Progress Toward Fully Noninductive, High Beta Conditions in DIII-D

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DIII–D AT Experiments Have Demonstrated Performance Required for an ITER Steady State Scenario

- DIII-D AT program goal: develop the scientific basis for steady state, high performance operation of fusion reactors
- Need to simultaneously achieve two goals:
  1) Steady-state:
     - 100% noninductive
     - High bootstrap current fraction $f_{BS}$
  2) High performance: Maintaining sufficient fusion gain with reduced engineering parameters:
     - high $\beta_T$
     - high $\tau_E$
     \[ \Rightarrow \text{High Normalized fusion performance } G = \beta_N H / q^2 \]
- Growing numbers of DIII-D discharges simultaneously achieved $f_{NI} \approx 100\%$ and $G \approx 0.3$
100% Noninductively Driven Plasmas Obtained With Good Current Drive Alignment

- Demonstrated ‘in-principle’ steady state condition at high $\beta$
- Inductive current is locally & globally close to zero $\Rightarrow$ good CD alignment
- $f_{\text{ind}} = 0.5\%$, $f_{\text{NI}} = 99.5\%$
- $\beta_T = 3.5\%$, $\beta_N = 3.6$, $q_{95} = 5.0$
- $G = \beta_N H_{89}/q_{95}^2 = 0.3$
Outline

- **Characteristics of full noninductive (NI), high performance discharges:**
  - Analysis of 100% NI discharge:
    - Measurements, analysis, simulation for validation of the models
    - MHD stability
    - Stationarity
  - How are fully NI, high beta conditions achieved?
    - Choice of operational parameters
    - choice of electron density
    - CD alignment
  - Validation of the modeling (GLF23)

- **Modeling applied to predictive simulations:**
  - DIII-D with upgrade capabilities
  - ITER steady state AT scenario

- **Conclusions**
Where We Were in 2003: 100% Noninductive Current Achieved, but Not Relaxed

- Motivated by modeling based on a $f_{NI}=90\%$ discharge in 2002, we increased $P_{NB}$
- $f_{NI} \approx 100 \%$ with $\beta_N \approx 3.5$, $\beta \approx 3.6\%$
- Locally inductive current is NOT zero
- Neutral beam overdrive near the axis decreases $q_0$, resulting in NTMs
- These discharges had:
  - Somewhat degraded confinement
  - Rotation velocity often slower
Several Improvements Made During 2004 Campaign Led to Confinement Improvement

- Error field control improved
- Early $\beta$ feedback
- Improved reproducibility of $q(\rho)$
- Restored $H_{89} = 2.4$

**ITER SS target:** $G = 0.3$

- $T_i(\rho \sim 0.1) (\text{keV})$
- $T_e(\rho \sim 0.27)$
- $V_i(0)$
- $V_i(\alpha)$

- $f_{NI} = 100\%$
- $N_e (10^{19} \text{m}^{-3})$
- $H_{89}$
With Improved Confinement, $f_{ni}=100\%$ Achieved with Good CD Alignment

- Equilibrium measurement: $J_{OH} = \sigma_{neo} E_{||} \propto \sigma_{neo} \partial \Psi_{pol} / \partial t \Rightarrow f_{NI} = 1 - f_{OH}$
- $f_{ind} = 0.5\%, \ f_{NI} = 99.5\%$
Transport Code Carries Out Data Analysis Based on Equilibrium Reconstruction with Kinetic Profile Information

- Measurements: $f_{\text{ind}} = 0.5\%$, $f_{\text{NI}} = 99.5\%$
- Analysis shows: $f_{\text{BS}} = 59\%$, $f_{\text{NB}} = 31\%$, $f_{\text{EC}} = 8\%$, $f_{\text{NI}} = 98\%$
- Equilibrium reconstruction (EFIT) lacks spatial resolution
  ⇒ Makes the current balance calculations difficult
Current Evolution Simulation Using Transport Code Allows Equilibrium with Sufficient Spatial Resolution Using Current Drive Models

