Ex4-4Ra:
Investigations of impurity seeding and radiation control for long-pulse and high-density H-mode plasmas in JT-60U


Japan Atomic Energy Agency, Naka

Ex4-4Rb:
Integrated Scenario with Type-III ELMy H-mode Edge: Extrapolation to ITER

J. Rapp¹,², Y. Corre³, M.R. de Baar², W. Fundamenski⁴, E. Joffrin³, P. Monier-Garbet³, I. Nunes⁵, M. Brix⁴, R. Felton⁴, D. Howell⁴, A. Huber¹, H.Leggate⁴, O.Sauter⁶, G.Telesca⁷, R.Zagorski⁸ and JET EFDA contributors*

1) IEF-4, Forschungszentrum Jülich GmbH, 2) FOM-Rijnhuizen, EURATOM Association (Co-authors Institutes are listed in the last page)

Contents

1. Introduction:
   Key issues for radiative edge and divertor operation

2. Impurity seeding experiments (JET, JT-60U)

3. ELM mitigation in Type-III H-mode plasmas (JET, JT-60U)

4. Radiation region and energy confinement for different radiators in long pulse ELMMy H-mode (JT-60U)

5. Confinement of Type-III ELMMy H-mode plasmas, core plasma dilution, ITER performance modelling (JET)

6. Summary and Conclusion
Introduction: Radiative edge and divertor research

- In tokamak reactor, large radiation loss from edge and divertor is required (radiation fraction: ITER $f_{\text{rad}} > 50\%$, Demo $f_{\text{rad}} > 70\%$)

Ar, Ne, N$_2$ seeding has been investigated during high power heating in JT-60U & JET

Four important key issues are summarized:

- Type-III ELM for ELM mitigation
- Radiation regions (main edge/ divertor) by different radiators
- Core confinement property
Radiative scenario has been carried out with D₂ and N₂ fuelling to sustain type-III ELMs and detached divertor.

\[ \delta = 0.44, \ \kappa = 1.7, \ \mathcal{P}_{NB} = 16 \text{MW} \]

\[ \mathcal{H}_{98} = 0.82 \]

\[ n_e = 1.2 \times 10^{20} \text{m}^{-3} \text{(max.)} \]

\[ \mathcal{P}_{heat} = \mathcal{P}_{rad} \]

\[ H = 0.82 \]

\[ \mathcal{P}_{NB} = 16 \text{MW} \]

\[ T_e (\text{keV}) \]

\[ n_e (10^{20} \text{m}^{-3}) \]
Sustainment of large radiation loss was performed with Ar seeding under the wall saturated (out gassing) condition.

**Ar seeding in ELMyH-mode:**

\[ I_p = 1.2 \text{MA}, \quad B_t = 2.3 \text{T}, \quad q_{95} = 3.5, \quad \delta = 0.31, \quad \kappa = 1.4, \]

\[ P_{\text{NB}} = 12 \text{MW} \]

Large radiation fraction \( \left( \frac{P_{\text{r}}}{{P_{\text{abs}}}} = 0.8-0.95 \right) \) with relatively good confinement \( (H_{89L} = 1.6-1.4, \quad H_{98y2} = 0.87-0.77) \) was continuously sustained.

Divertor detachment and wall saturation are discussed in Poster.
ELM reduction (Type-III) was obtained with increasing the main plasma radiation during Ar seeding.

Type-III ELM was obtained at $P_{\text{rad} \text{main}} = 0.35-0.5P_{\text{abs}}$ can be controlled by the radiation feedback.

ELM energy loss fraction ($W_{\text{ELM}}/W_{\text{ped}}$) was reduced from 4-5% to < 1%.

$H_{98}(y-\gamma)$ was decreased from 0.9 to 0.87-0.75 with increasing radiation power.
Type-III ELM heat loading

Type-III ELM heat load is acceptable for ITER operation:

\[ \Delta W / W \sim 0.1\% \] for JET type-III ELMs is translated to ITER divertor loading:

0.3 MJ or 0.1 MJ/m

Collisionality dependence of \( \Delta W / W \) is assumed like type-I ELMs, a factor of 3 higher at low \( \nu^* \) in ITER.

\[ \Delta W / W \sim 0.1\% \] is less than 0.5 MJ/m \(^2\) (acceptable for ITER)

