Gyrotron introduction for ECRIS 2008



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Content created by Steve Cauffman, Monica Blank and Kevin Felch

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Outline

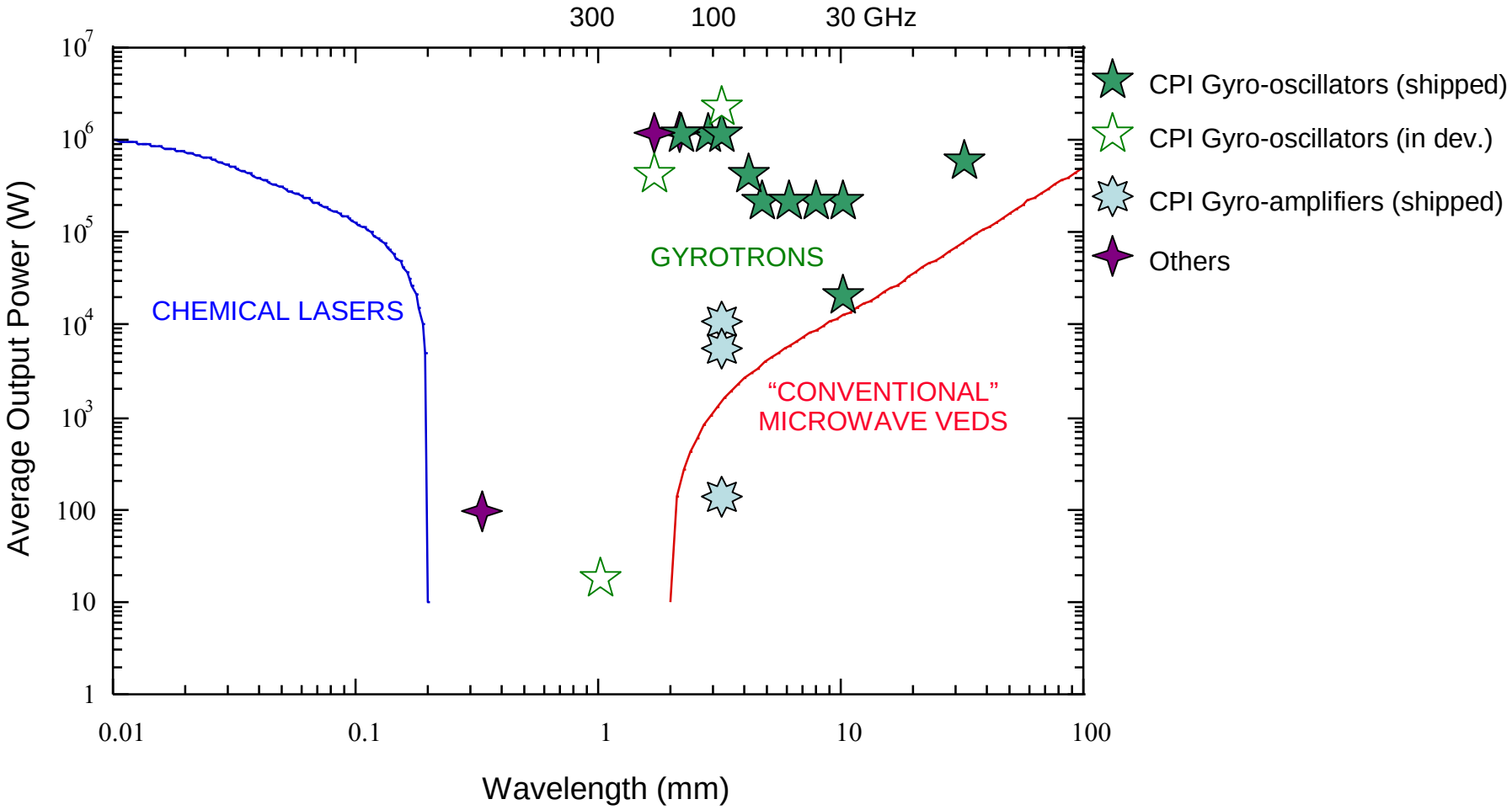


- Background/history
- Theory of operation
- Applications/markets/capabilities

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The Role of Gyrotrons

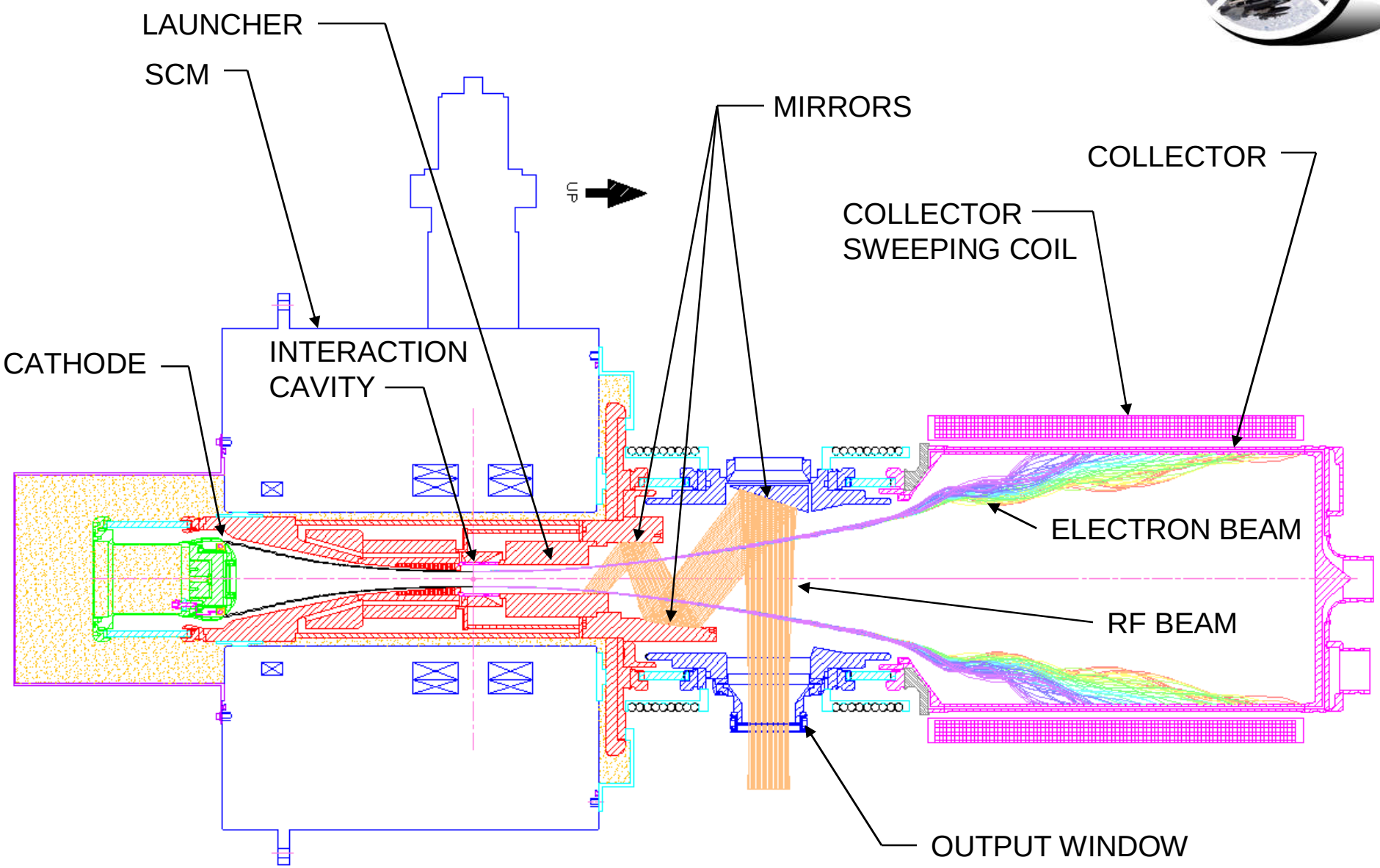
Gyrotrons fill an important gap in the spectrum of electromagnetic sources:



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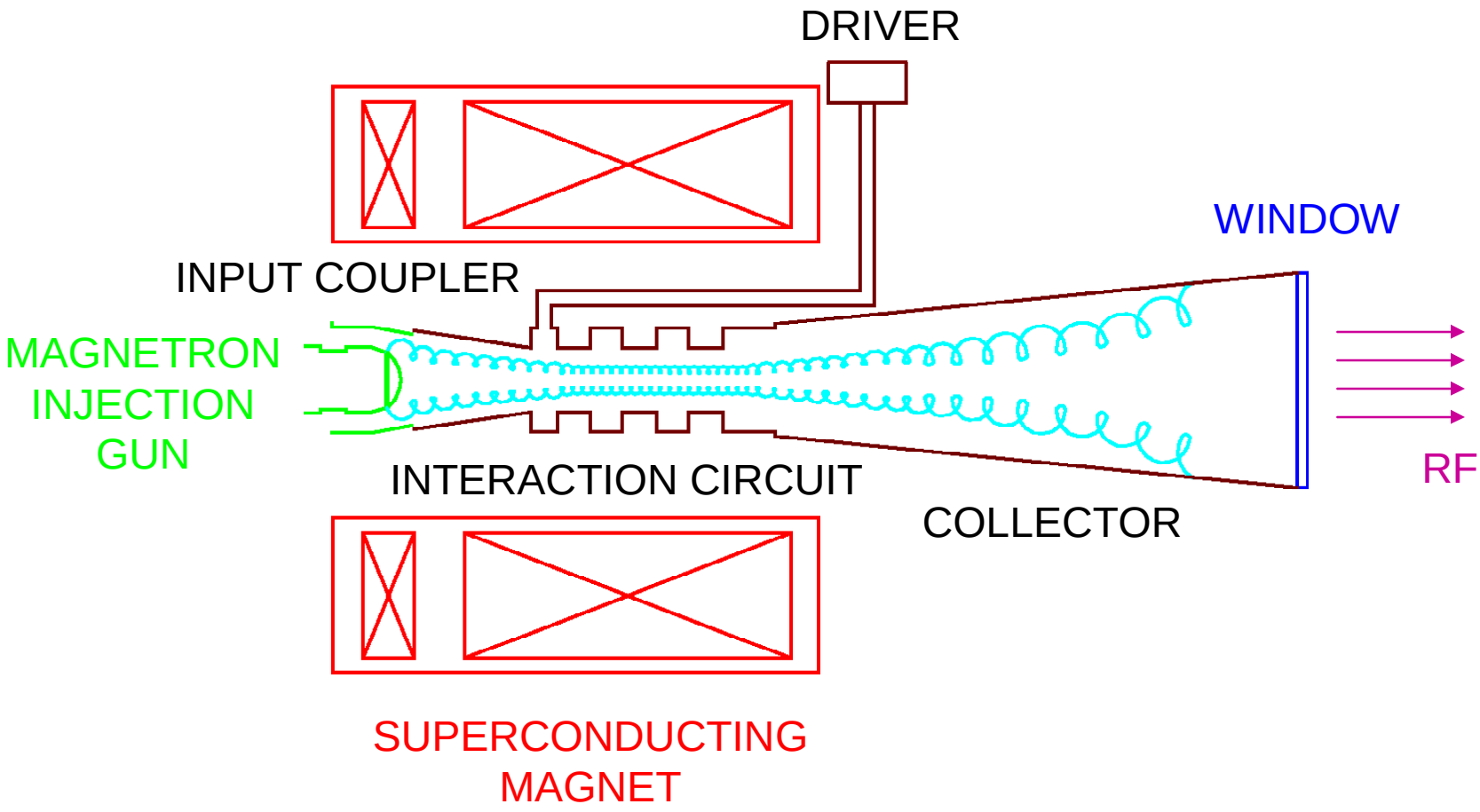
Oscillator Layout Example: VGB-8125





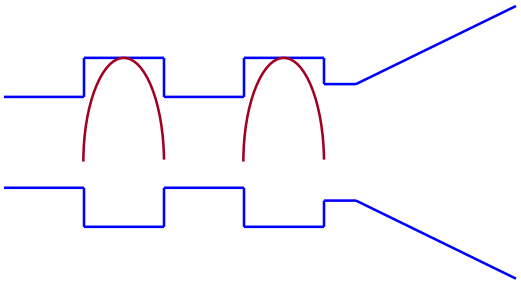
Gyro-Amplifier Schematic

- Gyroklystron:

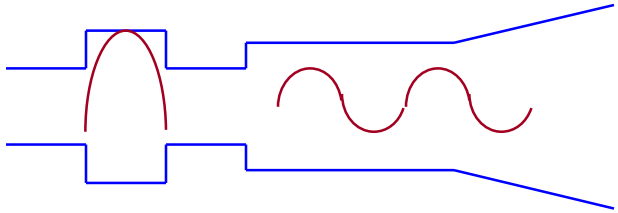


Other Gyro-Amplifier Flavors

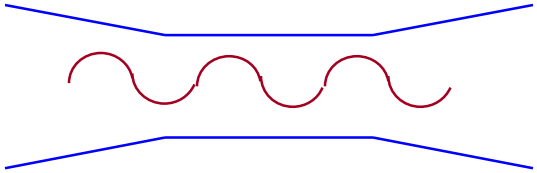
- Bandwidth determines a circuit type
  - Gyro-klystron for < 1% bandwidth
  - Gyro-twystron for 1% to 2% bandwidth
  - Gyro-twt for bandwidths > 2%