- Measurement: $f_{\text{ind}} = 0.5\%$, $f_{\text{NI}} = 99.5\%$
- Analysis: $f_{\text{BS}} = 59\%$, $f_{\text{NB}} = 31\%$, $f_{\text{EC}} = 8\%$, $f_{\text{NI}} = 98\%$
- Simulation shows: $f_{\text{BS}} = 54\%$, $f_{\text{NB}} = 32\%$, $f_{\text{EC}} = 8\%$, $f_{\text{NI}} = 94\%$
- How do we resolve the discrepancy of $J_{\text{ind}}(r)$ between the measurement and the simulation?
  - NBCD model
  - Bootstrap current model
Recent Fast Ion Diagnostic Data Suggests Beam Ion Redistribution in the Core

- Anomalous beam ion diffusion $\Rightarrow$ Flatter $J_{\text{NBCD}}(\rho)$

Y. Lou, CP 1.003
The Discrepancy of the Inductive Current Between the Simulation and Measurement Can be Reduced by Redistribution of Beam Ions

- **Measurement:** \( f_{\text{OH}} = 0.5\% \), \( f_{\text{NI}} = 99.5\% \)
- **Analysis:** \( f_{\text{BS}} = 59\% \), \( f_{\text{NB}} = 31\% \), \( f_{\text{EC}} = 8\% \), \( f_{\text{NI}} = 98\% \)
- **Simulation:** \( f_{\text{BS}} = 54\% \), \( f_{\text{NB}} = 32\% \), \( f_{\text{EC}} = 8\% \), \( f_{\text{NI}} = 94\% \)
- **Anomalous beam ion diffusion** \( \Rightarrow \) Flatter \( J_{\text{NBCD}}(\rho) \)
- **Other possible explanation:** Inaccuracy in bootstrap current models
  - Sauter and NCLASS \( \Rightarrow \pm 5\% \) in local and integrated values
  \( \Rightarrow \) Good CD alignment demonstrated
Pressure Evolution Resulted In n=1 Fast Growing Mode Which Triggered n=1 NTM

- Plasma at ideal wall limit to n=1
- Low ideal stability limit due to pressure peaking (primarily density peaking)
- Even with $\beta_N$ near the ideal-wall limit, the high beta phase almost always ends as a result of a tearing mode
Nearly Full Noninductive, Stationary Discharge Limited Only by Gyrotron Pulse Length

- MSE signals stationary
  \[ J_\phi(\rho) \] stopped evolving
- \( f_{NI} \approx 90\% \) for 1 \( \tau_{CR} \) (=1.8 s)
- \( \beta_T = 3.7\%, \ \beta_N = 3.5, \ q_{95} = 5.1 \)
- \( G = \beta_N H/q^2 = 0.3 \) with \( f_{BS} = 63\% \)
Noninductive Conditions Have Been Sustained up to One Current Relaxation Time With 60% Bootstrap Fraction

- Profile database based on TRANSP time-dependent profile analysis
- Typical $\tau_{\text{CR}} \approx 2$ s in these discharges
Global Parameter Database Suggests Noninductive Conditions Favor High $\beta_N$

- **Global database:**
  $\approx$160 shots selected with $\tau_{dur}(\beta_N>0.85\beta_N^{max})>5\tau_E$ or $>0.7s$, $\beta_N>2$, $H_{89}>2$, ...

