FIP/2-2Rb  Development of Dual Frequency Gyrotron and Launcher for the JT-60SA ECH/ECCD System

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FIP/2-2Ra  Prototype Development of the ITER EC System with 170GHz Gyrotron

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FIP/2-2Rc  Development of Over 1 MW and Multi-Frequency Gyrotrons for Fusion

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Introduction: Key components of high power Gyrotrons

Output diamond window

Main Magnet
Gun Magnet
SCM

Resonator Cavity

Diamond Window

Electron gun (Cathode)
Pitch factor $\alpha = \frac{V_{\text{prep.}}}{V_{\text{parallel}}}$

Electron beam

RF power profile
$TE_{31,8}$ mode

Resonator Cavity

Diamond Window

RF beam

DC break

Converter

Main Magnet
Gun Magnet

Magnetic field

Body

Anode

Electron gun (Cathode)

Pitch factor $\alpha = \frac{V_{\text{prep.}}}{V_{\text{parallel}}}$

21.5 deg.

Up-taper: 0.2 deg.

20 225

$r$ (mm)

$\theta$ (radian) $2\pi_0 z$ (mm)

Inner surface of dimpled wall mode converter
Introduction: Key point of multi-frequency gyrotron design

Window thickness and frequency

Case of window thickness $d_w=1.853$ mm $d_w = n_w \frac{\lambda}{2}$

Mode converter design and mode

Mode converter design and mode

Design of multi-frequency gyrotron in JAEA

<table>
<thead>
<tr>
<th>Cavity mode $\text{TE}_{m,n}$</th>
<th>$\text{TE}_{19,7}$</th>
<th>$\text{TE}_{25,9}$</th>
<th>$\text{TE}_{31,11}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency</strong></td>
<td>104 GHz</td>
<td>137 GHz</td>
<td>170 GHz</td>
</tr>
<tr>
<td><strong>Beam radius</strong></td>
<td>9.25 mm</td>
<td>9.19 mm</td>
<td>9.13 mm</td>
</tr>
<tr>
<td><strong>Radiation angle</strong></td>
<td>65.30°</td>
<td>65.32°</td>
<td>65.35°</td>
</tr>
<tr>
<td><strong>Cavity field</strong></td>
<td>4.08 T</td>
<td>5.32 T</td>
<td>6.63 T</td>
</tr>
<tr>
<td><strong>Beam voltage</strong></td>
<td>72 kV</td>
<td>76 kV</td>
<td>76 kV</td>
</tr>
<tr>
<td><strong>Anode-cathode</strong></td>
<td>24.5 kV</td>
<td>34 kV</td>
<td>38 kV</td>
</tr>
<tr>
<td><strong>Pitch factor $\alpha$</strong></td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
</tr>
</tbody>
</table>

$\theta_{\text{rad}} = N_r \cos^{-1} \left( \frac{m}{\chi_{m,n}} \right)$ Conventional

Multi Frequency
Dual-frequency Gyrotron for JT-60SA

Original specification: **110 GHz, 1MW, 100s**

**Scenario 5** ($B_t \sim 1.7 \, T$)  High-beta, Full non-inductive

Target of this development

Dual frequency (110 GHz, 138 GHz) 1MW, 100s

**138 GHz**

**Scenario 2** ($B_t \sim 2.3 \, T$)  Maximum $B_t$, $I_p = 5.5 \, MA$

Poster presented by T. Kobayashi
Thursday P5
FIP/2-2Rb

Remarkable results (2013-2014)

(i) Successful oscillations of 1 MW for 100 s at both 110 GHz and 138 GHz

- New record of a dual-frequency gyrotron.
- The target for JT-60SA fully satisfied

(ii) Demonstration of an oscillation at 82 GHz as an additional frequency

- A possibility of the use of fundamental harmonic waves (<1MW, <1s) in JT-60SA.
Achievement of 1 MW/100 s oscillations at both 110 GHz and 138 GHz

Key points on the design of dual-frequency gyrotron

Selection of oscillation mode in cavity

To satisfying design restriction of gyrotron for both frequencies, simultaneously

