High Frequency Gyrotrons and Their Applications

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Michigan Institute for Plasma Science and Engineering Seminar
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• **Introduction to Gyrotrons**
• Gyrotron Physics and Technology
• High Power Gyrotrons
• Applications
Gyrotrons - most powerful MM wave and THz sources

Updated from Granatstein et al. Proc. IEEE 1999
Gyrotron Concept

- MW gyrotron for plasma heating and current drive

JAEDA ITER 1 MW, 170 GHz gyrotron

Gyrotron is an electron cyclotron resonance maser

**Waveguide Mode:**

\[ \omega^2 - k_z^2 c^2 - k_{\perp}^2 c^2 = 0 \]

**Cyclotron Mode:**

\[ \omega - s\Omega / \gamma - k_z v_z = 0 \]

\[ \Omega = eB_0 / m_e \sim 28 \text{ GHz/T} \]

\( s = \text{harmonic number} \)

\( \gamma = (1 - v^2 / c^2)^{-1/2} \)

Lorentz Factor – Relativity
## Gyrotron Devices

<table>
<thead>
<tr>
<th>&quot;0&quot; Typ Devices</th>
<th>MONOTRON</th>
<th>KLYSTRON</th>
<th>TWT</th>
<th>TWYSTRON</th>
<th>BWO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Gyro-Device</td>
<td>GYRO-MONOTRON</td>
<td>GYRO-KLYSTRON</td>
<td>GYRO-TWT</td>
<td>GYRO-TWYSTRON</td>
<td>GYRO BWO</td>
</tr>
<tr>
<td>Model RF-Field Structure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model Orbital Efficiency</td>
<td>0.42</td>
<td>0.34</td>
<td>0.7</td>
<td>0.6</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Gyro-TWT: $\omega = \gamma^2 \Omega_c$

Waveguide Mode

Fast Cyclotron Mode

Velocity of Light Line

E.M. Wave

E-Beam

Gyro-BWO: $\omega < \Omega_c$

$\left\{ \begin{array}{l} v_\parallel > 0 \\ v_\perp < 0 \end{array} \right.$

Waveguide Mode

Velocity of Light Line

E.M. Wave

E-Beam

Flyagin IEEE MTT 1977
Topics

- Introduction to Gyrotrons
- **Gyrotron Physics and Technology**
- High Power Gyrotrons
- Applications
Diode Magnetron Injection Gun for a 110 GHz Gyrotron

- Adiabatic compression of annular electron beam from the cathode to the resonator
  - Conservation of $v_{\perp}^2 / B$; increase of $v_{\perp}$
  - Low velocity spread required

$V_a = 96$ kV
$I_{beam} = 40$ A
Interaction Structure

- Open Resonator with cutoff towards the electron gun
- Beam radius is optimized to interact with the desired mode

**TE\textsubscript{22,6,1} Cavity at 110 GHz**

- There are 282 modes at lower frequency than the TE\textsubscript{22,6} mode!
Linear Theory: Starting Current and Mode Competition
The equations of motion of an electron

\[ \frac{d\epsilon}{dt} = -e\vec{v} \cdot \vec{E} \]

\[ \frac{d\vec{p}}{dt} = -e\vec{E} - e\vec{v} \times \vec{B} \]

\[ r_\perp = \frac{v_\perp}{\Omega_c} \]

\[ \Omega_c = \frac{eB}{\gamma m_e} \]
Output Coupler

- Internal Mode Converter (IMC) converts the cavity mode into a Gaussian Beam
- Launcher is a waveguide section with profiled walls designed to generate a mode mixture resulting in a Gaussian-like pattern on the surface

J. Neilson, JIMT (2006)
Introduction to Gyrotrons
Gyrotron Physics and Technology
High Power Gyrotrons and Applications
  - Plasma Heating with Megawatt Gyrotrons
  - Spectroscopy with THz Gyrotrons
  - Materials Processing
  - Novel and Future Applications
Megawatt Gyrotrons

Megawatt

Vacuum Devices

Gyrotron

Gridded Tubes

Klystron

Helix TWT

CFA

TWT

BJT

SIT

FET

BWO

Solid State Devices

IMPATT

Average Power (W)

Frequency (GHz)
D-III D 110 GHz ECH System

- Highest Power ECH System
- up to 10 s pulses
- Corrugated aluminum transmission lines propagate HE_{11} mode with low loss

