Advanced Tokamak Profile Evolution in DIII–D

by

M. Murakami,(a)

for

M.R. Wade,(a) J.C. DeBoo,(b) C.M. Greenfield,(b) T.C. Luce,(b) M.A. Makowski,(c) C.C. Petty,(b) G.M. Staebler,(b) T.S. Taylor,(b) M.E. Austin,(d) D.R. Baker,(b) R.V. Budny,(c) K.H. Burrell,(b) T.A. Casper,(c) M. Choi,(b) J.R. Ferron,(b) A.M. Garofalo,(f) I.A. Gorelov,(b) R.J. Groebner,(b) R. La Haye,(b) A.W. Hyatt,(b) R.J. Jayakumar,(c) K. Kajiwara,(b) J.E. Kinsey,(g) L.L. Lao,(b) J. Lohr,(b) D. McCune,(e) R.I. Pinsker,(b) P.A. Politzer,(b) R. Prater,(b) H.E. St. John,(b) and W.P. West,(b) and the DIII-D Team

(a) Oak Ridge National Laboratory, Oak Ridge, Tennessee, 37831 USA
(b) General Atomics, P.O. Box 85608, San Diego, California, 92186-5608 USA
(c) Lawrence Livermore National Laboratory, Livermore, California 94551 USA
(d) University of Texas, Austin, Texas
(e) Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543 USA
(f) Columbia University, New York, New York USA
(g) Lehigh University, Bethlehem, Pennsylvania 18015 USA

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ATTRACTIONESS OF ANY FUSION POWER SYSTEMS RELIES ON PROVIDING HIGH POWER DENSITY AND HIGH DUTY FACTOR (OR STEADY STATE)

- Goal of DIII–D Advanced Tokamak (AT) Program: Develop physics basis and plasma control methods needed for steady state, high performance operation

- Steady-state operation requires:
  - Plasma current driven noninductively
  - High bootstrap current fraction ($f_{BS}$)

- Self-consistent solution to achieve simultaneously high performance and high $f_{BS}$ requires:
  - Moderately high $q$
  - High $\beta_N$

- Both experimental experience and simulations suggest that:
  - A relatively small (~10%) amount of current driven at $\rho \sim 0.5$
  - Combined with bootstrap current and NBCD

$\Rightarrow$ steady state current profile compatible with a high $\beta$ equilibrium
RECENT DIII-D EXPERIMENTS HAVE DEMONSTRATED OFF-AXIS ECCD AS AN EFFECTIVE TOOL TO CONTROL THE CURRENT PROFILE IN ADVANCED TOKAMAK OPERATION

- The experiment using off-axis ECCD has demonstrated integrated AT operation, combining:
  - High $\beta$ (> 3%) at high $q$ (q$_{95}$ ~ 5)
  - Good energy confinement ($H_{89}$ ~ 2.4)
  - High noninductive current fraction ($f_{BS}$ ~ 55%, $f_{NI}$ ~ 90%)

- Clear evidence of the effectiveness of off-axis ECCD demonstrated in high $\beta$ plasma with $q_{min}$ > 2
  - Internal transport barrier formed even in the presence of type I ELMs
  - Improvements observed in all transport channels
  - Increased peaking of profiles lead to higher bootstrap current in core

- In a separate experiment, current profile at high $\beta$ has been sustained with $q_{min}$ >1.5
  - Nearly steady-state current and pressure profiles maintained for 1 s
  - Good access to the regime demonstrated where higher $f_{BS}$ possible with higher $\beta_N$
MODELING AND SIMULATION HAVE BECOME ESSENTIAL TOOLS FOR THIS EXPERIMENTAL PROGRAM

- Predictive modeling prior to the experiment based on an existing DIII-D discharge:
  - Used to develop detailed experimental plans
  - Successfully predicted main features of the experiment with delightful surprises
- Simulations allow detailed comparison with theory and experiment
- Predictive modeling indicates that full noninductive sustainment is possible in near future
OUTLINE

