Gas Puff Fueled H-Mode Discharges with High Energy Confinement Above the Greenwald Density on DIII–D

by

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Presented at
the American Physical Society
Division of Plasma Physics Meeting
Quebec City, Canada

October 23–27, 2000
Outline, Summary

♦ $\frac{n}{n_{GW}} = 1.4$ at $H_{ITER-89P}=2$ with only $D_2$ puffing

♦ Continuous rise in $n$ and $W$ terminated by MHD not confinement loss

♦ High $n_e$ with high H-factor associated with spontaneous peaking of $n_e$ profile
  - anomalous particle pinch
  - stronger peaking at low central $T$

♦ Without $n_e$ peaking reduced $H$ at high density associated with reduced pedestal pressure with stiff temperature profiles.
  - $p_{PED}$ reduction related to loss of edge second stable access

♦ Achievable pedestal density improves with decreasing $B_T$ and triangularity at the X-point ($n_e^{PED}/n_{GW}$ up to 0.9)
Benefits of good energy confinement at high $n$ with gas puff fueling in H-mode based tokamak reactors

**Ignition Margin, Fusion power, L-H Threshold Margin**

\[
\frac{P_{FUS}}{P_{LOSS}} \propto n^{0.4} H^{2.9} (20 - T_{KEV})^2
\]

\[
\frac{P_{FUS}}{P_{LH}} \propto n^{1.2} T^{2.9} (20 - T_{KEV})^2
\]

\[n_{GW} (10^{20} m^{-3}) = I_p (MA) / \pi [a(m)]^2\]

**Reduced ELM Energy Loss**

\[30 < \Delta E_{ELM}^{ITER} < 100 \text{ MJ}\]

**Reduced Peak Divertor Heat Flux**

\[\text{Divertor Heat Flux (MW/m}^2)\]

\[n_e^{PED} / n_{GW} = 0.5\]

\[n_e^{PED} / n_{GW} = 0.7\]

\[\text{Thomson View Locations}\]

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\(^1\text{ITER Physics Basis, Nucl. Fusion, 39 2577}\]
Gas puff fueled discharges have performance comparable to pellet fueled and impurity enhanced high density discharges

- Single null with $\nabla B$ toward the x-point; triangularity $0 < \delta < 0.5$
- Reactor relevant $2.5 < q_{95} < 6.0$, most at $q_{95} = 3.2$, $I_p = 1.2$ MA
- $1 < \beta_N < 2$, ($\beta_N = 2$ at $\bar{n}_e / n_{GW} = 1.3$)
- Most with divertor pumping
Highest density discharges show continuous increase in n and W

- Plasma stored energy, W, increases with density after an initial decrease following the start of gas injection
- n and W increase limited by MHD not confinement reduction
- Stored energy is comparable to low density discharge at the same heating power.

\[ n_{GW} = 1.1 \times 10^{20} \text{ m}^{-3} \]
Peaking of the density profile compensates for loss of H-mode pedestal energy at high density

- Reduction in H correlated with reduction in pedestal pressure
- Stored energy is recovered with density profile peaking
Profile evolution in high density discharge

- H-mode pedestal density and temperature profile reach steady state while density profile peaks continuously after beginning of D$_2$ puffing
Reduction in $W$ at high $n$ can result from reduced $p^{\text{PED}}$ with stiff temperature profiles

\[ T(\rho) = T^{\text{PED}} f(\rho) \Rightarrow W_{\text{Total}} \propto p^{\text{PED}} g(n^0 / n^{\text{PED}}) \]

- GKS indicates ITG is fastest growing mode
- GLF23 transport simulation give stiff $T$ profile in agreement with experiment, no ITB

GLF23 SIMULATION FOR $n/n_G = 1.4$ Shot

$\rho = 0.4$

START OF GAS PUFFING

PEAK DENSITY

$T_e / T_e^{\text{PED}}$
Reduction in H-mode pedestal pressure at high density

- Pressure reduction begins in the range $0.6 < \frac{n_{e,\text{PED}}}{n_{GW}} < 0.8$.
- At higher triangularity reduction begins at similar $n_{e,\text{PED}}/n_{GW}$.
- Stronger reduction at higher triangularity.