GYRO-KLYSTRON



GYRO-TWYSTRON



GYRO-TWT

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Gyrotron Interaction

- electromagnetic mode:

$$\omega^2 = k_\perp^2 c^2 + k_{||}^2 c^2 \approx k_\perp^2 c^2$$

- electron beam mode

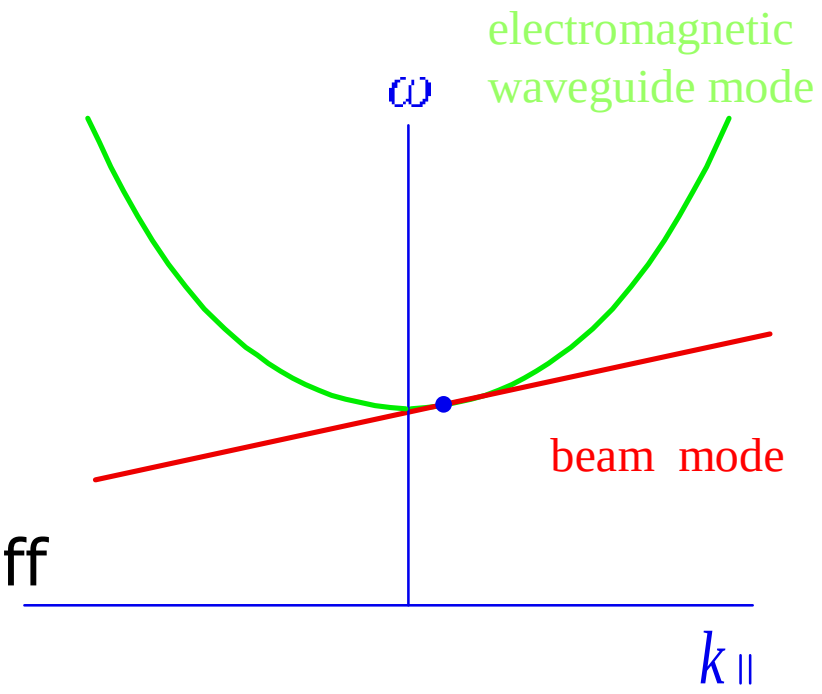
$$\omega - k_{||} v_{||} = \omega_c$$

$$\omega_c = \frac{eB_0}{mc\gamma} \qquad \text{(28 GHz/Tesla)}$$

- interaction occurs near cutoff

$$k_\perp \approx k, \quad k_{||} << k$$

$$v_{ph} = \frac{\omega}{k_{||}} > c$$



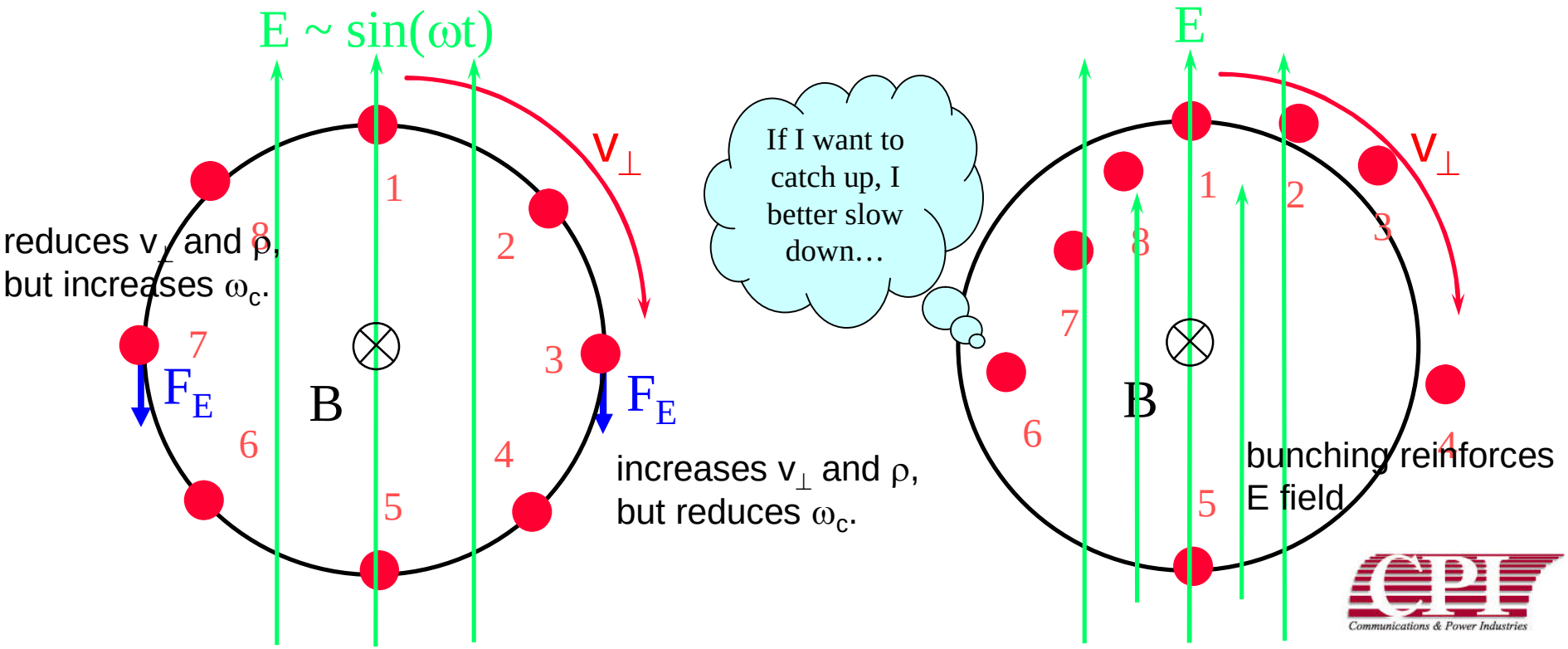
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Electrons in Magnetic Fields

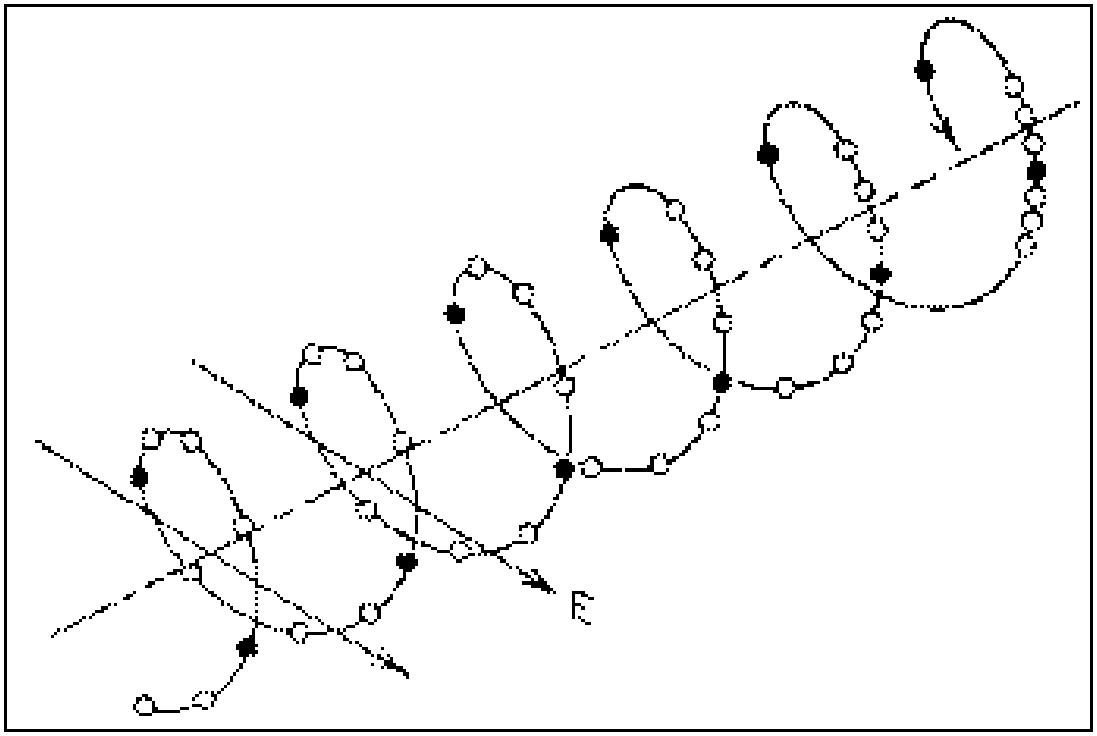


- **F**=q[**E**+(**v**/c)×**B**]
- In a constant B field: $\omega_c = \dfrac{eB_o}{mc\gamma}$
- Cyclotron radius $\rho = v_\perp/\omega_c$
- Dependence of ω_c on γ leads to azimuthal bunching for ω near ω_c.

