PROGRESS IN MHD STABILITY AND CURRENT DRIVE TOWARDS STEADY-STATE HIGH PERFORMANCE

by
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for
THE DIII-D TEAM

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## DIII–D INTERNATIONAL RESEARCH TEAM

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10/20/01
Progress in MHD Stability and Current Drive Towards Steady-State High Performance\textsuperscript{1} T.S. TAYLOR, DIII-D TEAM, General Atomics — The DIII-D steady-state high performance scenario requires an elevated axial q with weak or negative central shear, which is favorable to local stability, high bootstrap fraction, and reduced transport. Two key research elements of this scenario are MHD stability at high $\beta$ and off-axis current drive. Good progress has been made on stabilization of resistive wall modes (RWM) and neoclassical tearing modes (NTM), the main obstacles to sustaining high $\beta$. Identification of the error field amplification of a marginally stable RWM as the mechanism for the loss of rotation in high $\beta$ plasmas has led to stabilization of the RWM by plasma rotation and an increase in $\beta_N$ to approximately twice the free-boundary limit. In separate discharges, NTMs have been stabilized by feedback-localized electron cyclotron current drive (ECCD), and $\beta$ was increased 20% above the NTM onset value. The efficiency of off-axis ECCD, which at low $\beta$ suffers a reduction due to trapping effects, was found to increase with increasing $\beta_e$ and recover near axial values at $\beta_e = 2\%$, as predicted by theory. Scenario modeling indicates the planned 3.5 MW of ECCD plus existing neutral beam heating can sustain these high bootstrap fraction, high performance scenarios.

\textsuperscript{1}Work supported by the US DOE under Contract DE-AC03-99ER54463.
High normalized beta $\beta_N = \frac{\beta_T}{(I/aB)}$ is required for steady-state high performance.

Stabilization of resistive wall mode by plasma rotation allows reproducible stable operation above $\beta_{\text{nowall}}$, up to $\sim \beta_{\text{ideal wall}}$.

Neoclassical tearing modes are stabilized by active feedback control of the deposition location of electron cyclotron current drive (ECCD).

Modeling shows that 3.5 MW of off-axis electron cyclotron current drive (ECCD) can maintain favorable q-profile for advanced tokamak studies and avoidance of tearing modes.
FOCUS OF DIII–D RESEARCH IS ON ADVANCED TOKAMAK PHYSICS

— Discovering the Ultimate Potential of the Tokamak —

• Innovative concept improvement of the tokamak concept toward
  — High power density
    ★ Improved stability, $\beta_T \uparrow$, $\beta_N \uparrow$
  — Compact (smaller)
    ★ Improved confinement, $\tau \uparrow$, $H \uparrow$
  — Steady state
    ★ High bootstrap fraction $\Rightarrow$ high $\beta_N$
    ★ Current drive and divertor optimization

• A self-consistent optimization of plasma physics through
  — Magnetic geometry (plasma shape and current profile)
  — Plasma profiles (current, pressure, density, rotation, radiation)
  — MHD feedback stabilization

Simultaneously integrated
ULTIMATE POTENTIAL OF THE TOKAMAK
VISION: HIGH BOOTSTRAP FRACTION NCS SCENARIO

- Broad or hollow current profile and broad pressure profile
  - $q_{\text{min}} > 1 \rightarrow$ stability to central modes (ST, NTM, ...) 
  - $q_0, q_{\text{min}} > 1 \rightarrow$ high bootstrap fraction, $f_{\text{BS}}$
  - Low magnetic shear allows high core pressure gradients (ITBs) — second stable access
  - ITB gives good confinement
  - Strong coupling of external modes to wall $\rightarrow$ stabilization of resistive wall mode
  - Well-aligned bootstrap current, edge current (H-mode)

- Promise of exciting new physics in NCS regime, high $q_0, q_{\text{min}}$
  - Key is to maintain profile to investigate physics
  - High $f_{\text{BS}} (\beta_N, \beta_p)$ needed for high $q_0, q_{\text{min}}$

