

**N90-21805**

**HIGH POWER MILLIMETER WAVE SOURCE DEVELOPMENT PROGRAM**

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U.S. Department of Energy  
Washington, DC 20545

**HIGH POWER MILLIMETER WAVE SOURCES**  
**FOR FUSION PROGRAM**

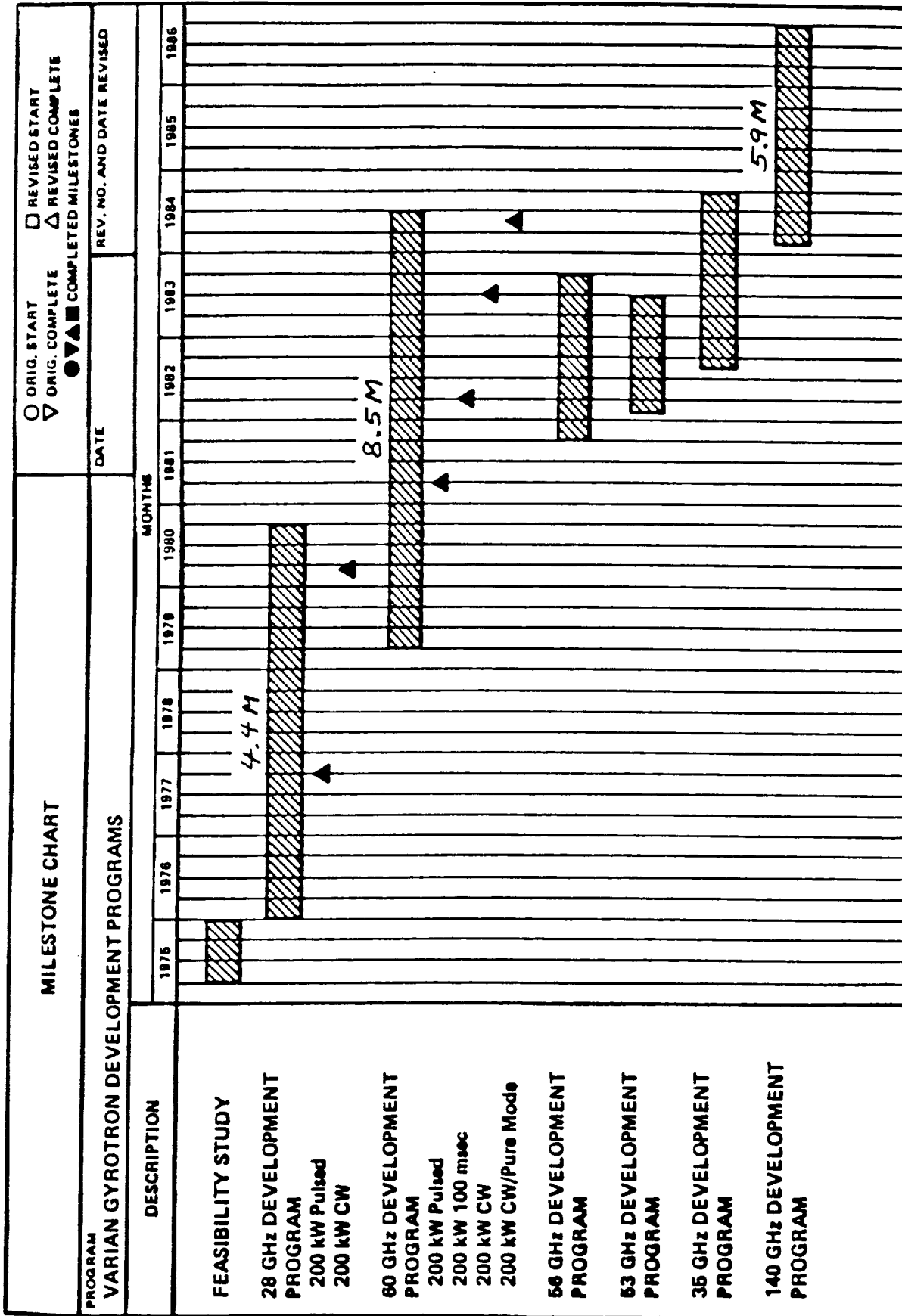
**MOTIVATION:**

- A) FUSION APPLICATIONS**
  - 1. BULK HEATING**
  - 2. CONTROL OF MHD MODES**
  - 3. RADIAL TEMPERATURE PROFILE CONTROL**
  - 4. PRE-IONIZATION AND START-UP**
  - 5. CURRENT DRIVE**
  - 6. DIAGNOSTICS**
  
