Study of Integrated High-Performance Regimes with Impurity Injection in JT-60U Discharges

K. W. Hill,1 W. Dorland,2 D. R. Ernst,3 D. Mikkelsen,1 G. Rewoldt,1 S. Higashijima,4 N. Asakura,4 H. Shirai,4 T. Takizuka,4 S. Konoshima,4 Y. Kamada,4 H. Kubo,4 and Y. Miura4

1Princeton Plasma Physics Laboratory, Princeton, NJ, USA
2Institute for Plasma Research, Univ. of Maryland, College Park, MD, USA
3Plasma Science and Fusion Center, MIT, Cambridge, MA, USA
4Japan Atomic Energy Research Institute, Naka-machi, Naka-gun, Ibaraki, Japan

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MOTIVATION

• Achieve good confinement at high density in ELMy H-mode discharges
• Reduce steady-state and ELM-induced heat loads to divertor.

OUTLINE

• Reactor requirements almost simultaneously achieved in JT-60U with Ar seeding
• Experimental results from JT-60U with Ar seeding
• Linear microinstability analysis with GS2 and FULL codes
• Predictive modeling with “stiff” models for Ar seeding cases
• Summary and future work
Summary – Argon seeded discharges

Part I

• Near reactor requirements of high confinement, density, radiated power fraction, and fuel purity achieved simultaneously in JT-60U.
• Transient ELM heat load reduced by factor ~1/5 – 1/3 in dome-top configuration
• Particle confinement increased.

Part II

• Confinement enhancement with argon seeding is consistent with gyrokinetic microstability calculations.
• Reduced ITG growth rate in outer region is largely a Ti-profile effect; dilution causes a smaller effect.
• Effect of rotation is small.
JT-60U has achieved near ITER performance requirements simultaneously with argon seeding

<table>
<thead>
<tr>
<th>Parameter</th>
<th>JT-60U (no Ar)</th>
<th>JT-60U (Ar)</th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{HH}_{98(y,2)}$</td>
<td>0.65</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$n_e/n_{GW}$</td>
<td>0.67</td>
<td>0.8</td>
<td>0.85</td>
</tr>
<tr>
<td>$P_{\text{rad}}/P_{\text{heat}}$</td>
<td>0.6</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>ELM-induced heat spikes</td>
<td>large</td>
<td>x 1/3-1/5 reduction</td>
<td>small</td>
</tr>
<tr>
<td>Fuel Purity $n_d/n_e$</td>
<td>0.8</td>
<td>0.7</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Two plasma configurations have been explored for high $n_e$.

lp=1.2MA, Bt=2.5T

- **Standard (S)**
  - $\delta = 0.36$, $q_{95} = 3.4$
  - E36916, 9.1s

- **Dome-top (D)**
  - $\delta = 0.37$, $q_{95} = 4.1$
  - E39530, 9.4s

**Motivation**

Dome top (outer strike point on divertor dome top); efficient fueling of D and Ar due to recycling near X-point
With Ar injection, high stored energy and low recycling are maintained at high density.

- Reference (D₂ only) standard config. small ELMs (type III)
- Standard (Ar) large ELMs (type I)
- Dome-top (Ar) grassy ELMs

\[ n_{GW} \sim 5 \times 10^{19} \text{m}^{-3} \]

With Ar injection

Grassy ELMs obtained in dome-top configuration. 
D₂ puffing rate and Dₐ intensity are low at high density. (Improvement of \( \tau_p \))
HH~1, $P_{\text{rad}} > 0.8P_{\text{net}}$ at $\bar{n}_e \sim 0.8n_{GW}$ in dome-top configuration with Ar injection.

By Ar injection, the confinement is improved by ~50% at 0.65 $n_{GW}$.

- Standard: $HH_{98}(y,2)$ decreases rapidly around 0.7 $n_{GW}$.
- Dome-top: $HH_{98}(y,2)$ ~1 even at 0.8 $n_{GW}$.

The radiation-loss-power fraction reaches 80% at high density.
Improved H-factor with Ar is correlated with increase in \( T_{i}^{\text{ped}} \).

With Ar injection, the pedestal ion temperature remains high at high density.
Standard; \( T_{i}^{\text{ped}} \) decreases rapidly around 0.7 \( n_{GW} \).
Dome top; \( T_{i}^{\text{ped}} \) remains high even at \( n_{e} \sim 0.8 n_{GW} \).
  (efficient fueling of D and Ar due to recycling near X-point?)

