Progress in high-power, long-pulse, multi-frequency ECH/CD system developments in QST


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JT-60SA ECH/CD system

- Introduction
- High-power, long-pulse, multi-frequency gyrotron
- Transmission line loss
- Launcher R&D
- Summary

ITER gyrotron

- Introduction
- TE$_{31,11}$ mode at 170 GHz
- Multi-frequency, 1 MW-class operation
- Summary
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Outline of the JT-60SA ECH/CD system

JT-60SA (Super Advanced)
Joint project of
• Satellite tokamak (BA)
• Japanese national project

Roles of ECH/CD System in JT-60SA
• Localized electron cyclotron heating and current drive
• Plasma start-up assist.
• Wall cleaning.

First plasma in 2019

<table>
<thead>
<tr>
<th>Frequency</th>
<th>110 GHz, 138 GHz 82 GHz (&lt; 1s)</th>
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</thead>
<tbody>
<tr>
<td>Max. Power into Plasma</td>
<td>7 MW</td>
</tr>
<tr>
<td>Max. Pulse Duration</td>
<td>100 s</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>1/18</td>
</tr>
<tr>
<td>Number of Gyrotrons</td>
<td>9</td>
</tr>
<tr>
<td>Number of Launchers</td>
<td>4</td>
</tr>
<tr>
<td>Max. Power at Gyrotron Window</td>
<td>1 MW</td>
</tr>
<tr>
<td>Transmission Line</td>
<td>Corrugated waveguide</td>
</tr>
<tr>
<td></td>
<td>Inner diameter 60.3 mm</td>
</tr>
<tr>
<td>Transmission Efficiency</td>
<td>75 - 80%</td>
</tr>
<tr>
<td>(including loss in MOU)</td>
<td></td>
</tr>
<tr>
<td>No. of Trans. Lines</td>
<td>9</td>
</tr>
<tr>
<td>Power modulation</td>
<td>5 kHz</td>
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</tbody>
</table>
Assembly of JT-60SA is going on schedule

Assembly started: 2013

340deg of VV welding completed: 2015

4 TFCs delivered

TFC in assembly hall

JT-60SA Assembly from Jan. 2013

Tokamak

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<tbody>
<tr>
<td>Construction</td>
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<td>Operation</td>
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</table>

ECH/CD system

Multi-freq. gyrotron
Power Supply (by EU)
Launcher/Waveguide
Control system

1st gyrotron Spec. achieved Conditioning/test PA signed Installation
Design/Development Fabrication test
JT-60SA gyrotron R&D target

- **Main target**
  - 1MW/100s at 110 GHz
  - 1MW/100s at 138 GHz
  - Achieved in 2014

- **Extended target 1**
  - 1MW/1s at 82 GHz
  - Achieved in 2015

- **Extended target 2**
  - Heating and current drive
    - Output power: 1 MW/gyro.
    - Pulse length: 100 s
    - $B_T \approx 1.7T$: 110 GHz (2nd)
    - $B_T \approx 2.3T$: 138 GHz (2nd)
    - 110 GHz (2nd) (edge heating only)

- **Plasma startup assist and wall cleaning**
  - Output power: 0.5 – 1 MW/gyro.
  - Pulse length: ~ 1 s
  - $B_T \approx 1.7T$: 110 GHz (2nd)
  - $B_T \approx 2.3T$: 138 GHz (2nd)
  - 82 GHz (1st)

- Capability of the gyrotron operation at multi-frequency significantly extends the regime of ECH/CD experiments in JT-60SA.
- QST successfully developed a gyrotron, which fully satisfied the above targets.
- Further developments toward higher power (Extended target 2) is going on.
Higher order mode oscillation to reduce cavity Ohmic loss

**JT-60 Gyrotron**
Cavity radius: 19.8mm
mode: $\text{TE}_{22,6}$ (110GHz)

Previous record: 1.4MW/9s, 1.5MW/4s
A. Isayama, T. Kobayashi et al., 24th IAEA FEC, FTP/P1-16 (2012).