- B) ISOTOPE SEPARATION**
  
- C) POWER TRANSMISSION**
  
- D) MILITARY APPLICATIONS**

**HIGH POWER MILLIMETER WAVE SOURCES**  
**FOR FUSION PROGRAM**

**HISTORY OF INDUSTRIAL DEVELOPMENT OF GYROTRONS:**

- INITIATED 28 GHZ, 200 KW, CW GYROTRON DEVELOPMENT IN 1976  
SUCCESSFULLY COMPLETED IN 1980**
  
- INITIATED 60 GHZ, 200 KW, CW GYROTRON DEVELOPMENT IN 1980  
SUCCESSFULLY COMPLETED IN 1984**
  
- INITIATED 140 GHZ, 100 KW, CW GYROTRON DEVELOPMENT IN 1984  
SUCCESSFULLY COMPLETED IN 1986**
  
- INITIATED 140 GHZ, 1 MW, PULSED/CW GYROTRON DEVELOPMENT IN 1986  
PROGRESSING SATISFACTORILY**



HIGH POWER MILLIMETER WAVE SOURCES  
FOR FUSION PROGRAM

MAIN TECHNICAL OBJECTIVE: PLASMA HEATING

REQUIREMENTS:

CURRENT: 200 KW - 2 MW @ 60 GHZ, CW

NEAR-TERM: 6 MW @ 115 GHZ, CW

MID 90'S: 10-30 MW @ 280 GHZ, CW

ECH SOURCE DEVELOPMENT PROGRAM STRATEGY

DEVELOP 140 GHZ, 1 MW, PULSED GYROTRON IN A COST-EFFECTIVE WAY USING

- VARIAN'S PAST EXPERIENCE
- ONGOING WHISPERING GALLERY EXPERIMENTS AT MIT

IN PARALLEL

- ESTABLISH DATA BASE FOR 280 GHZ, WHISPERING GALLERY MODE AT MIT
- ENGINEERING FEASIBILITY TESTS AND CONCEPTUAL DESIGNS AT VARIAN
- EVALUATE NEW CONCEPTS WHICH COULD BETTER MEET THE FUSION NEEDS
  - SMALL PERIODIC FEM
  - CARM
  - QUASI-OPTICAL GYROTRON
  - SDIO SUPPORTED PULSED FEL
  - TRW'S CW FEL
  - SCIENCE RESEARCH LAB'S PULSED FEL
  - RUSSIAN 2.1 MW COAXIAL CAVITY GYROTRON

**OFFICE OF FUSION ENERGY CURRENT DEVELOPMENT ACTIVITIES**

<u>TASK</u>	<u>INSTITUTION</u>	<u>P. I.</u>	<u>1987</u>	<u>BUDGET</u>	
				<u>1988</u>	<u>1989</u>
140 GHZ GYR.	VARIAN	JORY/FELCH	1000	1500	2000
140/280 GHZ	MIT	TEMKIN	400	450	?
Q-0 GYR.	NRL	MANHEIMER	205	250	?
SMALL PER. FEL	U. MD	GRANATSTEIN	250	250	?
TRANSM. SYSTEM	U. WISC.	VERNON	100	100	?
LLNL/FEL-DRIVER	LLNL	CAPLAN	0	1100	?
MISC. ----->					
TOTAL (APPROXIMATELY)			2000	3900	4100

***1 MW, 140 GHz GYROTRON EXPERIMENT  
DESIGN PHILOSOPHY***

- DEMONSTRATE 1 MW AT 140 GHz FOR SHORT PULSES WITHIN A SHORT TIME PERIOD WITH PROVIDED FUNDS  
(NOT A TRUE DEVELOPMENT EFFORT WITH MULTIPLE EXPERIMENTS AND PARALLEL DESIGN APPROACHES)
- DEMONSTRATE SEVERAL HUNDRED kW CW TO BEGIN BUILDING TECHNOLOGY BASE FOR 1 MW CW
- BUILD UPON
  - CURRENT 140 GHz DEVELOPMENT WORK
  - 1 MW STUDY OF 1983
  - 1 MW EFFORT AT MIT
  - VARIAN IR & D OVER PAST 1-1/2 YEARS

## **OSCILLATOR TECHNOLOGY CONCERNS**

- **WINDOWS**
- **MODE COMPETITION IN LARGER CAVITIES**
- **CAVITY WALL COOLING**
- **OUTPUT COUPLING**
- **BEAM TUNNEL LOADING**

