Progress Toward Fully Noninductive Discharge Operation in DIII-D Using Off-Axis Neutral Beam Injection

by

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The Need for Economical Fusion Power Motivates Steady-state Tokamak Operation at High Plasma Pressure

- Steady-state: 100% of the current driven noninductively, $f_{NI} = 1$

- Large bootstrap current fraction $f_{BS} \propto q_{95} \beta_N$
  - Minimize the external current drive power

- High fusion gain
  $\sim \beta_N H / q_{95}^2$

High pressure ($\beta_N$)
Future Steady-state Devices are Envisioned at Increasing Values of $\beta_N$

The DIII-D program aims to establish the physics basis for steady-state operation at $\beta_N = 5$
Broad Pressure Profiles Lead to MHD Stability at High $\beta_N$

- Low-n, ideal-wall $\beta_N$ stability limit increases with pressure profile width
Broad Current Profiles Also Improve MHD Stability at High $\beta_N$

Modeling study

- Increased off-axis current

- Better coupling to the wall for improved wall stabilization
- Increased $q_{\text{min}}$ (for fixed $q_{95}$)

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

Off-Axis Neutral Beam Injection Is Enabling Improved Access to Fully Noninductive Plasma Regimes

Experimental results

- Broader current profile: improved access to $q_{\text{min}}$ above 2
- Broader pressure profiles with $\beta_N$ up to 3.3
  increase of calculated ideal MHD stability limits: $\beta_N > 4$
- Thermal confinement as expected for H-mode;
  total pressure limited by enhanced fast ion transport at high $q_{\text{min}}$

Models of next step parameter regimes for DIII-D

- Fully noninductive solutions at $\beta_N = 4-5$, $q_{\text{min}} > 2$:
  parameter regime relevant to ITER through DEMO
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One DIII-D Beamline has been Modified for Downward Vertical Steering to Provide Substantial Off-axis Current Drive

- Beamline Tilt: 0-16.4°
- Maximum total co-injected power: 14.1 MW
- Maximum off-axis injected power: 5 MW

Beam into plasma D_α image at maximum tilt angle verifies injection geometry.
Measured Off-axis NBCD In Low $\beta_N$ Discharges Is Consistent with Classical Modeling

- $\beta_N = 1.5$, H-mode discharge with no coherent MHD
- Clear hollow NBCD profile
- Peak NBCD at $\rho \sim 0.5$
- Good agreement with modeling with $\beta_N$ up to 2.3

J.M. Park IAEA 2012, EX/P2-13
With Off-axis Injection, the Current Profile is Stationary for Twice the Current Relaxation Time at $q_{\text{min}}=1.5$

- Reduced $J_{\text{NBCD}}(0)$, low $J_{\text{ohmic}}$
- Does not evolve to sawtooth or $n=1$ tearing mode unstable profiles for $2\tau_R$, unlike with only on-axis NBI
- $\beta_N \frac{H_{89}}{q_{95}}^2 = 0.3$ sufficient for ITER steady-state mission
With Off-Axis Injection, $q_{\text{min}}$ can be Maintained Above 2

- Current density shifts outward as $q_{\text{min}}$ increases
- Pressure profile broadens
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- Pressure profile broadens

\( \beta_N \)

\( q_{\text{min}} \)

\( q_{95}=6.8 \)  

\( \rho \), normalized radius

\( J_\phi \) (A/cm\(^2\))

\( \rho \), normalized radius

\( \text{Pressure (10}^5 \text{ Pa)} \)

\( \text{Time (s)} \)
Experimental results
✓ Broader current profile:
improved access to $q_{\text{min}}$ above 2
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The Thermal Pressure Profile Broadens with Increasing $q_{\text{min}}$

- $T_e$ profile broadens with increasing $q_{\text{min}}$
- Also broadening of $T_i$ and $n_e$ profiles

$\beta_N = 2.7$
$q_{95} = 6.8$
$B_T = 2 \, T$

$\rho$, Normalized radius

$q$, Safety factor

$T_e$ (keV)

Thermal pressure ($10^5 \, \text{Pa}$)

With off-axis beams

On-axis beams only

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$\rho_d$, Normalized radius

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With off-axis beams

Pressure Peaking Factor

$f_{\text{pth}} = P_{\text{th}}(0)/\langle P_{\text{th}} \rangle$
Off-Axis Injection Results in a Broader Calculated Fast Ion Pressure Profile

- Two otherwise identical discharges
  - One has 45% beam power off-axis
- $q_{\text{min}} = 1.1$
Off-Axis Injection Results in a Broader Calculated Fast Ion Pressure Profile

- Two otherwise identical discharges
  - One has 45% beam power off-axis
- $q_{\text{min}} = 1.1$
- Computed fast ion stored energy plus measured thermal energy exceeds value from equilibrium reconstruction
  - Fast ion diffusion ($D_f$) added to model
  - Diffusion probably not the completely correct model; introduces uncertainty
Discharges with off-Axis Beam Injection and $q_{\text{min}} > 2$ Have the Lowest Pressure Peaking Factors

At fixed $q_{\text{min}}$, discharges with off-axis injection have the least peaked pressure profiles.