JT-60SA Gyrotron
Cavity radius: 22.9mm
Oscillation mode: $\text{TE}_{22,8}$ at 110GHz
*$H_{22,8} = 0.7 \times H_{22,6}$
(applicable up to 2 MW, in design)

Issue: Mode competition at high order mode
Solution: Optimization of anode voltage (Triode MIG)

- Experimental result consistent with design.
- Power limit due to the cavity heat load has been improved up to 2 MW.

Cavity heat load limited the output power of the previous gyrotron (1.2kW/cm$^2$ @ 1MW)
Criteria: $< 2$ kW/cm$^2$ (Gridcop®)

Heat load $H_{mn} \propto f^{2.5} \frac{\chi_{mn}^2 - m^2}{c_{mn}^2}$

Output power = 1.5MW
Boiling point of cooling water
Pressure: 0.4 - 0.5MPa
Initial temp.: 20 - 30 °C

Measured by a thermocouple at the cooled surface of the cavity for both JT-60 (TE22,6) gyrotron and the JT-60SA gyrotron (TE22,8).
High-power gyrotron oscillation at three frequencies

110 GHz:
- $\leq 2.0 \text{MW}$

138 GHz:
- $\leq 1.5 \text{MW}$

Main target
- 1 MW/100 s at 110, 138 GHz
  (Achieved in 2014)

Extended target-1
- 1 MW/1 s at 82 GHz
  (Achieved in 2015)

Extended target-2
- Power limit of JT-60 Gyrotron
  (limited by heat load to cavity)
- 1.5 MW/4 s
- 1.5 MW/5 s
- 1.3 MW/1.3 s
- 1.4 MW/9 s

Tentative results by Aug 2016.
- 1.9 MW/1.0 s, 1.5 MW/5 s

- Record of high power at >1 s has been updated.
- Further optimization of the anode voltage during the pulse, in future.
- Improved anode voltage control system has been developed by means of a real-time OS (INtime®) enabling to control the anode voltage every 1 ms with resolution of 0.2 kV.
Issue in the waveguide temperature rise during 1MW/100s operation in 2014.

Example of the waveguide temperature rise in 1MW/100 s operation with short TL (7m).

- Maximum temperature close to the operational limit of Aluminum. (~150 °C)
  (initial temp. ~ 30 °C)
- Averaged temperature rise ~ 60 °C results in too large waveguide expansion.

\[ 2.3 \times 10^{-5} \times 10 \text{m} \times 60 \text{°C} = 13.8 \text{mm} \]

Coefficient of thermal expansion for AL. Typical length of TL between two miter bends.

**Issue:**
- To clarify the temperature rise and transmission loss of with a long TL (60 – 80 m with 6 – 12 miterbends in JT-60SA).
- To develop effective cooling system.
Temperature distribution of long-TL

Length of TL ~ 37 m with 7-miterbends

110 GHz, 500kW, 20s = 10 MJ

- Temperature distribution similar to that of 110 GHz.
- Temperature rise of the WG close to the gyrotron is relatively small.
- Relatively high temperature rise > 1°C/1MJ (similar to the previous result at the short TL) at,
  - 1-m WG between miterbends
  - WG in front of dummy load

138 GHz, 500kW, 20s = 10 MJ

- Temperature rise at 138 GHz is lower than that of 110 GHz.
Beam pattern with relatively low HE11 purity at 138 GHz compared with 110 GHz. Detailed analysis of the mode purity is underway.

Similar results at many positions from MB4 to MB 7.

Confirmed cause of the temperature rise

- The higher order mode at the MOU nor that generated by misalignment is not a main cause of the temperature rise.
- Reflection from the dummy load is large but not important for tokamak.
- Mode conversion at the miterbend is the most important.
Evaluation of the temperature rise and decay length

- The higher order modes generated at the miter-bends are absorbed within ~2m.
- The reflection from the dummy load may have long decay length of ~10 m. (not a problem for tokamak experiments!)