• Current profile modification with $q_{\text{min}} > 2$
  
  — ECCD
  
  — Experiment versus Simulation
    • MSE
    • $J_{\text{OH}}$

• Sustainment of current profile with $q_{\text{min}} > 1.5$

• Predictive modeling for full noninductive operation
APPLICATION OF ECCD IN HIGH $\beta$ WITH $q_{\text{min}} > 2$ DISCHARGE RESULTS IN FAVORABLE CHANGES TO CURRENT PROFILE AND TRANSPORT

- Early H-mode used to access high $q_{\text{min}}$

- $\beta_N \approx 2.8$, $H_{89} \approx 2.4$ maintained by NBI feedback

- Robust operation at $\beta_N > \beta_N^{\text{no-wall}} \approx 2.5$ made possible by RWM stabilization

- ECCD causes increase in central magnetic shear

- Both $T_e$ and $T_i$ increases with application of ECCD

S. Allen: LO1.001
C. Greenfield: LO1.002
A. Garofalo: LO1.004
J. Ferron: LO1.004
CURRENT PROFILE MODIFICATION IS DUE TO CURRENT DRIVE RATHER THAN TO HEATING

- **ECH**: Radial launch; Heating only
- **ECCD**: Tangential launch; Heating and CD
- $\beta_N \approx 2.8$ maintained in both cases
- ECCD increases $q_0$ and reduces $q_{\text{min}}$ relative to reference case
- Local transport improves with increases in central $T_e$ and $T_i$ observed with ECCD
MSE MEASUREMENT OF $J_{\phi}$ SHOWS AN INCREASE IN CURRENT AT THE ECCD LOCATION

- Mortional Stark effect spectroscopy to measure magnetic pitch angle ($B_{\text{pol}}/B_{\text{tor}}$)

- At start of ECCD, current profiles are identical

- At 2.7 s
  - $J_{\phi}$ increased at ECCD location
  - Analysis indicates 130 kA ECCD, consistent with CQL3D prediction (120 kA)
  - Normalized CD efficiency consistent with that required for AT target scenario
MODELING AND SIMULATION ARE ESSENTIAL FOR THE EXPERIMENTAL PROGRAM

- TRANSP and ONETWO codes:
  
  **Simulation:** Solve \( J \) \( [B_p(\rho, t) \text{ diffusion equation}] \) with experimental kinetic profile inputs

  **Predictive modeling:** Solve \( J, T_e \) and \( T_i \) equations with experiment-based \( \chi_e \) and \( \chi_i \)

- TRANSP run using the Fusion Grid created by the National Fusion Collaboratory Project

- ECCD/ECH
  
  - Used \( 1.2 \times J_{\text{ECCD(TORAY-GA)}} \)

- NBCD
  
  - Monte-Carlo slowing down with a modest spatial diffusion of beam ions

- Bootstrap current
  
  - Used Hirshman 78 model (Large R/a approx.)
  
  - Underestimate by \( \sim 10\% \) compared with NCLASS and Sauter models
SIMULATIONS SHOW THAT ECCD PREVENTS INWARD CURRENT PENETRATION

- With ECH (no CD), the current peak continued to move in
SIMULATIONS SHOW THAT ECCD PREVENTS INWARD CURRENT PENETRATION

- With ECH (no CD), the current peak continued to move in
- ECCD clearly produced an off-axis peaked $J_\phi$
- Slight shift of the current peak position from the ECCD peak due to bootstrap current at $\rho < 0.35$
SYNTHETIC MSE SIGNALS GENERATED BY THE SIMULATION AGREE WELL WITH EXPERIMENTAL MSE SIGNALS

- Two procedures implemented:
  - Offset calibration adjusted at one early time
  - $E_r(\rho)$ from CER measurement

- Agreement in nearly all channels throughout the discharge

M. Makowski
LOCAL TOROIDAL CURRENT DENSITY PROFILE PREDICTED BY SIMULATION AGREES WELL WITH MSE INFERRED CURRENT PROFILE

- Broad current profile with ECH
LOCAL TOROIDAL CURRENT DENSITY PROFILE PREDICTED BY
SIMULATION AGREES WELL WITH MSE INFERRED CURRENT PROFILE

Local toroidal current density $J_\phi$ (A/cm$^2$)

Midplane major radius, $R$ (m)

Normalized minor radius, $\rho$ (approx.)