## **ECH SOURCE DEVELOPMENT PROGRAM PLAN**

**(BASED ON CURRENT FUNDING)**

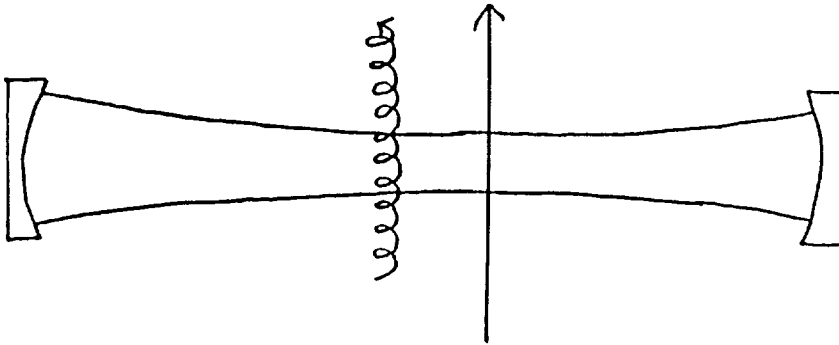
- **CONTINUE WITH THE 140 GHZ, 1 MW, GYROTRON DEVELOPMENT AT VARIAN**
- **INITIATE 280 GHZ WHISPERING GALLERY STUDIES AT MIT**
- **ESTABLISH A CW, MEGAWATT TEST FACILITY BY 1990**
- **CONDUCT SINGLE PULSE FEL HEATING EXPERIMENT ON MTX**
- **REEVALUATE DATA BASE AND INITIATE 280 GHZ, MEGAWATT INDUSTRIAL SOURCE DEVELOPMENT IN FY 1990**



## QUASI-OPTICAL GYROTRON DEVELOPMENT

Wallace Mannheimer  
Naval Research Laboratories  
Washington, DC 20375

### Quasi-Optical Gyrotron (NRL)



#### Advantages:

Much less of a problem with wall loading  
Beam collection and radiation extraction at different places;  
Especially important if depressed collection is used