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \approx 1 + \frac{KE}{512\ \text{keV}}$$



Electron Bunching When $V_{||} \neq 0$



- Oscillating E field leads to phase bunching, which reinforces the field, which leads to more bunching, which reinforces the field even more, which leads to even more bunching, which further enhances the field.

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So….



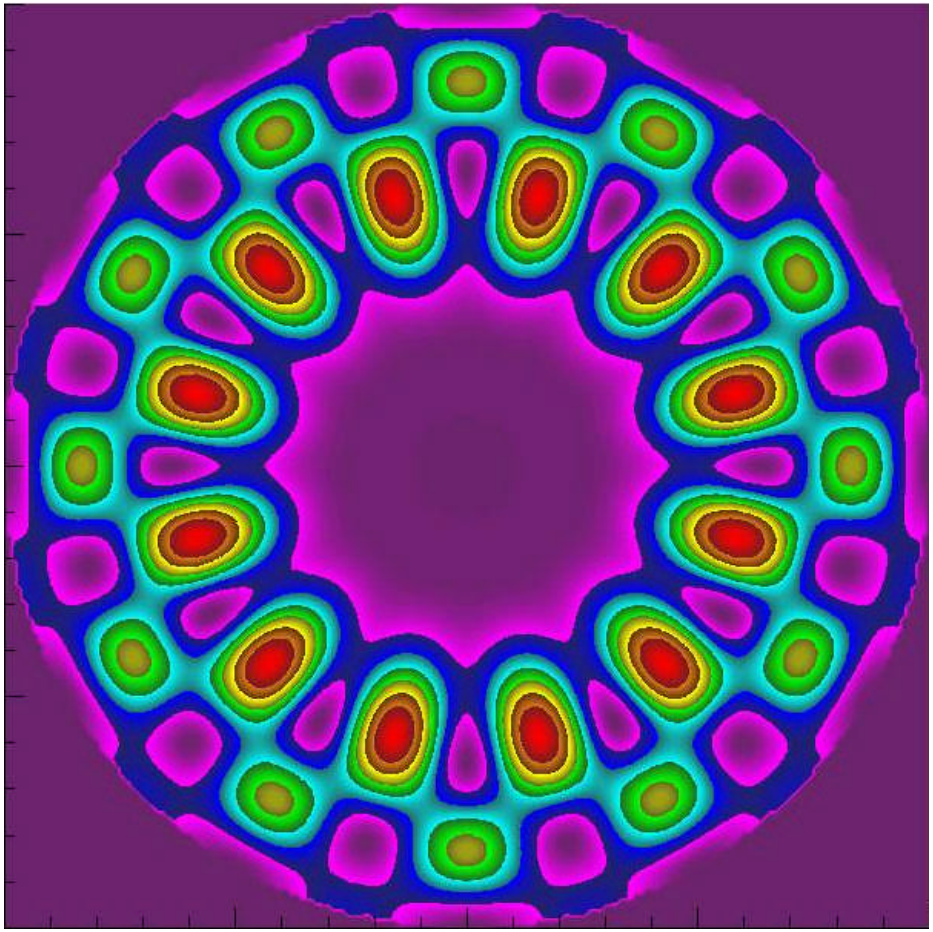
- We need the following setup:
  - A magnetic field such that $\omega_c = \frac{eB_o}{mc\gamma}$ is close to the desired operating frequency.
    - f/B ≈ 28 GHz/Tesla (so 140 GHz requires a 5T magnet)
  - A cavity that will support a resonant *transverse electric* mode at the same frequency.
  - Electrons with lots of transverse energy to transfer to the mode (and located to yield maximum coupling).

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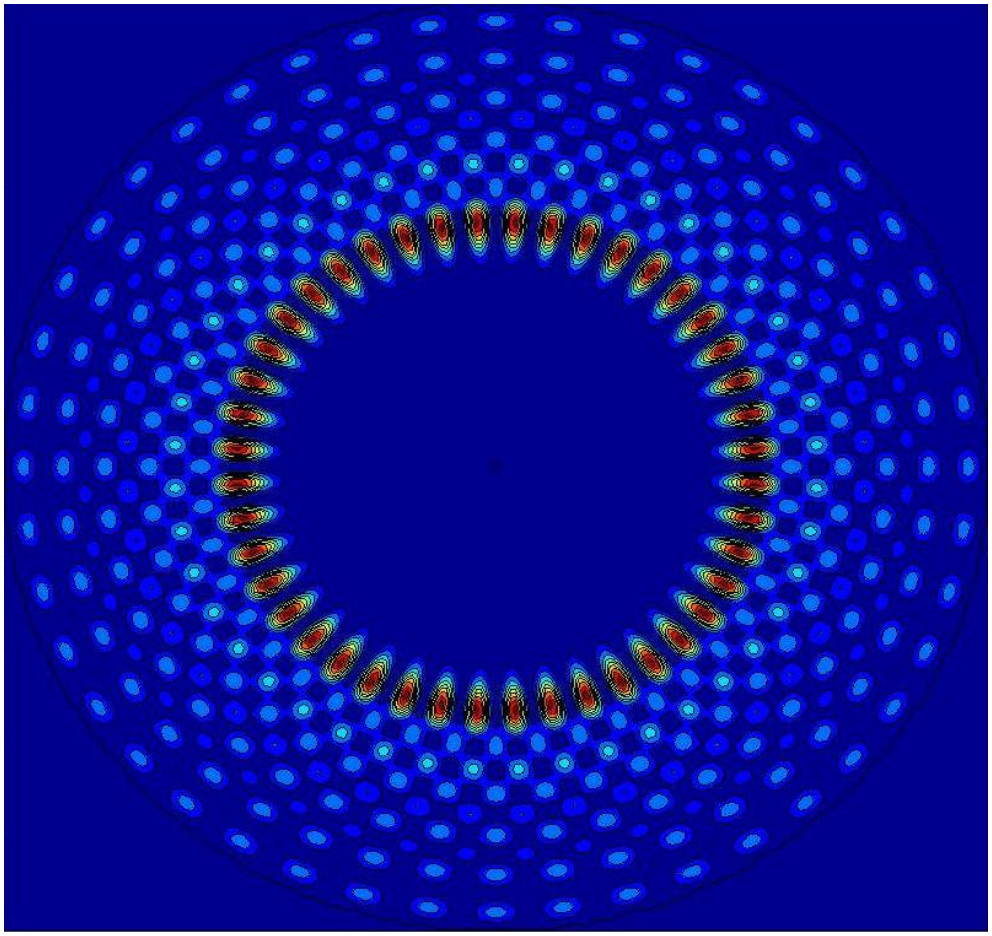
Plus, They're Pretty to Look At

