Overview of JT-60U Results Toward the Resolution of Key Physics and Engineering Issues in ITER and JT-60SA

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JT-60U has enough potential to resolve issues in ITER and JT-60SA although 2 years have passed since its shutdown.

**JT-60U experiment:**
- Successful completion in 2008 after 23-year operation
- → presentation at last IAEA FEC
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For resolving **physics** and **engineering** issues in ITER and JT-60SA, research/development have been performed extensively and continuously through **experiment analysis** and **theoretical analysis/simulation**.

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Contents

Focused topics in JT-60U: Key issues in ITER & JT-60SA

1. Rotation and Its Effect on/from Stability and Transport
2. Edge Pedestal Characteristics and Active ELM Control
3. Plasma-Wall Interactions (PWI)
4. Performance Enhancement of Heating & Current Drive Systems
1. Rotation and Its Effect on/from Stability and Transport

- Momentum transport
- Rotation effect on W transport
- Effect of rotation shear on ELM stability
- Effect of NTM island on rotation

Rotation Physics
- Momentum transport
  (incl. intrinsic rotation)
  \[\uparrow\]
  Low torque input in ITER & DEMO

Stability & transport
- Edge stability→ELM
- NTM→mode locking for slow rotation
- W accumulation→confinement degradation

Yoshida, EXC/3-2 (Wed/AM)
Hoshino, THC/P4-12 (Wed/PM)
Aiba, THS/P3-01 (Wed/AM)
Understanding of momentum transport progressed: formulation of residual stress including intrinsic rotation and observation of reduction in $\chi_\phi$ inside ITB.

- Correlation of $V_t$ at edge and core and deviation with increasing $\nabla p$

\[
\begin{align*}
0 & \text{ for steady state} \\
\frac{m_i}{\frac{\partial p}{\partial t}} & = - \nabla \cdot M + S \\
M & = -m_i \chi_\phi \frac{\partial n_i V_t}{\partial r} + m_i V_{\text{conv}} n_i V_t + \Pi_{\text{res}}
\end{align*}
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\frac{d}{dt} m_i \frac{p}{V_t} &= -\nabla \cdot M + S \\
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\end{align*}$

Yoshida, EXC/3-2 (Wed/AM)

![Graph showing correlation between $V_t$ and $\nabla p$]
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- Correlation of $V_t$ at edge and core and deviation with increasing $\nabla p$
- Reproduction of $V_t$ profile by residual stress in the form of $\Pi_{\text{res}} = \alpha_k \chi_\phi \nabla p_i$

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- Correlation of $V_t$ at edge and core and deviation with increasing $\nabla p$
- Reproduction of $V_t$ profile by residual stress in the form of $\Pi_{\text{res}} = \alpha_k \chi_\phi \nabla p_i$
- Observation of reduction of $\chi_\phi$ in ITB plasma: $\chi_\phi \sim \chi_i$

\[
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\]

- Yoshida, EXC/3-2 (Wed/AM)

\[\text{RV}_{\text{conv}}/\chi_\phi = -2.4\]

\[\chi_\phi^{\text{NC}}\]
Newly discovered pinch effects explain W accumulation for counter rotation in experiments.

- Quantitative evaluation of W content by spectroscopic method
- W accumulation in counter-rotating plasma
- H-mode even at $n_W/n_e \sim 10^{-3}$
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- Two effects affecting W orbit
  - ‘PHZ’ (Pinch of High Z impurity)
    Inward pinch driven by change in charge state due to change in temperature along the drift orbit
  - \( E_r \) pinch
    Inward/outward pinch by negative/positive \( E_r \) through Coulomb collisions

⇒ Larger inward velocity for counter-rotation

Consistent with experimental observation

Hoshino, THC/P4-12 (Wed/PM)
Newly discovered pinch effects explain W accumulation for counter rotation in experiments.

• Quantitative evaluation of W content by spectroscopic method
• W accumulation in counter-rotating plasma
• H-mode even at \( n_W/n_e \approx 10^{-3} \)

• Two effects affecting W orbit
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Consistent with experimental observation

Hoshino, THC/P4-12 (Wed/PM)
MINERVA analysis clarified destabilizing effects of rotation shear on ELM stability, explaining experimental observations.

- MINERVA code analysis shows that rotation shear has a destabilizing effect
  \[ \approx n^2 \int \langle \xi \rangle \rho (\omega^2 - \Omega^2) |\xi\rangle d\tau \]
  \( \omega \): mode frequency
  \( \Omega \): rotation frequency
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\(\omega\): mode frequency
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\[ \delta W_g = \delta W_{eq} + \delta W_{rot} \]

\(\delta W_g\): with rotation
\(\delta W_{eq}\): without rotation

\(\delta W_{rot}\): rotation contribution
MINERVA analysis clarified destabilizing effects of rotation shear on ELM stability, explaining experimental observations.