#### Difficulties

Complicated magnet design

#### DOE Requirement:

Tube for ECRH of CIT and subsequent reactors

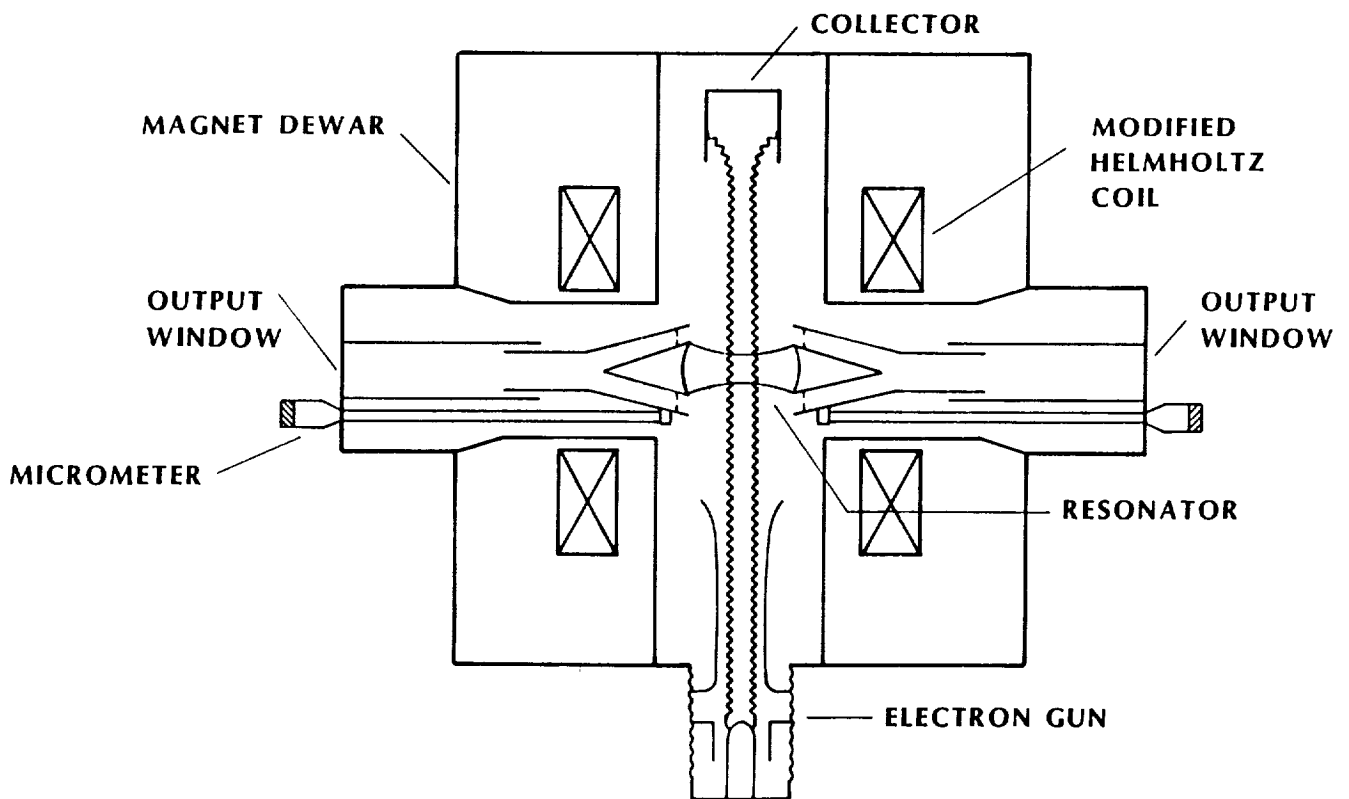
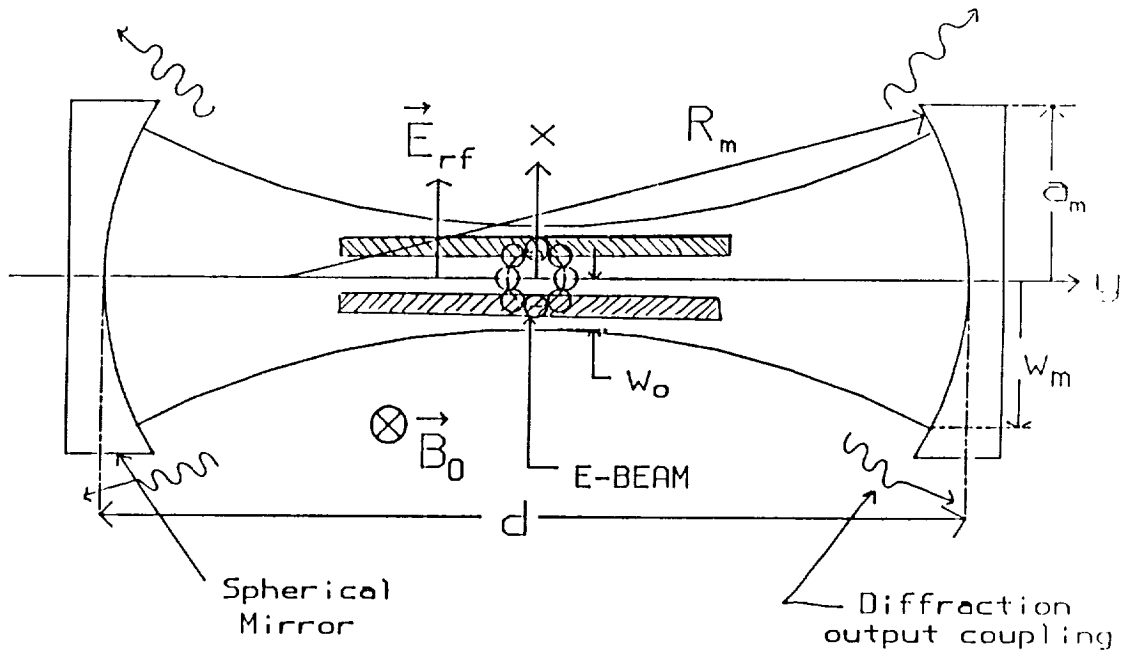
$$P > 1 \text{ MW}$$