Contours of $|E|^2$ for the…

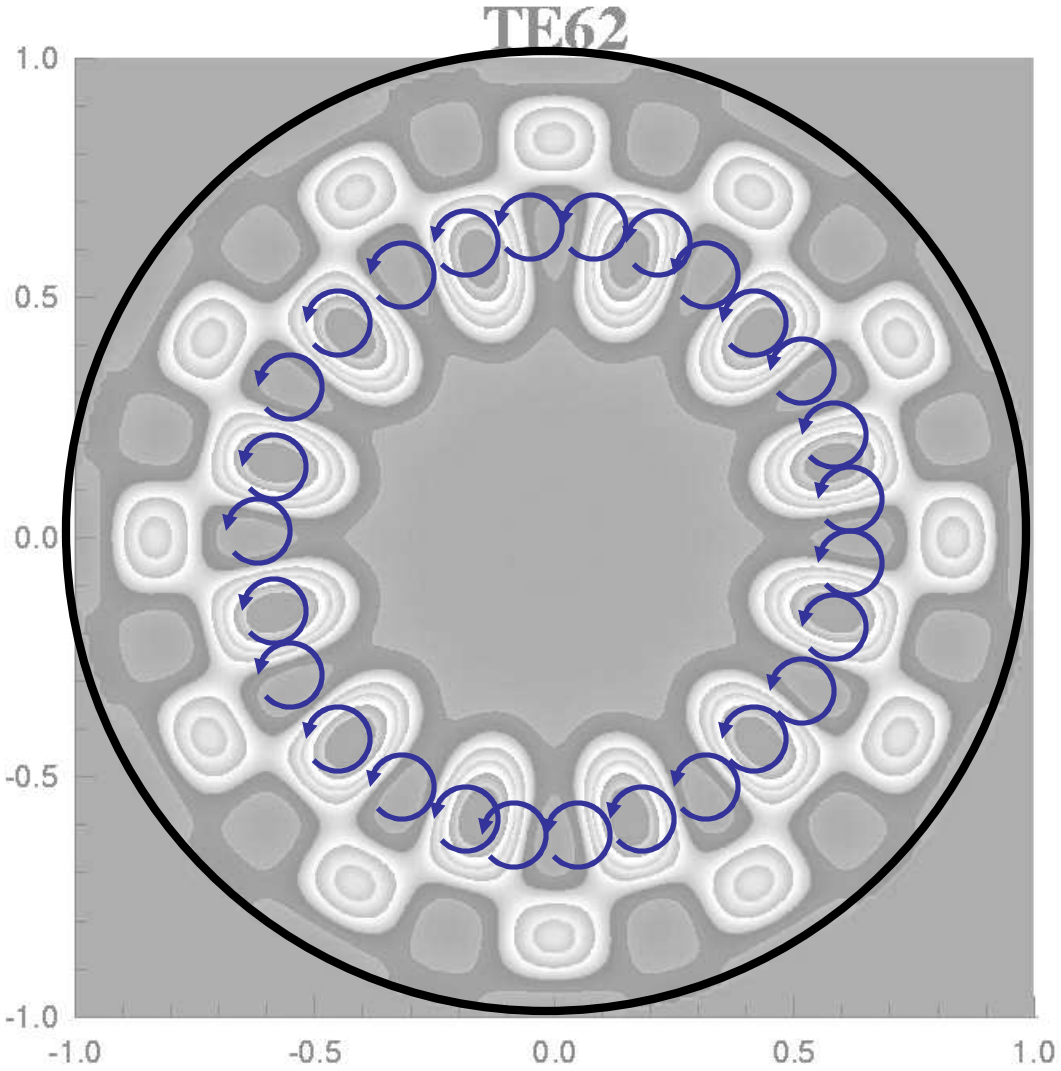
$TE_{6,2}$



$TE_{22,6}$



How to Excite a High Order TE Mode



- To maximize the interaction between the electron beam and the wave, we should:
  - Put the electrons in a ring at the location where $E_{\perp}$ for the desired mode is maximized
  - Choose B such that ω_c is close to the resonant frequency of the desired mode.
  - Give the electrons some perpendicular energy to transfer to the mode.

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Applications & Markets

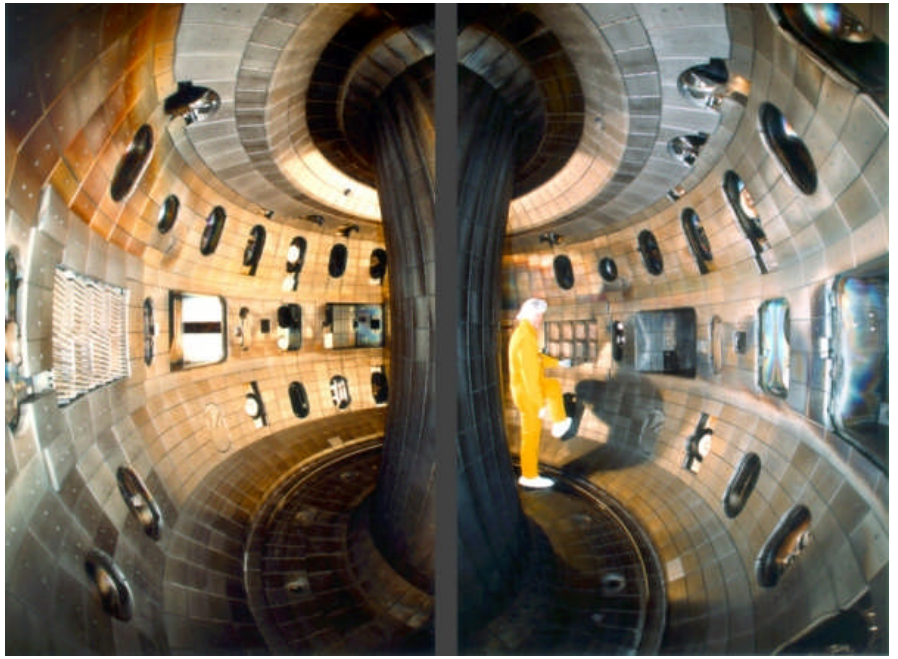


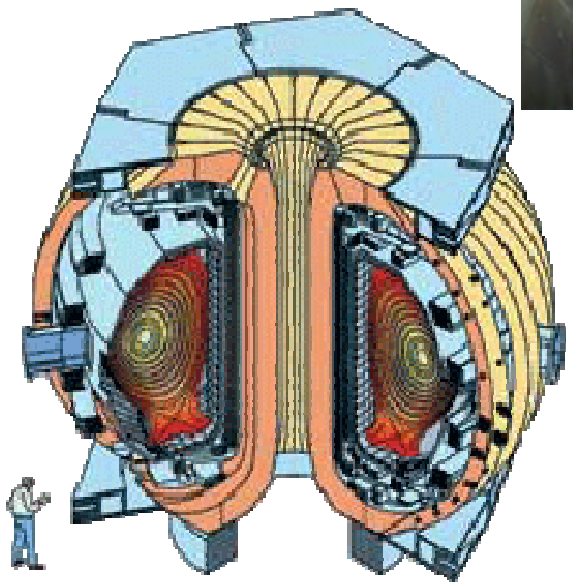
- Fusion plasma heating & current drive
- Human persuasion
- Material processing
- High-resolution radar
- Particle acceleration