- Broad current profile with ECH
- More off-axis peaked with ECCD
LOCAL TOROIDAL CURRENT DENSITY PROFILE PREDICTED BY SIMULATION AGREES WELL WITH MSE INFERRED CURRENT PROFILE

Local toroidal current density $J_\phi$ (A/cm²)

<table>
<thead>
<tr>
<th>Midplane major radius, R (m)</th>
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<tbody>
<tr>
<td>1.6</td>
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<tr>
<td>0</td>
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- Broad current profile with ECH
- More off-axis peaked with ECCD
- The current peak is broader than the ECCD driven current due to:
  - Substantial Phirsch-Schlüter current component which is averaged out in $\langle J_\phi \rangle$
  - Bootstrap current

ECH
ECCD

Simulation
- Tangential MSE
- Radial MSE
- Edge MSE

299-02/MM/JY
**Experimental** $J_{OH}$ from the loop voltage analysis:

$$E_{||} = \frac{d\Psi_{pol}}{dt} \Rightarrow J_{OH} = \sigma_{neo} \cdot E_{||}$$

Although ECCD contribution to total noninductive current is small, its effect on bootstrap current reduces ohmic current to less than ~15%.
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- Experimental $J_{OH}$ from the loop voltage analysis:
  
  $E_{||} = \frac{d\Psi_{pol}}{dt} \Rightarrow J_{OH} = \sigma_{neo} \cdot E_{||}$

- $f_{BS}$ increased by 10% when ECH $\Rightarrow$ ECCD
IMPROVEMENT IN BOOTSTRAP CURRENT ARISES FROM INCREASED PEAKING OF DENSITY AND TEMPERATURE

- Strong NCS triggered a weak internal transport barrier (ITB)
REDUCED TRANSPORT COEFFICIENTS OBSERVED IN ALL TRANSPORT CHANNELS IN CORE

\[ \chi_{i,\text{eff}}(\text{convective + conductive}) \approx \chi_{i,\text{eff}}(\text{neoclassical}) \text{ at } \rho < 0.35 \text{ with ECCD} \]
IN SEPARATE EXPERIMENTS, ECCD HAS BEEN USED TO SUSTAIN A STATIONARY CURRENT DENSITY PROFILE FOR UP TO 1.0 S WITH $q_{\text{min}} > 1.5$

- High power phase delayed until $q_{\text{min}} < 2.0$
- $\beta_N \sim 3.1$, $\beta \sim 3.3\%$, $H_{89} \sim 2.4$
- $q_0 > 2.0$, $q_{\text{min}} < 2.0$ maintained for 1.0 s
- Duration limited by onset of small $m=5/n=3$ NTM
CURRENT PROFILE IS STATIONARY
FOR FIRST SECOND OF ECCD

Direct inference of $J_\phi$ using MSE data

$J_\phi$ (MA/m$^2$)

$q$

Pressure

$J_{ECCD} @ \rho = 0.4$

$\rho = 0$

Normalizes Radius

R (m)

0.0 0.5 1.0 1.5 2.0 2.5

1.60 1.70 1.80 1.90 2.00 2.10 2.20

$10^5$ Pa

0.0 0.5 1.0 1.5

$10^5$ Pa

0.0 0.2 0.4 0.6 0.8 1.0

Normalized Radius
NONINDUCTIVE CURRENT FRACTION OF $\sim 85\%$ WAS OBTAINED IN THE $q_{\text{min}} \geq 1.5$ REGIME

t = 3.75 s

Simulation

Experiment

$A/\text{cm}^2$

Normalized Radius

0.0 0.2 0.4 0.6 0.8 1.0
NONINDUCTIVE CURRENT FRACTION OF \(~85\%\) WAS OBTAINED IN THE \(q_{\text{min}} \gtrsim 1.5\) REGIME

\[ f_{\text{NI}} \quad \text{(exp)} \]

Noninductive Current Fractions

- Simulation
- Experiment
- ECCD + NBCD + Bootstrap
- Hirshman 78 Model
- ECCD + NBCD
- ECCD