$$f = 300 \text{ GHz (Or maybe as high as 600 GHz)}$$

$$\eta \geq 20\%$$

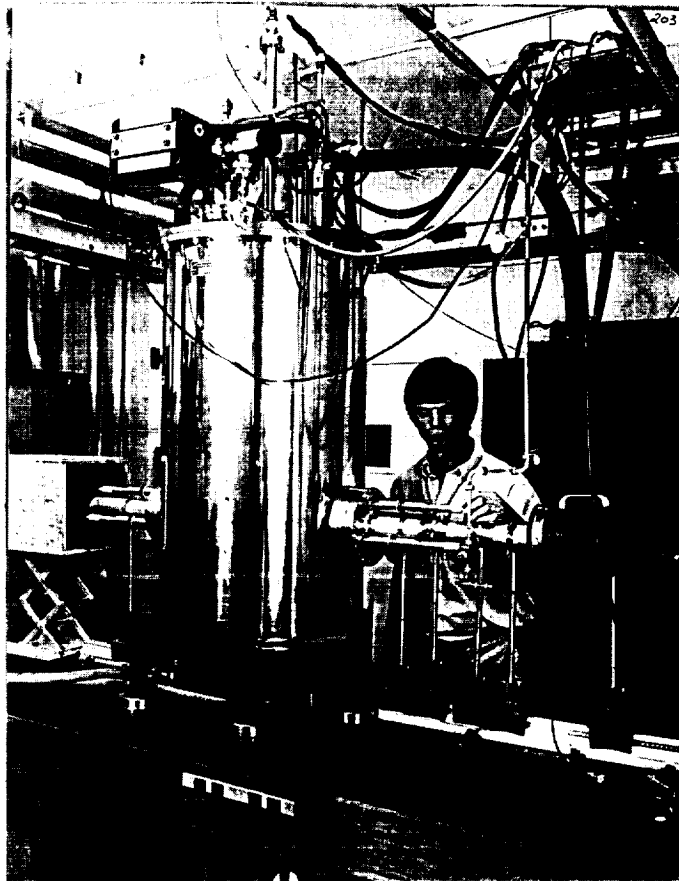
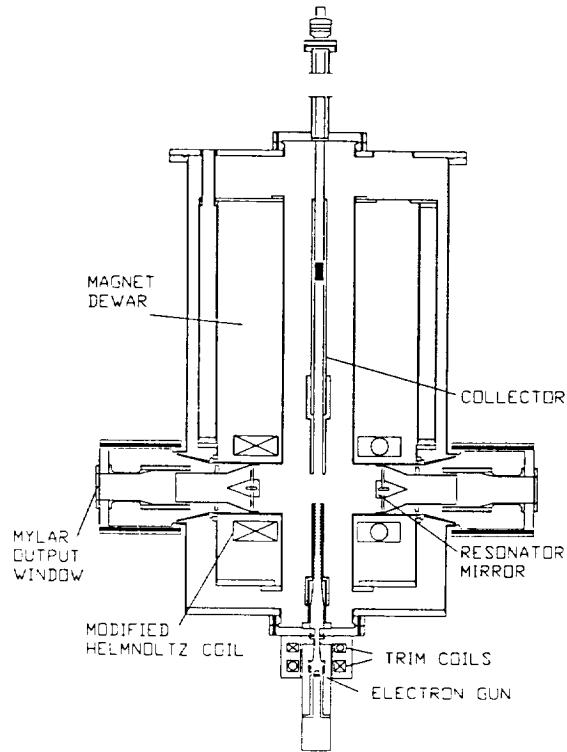
CW (Or at least 3 second) relevant