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Fusion: DIII-D Tokamak

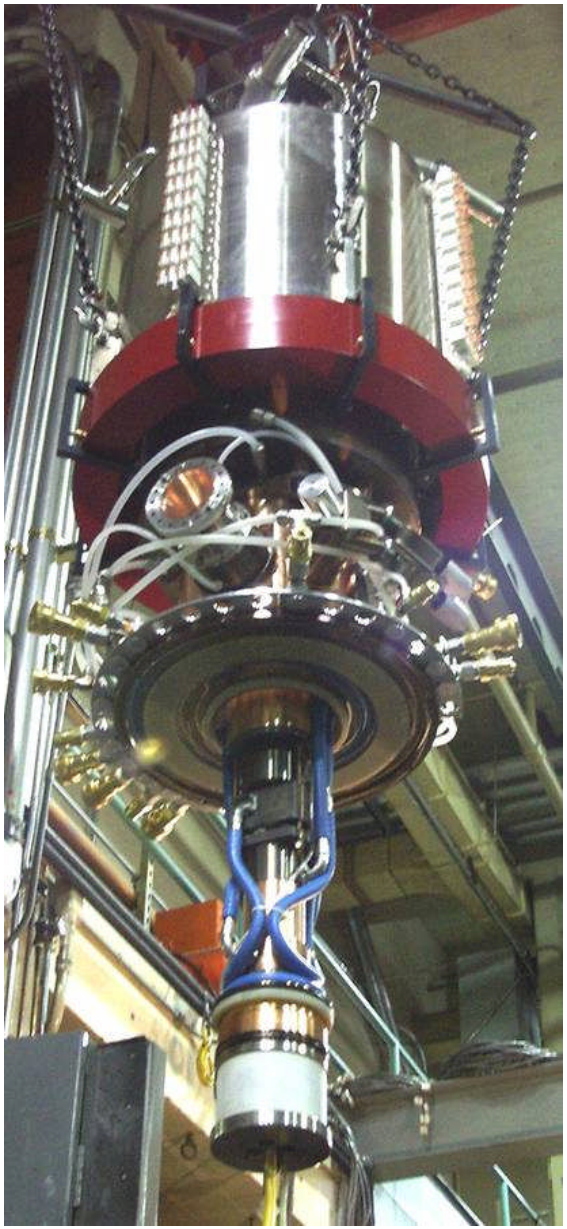
- Experimental vehicle for exploring advanced tokamak operating regimes
- In operation at General Atomics (San Diego) since the 1980s
- Currently boasts the largest array of MW-class CPI gyrotrons
  - 6 x 1 MW
  - 1 x 1.3 MW





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CPI 110 GHz Gyrotrons for DIII-D



- VGT-8110
  - 1 MW, 10 sec
  - 80 kV, 40A
  - Single-anode gun
  - CVD diamond window
  - $TE_{22,6}$ interaction
  - Gaussian output
  - 31% efficiency
- VGT-8115
  - 1.3 MW, 10 sec
  - 96 kV, 40A
  - Depressed collector (25 kV)
  - 45% efficiency



"Active Denial": The Power of Persuasion

- "Active Denial" is a nonlethal weapon program designed to provide an option "between shouting and shooting".

System 1



Systems 1 & 2



Active Denial Gyrotrons



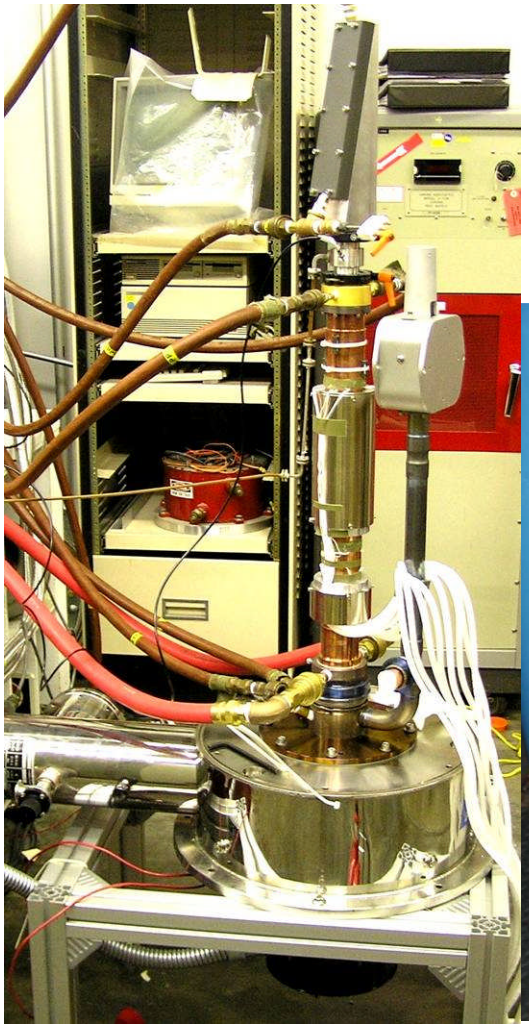
- 95 GHz, 30 kW (VGB-8030)
  - 1 delivered to Raytheon ("Silent Guardian")
  - Stationary "mid-range" system
- 95 GHz, 100 kW (VGB-8095)
  - 4 delivered to Air Force
  - Vehicle-mounted system development
- 95 GHz, 2.5 MW (VGB-8125)
  - Prototype now in factory test for Air Force
  - Airborne development program

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Active Denial Gyrotrons

- Size, weight, and durability are key for mobile apps.

