Development of high power gyrotron and mm-wave launching antenna for ITER and JT-60SA


Japan Atomic Energy Agency
Outline

- Introduction of ITER EC System
- Development of ITER Gyrotron
- Design of ITER Equatorial Launcher
- Development of JT-60SA EC System
- Summary/Outlook
ITER EC H&CD System

- 170GHz
- 20MW/CW
- 1~5kHz

Gyrotrons (8) & Power supply

Transmission line (150~170m)

Tokamak Building

RF bldg.

Assembly Building

• Equatorial
• Upper

Launcher

Introduction of ITER EC System

Development of ITER Gyrotron

Design of ITER Equatorial Launcher

Development of JT-60SA EC System

Summary/Outlook
 ваши задачи моральная ответственность

1MW operation of TE_{31,8} gyrotron was marginal due to the heat load, 2.0 kW/cm² at a cavity resonator.

To achieve safely and stably more than 1MW, higher mode gyrotrons are under development.

<table>
<thead>
<tr>
<th>Mode</th>
<th>TE_{31,8}</th>
<th>TE_{31,9}</th>
<th>TE_{31,11}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity</td>
<td>$R_c = 17.90$ mm 2.0 kW/cm²</td>
<td>$R_c = 18.89$ mm 1.6 kW/cm²</td>
<td>$R_c = 20.87$ mm 1.4 kW/cm²</td>
</tr>
<tr>
<td>Triode MIG</td>
<td>$R_c = 46.5$ mm</td>
<td>same</td>
<td>same</td>
</tr>
<tr>
<td>Beam radius</td>
<td>$R_b = 9.13$ mm</td>
<td>same</td>
<td>same</td>
</tr>
<tr>
<td>Diamond window</td>
<td>$D_w = 82$ mm $t_w = 1.853$ mm</td>
<td>same</td>
<td>same</td>
</tr>
<tr>
<td>Size</td>
<td>3m / 800 kg</td>
<td>same</td>
<td>same</td>
</tr>
<tr>
<td>Remark</td>
<td>1MW/55%/800s 0.8MW/57%/1h 5 kHz modulation</td>
<td>1.2 MW CW</td>
<td>1.5 MW CW Multi-frequency</td>
</tr>
</tbody>
</table>

Oscillation mode within selectable beam radius
- Radiation angle of modes $\leq 1^\circ$
  - Beam at each mode is radiated at $\sim$same direction.
- No reflection at window for each modes

\[ \Delta \theta_{\text{rad}} = N_r \left( \cos^{-1}\left( \frac{m_{\text{main}}}{\chi_{m,n,\text{main}}} \right) - \cos^{-1}\left( \frac{m_{\text{sub}}}{\chi_{m,n,\text{sub}}} \right) \right) \]

Possibility of multi-frequency oscillation
- with $\text{TE}_{31,11}$ gyrotron for ITER

<table>
<thead>
<tr>
<th>Cavity mode</th>
<th>$\text{TE}_{19,7}$</th>
<th>$\text{TE}_{25,9}$</th>
<th>$\text{TE}_{31,11}$</th>
<th>$\text{TE}_{37,13}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>104 GHz</td>
<td>137 GHz</td>
<td>170 GHz</td>
<td>203 GHz</td>
</tr>
<tr>
<td>Cavity field</td>
<td>4.08 T</td>
<td>5.32 T</td>
<td>6.63 T</td>
<td>7.98 T</td>
</tr>
<tr>
<td>Gun field</td>
<td>0.172 T</td>
<td>0.21 T</td>
<td>0.28 T</td>
<td>0.31 T</td>
</tr>
<tr>
<td>Beam radius</td>
<td>9.25 mm</td>
<td>9.19 mm</td>
<td>9.13 mm</td>
<td>9.10 mm</td>
</tr>
</tbody>
</table>
Radiation profile at each modes

Cal.

Exp.

✧ Measured radiation patterns were agreed with calculation results.
Oscillation tests at 3 frequencies

✧ 1 MW output power for 3 frequencies demonstrated.
✧ **Maximum output power of 1.24 MW (45 %)** at 80 kV / 56 A.
✧ Oscillation of 1MW, 200sec was performed.
- Introduction of ITER EC System
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Design Change Request
- Enhancing driven current at peripheral region of plasma -

Non-inductive weak negative shear
lp = 9 MA

Inductive 500MW, Q=10
lp = 15 MA

Toroidal steering
- 15MA : 350/240kA (ρ=0.4/0.45)
- 9MA : 640kA (ρ=0.4)
- Beam can reach.
  ρ > 0.4(9MA) and ρ > 0.45(15MA)

Change of steering direction

Poloidal steering
- 15MA : 350/240/200kA
  (ρ=0.4/0.5/0.6)
- 9MA : 640/530/430kA
  (ρ=0.4/0.5/0.6)

More driven current at edge!

