A sixth-harmonic magnetron cavity gyrotron has been built and is in the testing stage at UCD that is excited by a 70 kV, 3.5 A, axis-encircling electron beam produced by a state-of-the-art Northrop Grumman Cusp gun.

The W-Band slotted sixth-harmonic gyrotron is predicted to generate 40 kW with a device efficiency of 16%.

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## W-Band Sixth-Harmonic Gyrotron

<table>
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<th>Objectives</th>
<th>12-Vane Slotted Circuit</th>
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<tr>
<td>• Reduce magnetic field needed by 91 GHz gyrotrons in order to make HPM systems lighter and more practical</td>
<td><img src="image" alt="Diagram of 12-vane slotted circuit" /></td>
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<tr>
<td>• Develop 25-100 kW W-band high harmonic gyrotron</td>
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<td>• Basis for high-harmonic gyro-amplifiers</td>
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## Approach

- Operation at $s^{th}$-harmonic reduces magnetic field by factor of $s$
- Slotted circuit enhances interaction
- Cusp gun produces needed axis-encircling electron beam

## Accomplishments

- Received two Northrop Cusp guns
- 91 GHz 6$^{th}$-harmonic gyrotron design
  - 50 kW with 20% efficiency
  - Circuit has been fabricated
- 94 GHz 8$^{th}$-harmonic gyrotron design
  - Employs permanent magnet
Motivation -- 91 GHz Sixth-Harmonic Gyrotron

• Why 91 GHz?
  - Low attenuation in atmosphere

• Why Gyrotron?
  - Proven high efficiency source

• Why High Harmonic?
  - Reduces magnetic field requirement by harmonic number

Applications of Lightweight 91 GHz Sixth-Harmonic Gyrotron

• High resolution radar
• Radar tracking of space debris
• Atmospheric sensing, e.g., ozone mapping
• Material processing, e.g., high quality ceramics
Synchronism

Derivation of Harmonic Gyrotron Resonance Condition

\( \text{TE}_{m1} \text{ Wave: } E_\theta = E_o J'_m (k_r r) e^{-i(\omega t - k_\| z - m\theta)} \)

For Synchronism:

\( (\omega t - k_\| z - m\theta) = \text{constant} \)

\[ \frac{d}{dt} [\omega t - k_\| z - m\theta] = [\omega - k_\| \Omega - m\Omega_c] = 0 \]

Use: \( \theta = \Omega_c, \parallel = v_\parallel \)

Yields: \( \omega = m\Omega_c + k_\| v_\parallel \)
Electron Bunching

Axis-Encircling Beam Interacting with TE_{41} Mode

Beam progression through cavity leading to saturation
Slotted $\pi$ Mode

Axis-encircling electrons interacting with 12 vane slotted circuit

Slotted cavity provides
- Stronger interaction
- Higher device efficiency
- Lower start-oscillation current

$\pi$-mode yields strongest interaction
Projection Description / Overview

Innovative Sixth-Harmonic Slotted Gyrotron is under Development
- 91 GHz
- 50 kW
- 16% efficiency

Fabricated 91 GHz Gyrotron Circuit
UCD Slotted Cavity

Circuit Cross Section

Fabricated by Electric Discharge Machining
Frequency Scan of Modes in Slotted Cavity

- Cavity modes were measured using transmission through two sidewall couplers
- Lowest order axial mode for each series is shown below
Device will Generate 91 GHz Only

**Dispersion Diagram**

**Modes in UCD Slotted Circuit**

Mode Selection:
For axis-encircling electrons, interaction only for $m = s$
Predicted Gyrotron Power Curve

Fast-Timescale Large-Signal Code was Employed to Evaluate Slotted Gyrotron

6th Harmonic Output Power

![Graph showing 6th harmonic output power with efficiency and power output as variables.]

Parameters:
- Beam Voltage: 70 kV
- Beam Current: 3.5 A
- Velocity Ratio, $v_\perp/v_z$: 2.0
- Velocity Spread, $\Delta v_z/v_z$: 10%
- Magnetic Field: 6.2 kG
- Number of Vanes: 12
- Vane Depth, $b/a$: 1.25
- Inner Vane Radius, $a$: 1.9 mm
- Cavity Length, $L$: 3.1 cm
- Unloaded Q, $Q_o$: 3500
- Loaded Q, $Q_L$: 950
- Efficiency, Electron: 22%
- Efficiency, Device: 16%
- Efficiency, Depressed: 32%

40 kW Output Power is Predicted
Diffraction Coupled Cavity

Cavity $\pi$-Mode Transforms into TE$_{61}$ Mode as Slotted Circuit Tapers into Smooth Bore

Axis-Encircling Electron Beam

Cutoff Drift Tube

Slotted Cavity

Output Taper

Spent Electron Beam

RF Output

Smooth-Bore Output Tube
Cavity and Taper

*Slotted Cavity*

*Output Taper*
$\text{TE}_{61}/\text{TE}_{11}$ Beat-Wave Mode Converter

$\text{TE}_{61}$ Output Wave will be Transformed into Lowest Order $\text{TE}_{11}$ Mode

Mode Converter is the Beat Wave between Input and Output Waves

Previous $\text{TE}_{61}/\text{TE}_{11}$ Mode Converter Yielded 98% Efficiency

**Schematic of $m=7$ Converter**

**Predicted Bandwidth ($\eta=93\%$)**
Northrop Grumman Cusp Gun

State-of-the-art Cusp Gun will produce axis-encircling electron beam for UCD sixth-harmonic gyrotron
Cusp Gun Electron Trajectory

Simulation of cusp electron gun profile

Parameters: 70 kV, 3.5 A, $v_{\perp}/v_z = 1.5$, $\Delta v_z/v_z = 5\%$
Refrigerated Superconducting Magnet
Superconducting Magnet

Cusp Magnetic Gradient is Produced by
- Two Superconducting Coils and
- Two Copper Coils

![Graph showing the cusp magnetic gradient produced by two superconducting coils and two copper coils. The graph has a y-axis labeled 'Total' and an x-axis labeled 'z (cm).' The graph shows a combination of curves representing the magnetic gradient at different points along the z-axis.]
Future Work: Permanent Magnet 94 GHz Gyrotron

Eighth-Harmonic Gyrotron Can Employ Permanent Magnet to Generate 94GHz

Parameters

- Beam Voltage: 70 kV
- Beam Current: 3.5 A
- Velocity Ratio, $v_\perp/v_z$: 2.0
- Velocity Spread, $\Delta v_z/v_z$: 10%
- Magnetic Field: 4.6 kG
- Number of Vanes: 16
- Vane Depth, $b/a$: 1.22
- Inner Vane Radius, $a$: 2.4 mm
- Cavity Length: 2.5 cm
- Unloaded Q, $Q_o$: 3000
- Loaded Q, $Q_L$: 1000
- Efficiency, Electron: 13%
- Efficiency, Device: 9%
- Efficiency, Depressed: 20%

20 kW Output Power is Predicted
Summary

• High Harmonic Operation Reduces Magnetic Field Requirement

• Axis-Encircling Beam is Ideal for High Harmonic Interaction

• Slotted Cavity Provides Strong Beam/Wave Coupling

• Innovative Sixth-Harmonic Slotted Gyrotron has Been Designed
  - 91 GHz
  - 40 kW
  - 16% predicted efficiency

• Sixth-Harmonic Slotted Gyrotron has been Fabricated and is Under Test
  - Super-conducting magnet is being used to test gyrotron
  - Northrop Grumman Cusp Gun has been acquired
  - Cusp Gun will produce axis-encircling beam for the device