JT-60U Type-III ELM:

\[ \Delta W / W < 0.15\% \] for \( \nu^* = 0.46 - 0.6 \), where \( < T > = W_{th} / 3 < n_e > \)

\[ f_{ELM} = 150 \text{ Hz} - 1 \text{ kHz} \]

\[ \nu^* = 7.839 \cdot 10^{-4} \cdot q_{95} \cdot R \left( \frac{R}{a} \right)^{3/2} \cdot \tilde{n}_e \cdot Z_{eff} \cdot T^2 \]
Divertor radiation was largely enhanced with Ne puff in Ar seeding type-I ELMyH plasma with higher $H_H = 0.95-0.8$

Ar and Ne seeding in ELMyH-mode plasma with ITB

$I_p=1.05\text{MA}(\text{lower}), B_t=2\text{T}(\text{lower}), q_{95}=3.5, \delta=0.33, \kappa=1.4, P_{\text{NB}}=15.5 \text{ MW (higher power)}$

Good confinement ($H_89_L=1.73-1.5, H_{H98_y2}=0.95-0.8$) type-I H-mode with large radiation fraction ($P_{\text{rad}}/P_{\text{abs}}=0.8-0.9$) was sustained.
Divertor radiation was enhanced with Ne (lower Z) seeding

Ne seeding: $P_{\text{rad}}$ becomes large for the main gas puffing

Ar+Ne seeding: $P_{\text{rad}}$ was enhanced with small Ne puff rate ($1/10$-$1/4$) compared to the pure Ne seeding case.

Type-I ELM activity was observed up to $f_{\text{rad}} = P_{\text{rad}} / P_{\text{abs}} \approx 1$.

JT-60U:
- Ar(to main)+Ne(to divertor) puff
- Ne puff (to main)
- Ar puff (to main)

JET Type-III ELM:
- N +D puff (to divertor)

Threshold power $P_{\text{th}}^{\text{type-III}}$ for two results (plasma parameters) were different.
Better confinement plasma \((H_H > 0.9)\) was sustained for Ar+Ne seeding up to \(f_{\text{rad}} \sim 0.86\)

**Ar+Ne seeding:** Higher \(H\) -factor due to ITB formation was sustained up to \(f_{\text{rad}} \sim 0.86\) \((n_e/n_e \sim 0.8)\)

- JT-60U: Ar+Ne puff \((1.05\,\text{MA}/2\,\text{T}/15\,\text{MW})\)
  - Ne \((1.05\,\text{MA}/2\,\text{T}/17\,\text{MW})\)
  - Ar \((1.2\,\text{MA}/2.3\,\text{T}/12\,\text{MW})\)

- JET Type-III including JT-60U:
  - 
  - \(d<0.25, \, q95<3\)
  - \(d<0.25, \, q95>3\)
  - \(d>0.4, \, 2.5 \, \text{MA}\)
  - \(d>0.4, \, 2.75 \, \text{MA}\)
  - \(d>0.4, \, 3 \, \text{MA}\)
  - \(d>0.4, \, 1.7\,\text{MA} \, \text{Hybrid}\)
  - \(d>0.4, \, 3.25\,\text{MA}\)
Thermal confinement of Type-III ELMy plasmas vs collisionality

- Confinement for the radiating type-III ELMy H-modes was constant towards ITER-like collisionality

\[ H_{98(y,2)} \] between 0.65 and 0.88 for wide range of the average core plasma collisionalities (\( \nu^* = 0.06 - 0.5 \))

Collisionalities were similar in JT-60U

Transport property was consistent with gyro-Bohm scaling (Poster).
$Z_{\text{eff}}$ scaling[1] has been re-evaluated, including transport of impurity ions [2].

Trend of the scaling is applicable to different radiators in JT-60U (lower density):

**ITER predictions: higher than marginal at low $n_e$**

<table>
<thead>
<tr>
<th>Ip</th>
<th>$H_{98}(y, 2)$</th>
<th>N</th>
<th>$Z_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>17MA</td>
<td>0.75</td>
<td>1.0</td>
<td>1.9</td>
</tr>
<tr>
<td>15MA</td>
<td>0.75</td>
<td>1.0</td>
<td>1.95</td>
</tr>
<tr>
<td>15MA</td>
<td>1.0</td>
<td>0.85</td>
<td>2.5</td>
</tr>
</tbody>
</table>

(not including Helium)

\[
P_{\text{rad}} \propto C_z n_e^2 L_k \left( T_e, \tau_p \right)
\]

\[
\tau_{\text{ion}} \propto 1/n_e \quad \tau_p = \tau E
\]

\[
Z_{\text{eff}} = 1 + \frac{40 P_{\text{rad}} Z_{\text{eff}}^{0.12} \tau_E}{S^{0.94} n_e^{1.5} a_{\text{min}} R}
\]

**Benchmark to JET experiments**

$Z_{\text{eff}}, f_{\text{rad}}, H_{98(y,2)}$ as well as plasma profiles ($T_e, n_e$) in core plasma have been matched.