30 kW (VGB-8030)



100 kW (VGB-8095)

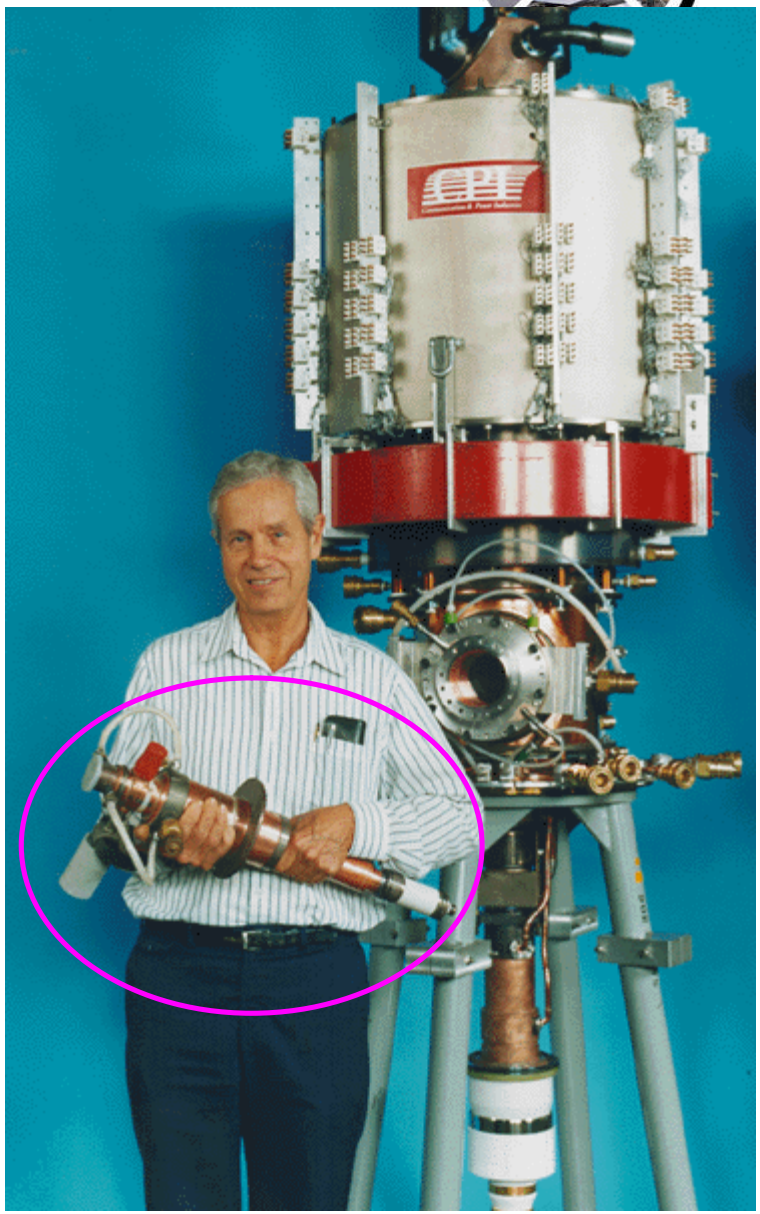


2.5 MW (VGB-8125)



Material Processing

- Ceramic sintering and industrial processing
  - typically requires 10-50 kW at 24-30 GHz
  - advantages of millimeter wave processing over conventional heating include:
    - volumetric heating for finer grain structure, greater fracture strength
    - shorter processing times
  - more uniform heating than with microwaves due to smaller wavelengths
- CPI VGA-8028
  - 28 GHz, 10 kW CW
  - 30 kV, 1.1A, 30% efficiency
  - TE_{02} interaction/output mode
  - 2^{nd} harmonic interaction (5kG magnet)



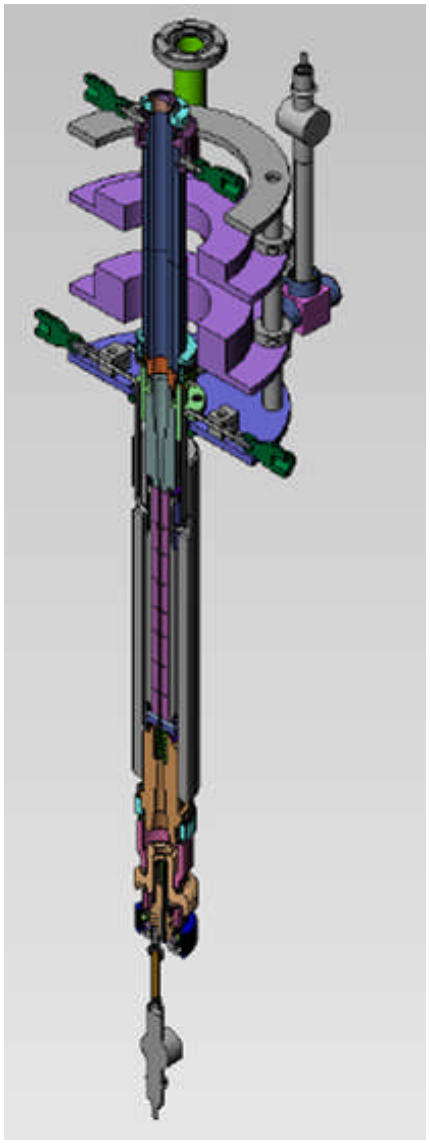
W-Band Gyrotron Amplifier Requirements for Haystack Radar Upgrade



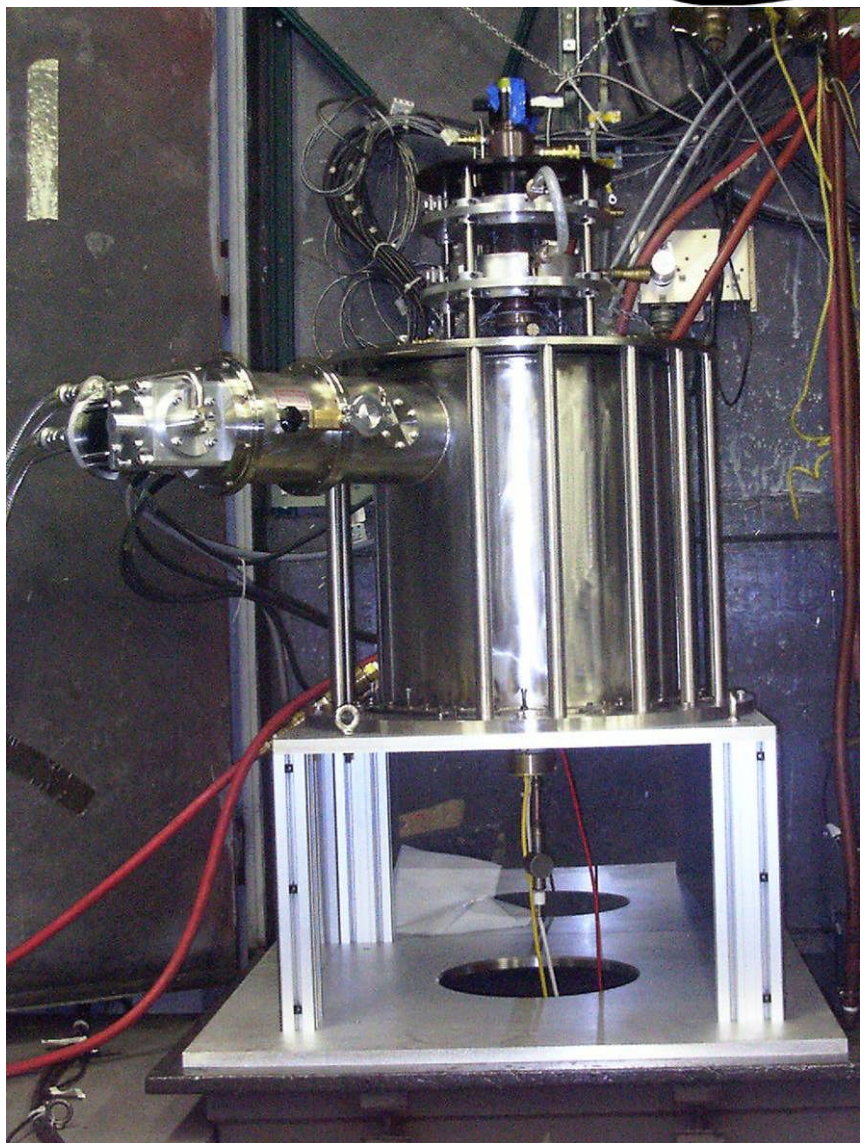
- 8 GHz bandwidth gyro-TWT
  - 500 W peak output power
  - > 250 W from 92 -100 GHz
  - 40% duty factor
  - to be used as driver for a set of…
- 1.5 GHz bandwidth high-power gyrotwystrons (16 total – 4 frequencies)
  - 55 kW peak output power
  - 1.5 GHz -3 dB bandwidth
  - 10% duty factor