- Building blocks for high performance plasmas represent important and rich scientific challenges
  - Density and impurity control
  - Current profile evolution and control ✔
  - Resistive wall mode stabilization ✔
  - Neoclassical tearing mode stabilization ✔
  - Transport barrier control
  - Pedestal optimization and control
STEADY STATE HIGH PERFORMANCE REQUIRES OPERATION AT HIGH $\beta_N$

$$Q_{ss} = \frac{P_{\text{fus}}}{P_{\text{CD}}} \propto \frac{\gamma_{\text{cur}}}{nq} \frac{\varepsilon_{\text{eff}} \beta_N^2}{(1 - \xi \sqrt{A q} \beta_N)} B^3 a \kappa$$

- High power density $\Rightarrow$ high $\beta_T$
- Large bootstrap fraction $\Rightarrow$ high $\beta_p$
- Steady state $\Rightarrow$ high $\beta_N$

$$\beta_T \beta_p \propto \left( \frac{1 + \kappa^2}{2} \right) \beta_N^2$$
HIGH $\beta_N$ OPERATION REQUIRES PLASMA SHAPING, BROAD PRESSURE PROFILES, AND WALL STABILIZATION

- $\beta_N \equiv \beta_T/(I/aB)$
- $\beta_N \sim 6$ with wall stabilization
- $\beta_N \sim 3$ without wall stabilization

$\beta_T \beta_p = 25 \left( \frac{1 + \kappa^2}{2} \right) \left( \frac{\beta_N}{100} \right)^2$

$f_{BS} = C_{BS} \varepsilon^{1/2} \beta_p$

$P_{FUS} \propto \beta_T^2 B_T^4$

Ideal Stability, $n = 1$, GATO

$\beta_N \sim 6$ with wall stabilization

$\beta_N \sim 3$ without wall stabilization

$P_0 / \langle P \rangle = 2.4$

$P_0 / \langle P \rangle = 4.8$
PROGRESS IN STEADY HIGH PERFORMANCE RELIES ON AVOIDANCE AND CONTROL OF MHD INSTABILITIES

- $\beta_N$ limited by resistive wall modes
  — RWM stabilization
- $q_0 < 1.5$, $\beta_N$ limited by neoclassical tearing modes
  — NTM stabilization
- Duration limited by current profile evolution
  — Profile control
STABILIZATION OF THE RESISTIVE WALL MODE

KEY RESULT
- Plasma pressure is stably maintained above the conventional pressure limit; up to a factor of two above the conventional limit

KEY PHYSICS
- Resistive wall mode is stabilized by plasma rotation
- Identification of "error field amplification" as mechanism for loss of plasma rotation
- Reduction of non-axisymmetric error field $\rightarrow$ continued rotation $\rightarrow$ stable to high pressure
PREVIOUS EXPERIMENTS: DURATION OF HIGH BETA PHASE WITH $\beta_N > \beta_{N\text{no-wall}}$ IS LIMITED BY SLOWING OF PLASMA ROTATION

- Wall stabilization sustained with $\beta_N$ up to $1.4 \times \beta_{N\text{no-wall}}$
- Plasma rotation slows as $\beta_N$ exceeds the no-wall limit
- Resistive wall mode grows when rotation drops below a critical value

![Graph showing plasma beta, no-wall limit, time evolution, and resistive wall mode onset](image)
LOSS OF PLASMA ROTATION IS CAUSED BY AMPLIFICATION OF NON-AXISYMMETRIC ERROR FIELD WHEN $\beta$ EXCEEDS $\beta_{\text{no wall}}$

- Plasma rotation sustained longer with decreasing error field
- Marginally stable RWM can be excited to finite amplitude by resonant, non-axisymmetric "error" field [A.H. Boozer, Phys. Rev. Lett. (2001)]

![Graphs showing error field component at 2/1 surface, plasma rotation at q = 2, and error field component on 2/1 surface](image)
MARGINALLY STABLE PLASMA MODE IS SHOWN BY RESONANT RESPONSE TO APPLIED n = 1 FIELD

- Vacuum response has no phase shift between arrays
- Toroidal phase shift agrees with phase shift predicted for m=3 mode
\[ \beta_N \sim 2\times \beta_N^{\text{no wall}} \text{ IS OBTAINED WITH ACTIVE RWM FEEDBACK} \]

- Optimized error field reduction found with high gain active feedback on RWM
- Same performance is obtained with preprogrammed error correction currents → stabilization is consequence of reduced error field and sustained plasma rotation
BRAKING EXPERIMENT AT DIFFERENT $\beta$ VALUES GIVES EXPERIMENTAL BENCHMARKING OF CALCULATED NO-WALL LIMIT

