Progress in ECRF system development for JT-60SA


Japan Atomic Energy Agency
Contents

• Background
  ➢ JT-60SA ECRF system

• High-power, long-pulse ECRF system development
  ➢ 110 GHz Gyrotron
  ➢ Transmission line

• Dual frequency ECRF system development
  ➢ Gyrotron design and operation results
  ➢ Antenna/Launcher
  ➢ Other activities

• Summary
JT-60SA ECRF system

JT-60SA (Super Advanced)

• Plasma current: 5.5 MA (maximum)
• Duration: typically 100s
• Highly shaped: \( S = q_{95} I_p / (a B_t) \sim 7, A \sim 2.5 \)
• High heating power 41MW. (NB, EC)

Contribute to ‘Success of ITER’, ‘Decision of DEMO design’ & Foster next generation leading scientists.

First plasma: March 2019.

Role of ECRF System in JT-60SA

- Localized electron cyclotron heating and current drive

<table>
<thead>
<tr>
<th></th>
<th>JT-60U</th>
<th>JT-60SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>110 GHz</td>
<td>110 GHz (+138 GHz)</td>
</tr>
<tr>
<td>Max. Power into Plasma</td>
<td>3 MW</td>
<td>7 MW</td>
</tr>
<tr>
<td>Max. Pulse Duration</td>
<td>5 s</td>
<td>100 s</td>
</tr>
<tr>
<td>Number of Units</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>Number of Launchers</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Max. Power at Gyrotron Window</td>
<td>1 MW</td>
<td>1 MW</td>
</tr>
<tr>
<td>Waveguide Dia.</td>
<td>31.75 mm</td>
<td>60.3 mm</td>
</tr>
<tr>
<td>Antenna power / beam</td>
<td>~ 0.75 MW</td>
<td>~ 0.78 MW</td>
</tr>
</tbody>
</table>
ECRF system in JT-60SA

7MW injection by 4 antennas and 9 gyrotrons enables ECH/CD for 100s
3MW by 4 gyrotrons will be prepared in the initial research phase and will be upgraded to the 9 gyrotron system in the integrated research phase.

Antennas and waveguides will be fabricated and installed by JAEA

Gyrotron

Power supply

BPS/AVD

MHVPS

To be improved for integrated phase

To be fabricated by EU

Fabricated or to be fabricated by JAEA

To be fabricated for integrated phase

JT-60SA Power Supply
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High power (> 1 MW) operation

Two results reported in IAEA FEC2010 (Daejeon)

• High efficiency operation technique
  1.5 MW for 4 s

• Improved mode convertor
  Reduction of diffraction loss by 1/3.
  Gaussian like rf profile was obtained at the output of mode convertor.

Before improvement
Loss ~ 9%  
(Exp.)

After improvement
Loss ~ 3%  
(Exp.)

In 2009, pulse length was limited by temperature rise in DCB cooling water

New record of high power operation in 2012
1.4 MW for 9 s

(This value is tentative, and will be increased near future).
Replacement of 31.75 mm waveguide with 60.3 mm waveguide.

A waveguide type dummy load (31.75 mm) was replaced with a new tank load.

Temperature rise of waveguides was reduced by about half.

**New result of long pulse operation in 2012**

1MW for 70 s

Ion pump current limited pulse length, so far.
The pulse length will be expanded by continuing conditioning operation.
The target parameter (1 MW for 100 s) at 110 GHz for JT-60SA will be achieved soon!
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• Summary
Requirement on dual frequency system

1\textsuperscript{st} frequency
110 GHz

- Reuse the existing JT-60 ECRF system (110 GHz)
- Sustainment of high-beta plasma at \( B_t \sim 1.7 \) T

EC driven current profile was evaluated for \( B_t = 2.25 \) T (maximum \( B_t \) in JT-60SA)


2\textsuperscript{nd} frequency
138 GHz

- ECH/ECCD at \( r < 0.8 \) for \( B_t \sim 2.25 \) T
- Discrete set of gyrotron frequencies

Frequency range of 130 ~ 140 GHz is suitable for core ECCD in this case.
Cavity design

Calculated peak heat load at 40 A

- 0.85 kW/cm² (110 GHz), 1.35 kW/cm² (138 GHz)
  - Good for 1 MW (< 2 kW/cm²).
  - 2 MW (110 GHz), 1.5 MW (138 GHz) may be possible.

