Development of a Multi-Purpose, Multi-Frequency Gyrotron for DEMO at KIT


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Overview

- Requirements for DEMO Gyrotrons
- Targets of DEMO Gyrotron Development at KIT
  - 1.5 - 2 MW, CW Coaxial-Cavity Gyrotron
    - Multi-Purpose, Multi-Frequency Gyrotron (136 – 272 GHz, $\Delta f = 33.8$ GHz)
    - Step-Frequency Tuning (227 – 248 GHz, $\Delta f = 2$ GHz)
  - 1 MW, CW Conventional-Cavity Gyrotron
    - Multi-Purpose, Multi-Frequency Gyrotron (136 – 270 GHz, $\Delta f = 33.0$ GHz)
- Summary and Acknowledgments
Requirements for DEMO Gyrotrons (I)

Current design studies on Electron Cyclotron Heating & Current Drive (ECH&CD) systems for the demonstration fusion power tokamak plant DEMO demand gyrotron frequencies of above 200 GHz for efficient CD and a total gyrotron efficiency above 60 % to achieve a sufficient fusion gain factor. (E. Poli, et al. Nuclear Fusion, 53, 013011 (10pp) (2013))

Required gyrotron frequency depends on the Aspect Ratio $A$ of DEMO and on the relevance of CD in plasma operation.

*Indicative frequencies for different Aspect Ratio $A$*

<table>
<thead>
<tr>
<th>$A = R/a$</th>
<th>2.6</th>
<th>3.1</th>
<th>3.6</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_t [T]$</td>
<td>4.2</td>
<td>5.8</td>
<td>7.0</td>
<td>7.6</td>
</tr>
<tr>
<td>$f_{\text{Heating}}$</td>
<td>118</td>
<td>161</td>
<td>197</td>
<td>213</td>
</tr>
<tr>
<td>$f_{\text{Current Drive}}$</td>
<td>144</td>
<td>197</td>
<td>240</td>
<td>280</td>
</tr>
<tr>
<td>$\gamma$ [Am$^{-2}$/MW] (Top Launch)</td>
<td>0.16</td>
<td>0.32</td>
<td>0.36</td>
<td>0.45</td>
</tr>
</tbody>
</table>
Requirements for DEMO Gyrotrons (II)

Gyrotron flexibility could compensate the rigidity of a DEMO reactor:

- **Multiple Frequencies**: distance between two frequency \( \sim 34 \) GHz. Selection between pulses. 3-4 frequencies possible. Single disk gyrotron window sufficient.

- **Step Tunability**: 2-3 GHz between step: max. span 10 GHz for NTM stabilization. During the pulse (but not very fast). Broadband gyrotron window required.

- **Output mm-Wave Beam Quality**: 95% demonstrated for ITER gyrotrons

- **Reliability**: ITER gyrotron (GYCOM) demonstrated 95% > 98% could be reasonable for DEMO (demonstrated for 140 GHz W7-X gyrotron (Thales))

- **Unit Power**: 1 – 2 MW (coaxial-cavity/backup: conventional cavity), Efficiency: up to 60%

- **Requirements for high gyrotron efficiency**: Excellent quality of electron beam Excellent alignment of tube components and magnetic field Multi-stage depressed collector
Towards DEMO: 240 GHz Coaxial-Cavity Gyrotron Development

- **Targets of KIT development**
  - $f = 230 - 240$ GHz, $P = 1.5 - 2$ MW, $\eta > 60\%$
  - Frequency step-tunability ($\Delta f \approx 2$ GHz, $+/-.10$ GHz tunability)

- **“Classic” technical limitations**
  - Emitter radius $\leq 65$ mm
  - Electric field at emitter surface $\leq 7$ kV/mm
  - Emitter current density $\leq 4$ A/cm$^2$
  - Magnetic compression $B_0/B_{gun} \leq 40$
  - Spread of electron guiding centers $\leq \lambda/5$
  - Ohmic loading on resonator wall $\leq 2$ kW/cm$^2$

