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10-100 kW SUBMILLIMETER GYROTRON

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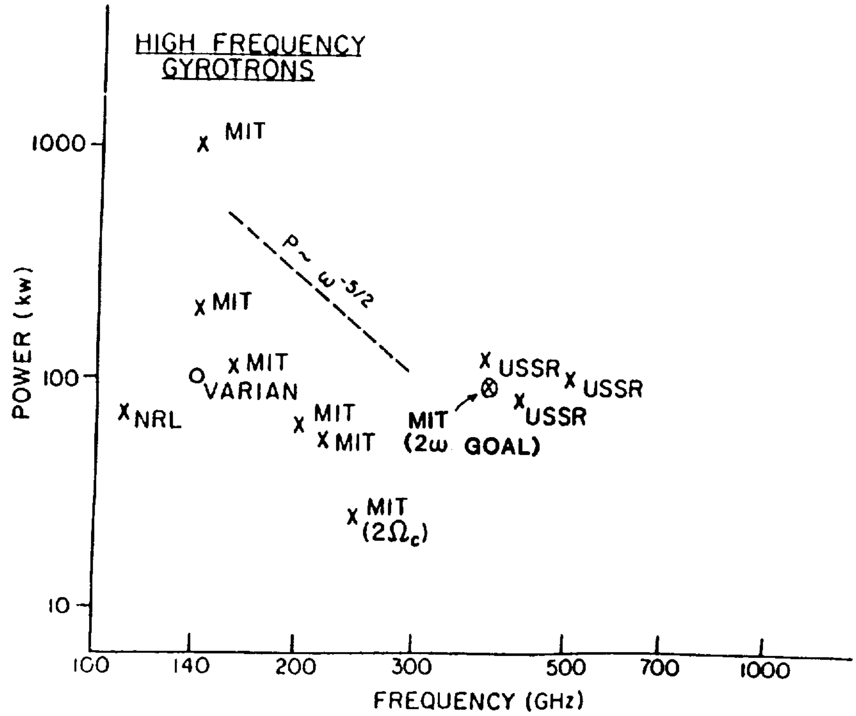
High Frequency High Harmonic Gyrotrons

[$\omega - \kappa_z v_z = N\omega_c$; $N = 1, 2, 3, 4, 5 \ldots$]

- Generalized nonlinear theory applied to gyrotrons for second through fifth harmonics.
- Numerical results for efficiency over a wide range of normalized paramenters have been obtained.
- High maximum efficiencies have been obtained:

Harmonic (N)	$\eta_{\perp\,max}$
2^{nd}	70%
3^{rd}	55%
4^{th}	45%
5^{th}	37%

- Results allow optimization of design of high harmonic gyrotrons.
- Reduced B-field required or go to higher wavelengths (ω, submillimeter).



Observed Second Harmonic Emission

65 kV, 3 A

B (T)	Mode	Frequency (GHz)	Power (kW) ±2 kW
8.40	$TE_{10,3,1}$	417.1	14
7.56	$TE_{16,1,1}$	372.6	3
7.41	$TE_{8,3,1}$	366.9	4
7.38	$TE_{11,2,1}$	363.3	7
6.88	$TE_{10,2,1}$	339.3	4
6.66	$TE_{14,1,1}$	329.6	5
6.14	$TE_{3,4,1}$	301.6	4

Gyrotron Results
Summary

- 750 kW, 140 GHz in 3 μs pulsed operation; 80 kV, 35 A.
- 500 kW step tunable from 140 – 250 GHz.
- 15 kW at 420 GHz at second harmonic.
- 100 kW, 140 GHz CW operation at Varian.