Millimeter wave transmission
- 170GHz, 20MW injection in total (However, 1.5MW/1line for future upgrade)
- As low heat load as possible
  Max peak HL on M1/M2 ~ 5.0 MW/m² / ~ 3.0 MW/m²
- As high transmission efficiency as possible : 99 %
- Poloidal steering (modified)
  Top : -10° ~ +10°, counter
  Mid.: -5° ~ -30°, co
  Bot. : 10° ~ 30°, co

Structural integrity
- Electromagnetic force
- Thermo-mechanical
- Seismic vibration

Nuclear shielding (Issue to be solved…)
- Nuclear heating for coils
- Shut down dose rate at the rear region of EL : ≤100 μSv/h
Transmission Efficiency
(Waveguide outlet – BSM outlet)

Initial condition
- Pure HE_{11} mode
- Waveguide – M1 : 500 mm
- M1 size : \geq(h) 360mm x \geq(w) 420mm
- M2 size : \geq(h) 240mm x \geq(w) 360mm
- BM size : showing in previous page

θ_p = 10°

θ_p = -10°

Optimized parameters (Top)
Mirror shape: Curved surface
M1 size: (h)365 mm x (w)460 mm
M2 size: (h)250 mm x (w)360 mm
M1: \( R_{M1x} \) 11.64 m, \( R_{M1y} \) 2.15 m
M2: \( R_{M2x} \) 20.50 m, \( R_{M2y} \) -3.3 9m
Waveguide installation:
M1 - Waveguide outlet: 500 mm
Angle: \( \Theta_1 \) 1.39°, \( \Theta_+ \) 1.53°
BSM opening:
BM1: (h)415 mm x (w)240 mm
BM2: (h)415 mm x (w)240 mm
BM2: (h)580 mm x (w)280 mm

Results of mm-waves (Top)
- Heat load on mirrors
  M1/M2: 4.95/3.0 MW/m²
  (Transmission power/line: 1.5MW)
- Trans. efficiency: ~ 99%
  (pure HE₁₁₁ mode)
- Beam radius: ~25 cm

\[ \Theta_p = 10^\circ \]

\[ \Theta_p = -10^\circ \]
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ECH system in JT-60SA

7MW injection by 9 gyrotrons and 4 antennas enables ECH/CD for 100s

Plan: 2-phase construction
Initial: 4 sets of 1MW gyrotron
   110GHz existing one and dual freq., 110 GHZ (TE_{22,8}) & 138 GHz (TE_{27,10})

Integrated: 5 sets
   Specification is TBD.

Purposes:
- Electron heating
- Current drive
- Instability control
  (particularly NTM)
- Plasma initiation
- Wall cleaning
  Expected for first plasma

The first **two-frequency gyrotron** (110 & 138GHz) has reached the development target of **1MW x 100s at both frequencies**.

Oscillation at **82GHz (0.5MW,1s)** was also confirmed with the two-frequency gyrotron.

- applicable for **start-up assist and wall cleaning at fundamental resonance**
- Conditioning and parameter adjustment toward 1MW, 1s is planned.
Launcher development for JT-60SA

Beam steering in poloidal/toroidal directions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
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<tbody>
<tr>
<td>Port size</td>
<td>480 mm x 480 mm (at narrower duct)</td>
</tr>
<tr>
<td></td>
<td>~ 3 m (length)</td>
</tr>
<tr>
<td>Aperture size</td>
<td>706 mm x 659 mm (at stabilizing plate)</td>
</tr>
<tr>
<td>Port angle</td>
<td>35.5° (from horizontal plane)</td>
</tr>
<tr>
<td>Location (R,Z)</td>
<td>(4033, 869) (at aperture center)</td>
</tr>
<tr>
<td>Target range of Poloidal (θ_p)</td>
<td>-40° ~ +20°</td>
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<tr>
<td>Target range of Toroidal (θ_t)</td>
<td>-15° ~ +15°</td>
</tr>
</tbody>
</table>

θ_p = -5° ~ +5° for NTM stabilization at q = 2 surface (ρ ~ 0.6)
θ_p = -35.5° ray goes to the plasma center
θ_t = +15° co-ECCD  θ_t = 0° pure heating  θ_t = -15° cntr-ECCD