- **Results in**

  $\Rightarrow$ Beam radius $R_b \geq 10$ mm, cavity radius $R_{cav} \geq 31$ mm $\Rightarrow \chi \approx 150$
Typical Spectra for Very-High-Order Modes

Spectra around the modes $\text{TE}_{47,31}$ and $\text{TE}_{51,27}$ from $f_0 - 12 \text{ GHz}$ to $f_0 + 15 \text{ GHz}$

$R_b = 9.60 \text{ mm}$

$R_{cav} = 31.78 \text{ mm}$

$R_b = 10.93 \text{ mm}$
Ohmic Losses at High Frequencies

- Ohmic loading on cavity surface

\[ w_\Omega \sim P \cdot \frac{f^{5/2}}{\sqrt{\sigma}} \cdot \frac{1}{\chi^2} \cdot \frac{1}{1 - C_c^2} \], \quad C_c = \frac{R_c}{R_{cav}}

- \text{TE}_{49,29} (\chi = 158): \text{Ohmic loading would allow 2 MW!}

- Power limitations:
  - frequency
  - emitter radius / bore-hole
  - electron gun design
  - emitter current density
Towards DEMO: Fundamental Studies of a 240 GHz Coaxial-Cavity Gyrotron

\[ p/m \sim 0.57 \quad (R_c/R_{cav} \sim 0.31) \]

\[ X_{m,p} = 140 \ldots 160 \]

- \( m = 1 \ldots 100; \ p = 1 \ldots 60 \)

1. \( \text{TE}_{28,16} \ 140/1.5 \) [Piosczyk et al. 1997]
2. \( \text{TE}_{31,17} \ 165/1.5 \) [Piosczyk et al. 1999]
3. \( \text{TE}_{34,19} \ 170/1.5 \) [Rześnicki et al. 2007]
4. \( \text{TE}_{52,31} \ 170/4.0 \) [Beringer et al. 2010, Design]

(too) large caustic radius
(conventional gyrotrons)

very small caustic radius

\( \text{TE}_{(m-3),p+1} \)

\( \text{TE}_{(m-2),p+1} \)
Optimum Features of Multi-Frequency Gyrotrons

Cavity Radius: \( R_{cav} \)

Bessel Zero of Cavity Mode \( TE_{m,p} \): \( X_{m,p} \)

Caustic Radius of Cavity Mode \( TE_{m,p} \) : \( R_c = (m/X_{m,p})R_{cav} = C_c R_{cav} \)

Relative Caustic Radius: \( C_c = R_c/R_{cav} = (m/X_{m,p}) \)

Electron Beam Radius: \( R_b \approx 1.05 R_c \)

Radius of Q.O. Launcher: \( R_L \)

Brillouin Angle: \( \theta_B = \arccos[1-(R_{cav}/R_L)^2]^{1/2} \)

Azimuthal Spread Angle: \( 2\phi = 2\arccos(C_c) \)

Length of Straight Launcher Cut: \( L = 2\pi R_L \sin\phi/(\phi \tan \theta_B) \)

If \( m/X_{m,p} \) of the modes is the same, \( R_b \), \( 2\phi \) and \( L \) are also the same and the mm-wave output beam hits the same point at the tube gyrotron output window!
### Multi-Purpose Multi-Frequency Coaxial-Cavity Gyrotron for DEMO with Different $A=R/a$