- With off-axis beams
- On-axis only

**Graph Details:**
- $f_p = P(0)/\langle P \rangle$
- $2.9 < \beta_N < 3.9$
- $4.5 < q_{95} < 6.8$
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Broader Pressure Profiles Combined with Increased Off-axis Current at High $q_{\text{min}}$ Result in Higher Calculated $\beta_N$ Limits

- At $q_{\text{min}} > 2$, current density peaked off-axis couples to the conducting wall to improve stability
- Ideal MHD, low-n $\beta_N$ limit with wall stabilization included
- Many time slices per shot

![Diagram showing calculated ideal-wall, n=1 $\beta_N$ limit with varying $\ell_i$, Internal inductance and Broader Current Profile.](image)
At $q_{\text{min}} > 2$, the Maximum Achieved $\beta_N \approx 3.3$ is Limited by the Available Power, Not Stability

- No ideal modes
- Tearing modes
  - No 2/1
  - 3/1 avoided by optimizing discharge evolution
  - 7/2 & 5/2 reduce $\tau_E$ by $\sim 15\%$ when present
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- Fully noninductive solutions at $\beta_N = 4-5$, $q_{\text{min}} > 2$; parameter regime relevant to ITER through DEMO
Steady-State Scenario Discharges Have Thermal Confinement Above the Level Expected for a Typical H-Mode

- No systematic decrease observed with off-axis injection or as $q_{\text{min}}$ increases

![Graph showing thermal confinement factor vs. $q_{\text{min}}$]
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\[ \frac{W_{\text{th}}}{\text{Heating power}} \times \frac{1}{\tau_{98}} \approx h_{98} \]

Entire database
$2.7 < \beta_N < 3.9$, $4.5 < q_{95} < 6.8$
Highest $q_{\text{min}}$ Plasmas Have Global (Thermal+Fast Ion) Confinement Below the Typical H-mode Level

- Implies increased fast ion transport as $q_{\text{min}}$ increases
  - Because thermal confinement shows no $q_{\text{min}}$ scaling

\[ q_{95} \approx 6.8, \beta_N \approx 2.7 \]

![Graph showing confinement factor vs. $q_{\text{min}}$](image)
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Global H-mode Confinement Factor

$$H_{89} = \frac{\tau_E}{\tau_{89}}$$

On-axis only
Typical H-mode level
Off-axis beams

A Change in Beam Injection Location to Off-axis Accounts for Only a Small Reduction in Confinement

- Discharges with equal $\beta_N$, $q_{\text{min}} \approx 1.1$
- Discharge with off-axis injection requires 13% more neutral beam power
  - $\tau_E$ reduced by 10% (including $P_{\text{ECCD}}$)
  - $H_{89} (\approx 2.3) \propto \tau_E \sqrt{P}$ reduced by 5%
- Injection in region with higher $\chi_e, \chi_i$ closer to the boundary
Increased Fast Ion Loss at High $q_{\text{min}}$ May be a Result of Increased Fluctuation Power in the Alfvén Eigenmode Frequency Range

- Calculated fast ion stored energy fraction increases with $q_{\text{min}} \Rightarrow$ instability drive
- Fluctuation power in Alfvén Eigenmode frequency range generally increases with $q_{\text{min}}$

\[ \frac{W_{\text{fast ion}}}{W}, \quad D_f = 0 \]

\[ \frac{\bar{n}}{W} \quad \text{average power} \quad f > f_{\text{TAE}} \]

\[ \frac{(\text{NBI power})}{\text{Max}(\text{NBI power})} \]

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Models of next step parameter regimes for DIII-D
- **Fully noninductive solutions at $\beta_N = 4-5$, $q_{\text{min}} > 2$:**
  parameter regime relevant to ITER through DEMO
At a Steady-State Operating Point, the Heating and Current Drive Input Powers Balance Transport and Collisional Losses

- Heating power
- Current drive power

Optimally equal

Pressure (Stability limited)