M. I. T.
CARM AMPLIFIER
PROGRAM

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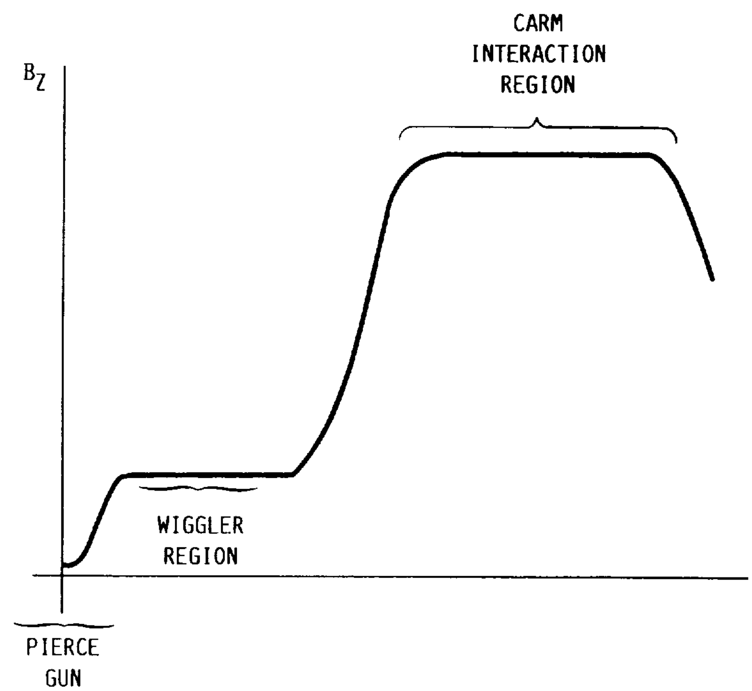
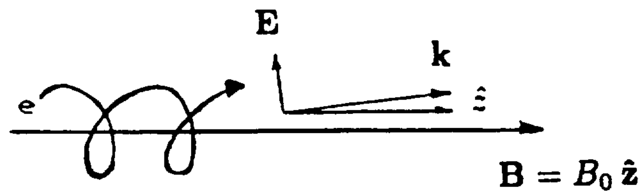
CARM AMPLIFIER EXPERIMENT AT M.I.T.

- 140 GHz AMPLIFIER EXPERIMENT
- TE_{11} OR TE_{12} MODE
- 450 kV PIERCE GUN (PHASE I)
- 700 kV, 50 A ELECTRON BEAM FROM PIERCE GUN (PHASE II)
- $\beta_\perp/\beta_\parallel$ PRODUCED ON BEAM BY WIGGLER



○ INTRODUCTION

- Cyclotron Autoresonace Maser (CARM) also known as Doppler-Shift Dominated Cyclotron Resonance Maser or the Wiggler-Free Free-Electron Laser.
- Basic Configuration:



- Resonance Condition:

$$\omega - k_{\parallel} v_{\parallel} = \frac{\omega_{c0}}{\gamma}$$

where $\omega_{c0} = eB_0/mc =$ cyclotron frequency.

- Doppler shift term large for CARM.
- Define $\beta_{ph} = v_{ph}/c = \omega/ck_{\parallel} =$ wave phase velocity.

$$\beta_{ph} \sim 1 \Rightarrow \textbf{CARM}$$

$$\beta_{ph} \rightarrow \infty \Rightarrow \textbf{GYROTRON}$$

$$\omega = \frac{\omega_{c0}}{\gamma(1 - \beta_{\parallel}/\beta_{ph})}$$

○ CARM Autoresonance Condition

- **For single electron emitting photon:**

$$\Delta E = \hbar\,\omega$$

$$\Delta p_{\|} = \hbar\,k_{\|}$$

$$\Rightarrow \frac{\Delta E}{\Delta p_{\|}} = \frac{\omega}{k_{\|}} = \beta_{ph}\,c = \text{const.}$$

$$\Rightarrow \Delta\left(\gamma_0 - \gamma_0\,\beta_{\|0}\,\beta_{ph}\right) = 0$$