- MINERVA code analysis shows that rotation shear has a destabilizing effect
  \[ \approx n^2 \int \left| \langle \xi \rangle \rho (\omega^2 - \Omega^2) \langle \xi \rangle \right| d\tau \]
  \( \omega \): mode frequency
  \( \Omega \): rotation frequency

- Shift of stability boundary to smaller \( \nabla p \) side by the rotation effect: \( \sim \)ELM stability in exps.
- Lower critical \( \nabla p \) for ctr-rotation \( \rightarrow \) higher \( f_{\text{ELM}} \)

JT-60U experiments

**MINERVA calculation**

\[ \delta W_{\text{g}} = \delta W_{\text{eq}} + \delta W_{\text{rot}} \]

\( \delta W_{\text{g}} \) w/o rotation

\( \delta W_{\text{eq}} \)

\( \delta W_{\text{rot}} \)

E49228 (CO) solid : boundary with rot.
broken: boundary w/o rot.

E49229 (CTR) solid : boundary with rot.
broken: boundary w/o rot.
Growth of NTM island causes rotation slowdown and mode locking at half the natural mode frequency.

- Active stabilization/destabilization of m/n=2/1 NTM island by aligned/misaligned ECCD
- Gradual decrease in mode frequency (~ rotation) with increasing island width
Growth of NTM island causes rotation slowdown and mode locking at half the natural mode frequency.

- Active stabilization/destabilization of m/n=2/1 NTM island by aligned/misaligned ECCD
- Gradual decrease in mode frequency (~ rotation) with increasing island width
- ‘Transition’ in mode frequency
- Hysteresis in downward and upward transition

Isayama, Plasma Fusion Res. 5 (2010) 037
2. Edge Pedestal Characteristics and Active ELM Control

- Effect of toroidal field ripple on pedestal
- Characteristics of type I ELM
- ELM effect from EWM
- Active ELM control by ECH

TF ripple of 0.5-1% in ITER: pedestal characteristics?

Requirement for small ELM energy loss in ITER

ELMy H-mode at $\beta_N > \beta_N^{\text{no-wall}}$ in JT-60SA

Type I ELM: common issue in ITER & JT-60SA

Urano, EXC/P8-17 (Fri/PM)
Oyama, EXS/8-3 (Fri/AM)
Matsunaga, EXS/5-3 (Thu/PM)
TF ripple scan in JT-60U and JET shows no large effect on pedestal pressure at $\delta_{\text{ripple}} < 1\%$.

- Same shape, similar profile
- TF ripple scan up to $\delta_{\text{ripple}} = 1\%$: comparable $\delta_{\text{ripple}}$ in ITER (w/o FI)
- With increase in $\delta_{\text{ripple}}$:
  - Shift of $V_{T\text{ped}}$ toward counter direction
  - No large difference in thermal pressure
- Very similar change in $n_e$ and $T_e$

Urano, EXC/P8-17 (Fri/PM)
Precursor of type I ELM has a small growth rate of $\gamma/\omega_A \approx 10^{-3}$ with $n=8-10$ or $14-16$, indicating P-B mode.

- Statistical analysis of growth of ELM precursor → peak at $\sim 200\mu s$ ($\gamma/\omega_A \approx 10^{-3}$)
Precursor of type I ELM has a small growth rate of $\gamma/\omega_A \sim 10^{-3}$ with $n=8-10$ or 14-16, indicating P-B mode.

- Statistical analysis of growth of ELM precursor
  → peak at $\sim 200\mu$s ($\gamma/\omega_A \sim 10^{-3}$)

- Precursor measurement with ECE at different toroidal locations (60° apart)
  → $n = 8-10$ or 14-16

- Stability analysis by MARG2D:
  unstable/marginally unstable for $n=12-17$

Oyama, EXS/8-3 (Fri/AM)
Energetic particle driven Wall Mode triggers ELM with decreasing ELM amplitude

- EWM (Energetic particle driven Wall Mode): destabilized at $\beta_N > \beta_{N_{no-wall}}$, around $q=2$ ($\rho \sim 0.6$)
- EWM-triggered ELM: $f_{\text{ELM}}$ and $\Delta W_{\text{dia}}$ → ELM loss by half
- Divertor diagnostics: oscillations in synchronization with EWM $\rightarrow$ ion loss $\rightarrow$ increase in $\nabla p_{\text{edge}}$ → ELM trigger

Effect of fast-ion component on ELM stability
Edge ECH can increase ELM frequency and thereby reduce energy loss per ELM.

- Increase in $f_{\text{ELM}}$ just after ECH
- Increase in $f_{\text{ELM}}$ beyond input power dependence ($\Delta f_{\text{ELM}}/P_{\text{input}} = 34.8 \text{ Hz/MW for ECH, } 8.3 \text{ Hz/MW for NB}$)
- Decrease in $\Delta W_{\text{ELM}}/W_{\text{ped}}$ with increasing $f_{\text{ELM}}$
  $\Rightarrow$ Possibility of another tool for ELM control
- Clear effect only for HFS deposition

Oyama, EXS/8-3 (Fri/AM)
3. Plasma-Wall Interactions

- Transport and deposition of dust
- D & C retention in W tiles

Asakura, EXD/P3-02 (Wed/AM)
Fukumoto, EXD/P3-10 (Wed/AM)

- Dust influence on core plasma performance
- Limit of T retention in ITER
Dust transport during discharges and dust deposition in vacuum vessel have been clarified.