**Simulations of fusion performance, dilution and radiation fraction for ITER(17MA, high $n_e$) with Ne impurity seeding ($Z_{\text{eff}}$ is uncertainty)**

**Note:**
- Erosion by nitrogen not included
- Carbon erosion by deuterium and self sputtering
- Chemical erosion according to Roth formula
- No main chamber erosion
Summary and Conclusion (1/2)

- Steady-state sustainment of radiative plasma scenario \( (f_{\text{rad}} > 60\%) \) has been progressed in JT-60U (Ar and/or Ne seeding) and JET (\( N_2 \) seeding with \( D_2 \)).

**JT-60U:** Long sustainment of large radiation fraction \( (f_{\text{rad}} > 0.8) \) in ELMy H-mode plasmas:
  - (case-1) Type-III ELMs \( (H_{H98y2} = 0.87-0.75) \) by Ar seeding, and
  - (case-2) Type-I ELMs \( (H_{H98y2} = 0.95-0.8) \) for Ar&Ne seeding to ITB target plasma, was demonstrated under the wall saturated (out gassing) condition.

**JET:** Type-III ELMy H-mode operations with \( f_{\text{rad}} = 0.6-1 \) and mitigating ELM heat load \( (W_{\text{ELM}}/W_{\text{dia}} < 0.1\%) \) were demonstrated in a wide range of plasma currents \((1 - 3.25 \text{ MA})\) and heating powers \((2 – 33 \text{ MW})\).

\( H_{H98y2} = 0.65-0.87 \) was sustained over a wide range of collisionality \((0.06<\nu^*<0.5)\).

**Important issues for a radiative plasma scenario were summarized:**

- **Type-III ELM for ELM mitigation and Core confinement:**
  Type-III ELM heat load will be acceptable for the ITER divertor, expecting from \( W_{\text{ELM}}/W_{\text{dia}} \) in JT-60U and JET with higher collisionality \((\nu^*=0.2-0.6)\).

\( H_H \)-factor \(< 0.87\) for Type-III ELM scenario was lower than the Type-I ELMy H-mode plasmas, thus higher density \((0.9-1xn^{GW})\) operation will be required.
Summary and Conclusion (2/2)

- Radiation regions (main edge/ divertor) by different radiators
  - $N_e/ N_2$ (lower $Z$) seeding enhanced radiation particularly in the divertor, while Ar seeding increased radiation both at the main edge and divertor.
  - Type-III power threshold and operation range for the two results were different: further study (plasma parameters) and analysis are required.

- Sustaining detached divertor during long pulse under “wall saturated condition”, and application of radiation feedback control

- Integrated-code (COREDIV: 1D plasma & impurity core transport + 2D multi-fluid SOL) was applied to $N_2$ seeding in JET and Ne seeding in ITER

$Z_{\text{eff}}$ scaling was evaluated from JET Type-III results: marginal ($n^{GW}$ case) and higher (lower $n_e$ case) for the ITER physics design.
List of co-author institute for Ex4-4Rb:

1) IEF-4, Forschungszentrum Jülich GmbH, EURATOM Association, Trilateral Euregio Cluster, Jülich, Germany

2) FOM-Rijnhuizen, EURATOM Association, Trilateral Euregio Cluster, Nieuwegein, The Netherlands

3) Association EURATOM-CEA sur la Fusion Controlee, Cadarache, Saint-Paul-lez-Durance, France

4) EURATOM-UKAEA/Fusion Association, Culham Science Centre, Abingdon, UK

5) Association EURATOM/IST, Centro de Fusao Nuclear, Lisbon, Portugal

6) CRPP, Association EURATOM-Confederation Suisse, EPFL, Lausanne, Switzerland

7) Department of Applied Physics, Ghent University Rozier 44, Gent, Belgium

8) Institute of Plasma Physics and Laser Microfusion, EURATOM Association, Warsaw, Poland