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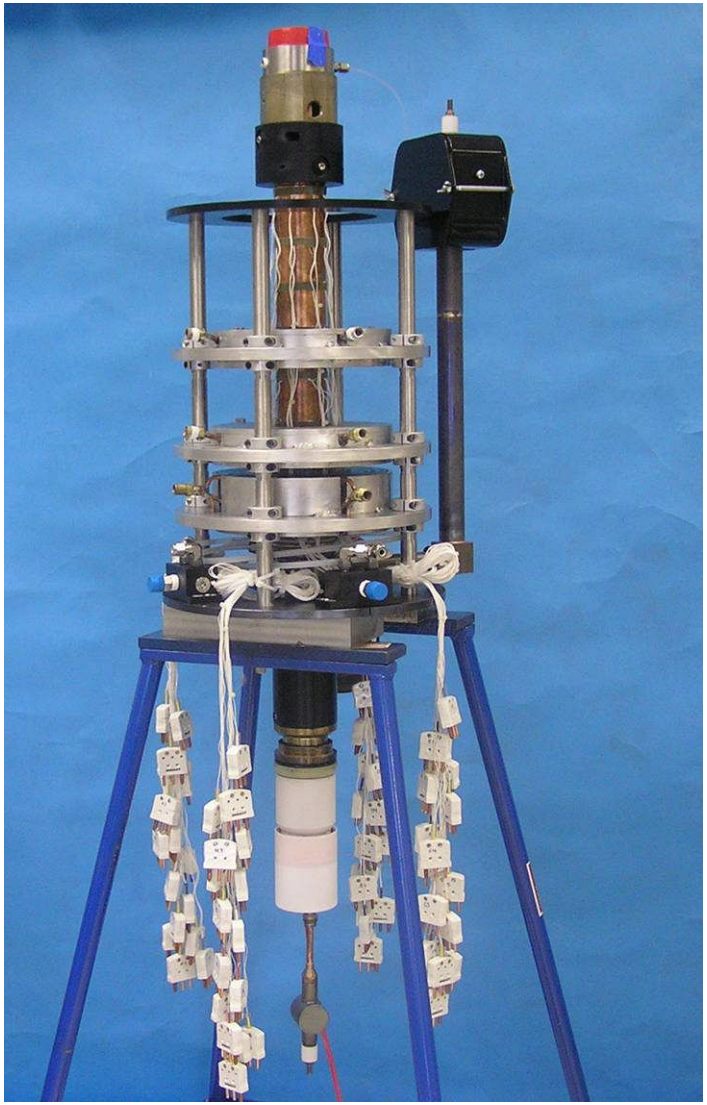
Gyro-TWT Amplifier

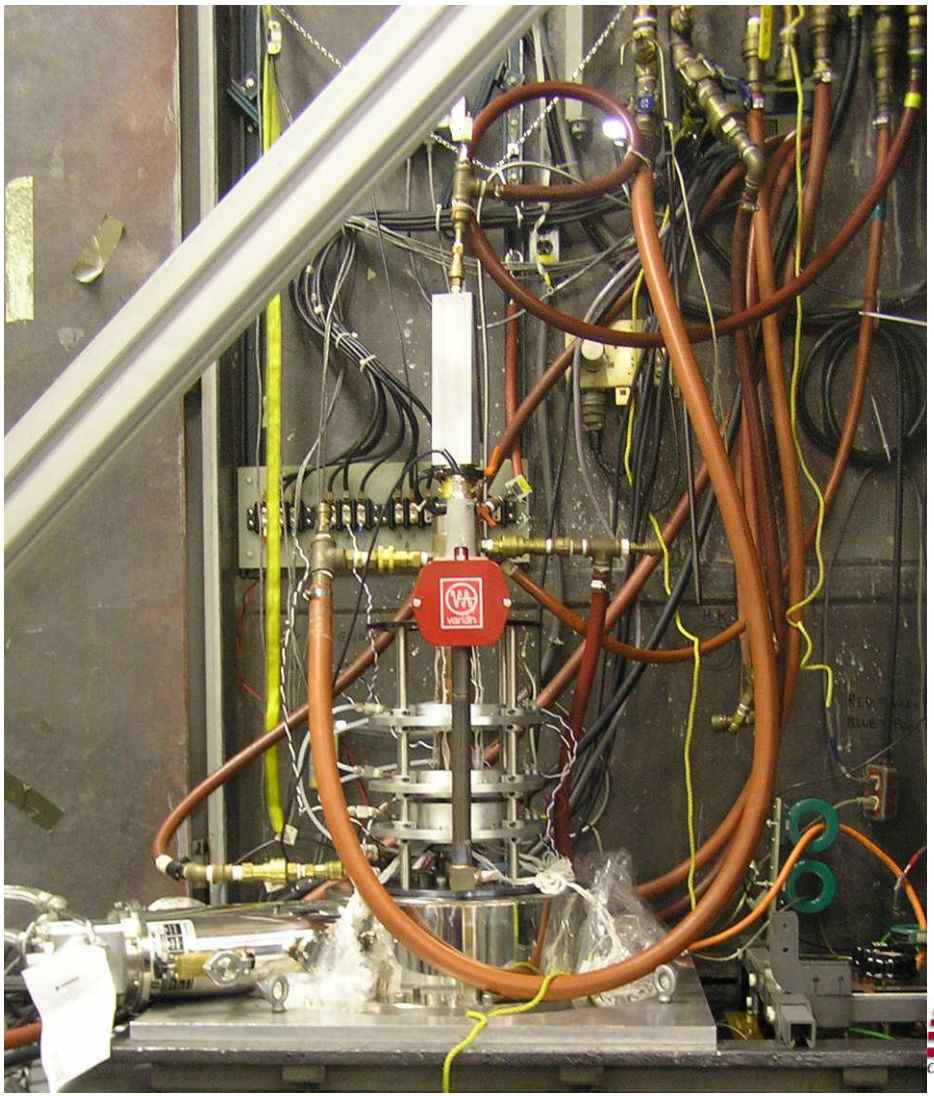






1.5 GHz Bandwidth Gyrotwystrons





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Summary



- Gyrotrons are useful for generating high power at frequencies from 30 GHz to 1 THz
- Applications vary widely, and new ones are emerging.
- Capabilities are expanding rapidly

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