- Increase error field during discharge

$\beta_N \leq \beta_{N\text{ no wall}}$
- RWM strongly damped
- Rotation sustained
- Stable plasma

$\beta_N > \beta_{N\text{ no wall}}$
- Large amplification of applied error field
- Rotation decreases
- Unstable RWM

- Independent confirmation of $\beta_{N\text{ no wall}}$
- Agreement with ideal stability calculations (GATO)
FUTURE DIRECTIONS FOR STABILIZATION OF THE RESISTIVE WALL MODE

- Stabilization of the resistive wall mode by plasma rotation demonstrates stable operation at $\beta_N > \beta_N^{\text{no wall}}$ is feasible and validates theoretical models.

- Active stabilization with non-axisymmetric coils is calculated to open this high beta regime to plasmas with no rotation.

**VALEN Calculations**

- No Feedback
- Internal $B_p$ sensors
- 12-coil set (internal) with internal $B_p$ sensors

**Growth Rate ($s^{-1}$)**

- Resistive Wall Mode
- Ideal Kink

- $\beta_N - \beta_N^{\text{no wall}}$
- $\beta_{\text{ideal wall}} - \beta_N^{\text{no wall}}$

**Coils Being Installed in DIII–D**
NEOCLASSICAL TEARING MODE STABILIZATION

KEY RESULTS

● m/n = 3/2 neoclassical tearing mode stabilized by active feedback control of the location of electron cyclotron current drive (ECCD)
  — ECCD replaces missing bootstrap current in the island
  — Accurate positioning of EC deposition with respect to the island is required; ~1 cm
  — Rigid plasma shift (or small change in $B_T$) under active feedback control aligns the EC deposition with the island location
  — $\beta$ is increased after NTM stabilization, by approximately 60%
CO-ECCD RADIAILY LOCALIZED AT ISLAND CAN REPLACE THE "MISSING" BOOTSTRAP CURRENT AND COMPLETELY STABILIZE THE NEOCLASSICAL TEARING MODE

\[
\frac{\tau_R}{r} \frac{dw}{dt} = \Delta \dot{r} + \varepsilon^{1/2} \left( \frac{L_q}{L_p} \right) \beta_\theta \left[ \frac{rw}{w^2 + w_d^2} - \frac{rw_{pol}^2}{w^3} - \frac{8qr \delta_{ec}}{\pi^2 w^2} \left( \frac{\eta j_{ec}}{j_{bs}} \right) \right],
\]

- NTM amenable to complete suppression because \( \dot{w} < 0 \) for \( w < w_{pol} \)
- ECCD must be within island
- no effect for \( \Delta R > \delta_{ec} \)

\[
m/n = 3/2 \\
\beta_\theta = 0.9 \\
\Delta \dot{r} = -3 \\
r = 0.36 \text{ m} \\
\varepsilon^{1/2} = 0.5 \\
L_q/L_p = 1.5 \\
w_{pol}/r = 0.05 \\
\delta_{ec}/r = 0.08 \\
\eta_0 = 0.4 \text{ (no mod)} \\
\Delta R/\delta_{ec} = 0
\]
- Execute $\Delta R$ “Blind Search” pattern when mode (3/2 island) amplitude exceeds threshold.
- Move plasma major radius (and island) “rigidly” ($\Delta R_{\text{step}} = 1 \text{ cm}$).
- Detect alignment of ECCD current deposition with island (“sweet spot”) by sufficient change in mode amplitude over the specified “dwell” time (100 ms).
- If mode decays at > threshold rate, continue to dwell. If not, continue search (or “jitter” . . . )
REAL-TIME CONTROL OF MAJOR RADIUS FOR ECCD SUPPRESSION
(m/n = 3/2 NTM, 3 GYROTRONS, 1.5 MW, 3000 TO 4800 ms)

PCS optimization starting from $\Delta R \approx -2$ cm
#106654
Dwell

NTM restrikes on a sawtooth crash

Search

PCS reset at 4500 ms

No PCS optimization #106642

Dwell

Search

PCS reset at 4500 ms

MAJOR RADIUS (m)

n=2 MIRNOV AMPLITUDE (T/s)
OPTIMUM LOCATION OF ECCD IS FOUND
BY SWEEPING TOROIDAL FIELD

- Toroidal field was ramped down to scan ECCD past the island
- Alignment within ±1 cm is required
- \( j_{\text{ECCD}} > j_{\text{BS}} \) is satisfied (TORAY-GA)
  