- Constant of Motion: $(\gamma - \gamma\,\beta_{\|}\,\beta_{ph})$

- **Compare with resonance condition:**

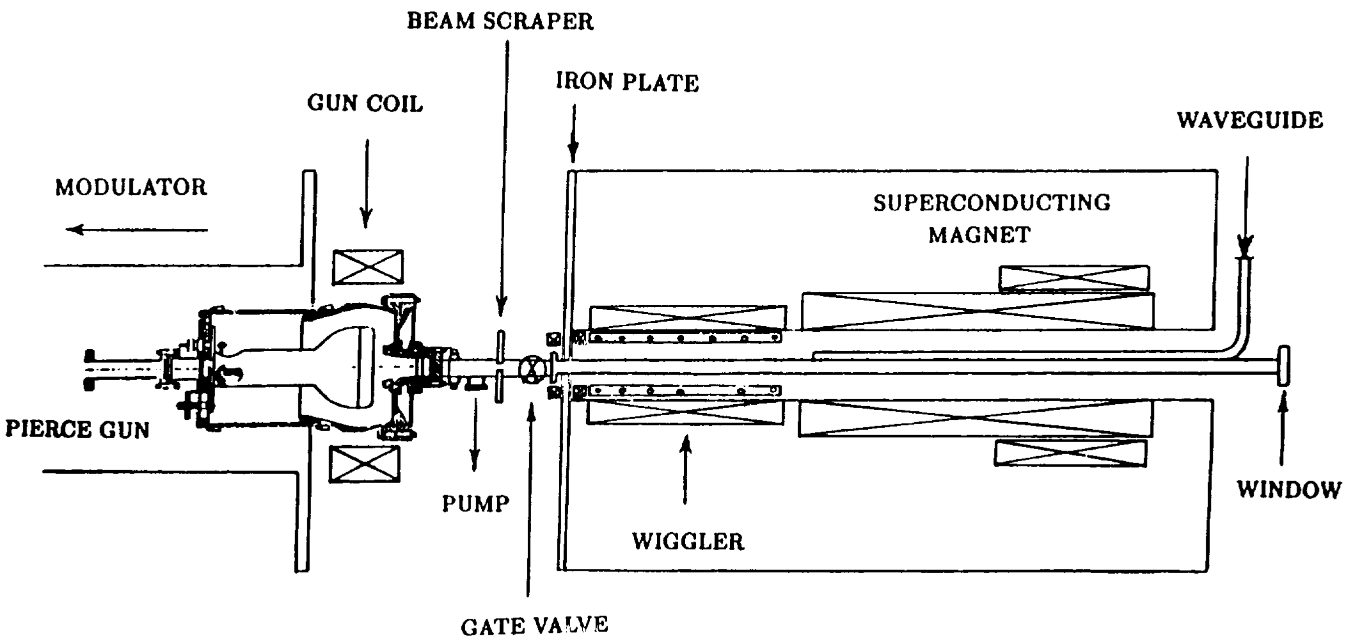
$$\omega = \frac{\omega_{c0}}{\gamma_0(1 - \beta_{\|0}/\beta_{ph})}$$

- For $\beta_{ph} = 1$, particles initially in resonance will remain in resonance as γ decreases. This is termed Autoresonance.

- At autoresonance, change in Doppler shift term is compensated by change in cyclotron resonance term. Azimuthal and axial bunching compensate each other.

- This constant of the motion is valid only for uniform amplitude EM fields.