JT-60SA manufacture and assembly going on schedule

Assembly started: Jan. 2013

340/360deg of VV was installed in Jan. 2015

First Plasma in Mar. 2019

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<td>Construction</td>
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<td>Disassembly</td>
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<td>Commissioning</td>
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<td>Integrated Commissioning</td>
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<td>ECH system</td>
<td>Dual freq. gyrotron</td>
<td>1st gyrotron</td>
<td>Conditioning/test</td>
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<tr>
<td></td>
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<td>Fabrication</td>
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<td>Installation</td>
<td>test</td>
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</tbody>
</table>

Summary

1. Gyrotron
   - TE_{31,11} mode gyrotron with 1MW, multi-frequency oscillation was developed.
     - 1.24 MW/45% (170 GHz), 1.01 MW/42% (137 GHz), 1.04 MW/41% (104 GHz)
   - Operation of 1MW-200sec was demonstrated.
   - TL experiment at 3 frequencies were demonstrated on ITER relevant TL.
     Power transmission efficiency in 40 m TL:
     - 94% (170 GHz), 95% (137 GHz), 94% (104 GHz)

2. Equatorial EC Launcher
   - MM-wave design modification
     - Optimum beam path is obtained under pure HE_{11} mode propagation.
     - Transmission efficiency: 99%, Peak heat load on M1/2: 3.0/4.95 MW/m^2 ≤ Criteria
     - 0.9\cdot HE_{11} + 0.1\cdot HE_{21} : wider BSM opening is necessary.

Outlook

- CW operation of TE_{31,11} mode with > 1 MW / 50% for ITER experiment
- Demonstration of 203 GHz oscillation for a Demo-reactor-class
- Detail design of poloidal EL with resolving the uncertainty of port environment
- Optimization of nuclear shield compliant with the requirements
Summary of R&Ds for JT-60SA EC system

1. Dual frequency gyrotron
   - The first two-frequency gyrotron (110 & 138GHz) has reached the development target of 1MW x 100s at both frequencies.
   - Oscillation at 82GHz (0.5MW, 1s) was also confirmed.
     - Power increase is planned at 82GHz and 110GHz.

2. Launcher
   - Repetition steering test of bellows in mock-up was successful.
   - Manufacturing process was checked with mock-up of large curved 2nd mirror having water cooling channels.
     - Further repetition steering test for bearings will be in 2015.
## Transmission line tests at 104, 137 and 170 GHz

<table>
<thead>
<tr>
<th>Power measurement with 20 sec operation</th>
<th>170 GHz</th>
<th>137 GHz</th>
<th>104 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power at gyrotron window</td>
<td>430 kW</td>
<td>328 kW</td>
<td>264 kW</td>
</tr>
<tr>
<td>Power at MOU output</td>
<td>416 kW</td>
<td>309 kW</td>
<td>238 kW</td>
</tr>
<tr>
<td>Diffraction loss ratio at MOU</td>
<td>(3.3%)</td>
<td>(5.8%)</td>
<td>(9.8%)</td>
</tr>
<tr>
<td><strong>Power at Dummy load I (Short TL)</strong></td>
<td>411 kW</td>
<td>305 kW</td>
<td>236 kW</td>
</tr>
<tr>
<td>Transmission efficiency at Short TL</td>
<td>(98.8%)</td>
<td>(98.7%)</td>
<td>(99.1%)</td>
</tr>
<tr>
<td><strong>Power at Dummy load II (Long TL)</strong></td>
<td>390 kW</td>
<td>294 kW</td>
<td>223 kW</td>
</tr>
<tr>
<td>Transmission efficiency at Long TL</td>
<td>(93.8%)</td>
<td>(95.1%)</td>
<td>(93.7%)</td>
</tr>
</tbody>
</table>
MM-Wave Design output 3
- Dependence of modes on transmission efficiency (Top) -

- Dependence of modes on transmission efficiency (Top) -

Pure HE_{11}

Oblique

Offset

Launcher development for JT-60SA

Repeated motion test of 1\textsuperscript{st} mirror has been successful with mock-up \textit{launcher} to check bellows.
- $10^5$ cycles of linear motion for poloidal beam steering
- $10^4$ cycles of twist for toroidal beam steering

Test with real full-size mock-up with 3m of shaft is ready to check durability of the bearings.

Manufacturing process was checked with mock-up of 2\textsuperscript{nd} mirror having water cooling channels

Full-size mock-up with shortening shaft for 1\textsuperscript{st} Mirror