Normalized Radius

\[ t = 3.75 \text{ s} \]

A/cm²

Time (s)

DIII-D
NATIONAL FUSION FACILITY
DISCHARGE WITH $\beta_N \sim 4$ HAS BEEN OBTAINED WITH NBI IN THE $q_{\text{min}} \sim 1.5$ REGIME

- $\beta_N \sim 4$
- $\beta_N H_{89} > 10$ for $4\tau_E$
- Minimal MHD activity
- Small RWM amplitude due to sustained plasma rotation
PREDICTIVE MODELING BASED ON ONE OF THE HIGH $\beta_N$ TARGET DISCHARGES WITH $q_{\text{min}} \sim 1.5$ INDICATES THAT THE FAVORABLE CURRENT PROFILE CAN BE MAINTAINED INDEFINITELY

- Assumed a broadly distributed off-axis ECCD at $P_{\text{EC}} = 3.5$ MW
- Sustaining this high $\beta_N$ value requires reliable RWM stabilization which we are still developing
PREDICTIVE MODELING SHOWS THAT THE EXISTING $q_{min} > 1.5$ ECCD DISCHARGE CAN BE EXTENDED TO FULL NONINDUCTIVITY USING THE HARDWARE CAPABILITIES AVAILABLE IN THE NEAR TERM.

- Estimated power requirements are conservative: $H98y2$ scaling power degradation ($\chi \propto \chi_{exp} \cdot P^{0.69}$); kinetic (not magnetic) $\beta_N$; and bootstrap model.

- The DIII-D ECCD capability expected in 2003 includes 4 s ($> \tau_{CR}$) of ECCD at $P_E \sim 2.5$ MW.

J. Lohr: LO1.006
SUMMARY

- Current profile at high $\beta$ has been modified using off-axis ECCD with $q_{\text{min}} > 2$
  - Strong negative central shear produced
  - Improvements observed in all transport channels
  - $f_{\text{BS}} \sim 55\%$; $f_{\text{NI}} \sim 90\%$ achieved; higher values limited by attainable $\beta_N$

- Current profile at high $\beta$ has been sustained with $q_{\text{min}} > 1.5$
  - Nearly steady-state current and pressure profiles maintained for 1 s
  - Good access to the regime demonstrated where higher $f_{\text{BS}}$ possible with higher $\beta_N$

- Predictive modeling validated for full noninductive operation with $q_{\text{min}} > 1.5$ using near-term hardware capabilities
THE CORE REGION OF THE ECCD DISCHARGE MAY BE LIMITED BY RESISTIVE INTERCHANGE MODES

- GKS $\Rightarrow a/L_{\parallel}(\text{exp})$ limited by $a/L_{\parallel}(\text{ITG})$ in the ECH case
- Stronger NCS, $\alpha$-stabilization (and ExB shear) stabilize ITG in the ECCD discharge
- Why not $a/L_{\parallel}(\text{exp})$ goes up as high as $a/L_{\parallel}(\text{ITG})$?
- Resistive interchange modes are found to be unstable in core ($\rho = 0.15 - 0.41$) with ECCD, as shown by $D_R > 0$ there
  - Some bursts observed in Mirnov signals
- Since GKS code uses the ballooning representation, the code calculation in this region is invalid
- We also note that $\chi_i^{\text{eff}}(\text{exp}) \sim \chi_i^{\text{eff}}(\text{neo})$ in region $\rho < 0.35$ for the ECCD case
ATTAINABLE $\beta_N$ OBSERVED TO DECREASE AS $q_{\text{min}}$ INCREASES

- So far, $\beta_N = 3.5 - 4.0$ possible with $q_{\text{min}} < 2$

- Robust operation above no-wall, ideal $n = 1$ limit made possible by RWM stabilization

- Stability calculations $\Rightarrow$ with suitable broad pressure profiles and RWM stabilization, higher $\beta_N$ may be possible with $q_{\text{min}} > 2$

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**Graph:**
- Maximum experimental $\beta_N$
- ECCD Cases
- Measured no-wall $\beta$-limit

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J. Ferron: LO1.005  
A. Garofalo: LO1.004