CVD-Diamond Window: $t = 1.854$ mm, - 20 dB Reflection Bandwidth = 2.2 GHz

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>Application</th>
<th>Cavity Mode</th>
<th>Bessel Zero</th>
<th>Relative Caustic Radius $C_c$</th>
<th>Normalized Window Thickness [$\lambda$]</th>
<th>Window Center Frequency [GHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>136.3</td>
<td>CD, $A=2.6$</td>
<td>$TE_{28,17}$</td>
<td>90.6697</td>
<td>0.3088</td>
<td>4/2</td>
<td>135.9</td>
</tr>
<tr>
<td>170.0</td>
<td>H, $A=3.1$</td>
<td>$TE_{35,21}$</td>
<td>113.1329</td>
<td>0.3094</td>
<td>5/2</td>
<td>169.8</td>
</tr>
<tr>
<td>203.8</td>
<td>H, $A=3.6$</td>
<td>$TE_{42,25}$</td>
<td>135.5957</td>
<td>0.3097</td>
<td>6/2</td>
<td>203.8</td>
</tr>
<tr>
<td>237.5</td>
<td>H, $A=4.0$</td>
<td>$TE_{49,29}$</td>
<td>158.0584</td>
<td>0.3100</td>
<td>7/2</td>
<td>237.8</td>
</tr>
<tr>
<td>271.3</td>
<td>CD, $A=4.0$</td>
<td>$TE_{56,33}$</td>
<td>180.5209</td>
<td>0.3102</td>
<td>8/2</td>
<td>271.7</td>
</tr>
</tbody>
</table>

Max. deviation of $C_c$ is 0.27%, therefore max. horizontal output beam shift of only $\approx 50 \mu m$
## Step-Frequency Tunable Coaxial-Cavity Gyrotron

226.6 GHz < 237.5 GHz < 248.4 GHz

<table>
<thead>
<tr>
<th>Freq. [GHz]</th>
<th>226.6</th>
<th>228.6</th>
<th>230.6</th>
<th>232.5</th>
<th>233.5</th>
<th>235.5</th>
<th>237.5</th>
<th>239.5</th>
<th>241.5</th>
<th>242.5</th>
<th>244.5</th>
<th>246.4</th>
<th>248.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆f [GHz]</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>1.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>1.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Cavity Mode</td>
<td>TE\textsubscript{46,28}</td>
<td>TE\textsubscript{47,28}</td>
<td>TE\textsubscript{48,28}</td>
<td>TE\textsubscript{49,28}</td>
<td>TE\textsubscript{47,29}</td>
<td>TE\textsubscript{48,29}</td>
<td>TE\textsubscript{49,29}</td>
<td>TE\textsubscript{50,29}</td>
<td>TE\textsubscript{51,29}</td>
<td>TE\textsubscript{49,30}</td>
<td>TE\textsubscript{50,30}</td>
<td>TE\textsubscript{51,30}</td>
<td>TE\textsubscript{52,30}</td>
</tr>
<tr>
<td>Rel. Caust Rad. $C_c$</td>
<td>0.305</td>
<td>0.309</td>
<td>0.313</td>
<td>0.317</td>
<td>0.302</td>
<td>0.306</td>
<td>0.310</td>
<td>0.314</td>
<td>0.317</td>
<td>0.304</td>
<td>0.307</td>
<td>0.311</td>
<td>0.315</td>
</tr>
</tbody>
</table>

\[ f_0 - 11 \text{ GHz} \quad f_0 \quad f_0 + 11 \text{ GHz} \]

Max. deviation of $C_c$ is 2.8 %, therefore horizontal output beam shift of max. $\approx 2 \text{ mm}$
**TE\textsubscript{49,29}-Mode Coaxial Cavity**

Preliminary cavity design for a coaxial gyrotron operating in the TE\textsubscript{49,29} mode. Outer wall is shown in blue (upper edge), the tapered coaxial insert in red (lower edge) and the electron beam in brown.

\begin{align*}
\text{frequency} & \quad = \text{237.5 GHz} \\
R_{\text{cav}} & \quad = 31.78 \text{ mm (loading: 2.0 kW/cm}^2) \\
R_{\text{coax}} & \quad = 8.55 \text{ mm (loading: 0.2 kW/cm}^2) \\
\text{n} & \quad = 91 \text{ longitudinal corrugations (0.3/0.3 mm)} \\
Q_D & \quad \approx 2700 \quad (L_{\text{cyl}} = 15 \text{ mm}) \\
R_{\text{beam}} & \quad = 10.24 \text{ mm}
\end{align*}
Startup Scenario for the $\text{TE}_{49,29}$ Mode