**Results:** Expected temperature rise and required cooling in JT-60SA

- **Near miter-bends (<2m):** 0.5 – 1 °C/MJ (50-100°C for 1MW/100s)

  Efficient cooling (short time constant << 100 s) to cool waveguide during the pulse (100 s).

- **Far from miter-bends (>2m):** 0.2-0.5 °C/MJ (20-50 °C for 1MW/100 s)

  Simplified cooling with long time constant to avoid heat accumulation during the day of operation (duty cycle 1/18).
Design of the launcher is going on.

1. Quasi-optical calculation of mm. wave propagation of the antenna mirrors,
2. ECH/CD calculation (ray tracing code),
3. 3D CAD modeling (size, space, position, clearance, etc.),
4. Thermal/structural/electro-magnetic force analyses,
5. Mock-up tests (mechanical/low power mm. wave)
Poloidal beam steering by Linear motion

- Realizing wide poloidal angle range (~ 60 deg.) by linear motion (~ 30 cm) of M1 and large (fixed) curved mirror.
- Injection angles of two waveguide lines are independently controllable.
• Realizing wide poloidal angle range (~ 60 deg.) by linear motion (~ 30 cm) of M1 and large (fixed) curved mirror.
• Injection angles of two waveguide lines are independently controllable.
• Realizing total toroidal angle range (~ 30 deg.) by rotation of M1 around the steering shaft.
• Injection angles of two waveguide lines are independently controllable.
Toroidal beam steering by shaft rotation

- Realizing total toroidal angle range (~ 30 deg.) by rotation of M1 around the steering shaft.
- Injection angles of two waveguide lines are independently controllable.
R&Ds for launcher

1. Fabrication of a mock-up of a large curved mirror (width = 400 mm, R = 700 mm) with cooling pipes by HIP.

2. Cyclic test of full length (~ 7 m) mock-up of the steering structure.
   - Bellows for rotation: successfully finished
   - Bellows for linear motion: successfully finished
   - Bearing for rotation: successfully finished

**Target**
Rotation (toroidal steering): +/- 20 deg., 10,000 cycles
Linear motion (poloidal steering): 400 mm, 100,000 cycles
Summary: JT-60SA ECH/CD system

- High-power records have been updated by the JT-60SA multi-frequency gyrotron.
  - 110 GHz: 1.9 MW/1s, 1.5MW/5s
  - 138 GHz: 1.3 MW/1.3s
  - 82 GHz: 1 MW/1s

- The spatial distribution of the temperature rise of the TL with 7-miterbends (~37 m) have been measured in high-power (0.5MW/20s) transmission experiments and it has been confirmed that the mode conversion at the miterbends are the most important cause of the temperature rise.

- The higher order modes generated at the miterbends are absorbed within ~ 2m.

- The design and R&D of the launcher is going on by fabricating mock-ups of mirror and steering structure.

- Cyclic test of bellows was successful for both rotation (+/- 20 deg.) and linear motion (400 mm). Cyclic test of bearing structure was successful for rotation and in preparation for linear motion.

Fabrication of the transmission line components and control systems for operation of JT-60SA ECH/CD system has been started.
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Cavity oscillation mode of JA ITER gyrotron was defined as TE_{31,11} mode.
Development of long pulse operation with over-1 MW power is underway. (Target : 80 kV (CPD : ~33 kV) / 55 A / 50%effi. ~ 1.3 MW)

<table>
<thead>
<tr>
<th>Mode</th>
<th>TE_{31,8}</th>
<th>TE_{31,11}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity radius</td>
<td>$R_c = 17.90$ mm</td>
<td>20.87 mm</td>
</tr>
<tr>
<td>Triode MIG</td>
<td>$R_e = 46.5$ mm</td>
<td>Same</td>
</tr>
<tr>
<td>Beam radius</td>
<td>$R_b = 9.13$ mm</td>
<td>Same</td>
</tr>
<tr>
<td>Diamond window</td>
<td>$D_w = 82$ mm</td>
<td>Same</td>
</tr>
<tr>
<td></td>
<td>$t_w = 1.853$ mm</td>
<td>Same</td>
</tr>
<tr>
<td>Remark</td>
<td>1MW/55%/800s</td>
<td>Up to 1.4 MW</td>
</tr>
<tr>
<td></td>
<td>0.8MW/57%/1hr</td>
<td>Multi-frequency</td>
</tr>
</tbody>
</table>