# QUASI-OPTICAL RESONATOR CONFIGURATION

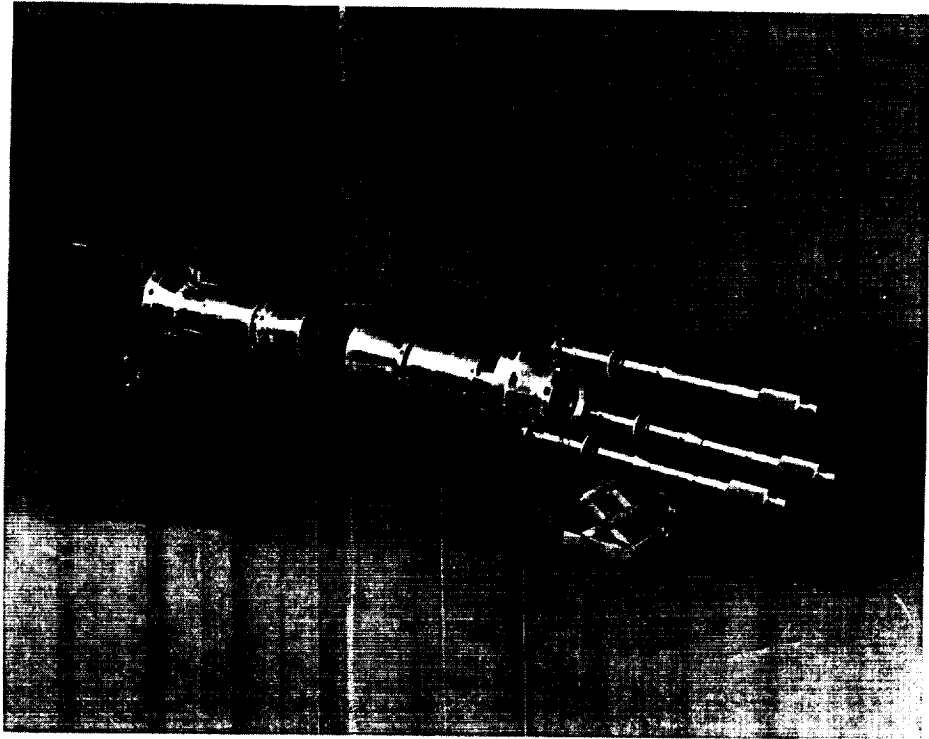




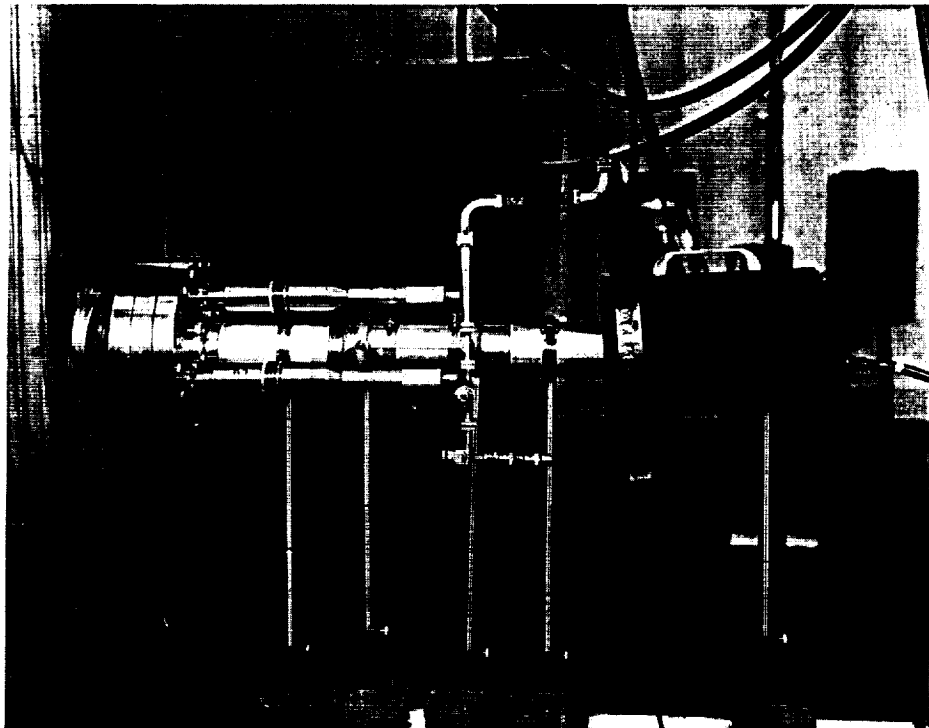
# NRL QUASI-OPTICAL GYROTRON



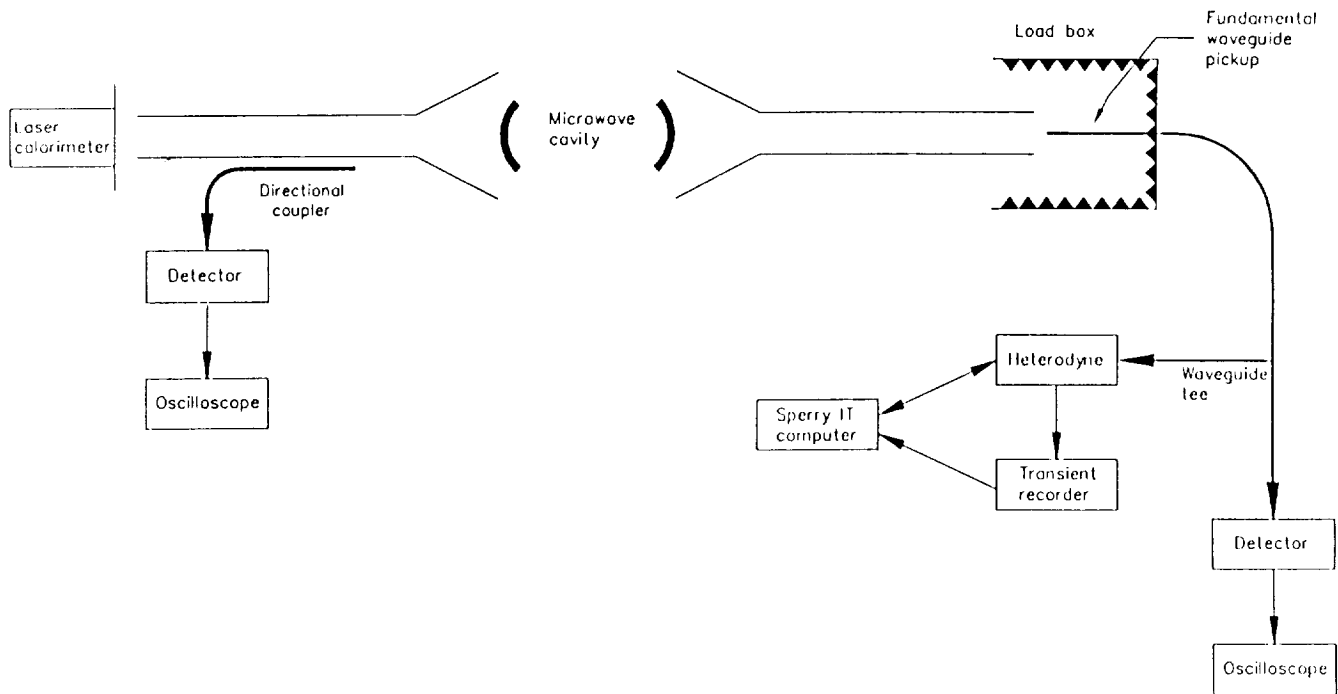
