}} \geq 1.5 \)
  - Neoclassical tearing modes limit \( \beta \) in discharges with \( q_{\text{min}} \sim 1 \) and sometimes limit the duration of higher \( q_{\text{min}} \) discharges

- Confinement
  - Local heat diffusivity on high \( q_{\text{min}} \) plasmas similar to that found on conventional sawtoothing H-mode plasmas
  - Electron and ion temperature profiles are well simulated by an ITG model including \( E \times B \) shear

- Current evolution
  - Non-inductive current fraction is 60%–75% in high \( q_{\text{min}} \) discharges
  - Remaining inductive current is peaked off-axis

- Control tools
  - Density and \( \beta \) control demonstrated by operating at \( \beta_N H_{89} \sim 7 \) for \( 6.3 \) s with \( \beta \) at >90% of the 2/1 tearing mode limit
SIGNIFICANT PROGRESS HAS BEEN MADE IN LONG-PULSE HIGH PERFORMANCE

- Open symbols: $q_{\text{min}} \sim 1$
- Filled symbols: $q_{\text{min}} > 1.5$

Large points with numbers are discharges since 1998 IAEA

 ITER Reference

DIII-D Advanced Tokamak Target

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO
ADVANCED TOKAMAK DISCHARGES SEEK TO MAXIMIZE FUSION GAIN AND BOOTSTRAP FRACTION SIMULTANEOUSLY

Open symbols: $q_{\text{min}} \sim 1$
Filled symbols: $q_{\text{min}} > 1.5$

$\beta_p$ (∞Bootstrap Current Fraction)

$\beta_{\tau E}$ (∞Fusion Gain)

$q = 3$ AT Reference shot
$q = 5.5$ AT Discharges

ITER reference shot
Near-term target simulation

ADVANCED TOKAMAK DISCHARGES SEEK TO MAXIMIZE FUSION GAIN AND BOOTSTRAP FRACTION SIMULTANEOUSLY
HIGH NORMALIZED PERFORMANCE (~10)
SUSTAINED FOR 5 $\tau_E$

- $\beta_N \leq 4.7\%$
- $\beta_N H_{89}$
- $q_{min}$, $q(0)$, $f_{bs} \sim 0.5$
- $n = 1$ Mirnov Amplt. (G)
- $n = 1$ Saddle Loop (G) $\times 10$
- $I_p$ (MA) $\times 10$
- $P_{NB}$ (MW)
- $<n_e>$

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Limiting modes have the characteristics of resistive wall modes:

- Onset is at or above the no-wall ideal limit ($\beta_N \geq 4\ell_i$)
- Growth rate consistent with characteristic wall time
- Real frequency (<100 Hz) consistent with wall time, not fluid rotation
CONFINEMENT REMAINS GOOD AT HIGHER $q$

- Neoclassical theory and empirical measurements predict $q^2$ scaling
- One-fluid diffusivity is nearly the same in low $q$ and high $q$ discharges

Drift-wave model simulation gives good agreement with measured profiles
- Model contains ITG, TEM, and ETG with effects of $E \times B$ shear

Graphs showing heat diffusivity and temperature profiles with lines indicating simulation results.
NON-INDUCTIVE CURRENT NEEDS TO BE SUPPLIED AT THE HALF RADIUS FOR STEADY STATE

- $E_{\parallel}$ measured; with assumption of neoclassical conductivity, gives $J_{OH}$
- Edge current drive consistent with bootstrap current calculations
- Central current drive consistent with bootstrap and neutral beam current drive calculations
- ECCD at the half radius will be required for steady-state

![Graph showing current density distribution](image)
FULLY NON-INDUCTIVE OPERATION REQUIRES DENSITY CONTROL AND OFF-AXIS CURRENT DRIVE

- Current evolves to unstable profile at constant pressure

- Density rises steadily at constant pressure without pumping
SHAPE STRONGLY AFFECTS STABILITY LIMIT

Data windowed to $0.75 < \ell_i < 0.85$, $\beta_N > 4\ell_i$

$S \equiv (l/aB) q_{95}$

Optimized Shape

Pumping Shape

S = 5.2

S = 6.7

β

3.0

3.5

4.0

4.5

5.0

5.5

6.0

6.5

7.0

$\beta_N$
DENSITY AND $\beta$ FEEDBACK CONTROL DEMONSTRATED IN ELMING H–MODE

- $\beta$ control by real-time control of NB power
- $\beta > 90\%$ of 2/1 tearing mode limit
- $\beta_{NH89} \sim 7$ for $34\tau_E, 3.4\tau_R$
- Density regulation by pumping and gas puffing
- $q_{min} > 1$
To extend the duration of present high performance discharges and reach fully non-inductive operation requires:

- Understanding stability dependence on shape and $q$  
  Turnbull TH3/6
- Density control
- Current profile of sustainment by off-axis ECCD  
  Prater EX8/1

To reach higher levels of performance requires:

- Active control of resistive wall modes  
  Garofalo EXP3/01