  - 2 gyrotrons for \( \approx 1 \) MW injected

\( n = 2 \) Mirnov (G)

\( R (\text{cm}) \) of \( 2\Omega_e \)

\( j (\text{A/cm}^2) \)

\( \rho \)

ISLAND

\( w \approx 7 \text{ cm} \)

from ECE radiometer
$\beta_N$ IS INCREASED ~60% FOLLOWING SUPPRESSION OF $m/n = 3/2$ NTM WITH ECCD
CURRENT PROFILE CONTROL: MAINTAIN $q_{\text{min}} > 1.5$
TO AVOID NTM AND EXTEND HIGH PERFORMANCE DURATION

- High performance discharges near DIII–D AT target obtained
  - Duration limited by growth of $m/n = 2/1$ tearing mode
  - Experimental observable: mode grows as $q_{\text{min}}$ approaches 1.5

- $m/n = 2/1$ island appears when $\Delta'$ approaches a pole, near ideal stability limit

- ECCD current drive will be used to maintain $q$-profile
  - ECCD physics model validated; normalized CD efficiency increases with $\beta_e$
  - Modeling indicates 3.5 MW ECCD can keep $q_{\text{min}} > 1.5$ and extend duration of AT discharge
HIGH PERFORMANCE ($\beta_{NH} > 10$), HIGH BOOTSTRAP FRACTION ($f_{BS} > 60\%$) SUSTAINED FOR $\sim 10\ \tau_E$

- Duration limited by growth of $m/n = 2/1$ NTM
- $m/n = 2/1$ growth experimentally correlated with $q_{min} \sim 1.5$
- ECCD will be used to sustain favorable current profile ($q_{min} > 1.5$)
ELECTRON CYCLOTRON CURRENT DRIVE PROVIDES LOCALIZED CURRENT WITH GOOD CONTROL

— Excellent Tool for Profile Control —

- Four 1 MW class gyrotrons available for 2001
- Six gyrotrons planned for 2002
- Radial deposition is controlled by poloidal launch angle and resonance location ($B_T$)
- Independent control of toroidal and poloidal launch angle facilitates science (independent $n ||$ and $\rho$ scans)
  - For 2 gyrotrons in 2001
  - For 4 gyrotrons in 2002
  - Two gyrotrons fixed toroidal, variable poloidal (2001 and 2002)
OFF-AXIS ELECTRON CYCLOTRON CURRENT DRIVE EFFICIENCY INCREASES IN HIGH $\beta$ PLASMAS

- Good agreement between measured efficiency and theory
- Measured efficiency consistent with AT target scenario requirements
MODELING PREDICTS DISTRIBUTED 3.5-MW ECCD CAN SUSTAIN $\beta_N = 4$, $H_{89P} = 3.1$ WITH $f_{BS} = 65\%$ FOR MORE THAN 10 s
High normalized beta $\beta_N = \beta_T/(l/aB)$ is required for steady-state high performance.

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SAME PHYSICS OF ERROR FIELD-RWM INTERACTION OBSERVED FOR PLASMAS WITH $\beta^\text{no wall}_N \sim 4 \ell_i$ OR $\sim 2.4 \ell_i$

- Error field amplification at $\beta_N > 4 \ell_i$ enhances efficiency of magnetic braking of plasma rotation, leading quickly to RWM-induced beta collapse
AT HIGH PRESSURE ($\beta$), THE PLASMA BECOMES UNSTABLE TO A GLOBAL KINK MODE DEFORMING THE PLASMA SURFACE

- Stable plasma with axisymmetric surface
  - Plasma rotation in the presence of a conducting wall

- Unstable plasma with helical surface deformation
  - Deformation is exaggerated about 10 times
APPROACH TO AN IDEAL STABILITY BOUNDARY (POLE IN $\Delta'$) MAY BE AN ONSET MECHANISM FOR NEOCLASSICAL TEARING MODES

- No seed island evident
- $\Delta'$ becomes large prior to onset on $m/n = 2/1$ mode
- Large standard deviation of $\psi_S^{2\mu}\Delta'$ indicates pole

Shot # 98549

Ideal Pole May Cause Tearing Mode Onset