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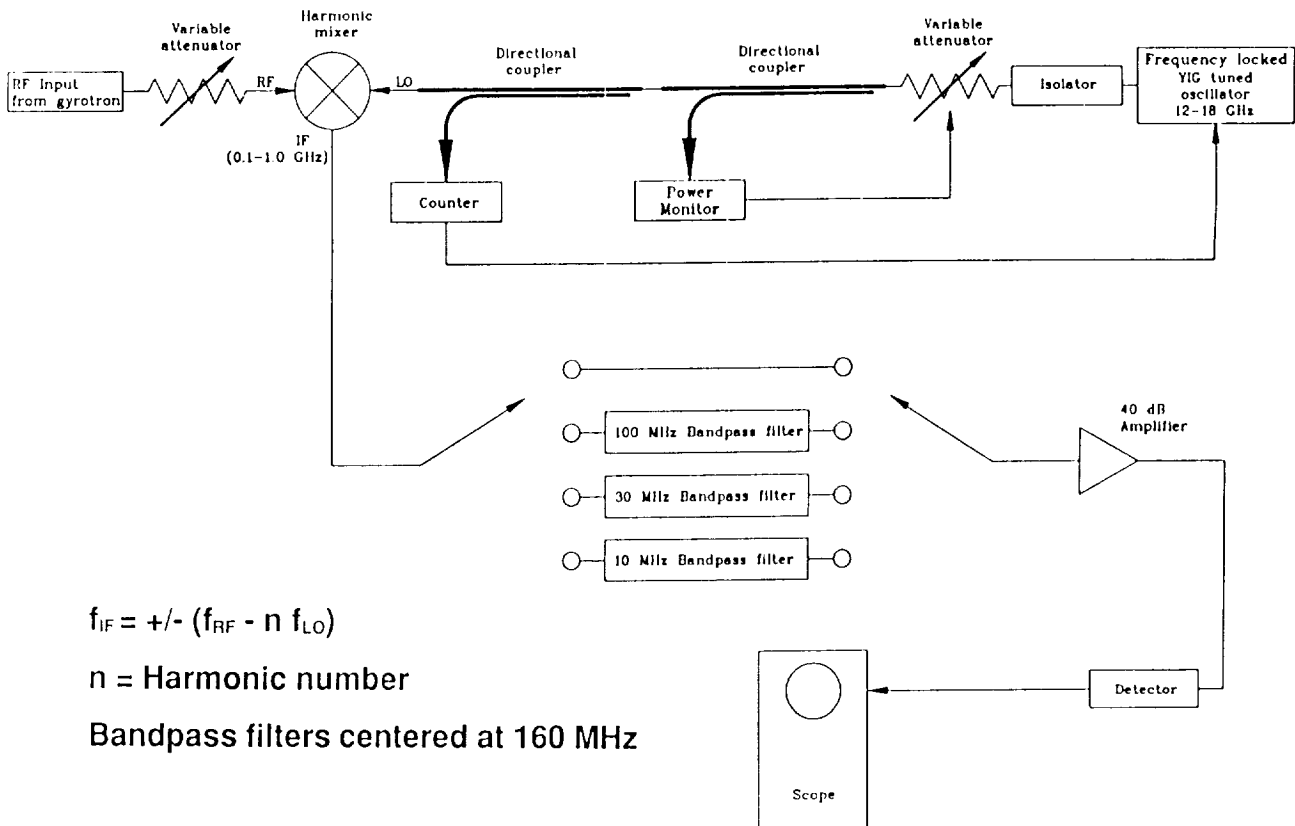
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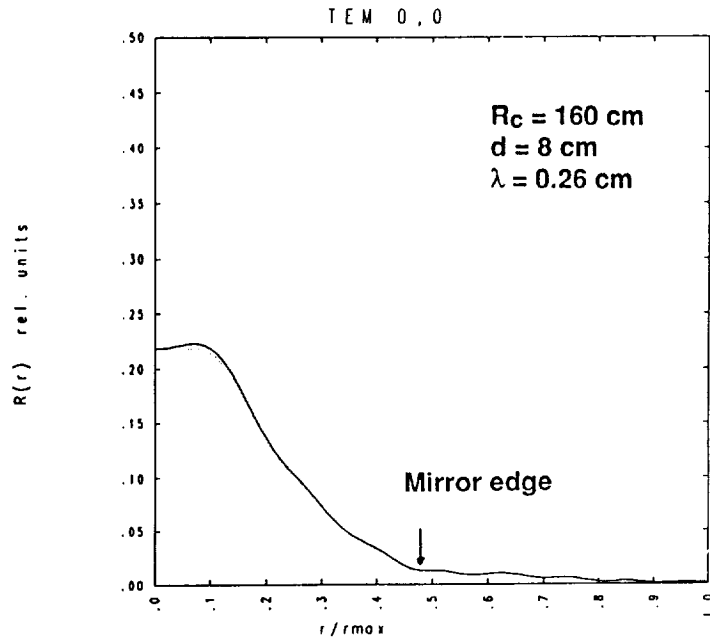
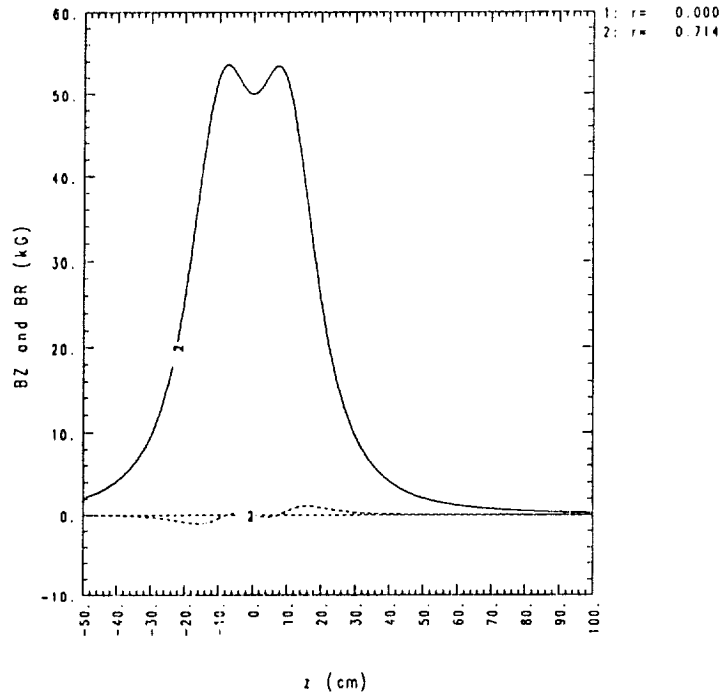
## Diagnostic Setup