Efficiency much higher than 30% was obtained at 1 MW for both frequencies with acceptable cavity heat load for CW operation.
Quasi-optical mode converter

Window pattern and transmission efficiency

Diffraction loss lower than 4% with low edge field (< -20dB) at window was obtained for both frequencies.

Long pulse
110 GHz gyrotron (2007)

Diffraction loss ~ 3%

Launcher design: Surf3D/LOT
Mirror design: JAEA code and Toshiba code
Conditioning operation in 2012 - 2013

Tentative results in conditioning operations. (not optimized for obtaining high efficiency)

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>$V_{beam}$ [kV]</th>
<th>$I_{beam}$ [A]</th>
<th>$P_{out}$ [MW]</th>
<th>$h_{osc}$ [%]</th>
<th>Pulse [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>80</td>
<td>20</td>
<td>0.49</td>
<td>30</td>
<td>0.1</td>
</tr>
<tr>
<td>110</td>
<td>80</td>
<td>42</td>
<td>1.12</td>
<td>32</td>
<td>0.1</td>
</tr>
<tr>
<td>138</td>
<td>80</td>
<td>21</td>
<td>0.49</td>
<td>29</td>
<td>0.1</td>
</tr>
<tr>
<td>138</td>
<td>80</td>
<td>21</td>
<td>0.5</td>
<td>30</td>
<td>1.0</td>
</tr>
</tbody>
</table>

$P_{out}$: Power

Design: 110.1 GHz

Design: 137.6 GHz

New gyrotron

New magnet

Measured frequency, power, efficiency at each parameter were consistent with the design.
Development of Antenna/Launcher

**Linear motion antenna concept**

**Advantage:**
Small risk of water leakage in vacuum / Wide range steering

- **Toroidal injection angle**
  - \(b = 0^\circ\)
  - \(b = -10^\circ\)

- **Flexible tubes for water inlet/outlet**

- **Mock test of steering mechanism**

- **Low power confirmation of optical characteristics**

- **Movable first mirrors**
Scenario 5 at 110 GHz
steady-state sustainment of a high-beta plasma with negative central magnetic shear.

\[ I_p = 2.3 \text{MA}, \quad B_t = 1.7 \text{T}, \quad q_{95} = 5.7, \quad T_e(0) = 5.85 \text{keV}, \quad n_e(0) = 6.8 \times 10^{19} \text{m}^{-3}. \]

Scenario 2 at 138 GHz
full-\(I_p\) operations with a single-null divertor and full injection power (41MW).

\[ I_p = 5.5 \text{MA}, \quad B_t = 2.3 \text{T}, \quad q_{95} = 3.0, \quad T_e(0) = 13.5\text{keV}, \quad n_e(0) = 7.7 \times 10^{19} \text{m}^{-3}. \]

Calculation by EC-Hamamatsu code

- ECCD calculation shows: Toroidal injection angle, \(\pm 15^\circ\) is appropriate for Scenario 5 at 110 GHz.
  For Scenario 2 at 138 GHz, the angle may be larger, e.g., \(+20^\circ\), for higher ECCD efficiency.
- Angle range is limited by the rotation mechanism
  - the angle may be compromised to -10°~+20°. (Discussion is in progress to decide the angle range)
Other components for dual frequency system

External control of MOU mirror angle

SCM magnet current can be changed remotely within 10 min. (72A@110GHz ↔ 90A@138GHz)

Wide band polarizer development (collaboration: JAEA and Ibaraki Univ.)

Ultra-sonic motors

RF beam injection angle to the waveguide can be changed within 1 min. No need to open the vacuum vessel.
Developments high-power, long-pulse and dual frequency ECRF system for JT-60SA are in progress.

- High-power and long-pulse operation.
  - Improved gyrotron and high efficiency operation technique
    1.4 MW for 9 s
  - Improved gyrotron and large diameter waveguide transmission line.
    1 MW for 70 s

- Dual frequency ECRF system (110 GHz and 138 GHz).
  - Gyrotron design finalized and fabricated in 2011.
  - Conditioning operation in 2012 - 2013.
    - 110 GHz: 1 MW for 0.1 s
    - 138 GHz: 0.5 MW for 1 s
  - ECCD efficiency was evaluated for typical experimental scenarios
    Further discussion of toroidal injection angle (in progress).