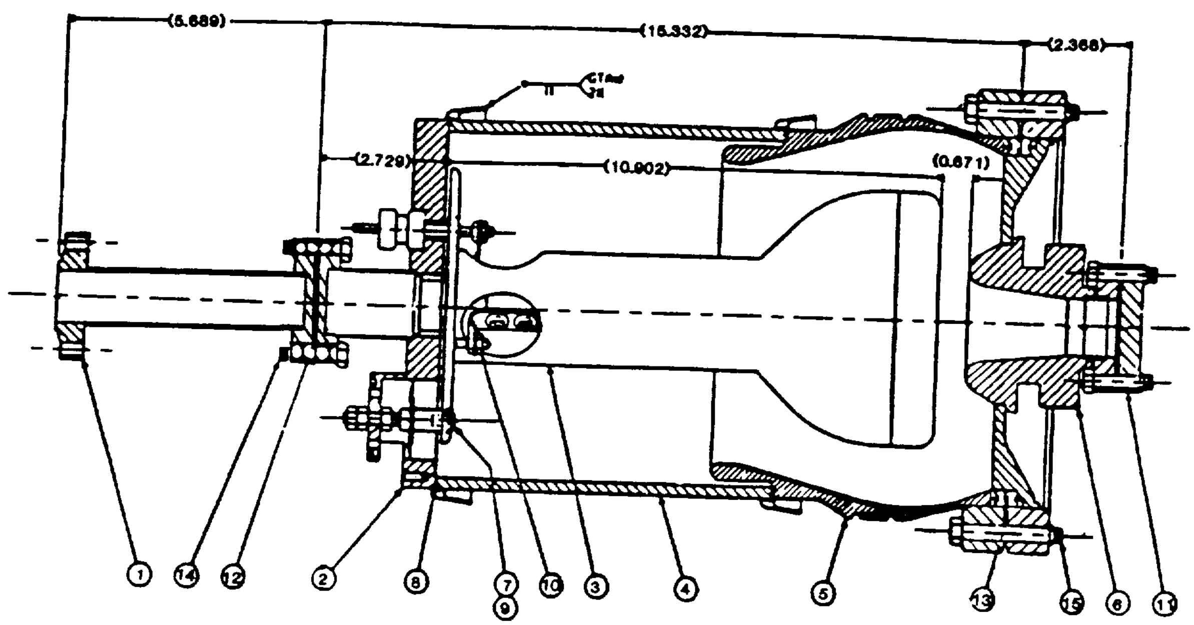
CARM AMPLIFIER SCHEMATIC

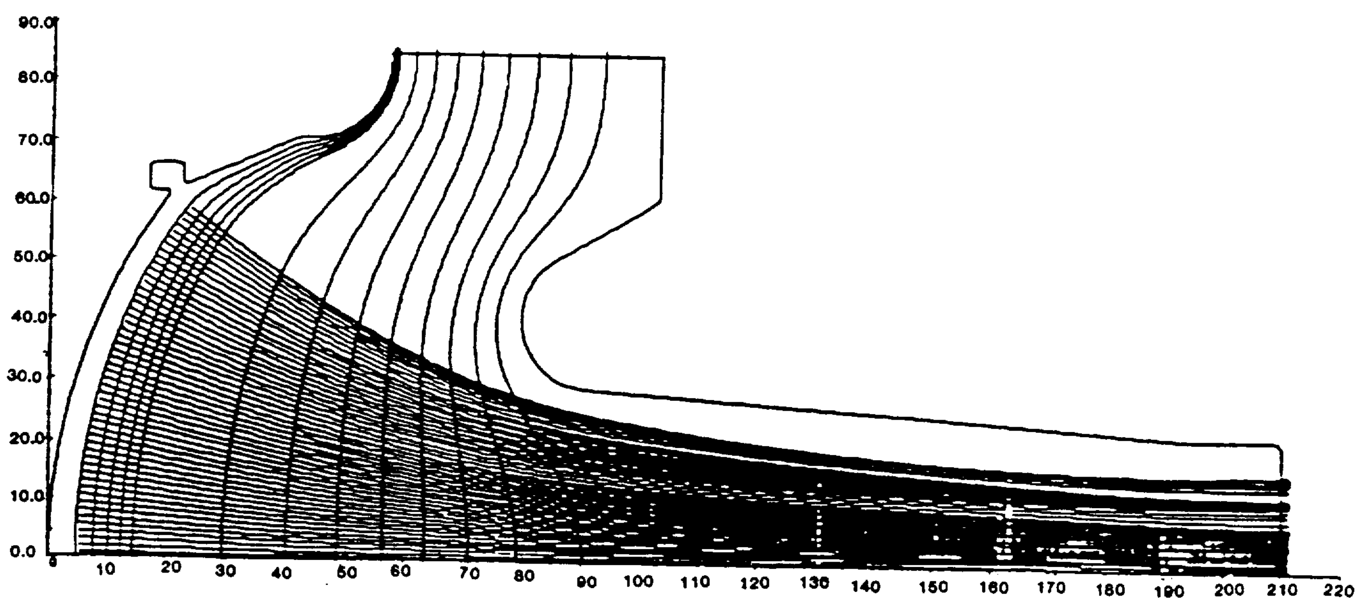


MIT ELECTRON GUN

450 kV, 600 A, 2 μP

(BUILT BY SLAC, STANFORD)



