Really, Really Efficient
ECH Heating Systems

Presented by Richard Temkin
MIT Physics Dept. and Plasma Science and Fusion Center

VLT Conference Call
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Topics

- Challenges / Opportunities for ECH Technology
  - DIII-D ECH Upgrade
  - ITER

- Recent Advances for Higher Efficiency
  - Internal Mode Converters
  - Depressed Collector
  - Gyrotron Cavities
  - Transmission Lines

- Efficiency 30 → 40 → 50 → 60 → 70% (?)
6 MW ECH System at DIII-D

Achieved:
• 1 MW
• 110 GHz
• 10 sec

Planned Upgrade to 12 MW using 1.5 MW gyrotrons by 2012
DIII-D ECH System

- Two of the six 1 MW, 110 GHz gyrotrons
Motivation

-The efficiency of 1 MW CW gyrotrons can be low.

- CPI 1 MW, 140 GHz gyrotron efficiency is < 40%.
- But CPI 100 kW, 95 GHz gyrotron efficiency > 50%.
- Why? Physics is not yet fully understood.

-Higher efficiency means:

- Lower heat loading on the collector.
- Smaller power supplies.
- Reduced water flow.
- Lower Cost.
US supplies all transmission lines
- Can we improve the efficiency of the lines?
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Gyrotron Schematic

TE_{22,6} Mode

Gaussian Output Beam

Internal Mode Converter

Superconducting magnet

Mirror 1

Mirror 2

Mirror 3

Mirror 4

Cathode

Cavity

Launcher

Single-stage depressed collector

Gyrotron Schematic

MIT
New Internal Mode Converter Code

- New Launcher Design produces excellent, near-Gaussian microwave beam
- Improves internal mode converter efficiency from 92% to > 98%; critical advance
- In use in US, Europe, Japan
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Depressed Collector

Prime Power = 3.84 MW

Prime Power ~ 2.84 MW

-96 kV

96 kV, 40 A

0 kV

+25 kV, < 10 mA

-71 kV

-71 kV, 40 A

0 kV

0 kV
Experimental Setup

<table>
<thead>
<tr>
<th>Frequency</th>
<th>110 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>1.5 MW</td>
</tr>
<tr>
<td>Voltage</td>
<td>96 kV</td>
</tr>
<tr>
<td>Current</td>
<td>40 A</td>
</tr>
<tr>
<td>Operating Mode</td>
<td>TE&lt;sub&gt;22,6&lt;/sub&gt;</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>3 µs</td>
</tr>
<tr>
<td>Magnetic Field</td>
<td>4.3 T</td>
</tr>
<tr>
<td>Efficiency (w/o Depr. Col.)</td>
<td>40 %</td>
</tr>
<tr>
<td>Efficiency (w/ Depr. Col.)</td>
<td>&gt; 50 %</td>
</tr>
</tbody>
</table>
Max. power of 1.5 MW obtained at 96 kV, 42 A.
Depressed Collector Operation

- $V_{dep}$ is limited to $\leq 25$ kV by the onset of body current.

- Operating point: $1.5$ MW, $50\%$ efficiency

- $V_k = 96$ kV, $I_{beam} = 42$ A

- $V_{dep}$ is limited to $\leq 25$ kV by the onset of body current.
What about theoretically predicted collector depression?

Theory and Experiment

V_{\text{dep}} (kV) vs I_{\text{beam}} (A)

MAGY Prediction

Experimental Results

V_k = 96 kV
After Cavity Interaction

Locations of Cyclotron Resonance

\[ \omega - k_z v_z \approx s \Omega_c / \gamma \]

Power Generated in Cavity

Unwanted power loss after cavity

3 % drop in Power
Theory and Experiment

- Good agreement between experiment and simulation when After Cavity Interaction is included
- Future Work: New gyrotron cavity and waveguide system to eliminate this effect!
110 GHz, 1.5 MW CPI Gyrotron

- 1.3 MW at 96 kV, 40 A (ms pulses)
- 0.5 MW, 10 s at 25 A
- Efficiency = 42%

Achieved

- Sent to DIII-D for test but failed due to vacuum leak
- Rebuild could incorporate these new ideas for high efficiency operation.
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Acknowledgments

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- ITER ECH Technology (ORNL)