$> 2$ MW output power

$\eta_{el} = 34 \%$ with margins

Initial operating point:

9.58 T, 85.6 keV, 69.3 A,

velocity ratio $\alpha = 1.22$

Assumptions

- 16 % spread in velocity ratio
- infinitely thin beam
- axial B-field not tapered
First Magnet Design

**Difficulty:** 10 Tesla at Ø 270 mm warm bore-hole!

- **9 Main Coils**
- **Gun Coil** (subject to discussion)

**Coil Currents:** ~ 150 A

(ARIADNE)
Coaxial Magnetron Injection Gun (MIG)

- Triode-Type MIG
- Emitter radius: 65 mm
- Emitter width: 4.3 mm
- Laminar beam (at boundary to nonlaminar)
- Velocity ratio ($\alpha$) spread: 3.1 % (Emitter roughness not yet considered)
Multi-Frequency Conventional Cylindrical-Cavity Gyrotron (JAEA Mode Series)

CVD-Diamond Window: $t = 1.861 \text{ mm}$, - 20 dB Reflection Bandwidth = 2.2 GHz

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>Application</th>
<th>Cavity Mode</th>
<th>Bessel Zero Relative Caustic Radius $C_c$</th>
<th>Normalized Window Thickness [$\lambda$]</th>
<th>Window Center Frequency [GHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>136.9</td>
<td>CD, A=2.6</td>
<td>$\text{TE}_{25,9}$</td>
<td>59.8813 $0.4175$</td>
<td>4/2</td>
<td>135.4</td>
</tr>
<tr>
<td>170.0</td>
<td>W7-X UG</td>
<td>$\text{TE}_{31,11}$</td>
<td>74.3257 $0.4171$</td>
<td>5/2</td>
<td>169.2</td>
</tr>
<tr>
<td>203.0</td>
<td>H, A=3.1</td>
<td>$\text{TE}_{37,13}$</td>
<td>88.7696 $0.4168$</td>
<td>6/2</td>
<td>203.0</td>
</tr>
<tr>
<td>236.1</td>
<td>H, A=3.6</td>
<td>$\text{TE}_{43,15}$</td>
<td>103.2132 $0.4166$</td>
<td>7/2</td>
<td>236.8</td>
</tr>
<tr>
<td>269.1</td>
<td>CD, A=4.0</td>
<td>$\text{TE}_{49,17}$</td>
<td>117.6566 $0.4165$</td>
<td>8/2</td>
<td>270.6</td>
</tr>
</tbody>
</table>

Max. deviation of $C_c$ is 0.22%, therefor max. horizontal output beam shift of only $\approx 50 \mu\text{m}$
### Cold Cavity Design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (GHz)</td>
<td>170 / 203 / 236 / 269</td>
</tr>
<tr>
<td>Cavity Mode</td>
<td>$TE_{31,11}, TE_{37,13}, TE_{43,15}, TE_{49,17}$</td>
</tr>
<tr>
<td>Cavity Radius $R_0$ (mm)</td>
<td>20.88</td>
</tr>
<tr>
<td>Beam Radius $R_e$ (mm)</td>
<td>9.13 / 9.10 / 9.06 / 9.04</td>
</tr>
<tr>
<td>L1 (mm)</td>
<td>16</td>
</tr>
<tr>
<td>L2 (mm)</td>
<td>12</td>
</tr>
<tr>
<td>L3 (mm)</td>
<td>16</td>
</tr>
<tr>
<td>D1 (mm)</td>
<td>2</td>
</tr>
<tr>
<td>D2 (mm)</td>
<td>2.5</td>
</tr>
<tr>
<td>$\theta_1/\theta_2/\theta_3$</td>
<td>2.5°/0°/2°</td>
</tr>
<tr>
<td>Diffraction Quality factor $Q_D$</td>
<td>858 / 1175 / 1443 / 1852</td>
</tr>
</tbody>
</table>