![Graph showing the relationship between $T_{e,\text{PED}}/n_G$ and $n_{e,\text{PED}}/n_G$ for different values of $\frac{n_{e,\text{PED}}}{n_{GW}}$. The graph includes data points and lines indicating the pressure profile $p = c$.](image-url)
Loss of edge second stable access may account for the reduction in edge pressure gradient at high density

- With increasing edge density or $\nu^* \propto n/T^2$.
  - Calculated $j_{\text{BOOT}}$ decreases $\Rightarrow$ edge magnetic shear increases, $S \approx S_0 - 2\left(\frac{j_{\text{EDGE}}}{j_{\text{TOR}}}\right)^2$, $\Rightarrow$ SS access lost
  - ELM modes increase in n.
  - Pressure gradient is reduced from calculated limit for $n=5$ edge localized ideal kink/ballooning (GATO) to ideal high $n$ ballooning mode limit (BALOO).
Density peaking is stronger under conditions that reduce central T or improve central confinement

- Low heating power $\Rightarrow T_0$ reduced and $\tau$ increased
- Higher Gas Puff $\Rightarrow T_0$ reduced through profile stiffness.
- Low $B_T$ $\Rightarrow T$ less peaked at lower $q$
- High $I_p$ $\Rightarrow T$ less peaked at lower $q$, $\tau$ increases with $I_p$. 

![Graphs showing $n_e$ and $T_e$ profiles with varying heating power and $I_p$.](image)
High density discharges develop large particle pinch and have decreasing particle diffusivity

- Inverse scaling with central temperature suggests neoclassical pinch
- Pinch speed measured from He density profile evolution (CER) much larger than neoclassical.

\[
\Gamma_{\text{WARE}} \propto n/T^{3/2}
\]

\[
(n^0 - n^{\text{PED}})/n_G
\]

\[
0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1
\]

\[
\rho \quad 0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1
\]

\[
D(m^2/s)
\]

\[
\begin{align*}
\text{Helium} \\
\text{Near } \bar{n}_e/n_G = 1
\end{align*}
\]
Achievable H-mode pedestal density increases at low x-point triangularity and low $B_T$

- Transition condition to L-mode or Type III dependent on triangularity at X-point and $B_T$
Rising core $p'$ may trigger MHD that ends good confinement phase of high density discharges

- Modes in region $1 < q < 1.5$, $m/n = 3/2, 4/3, 5/4, 6/5$.
- Both classical, $\Delta r_s$, and neoclassical, $\varepsilon^{1/2} \beta_p L_q / L_p (r_s / w)$, tearing mode drives increase as $p'$ increases due to $n_e$ profile peaking.

![Graphs and diagrams illustrating the behavior of $p'$ and $\Delta r_s$ over time.](image-url)
Summary, Conclusions

♦ ELMing H-mode discharges with good energy confinement, $H_{89P} = 2$ well above the Greenwald density, $n/n_G = 1.4$, were obtained with gas puffing
  o Limited by core MHD rather than transport or divertor effects
♦ Density profile peaking is important in obtaining high H factor
  o Peaking is enhanced under conditions that reduce central temperature.
  o He transport studies indicate an anomalous inward pinch
  o Neoclassical pinch would be very weak in a reactor scale tokamak however scaling of anomalous pinch is not known
♦ Confinement degradation at high density on DIII-D is related to the reduction in H-mode pedestal pressure.
  o Edge pressure gradient may be reduced at increased collisionality through loss of edge second stability at reduced bootstrap current.
    – Should not be important in a reactor scale tokamak
Summary, Conclusions

♦ Low triangularity of the x-point or low toroidal field increases the H-mode pedestal density that can be obtained without transition to a regime of reduced energy confinement.

♦ Termination event is possibly a NTM triggered by an increase in the pressure and density profile peaking.
Related Presentations

MO1.011 M.A. Mahdavi, Confinement and Stability of H-mode Discharges above the Greenwald Limit
GP1.135 A. Leonard, Edge Pedestal and ELM Scaling with Density in DIII-D
GP1.136 T. Petrie, Recent High Density Experiments in Open and Closed Divertors in DIII-D