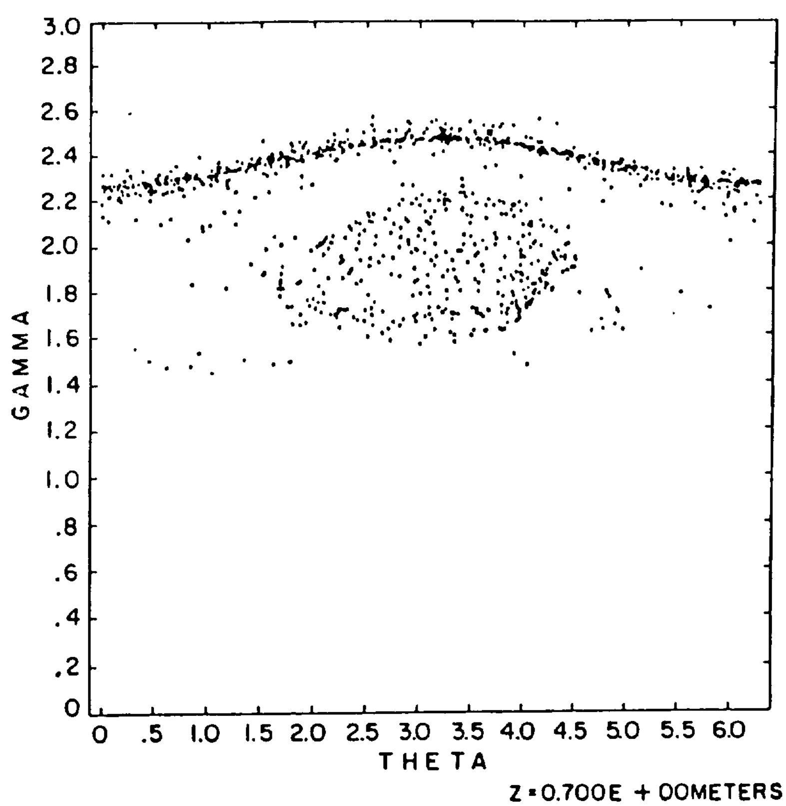


Baseline Design for 140 GHz CARM Amplifier
(700 kV Electron Gun)

Parameter	Design Value
Mode	TE_{11}
β_{ph}	1.066
$\beta_{\perp 0}/\beta_{\parallel 0}$	0.5 (variable)
a	1.8 mm
r_b	1.0 mm
Voltage	700 kV
Peak Current	50 A
Beam Quality ($\sigma_{\beta\parallel}/\beta_{\parallel}$)	1.0%
Peak Output Power	6.8 MW
Peak Input Power	~50 W
Efficiency	20 % (untapered)
B-Field	~ 2.64 T

Phase space of the CARM interaction with a tapered magnetic field

$\sigma_\gamma = 0.02$, $\sigma_{\beta\parallel} = 0.06$, $z_{tap} = 40$ cm



CONCLUSIONS

- GYROTRON HAS MADE VERY IMPRESSIVE ADVANCES IN LAST DECADE. INDUSTRIAL DEVELOPMENT AND RESEARCH.
- SCALING OF GYROTRONS TO HIGHER FREQUENCY AND POWER IS VERY PROMISING. NEW APPROACHES MAY BE NEEDED.
- 1 MW, 250 GHz CW GYROTRON APPEARS FEASIBLE. BASELINE DESIGN PRESENTED.
- HIGH PEAK POWER DEVICES (SUCH AS RELATIVISTIC GYROTRON) ARE ALSO PROMISING, BUT ARE NOT AS WELL UNDERSTOOD.