138 GHz : TE_{27,10}  
110 GHz : TE_{22,8}

Progress in long-pulse operations

Successful oscillations of 1 MW for 100 s at both 110 GHz and 138 GHz

The target for JT-60SA fully satisfied.
An additional frequency of 82 GHz enables to use fundamental harmonics waves

**Motivation**

Use of the fundamental harmonic waves for
- EC-wall cleaning between plasma discharges (In JT-60SA, TDC is not available)
- EC assisted start-up (reduced power compared with 2\textsuperscript{nd} harmonics)

**Challenge for additional frequency operation**

- Oscillation at 82 GHz was demonstrated.
- Target at 82 GHz
  - Output power < 1MW
  - Pulse length < 1 s
Recent results

- **TE\textsubscript{31,11}** mode 170 GHz gyrotron demonstrated 1.4 MW (short pulse)
- Multi-frequency operation with **>1MW output at 170/137/104GHz**.
- High power RF transmission demonstrated **91~85% efficiency at 40m ITER-relevant transmission line at 170/137/104 GHz**.
- **5kHz power modulation** with prototype of ITER power supply system.
# JAEA Multi-Frequency Gyrotron

<table>
<thead>
<tr>
<th>Frequency</th>
<th>170 GHz</th>
<th>137 GHz</th>
<th>104 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode</td>
<td>TE31,11</td>
<td>TE25,9</td>
<td>TE19,7</td>
</tr>
<tr>
<td>Beam current</td>
<td>50 A</td>
<td>51 A</td>
<td>52 A</td>
</tr>
<tr>
<td>Power</td>
<td>1.02 MW</td>
<td>1.0 MW</td>
<td>1.04 MW</td>
</tr>
<tr>
<td>Gyrotron Efficiency</td>
<td>45 %</td>
<td>42 %</td>
<td>41 %</td>
</tr>
<tr>
<td>RF pattern @gyrotron window</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>WG coupling eff. HE$_{11}$ mode purity</td>
<td>94 %</td>
<td>93 %</td>
<td>93 %</td>
</tr>
<tr>
<td>Transmission Eff.</td>
<td>=Dummy load power/ Gyrotron power</td>
<td>91 %</td>
<td>90 %</td>
</tr>
</tbody>
</table>

- Transparent at 1.853mm Diamond window
- Same bounce angle $\theta \sim 65.3$deg.
  Mode converter works similarly.
  Gaussian beams are obtained at the window center for all modes.
- Very good RF beam coupling into transmission line (>93%) was realized even using the same coupling mirror.
- High power RF transmission with 91～85% of efficiency were successfully demonstrated for multi frequency operation.
ITER EC system prototype in JAEA

JAEA EC lab. has major EC components, Gyrotron, TL test stand, and EL mockup

ITER EC system prototype
Validation of EC system operation for ITER EC system.

ITER relevant TL experiment
RF transmission demonstration
Coordination of multi subsystem
Gyrotron and TL

Gyrotron power modulation
Modulation with ITER relevant PS
Demonstration of 5 kHz mod.

ITER relevant control system
Gyrotron and EC system control with ITER CODAC system / EPICS
Synchronous control via network
Prototype of ITER Power Supply System

ITER relevant gyrotron PS system

Modulation control with anode switch

Anode switch can directly control on/off of gyrotron beam current

Advantage of double switch

The double switch avoids influence of the stray capacity of PS system for *sharp ramp up of voltage*.

Graph showing:
- Anode-cathode voltage [kV] vs Time [μsec]
- Ramp up in pulse start was improved

Single switch
- Double switch

(1) Single switch
(2) Double switch
High Frequency Power Modulation

Key point for 5 kHz modulation

Reduction of heat load on collector.
Spurious RF oscillation (167GHz) of pulse start must be minimized to reduce internal loss.

Double switch can adapt
- 100% beam modulation
- Sharp ramp up at pulse start

The sharp ramp up by double switch system minimized spurious mode excitation at pulse start during modulation.