Transport

Bootstrap current

Plasma Current $\propto B_T/q_{95}$

Collisions

- Goal: find externally selectable parameters so that $f_{NI}$ is exactly 1
- $\beta_N$, $q_{95}$, $B_T$, $n$, external current drive profile
Extrapolation from DIII-D Steady-state Scenario Discharges Allows Scaling to $f_{NI} = 1$ without use of a Transport Model

- $H_{98}$ confinement scaling $\Rightarrow$ pressure
- Current sources from fits of the database to theory-based models
- Typical experimental profile shapes reflected in fitting coefficients
- Inputs $f_p$, $H_{98}$, $Z_{eff}$ chosen to match the database

\[
 f_{BS} = \beta_{Nthermal} (Aq_{core}f_{pi}^B + Cq_{95}f_{po}^D)
\]

$q_{core} = \text{average } q(0.0 < \rho < 0.3)$
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$$f_{NBCD} \propto P_B \frac{T_e}{n_e} \frac{q_{95}}{B_T} f(T_e, n_e, Z_{eff}, E_B, \text{geometry,} \ldots)$$

$$f_{ECCD} \propto P_{EC} \frac{T_e}{n_e} \frac{q_{95}}{B_T} f(\text{geometry})$$
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$$f_{NI} = f_{BS} + f_{NBCD} + f_{ECCD}$$
At the $f_{NI} = 1$ Operating Point, the Current Drive Input Power Exactly Matches the Losses Resulting from Transport

- $\beta_N$ scanned to find $f_{NI} = 1$

\[ n_e = 4.7 \times 10^{19} \text{ m}^{-3} \quad B_T = 1.75 \text{T} \quad H_{98} = 1.2 \quad q_{95} = 5.75 \]
At the $f_{NI} = 1$ Operating Point, the Current Drive Input Power Exactly Matches the Losses Resulting from Transport

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At the $f_{NI} = 1$ Operating Point, the Current Drive Input Power Exactly Matches the Losses Resulting from Transport

- $\beta_N$ scanned to find $f_{NI} = 1$
- Constraint: $P_{heating} = P_{CD}$

- $f_{BS} \approx f_{CD} \approx 0.5$
- $f_{BS}$ scales more slowly than $\beta_N$
- Increase in fast ion stored energy with $P_B$

$n_e = 4.7 \times 10^{19} \text{ m}^{-3}$  $B_T = 1.75 \text{T}$  $H_{98} = 1.2$  $q_{95} = 5.75$
Projected $f_{\text{Ni}} = 1$ Operating Points in DIII-D have $\beta_N > 4$

- $q_{\text{core}}$ increases with off-axis injection

\[ q_{\text{core}} \text{ (off-axis)} = 5 \text{ MW} \]

\[ q_{\text{core}} \text{ (0 MW)} \]

\[ \beta_N \]

\[ n_e = 4.7 \times 10^{19} \text{ m}^{-3} \]

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Projected $f_{NI} = 1$ Operating Points in DIII-D have $\beta_n > 4$

- Compromise between reduced current drive power and increased fusion gain to choose $q_{95}$

$n_e = 4.7 \times 10^{19} \text{ m}^{-3}$

$B_T = 1.75 \text{ T}$

$H_{98} = 1.2$
An MHD Stable Solution at $\beta_N = 5$ is Projected with Optimum use of the Full Set of DIII-D Heating and Current Drive Tools

- **TGLF transport model $\Rightarrow T_e, T_i$ profiles**
  - Accounts for $P(0)/\langle P \rangle$ changes with heating power

- **Utilizes increased current drive flexibility from proposed upgrades**
  - 9 MW ECCD absorbed power
  - Second off-axis beamline
  - Beam energy 75-100 keV

- **Off-axis ECCD, off-axis beam injection provides current drive for large $\rho(q_{min})$**
  - Current profile broader than in present experiments
  - Retains broad pressure profile
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Solutions in DIII-D at $\beta_N \geq 4$ are Accessible Using Off-axis Neutral Beam and Electron Cyclotron Current Drive

- Broader current and pressure profiles are obtained with off-axis neutral beam injection
  - Increases in predicted ideal-wall $\beta_N$ limits

- Achieving high $\beta_N$ with $q_{min} > 2$ will require optimizing for good $\tau_E$
  - Requires understanding of fast ion transport at high $q_{min}$ or compensation with higher thermal confinement

- Anticipated $\beta_N \approx 5$ operating point is well-placed to inform ITER, FNSF, and DEMO steady-state solutions