- **Average noninductive fraction:** $\langle f_{NI}\rangle = 1 - \langle V_{surf}\rangle/\langle R \rangle/Ip$

- **Achieving NI conditions at higher $q_{95}$ substantially compromises fusion performance, $G=\beta_N H_{89}/q_{95}^2$
Noninductive Current is Maximized at Lower Density

- $f_{NI}$ decreases with density
- $f_{BS}$ increases with density, but more slowly than $f_{NB}$ and $f_{EC}$ decrease
- CD alignment figure of merit: $\xi_{tot} = 1 - \frac{\int (n_e/T_e) |J_{OH}| dA}{\int (n_e/T_e) |J_{tot}| dA}$
- CD alignment improves with decreasing density
Glfc3/ONETWO Can Reproduce Experimental Profiles Reasonably Well

- Experimental data chosen in stationary phase independent of ELM timing
- Solve \((T_e, T_i, \Omega_{\text{tor}})\) equations with a fixed \(n_e(r)\) using GLF23 model
- Simulation tends to overestimate \(\Omega_{\text{tor}}\) in the core.
- Simulation without ExB shear stabilization indicates importance with rotation
GLF23 Model Indicates that the Noninductive Current Fraction Increases with Decreasing Density

- GLF23 simulation based on single-null discharge with $f_{NI} \approx 90\%$
  - Trends reproduced well
  - Validate the model
- Similar dependencies found for higher density double-null discharges
- $f_{NI}$ increase with peaked density profile consistent with pumping
- Balanced DN discharge shape increases the ideal, low-n beta limit
Upcoming Work in DIII-D will Allow Noninductive Operation with Optimized Current Profiles at High Beta

- Modeling shows the impact of hardware improvements carried out in DIII-D:
  - Better control of $J(\rho)$ and $p(\rho)$ at high beta with more EC and FW power with long duration
  - Co- and Counter-beams CD/heating inputs and to control momentum
  - DND with pumping for higher $\beta_N$
Density Scan Simulation for ITER with Day-1 H/CD Capabilities Finds $f_{NI} \approx 100\%$, $Q \approx 5$ and $f_{bs} \approx 75\%$ at $N_{GW} \approx 1$

- Simulation carried out with 100-s time-stepping simulations of $(T_e, T_i, \Omega_{rot}, j, \text{equilibrium})$ with a fixed $n_e(\rho)$ shape using GLF23 model

- A few more iterations of the time-stepping simulations are needed for more relaxed internal loop voltage

GLF23/ONETWO
\begin{align*}
B_T &= 5.3 \text{ T} \\
I_p &= 9 \text{ MA} \\
q_{95} &= 5 \\
P_{NB} &= 33 \text{ MW} \\
P_{IC} &= 20 \text{ MW} \\
P_{EC} &= 20 \text{ MW}
\end{align*}
GLF23/ONETWO Modeling for ITER
Steady State Scenario

- Beta value where the boundary conditions imposed ($\rho=0.9$) on the simulation is only slightly above the DIII-D case (1.3% vs. 1.0 %)
- A larger pedestal width is assumed, as observed in the experiment, gives bigger stability margin for peeling-ballooning mode
Conclusions

- 100% noninductively driven plasmas obtained with good CD alignment at $\beta_T \leq 3.6\%$, $\beta_N \leq 3.5$ and $H_{89} = 2.4$; duration was limited by pressure profile evolution to unstable MHD for $0.5 \tau_{CR}$.
  - Validated the current balance calculation
- Nearly (~90%) noninductive, stationary discharges were sustained for 1 $\tau_{CR}$, only limited by present hardware limits
- These experiments have achieved normalized fusion performance $G=0.3$ and $f_{BS}=60\%$, consistent with requirements for the ITER $Q=5$ steady state scenario
- With good coupling between experiment and modeling, progress has been made in several important areas:
  - Current drive alignment
  - Optimization and density for noninductive operation
Conclusions (continued)

- Future plans of DIII-D include exploring stability boundaries using more EC and FW power with long duration, double-null divertor with pumping and co + counter NBI
- Modeling tools that were successfully employed to devise experiments in DIII-D, when applied to ITER, indicate full noninductive operation is plausible for steady state operation with $Q \approx 5$

⇒ The scientific basis being developed on DIII-D is leading to increased confidence in establishing steady state scenarios for ITER and beyond