<table>
<thead>
<tr>
<th>#</th>
<th>Frequency</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>110 GHz</td>
<td>1.0 MW</td>
</tr>
<tr>
<td>1</td>
<td>110 GHz</td>
<td>1.2 MW</td>
</tr>
<tr>
<td>1</td>
<td>117.5 GHz</td>
<td>1.5 MW</td>
</tr>
</tbody>
</table>

J. Lohr, General Atomics, 2012
Megawatt Gyrotrons at DIII-D

- 1MW, 110 GHz gyrotron installed in SC Magnet

- 1.2 MW, 110 GHz Gyrotron

K. Felch, EPJ Conf. Web, 2012
W7-X Stellarator Germany

10 MW, 140 GHz ECH System

FZK, CRPP, THALES
US/CPI (0.9 MW, 1800 s)
(0.92 MW, 1800 s)
(cryo-free magnets)

V. Erckmann, W7-X, 2012
ITER ECH System

- Tokamak Assembly Hall
- RF Building
- Tokamak Building
- 5 Launchers (20MW)
- ≤24 Transmission lines
- ≤26 sources (24MW)
- Power Supplies (50MW)

M. Henderson, ITER, 2012
Low Loss Transmission Lines

- 24 MW of gyrotron power at 170 GHz; 20 MW at the plasma
  - Gyrotron Gaussian Beam mode purity >95%
  - Loss budget <17%
- 63.5 mm diameter corrugated Al waveguides transport the HE$_{11}$ mode
- Losses occur due to both ohmic loss and mode conversion loss to non-HE$_{11}$ modes
- US responsible for supplying the transmission lines

E. Kowalski, IEEE MTT, 2010
M. Shapiro, FS&T, 2010
D. Rasmussen, US ITER, 2012
170 GHz, 1 MW JAEA Gyrotron

Previous results

Target Performance for ITER
(>1MW, >500s, >50%)

TE31,8 mode gyrotron
- 1MW/800s
- 0.8MW/1hr operation
- Max. efficiency: ~60%
- Total output energy: >250GJ

Higher power
- Modulation
- Multi-frequency

K. Sakamoto, 2012
170 GHz, 1 MW Gyrotron - Russia

- TE_{25,10} Mode Gyrotron
  - 70kV, 45 A
  - 0.96 MW
  - 55% efficiency
  - 1000 seconds
THz Gyrotrons

- High power at THz freq. is tens to hundreds of Watts
THz Gyrotrons for DNP/NMR

- Transfer of $e^-$ spin polarization to nuclear spin polarization

**DNP signal enhancement = 80**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>140-600 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuning range</td>
<td>~ 1 to 2 GHz</td>
</tr>
<tr>
<td>Power</td>
<td>10 – 100 W (CW)</td>
</tr>
<tr>
<td>Power stability</td>
<td>1% for 24 hours</td>
</tr>
<tr>
<td>Frequency stability</td>
<td>1 MHz</td>
</tr>
</tbody>
</table>

$^{13}$C Chemical Shift (ppm)

20 mM TOTAPOL in frozen glycerol/water with 2 M $^{13}$C Urea

250 GHz Gyrotron for DNP/NMR

- Operation Voltage, $V_0$ (kV) 12
- Beam Current, $I_0$ (mA) 180
- Operating Mode TE$_{521}$
- Gyrotron Tube Output Mode HE$_{11}$
- Magnetic Field, $B_0$(T) 9.0
- Cyclotron Harmonic Number 1
- Output Power (W) 30

- Dynamic Nuclear Polarization NMR yields signal increase up to 600!
- Gyrotron has 3 GHz tuning range

Moving to Second Harmonic: 460 GHz

- $\omega \approx 2\omega_c$ second harmonic
- Gain $\sim (v_\perp/c)^{2n}$
- $(v_\perp/c)^2 = 0.04$ at 12 kV

$B_0 = 8.43 \, T$, $I_b = 100 \, mA$

- Broadband frequency tuning @ $2\omega_c$: 1 GHz

Gyrotron Stability

**Stability**

- 24 hour run at 460 GHz; output power stable to $\pm 0.5\%$

**Bandwidth**

- 140 GHz oscillator bandwidth $< 1 \text{ MHz}$

S-T Han et al., IEEE Trans Plasma Sci 2007
Bruker DNP/NMR Systems

263 GHz for 400 MHz NMR

527 GHz for 800 MHz NMR

Materials Processing Gyrotrons

- Materials Processing
- Gyrotron
- Klystron
- CFA
- Helix TWT
- Grided Tubes
- Vacuum Devices
- Solid State Devices
- IMPATT
- BWO
- FET
- BJT
- SIT

Graph showing average power (W) vs frequency (GHz).
- Non-contact, rapid heating of ceramics, glass, semiconductors
- Power ~ 1 - 20 kW
  - Frequencies ~ 24 to 84 GHz
- Used with materials of low loss tangent at lower frequencies – power absorption increases with frequency
- Large scale applications?