![Diagram of cavity geometry and field profile](image-url)
Conventional Cavity $\text{TE}_{43,15}$-Mode Gyrotron Multi-Mode Calculations

- $f_0 = 236.04$ GHz ($\lambda_0 = 1.27$ mm)
- Cavity radius 20.88 mm (loading: 2 kW/cm²)
- Beam radius 9.06 mm
- Operating parameters: 9.130 T, 58 keV, 39 A, velocity ratio $\alpha = 1.25$
- 0.83 MW output power ($\eta_{\text{el}} = 36\%$; with margins)

Multi-mode Self-consistence time dependence calculation using the EURIDICE package supports the single mode stable RF output.
(Main mode: $\text{TE}_{43,15}$, 99 neighboring modes)
Gyrotron Simulations with Realistic Beam Parameters

- With consideration of the *perpendicular velocity spread* (Gaussian Spread)

<table>
<thead>
<tr>
<th>$\beta_1$ spread (rms) (%)</th>
<th>$\alpha$ spread (rms) (%)</th>
<th>Output Power ($P_{out}$) (kW)</th>
<th>Efficiency ($\eta$)(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>829</td>
<td>37.7</td>
</tr>
<tr>
<td>6</td>
<td>15.4</td>
<td>780</td>
<td>36.0</td>
</tr>
<tr>
<td>8</td>
<td>20.5</td>
<td>744</td>
<td>34.7</td>
</tr>
<tr>
<td>10</td>
<td>25.63</td>
<td>700</td>
<td>33.4</td>
</tr>
</tbody>
</table>

- With consideration of the *radial beam width*

<table>
<thead>
<tr>
<th>Radial width (RL = Larmor Radius)</th>
<th>Radial Width/$\lambda_0$</th>
<th>Output Power ($P_{out}$) (kW)</th>
<th>Efficiency ($\eta$)(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2*RL</td>
<td>0.113</td>
<td>827</td>
<td>37.72</td>
</tr>
<tr>
<td>3*RL</td>
<td>0.169</td>
<td>821</td>
<td>37.48</td>
</tr>
<tr>
<td>4*RL</td>
<td>0.225</td>
<td>815</td>
<td>37.15</td>
</tr>
<tr>
<td>5*RL</td>
<td>0.282</td>
<td>801</td>
<td>36.46</td>
</tr>
<tr>
<td>6*RL</td>
<td>0.338</td>
<td>Unstable mode</td>
<td>64------</td>
</tr>
</tbody>
</table>
Output Power and Operating Parameters of Conventional Cavity Gyrotron with Wall Loading $> 2 \text{ kW/cm}^2$

<table>
<thead>
<tr>
<th>Maximum Wall Loading (kW/cm$^2$)</th>
<th>Output Power (kW)</th>
<th>Beam Energy (keV)</th>
<th>Beam Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.00</td>
<td>830</td>
<td>58.00</td>
<td>39.00</td>
</tr>
<tr>
<td>2.30</td>
<td>965</td>
<td>60.00</td>
<td>42.00</td>
</tr>
<tr>
<td>2.48</td>
<td>1050</td>
<td>60.00</td>
<td>47.00</td>
</tr>
</tbody>
</table>
Summary & Acknowledgments

Conclusions

- DEMO-compatible 1 – 2 MW, CW gyrotrons at an operating frequency of 237.5 GHz are under investigation at KIT.

- Mode selection strategy including aspects of multi-frequency and step-tuning operation has been shown in this presentation.

- Design of the other gyrotron components (MIG, quasi-optical converter) is currently progressing.

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