HH increases with the pedestal ion temperature.
\( T(r) \) is stiff inside the pedestal.
\( n_{e}(r) \) is slightly peaked with Ar injection.
  -> Ar modifies pedestal physics
    • Dilution
    • Reduces drive for ITG/TEM
With Ar injection, large ELM heat flux reduced by factor 1/3 - 1/5.

- **Reference (without Ar, 0.49 n_{GW})**
- **Standard (0.64 n_{GW})**
- **Dome-top (0.70 n_{GW})**

With Ar injection:
- Standard: Although f_{ELM} decreases, the maximum heat flux does not decrease.
- Dome-top: Frequency and amplitude of ELM heat flux lower (factor of 1/3~1/5)
In dome-top case, $n_D/n_e \sim 0.7$ at 0.8 $n_{GW}$: ITER $n_D/n_e \sim 0.8$.

At 0.65 $n_{GW}$, Ar injection increases $n_Dx\tau_E$ by $\sim 25\%$ despite a reduction in $n_D/n_e$ from $\sim 80\%$ to $\sim 65\%$, because of a significant confinement improvement.

At 0.8 $n_{GW}$, $n_D$ reductions due to intrinsic impurity (\sim C) and Ar are 15\% each. Ar density optimization and carbon density reduction are required for high purity.
Core microstability analysis of argon-seeded discharge

- Linear stability analyses with FULL and GS2 codes indicate:
  - ITG maximum growth rate significantly lower in outer region of Ar-seeded discharge, relative to reference discharge.
  - ETG maximum growth lower across entire profile.
  - Rotation effect very small.
  - Effect of adding argon to reference discharge or removing argon from Ar-seeded discharge (change in dilution) relatively small.
Plasma profiles with and without argon seeding

- $T_e, T_i, Z_{eff}$ higher with argon
- $n_e$ more centrally peaked
ITG growth rate, $\gamma$, reduced in outer region ($r/a>0.5$) of Ar shot

- $\gamma_{\text{ETG}}$ reduced everywhere
- $\omega_{\text{ExB}}$ much smaller than $\gamma_{\text{ITG}}$
- Rotation not a factor
Dilution does not significantly change ITG growth rate

Adding argon to reference discharge

Removing argon from Ar-seeded discharge

$k_\theta \rho_s = 0.0 - 0.6$
Models qualitatively different in core for Ar discharge

- Shear effects not significant

• Measurement
  - Argon, dome top

- IFS-PPPL

- Multimode
  - RLWB
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Future work

- Increased ExB shearing, as well as impurity-induced reduction in drift-wave turbulence important in DIII-D (Murakami); particle pinch a factor leading to density peaking in RI mode, according to modeling (Tokar)

- Analyze JT-60U discharges for effect of ExB shearing during evolution to final, high density discharges.

- Evaluate particle fluxes with FULL code for JT-60U discharges.
Rotation has little Effect on ITG growth rate

JT-60U E39532A07, t = 7.35 s
electrostatic toroidal drift mode
with carbon and argon impurities
and slowing-down beam; $k_q \rho_i = 0.66$

FULL Code

no rotation

with rotation (no eigenfunction shearing)
Maximum ITG growth rate is near \( k_\theta \rho_s \sim 0.5 \)

\[
\begin{align*}
36349 \\
\rho &= 0.61 \\
\text{No Ar}
\end{align*}
\]
Critical $T_e$ gradient for ETG mode is higher in Ar-seeded discharge.
TEM/ETG mode dominates near edge

\[ \rho = 0.73 \]

No Ar

Growth rate

Real frequency / 10
Maximum ETG growth rate is near \( k_\theta \rho_s \sim 40 \)

\[ 36349 \quad \rho = 0.61 \quad \text{No Ar} \]

Growth rate

Real frequency / 10
ETG Stabilized Over Significant Region In Ar-Seeded Discharge

- No Argon
  - 36349
  - $R/L_{Te}$
  - $R/L_{Te_{crit}}$

- With Argon
  - 39532
  - $R/L_{Te}$
  - $R/L_{Te_{crit}}$

Normalized Minor Radius (r/a)