- Dust transport measurement by fast camera
- Dust distribution measurement by Mie scattering using YAG laser
  - Dust ejection/transport from divertor and outer baffle tiles
  - Distribution peak in far-SOL

⇒ No significant penetration into the edge and core plasma

- Dust collection: Dominant accumulation in shadow area particularly under divertor

Asakura, EXD/P3-02 (Wed/AM)
Depth profile of C and D in W-coated tiles suggests simultaneous use of W-coating and C may enhance T retention through T trapping by C.

- **W-coated CFC tiles** (50 μm thickness), 5% coverage of toroidal length
- **D retention measurement** (Thermal Desorption Spectroscopy): $10^{22}$ D/m²
  → D retention $>1$-order higher compared with laboratory exps. without C
- **C & D density measurement** (Secondary Ion Mass Spectroscopy)
  → Similar D/C ratio into deep region: D/C = 0.06 ± 0.02 ... D trapping by C

Fukumoto, EXD/P3-10 (Wed/AM)

25 shots: W config.
978 shots: usual config.
4. Performance Enhancement of Heating and Current Drive Systems

• Negative-ion-based Neutral Beam (NNB) system
• Electron Cyclotron Range of Frequency (ECRF) system

  • NNB: main current driver
  • ECRF: preionization, MHD control, discharge cleaning etc.

Kojima, FTP/1-1Ra (Wed/PM)
Kobayashi, FTP/P6-13 (Thu/PM)

NNB system for JT-60U
ECRF system for JT-60U
New records of H/CD systems have been achieved:
- Highest acceleration energy and beam current of NNB
- Highest ECRF output for >1s from 1 gyrotron.

NNB
• Improvement in voltage-holding capability of ion source by gap tuning
• $V_{\text{acc}} = 500\text{kV}$ at 2.8A
• $\sim 200\text{kV}$ per single stage (~ITER)

![Graph showing beam energy and negative ion current]
New records of H/CD systems have been achieved:
- Highest acceleration energy and beam current of **NNB**
- Highest ECRF output for >1s from 1 gyrotron.

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- Improvement in voltage-holding capability of ion source by gap tuning
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**ECRF**
- New scenario: startup with high beam-extraction voltage and shift to usual setting after gyrotron oscillation
- **1.5MW generation for 4s**

Stationary operation at hard self-excitation regime
New records of H/CD systems have been achieved:
- Highest acceleration energy and beam current of NNB
- Highest ECRF output for >1s from 1 gyrotron.

**NNB**
- Improvement in voltage-holding capability of ion source by gap tuning
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Kojima, FTP/1-1Ra (Wed/PM)

**ECRF**
- **New scenario**: startup with high beam-extraction voltage and shift to usual setting after gyrotron oscillation
- **1.5MW generation for 4s**

Kobayashi, FTP/P6-13 (Thu/PM)

Promising engineering achievements toward ITER and JT-60SA
**Summary**

Research and development activities in JT-60U toward ITER and JT-60SA have made a steady progress

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<th>( \Pi_{\text{res}} \propto \chi_\phi \nabla p_i ; \chi_\phi \sim \chi_i ) inside ITB</th>
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<td>New models for W accumulation: PHZ &amp; ( E_r ) pinch</td>
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<td>Slowdown by NTM islands: need of NTM suppression</td>
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<td>Pedestal &amp; Type I ELM</td>
<td>No large effects on ( p_{\text{ped}} ) at ( \delta_{\text{ripple}} &lt; 1% )</td>
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<td>Precursor: linear growth phase of P-B mode</td>
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<td>Effects of localized and/or transient parameter/event on ELM: rotation shear, energetic particles, edge ECH</td>
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<td>PWI</td>
<td>Core penetration of C dust: not a concern</td>
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<td>C dust distribution in shadow area: potential T source</td>
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<td>D retention in W-coating: Care needed for simultaneous use with C</td>
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| H/CD systems      | Satisfactory & promising results \[\begin{align*} 
   \text{NNB:} & \ 500kV, 2.8A \\
   \text{ECRF:} & \ 1.5\text{MW, 4s} \end{align*}\] |
# Presentations in this conference from JT-60U/JT-60SA

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<td>EXC/P4-12  JT-60U/JET ITB comparison (Litaudon)</td>
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<td>* FTP/1-1Ra  Development of JT-60 NNB (Kojima)</td>
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- Only papers marked * have been introduced in this talk
- Many JT-60SA papers (incl. OV) will be also presented in this Conference