TE_{31,11} mode group has great advantage for multi-frequency oscillations because these beam directivity is almost uniform.
Experiments of 1 MW-level operation (170 GHz)

- **Output power**
- **Total efficiency**
- **Output efficiency**

2 sec pulse shot

- **Output power**
  - CPD voltage
  - Total efficiency
  - Output efficiency

- **Output power**
  - CPD voltage: 32kV
  - Cathode $V_k$: 48kV
  - Anode $V_a$: 0kV

- **Beam current**
  - $I_{\text{beam}}$: 45.5 A

- **CPD voltage**
  - $V_{\text{beam}}$: ~71.5kV
  - $I_{\text{beam}}$: ~52.5 A

- **Output power**
  - $P_{\text{out}} = 1.01$ MW
  - Efficiency: $\eta_{\text{out}} = 27.7\%$, $\eta_{\text{tot}} = 46.2\%$

- **1.13 MW shot with 47\% (30\%).**
- **Max power:** 1.23 MW/47\% (2s).
- **1 MW long pulse was achieved 300s.**

Korea-Japan Workshop on Physics and Technology of Heating and Current Drive, December 14 (Wed) - 16 (Fri), 2016, Pohang Accelerator, Pohang, Korea
Multi-frequency oscillation by ITER-gyrotron

Oscillation frequency | Transmission efficiency
---|---
104GHz (TE19,7) | 95.5%
137GHz (TE25,9) | 96.9%
170 GHz (TE31,11) | 98.5%
203 GHz (TE37,13) | 97.6%

(Model converter design was optimized for 170 GHz beam.)

<table>
<thead>
<tr>
<th>Oscillation frequency</th>
<th>Cavity Field</th>
<th>Gun Field</th>
<th>Beam radius</th>
<th>Anode-cathode voltage</th>
<th>Pitch factor</th>
<th>Oscillation power</th>
<th>Oscillation efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>104GHz</td>
<td>4.08 T</td>
<td>0.172 T</td>
<td>9.25 mm</td>
<td>28 kV</td>
<td>1.32</td>
<td>1.12 MW</td>
<td>39%</td>
</tr>
<tr>
<td>137GHz</td>
<td>5.32 T</td>
<td>0.21 T</td>
<td>9.19 mm</td>
<td>36 kV</td>
<td>1.35</td>
<td>1.26 MW</td>
<td>44%</td>
</tr>
<tr>
<td>170 GHz</td>
<td>6.63 T</td>
<td>0.28 T</td>
<td>9.13 mm</td>
<td>42 kV</td>
<td>1.35</td>
<td>1.3 MW</td>
<td>45%</td>
</tr>
<tr>
<td>203 GHz</td>
<td>7.98 T</td>
<td>0.31 T</td>
<td>9.10 mm</td>
<td>50 kV</td>
<td>1.35</td>
<td>1.3 MW</td>
<td>45%</td>
</tr>
</tbody>
</table>

(Beam voltage: 72 kV, Beam current: 40 A)
Achieved power and pulse length

- Over-1MW long-pulse at 170GHz will be planned after improvement of PS and control system (This winter).
- Demonstration of 1MW at 203 GHz oscillation will be started soon.
Progress on development of ITER gyrotron

Quad-frequency 1MW-level oscillations have been demonstrated in the range of 100GHz-200GHz by single gyrotron.

1MW/46% for 300s and 1.2 MW(up to 5s) was achieved at 170 GHz.

0.9MW/5s at 104GHz, 1MW/6s at 137GHz, 0.4MW(0.9MW)/5s(0.3ms) at 203GHz were achieved in long pulse shots (> 1 sec).