Succeeded 5kHz modulation with prototype of ITER PS system.
Development of Lower Freq. (28, & 35 GHz)

1.1. 28 GHz Gyrotron
1. Electron gun improvement for over 1MW tube development. 
   - Demonstrated more than 1.25 MW (2 ms), 0.6 MW for 2 s at 28 GHz (TE8,3). Applied to QUEST (66 kA ECCD)
2. Installation of 28/35 GHz window for dual-frequency test 
   - 0.9 MW-35GHz (TE9,4) correspond to 1.2MW osc. power.

1.2. New 28/35 GHz gyrotron Design
Selection of cavity mode for multi frequency design
TE8, 5 (28 GHz) & TE10, 6 (35 GHz)
Designed output: 2 MW at 28/35 GHz.
   - Gyrotron fabrication started.
Higher frequency (77 – 300 GHz) MW ECH Gyrotron

2.1. Over-1MW Gyrotron for LHD (NIFS collaboration)

Demonstr. 2 MW performance
77GHz : 1.8 MW for 1 s (World Rec.)
154GHz: 1.16 MW for 1 s
4.4 MW into LHD-plasma with three 77 GHz tubes,
Contributed to Te ~ 20 keV

2.2. 300 GHz Challenge for Demo Reactor (JAEA, collaboration)

~ 0.5 MW for 1 ms
( $\eta = 19 \%$ ) achieved with $V_k = 80$ kV.
(Joint Exp. with JAEA)
Appeared 300GHz-TE$_{32,18}$ from the burned pattern.

<table>
<thead>
<tr>
<th>Gyrotron No.</th>
<th>Pulse</th>
<th>CW</th>
</tr>
</thead>
<tbody>
<tr>
<td>77GHz - #1</td>
<td>1.4 MW-0.1 s</td>
<td>0.13 MW - 935 s</td>
</tr>
<tr>
<td></td>
<td>1 MW-5 s</td>
<td></td>
</tr>
<tr>
<td>77GHz - #2</td>
<td>1.3MW-0.45 s</td>
<td>0.24MW - 1800 s</td>
</tr>
<tr>
<td></td>
<td>1MW-5 s</td>
<td></td>
</tr>
<tr>
<td>77GHz - #3</td>
<td>1.9MW-0.1 s</td>
<td>0.3MW - 1800 s</td>
</tr>
<tr>
<td></td>
<td>1.8MW-1 s</td>
<td></td>
</tr>
<tr>
<td>154GHz - #1</td>
<td>1.16MW-1 s</td>
<td>0.35MW - 1800 s</td>
</tr>
</tbody>
</table>

U. Tsukuba is Challenging to 14 GHz - 300 GHz Gyrotron Devlop. for present & future Demo ECH and obtained MW level or over 1 MW in 28, 35, 77, 154, and 300 GHz.
Summary

JT-60SA EC H&CD system (FIP/2-2Rb T. Kobayashi et al.)

- 1 MW / 100 s achievement of the dual freq. gyrotron (110 GHz/138 GHz)
  - Achieved parameters fully satisfied the target for JT-60SA.
  - Demonstration of an oscillation at 82 GHz as an additional frequency

ITER EC H&CD system (FIP/2-2Ra Y. Oda et al.)

- 170 / 137 / 104 GHz operation with 1 MW of the multi freq. gyrotron
  - Multi frequency high power RF transmission in ITER relevant TL were demonstrated 91～85% efficiency for 3 frequencies.

- Development of EC system prototype
  - Gyrotron operation with ITER relevant PS and control system.
  - 5kHz modulation was successfully demonstrated with prototype of ITER PS system.

U. Tsukuba gyrotron (FIP/2-2Rc T. Imai et al.)

- Over 1 MW oscillation of dual / single freq. gyrotrons.
  - 1.25MW at 28 GHz and 1.2MW cavity oscillation at 35 GHz were achieved.
  - 77 / 154 GHz single freq. gyrotrons for LHD achieved 1.8 / 1.16 MW output respectively.
  - JAEA / U. Tsukuba joint project succeeded 0.5 MW oscillation at 300 GHz.