CPI 28 GHz 10 kW Industrial Gyrotron
Gycom 30 GHz Gyrotron and Applicator
Gyrotron Amplifiers

- Applications: radar, spectroscopy
- Amplifiers have new physics challenges:
  - Instabilities; single pass gain; role of velocity spread

\[ \frac{\partial \vec{p}}{\partial t} = -e\vec{v} \times \vec{B}_0 - e\vec{E}_{RF} \]

\[ \omega_c = \frac{eB}{\gamma m_e} \]

Note: \( \omega_c \propto \frac{1}{\gamma} \)
Ultra High Gain Gyro-TWT

- Instability stopped by highly lossy circuit
- 93 kW, 70 dB gain at 35 GHz, with 3 GHz Bandwidth

Gyrotron Amplifier Research at MIT

- High power microwave amplifiers for time-domain DNP NMR spectroscopy based on novel structures

140 GHz Gyrotron Amplifier
Confocal Structure
34 dB Gain, 820 W

250 GHz Gyrotron Amplifier
Photonic Band Gap Structure
38 dB Gain, 45 W

Electron gun
6 T magnet
Output window
Power supplies and control
25 W / 139-141 GHz EIK tunable source
TE\textsubscript{03}-Like Mode

- Defect region in photonic structure confines waveguide mode

Circular Waveguide: TE\textsubscript{03} Mode

PBG Waveguide: TE\textsubscript{03}-like Mode

10 mm

4 mm
Experimental Setup

- 9.6 T Magnet
- Electrode Gun
- HV Modulator
- Transmission Line
- Solid State Source
  30 mW 248 GHz – 258 GHz
- Gyrotron Amplifier
- Heterodyne Frequency Detector
- Control System

9.6 T Magnet
Electrode Gun
Heterodyne Frequency Detector
Control System
Peak Power and Gain

- 7.5 mW Input Power (after isolator)
- 45 W Output Power
- 37.8 dB Gain (50 dB Circuit Gain)
- Bandwidth = 400 MHz, limited by input coupler

$\begin{align*}
    f &= 247.7 \text{ GHz} \\
    V_k &= 32 \text{ kV} \\
    I_b &= 0.345 \text{ A} \\
    \alpha &= 1.12 \\
    B_0 &= 8.90 \text{ T}
\end{align*}$

Novel Applications
Imaging and Inspection

- 200 – 400 GHz gyrotron radiation images material on a conveyor belt
  - Application to the food industry
- Metal or other foreign objects are identified

S-T Han, J. Phys. Soc. Korea 2012
S-T Han, IRMMW-THz Conf. 2011, 2012
MIT Study of Air Breakdown

- Air breakdown using 1 MW, 110 GHz pulsed (3 µs) gyrotron

**Open-shutter photographs of free-space breakdown.**

- 2D arrays, 50-100 filaments
- Quarter-wavelength separation
  - $\lambda/4 \sim 0.68$ mm

Y. Hidaka, PRL, 2008
J. Hummelt, PoP, 2012
Radioactive Material Detection

- 210 kW, 670 GHz gyrotron built with a pulsed solenoid
- Remote detection of radioactive materials
- Seed electrons produced by radioactivity will allow air breakdown by the THz radiation, leading to detection

G. Nusinovich, JIMT, 2011
M. Glyavin, APL, 2012
Rocket Launcher

Beamed Energy Propulsion Concept

Lab test of rocket at JAEA by Univ. Tokyo team

J. Oda, JAEA, 2012

Rocket Launch – Artist’s Concept, NASA

A. Murakami, AIAA, 2012
Conclusions

- Gyrotrons are the most powerful sources of radiation in the millimeter wave and the Terahertz regions
- Gyrotron oscillators have three major applications
  - Plasma Heating
  - Materials Processing
  - Spectroscopy including DNP/NMR
- Gyrotron amplifiers are less well developed but have significant applications
  - Radar, Spectroscopy
- High power gyrotrons and applications have a promising future!
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