## Heterodyne Diagnostic



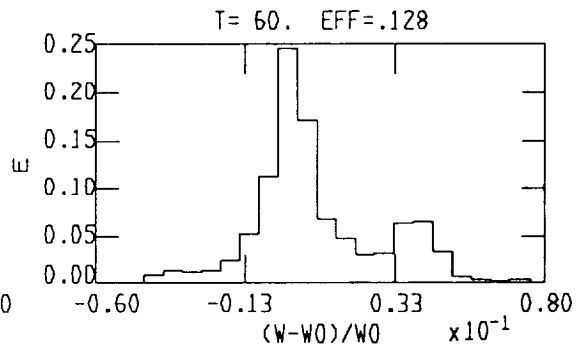
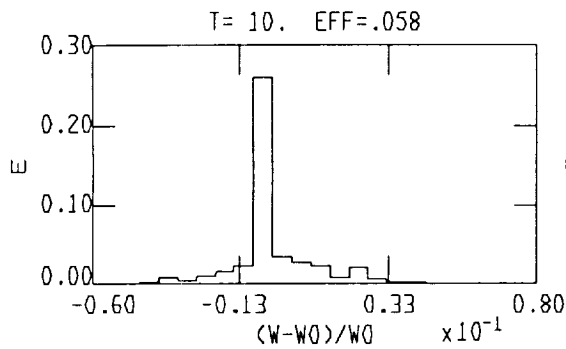
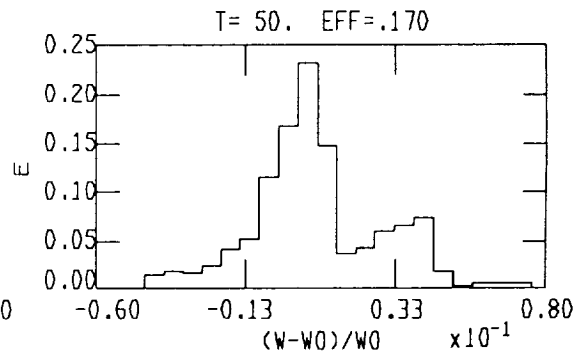
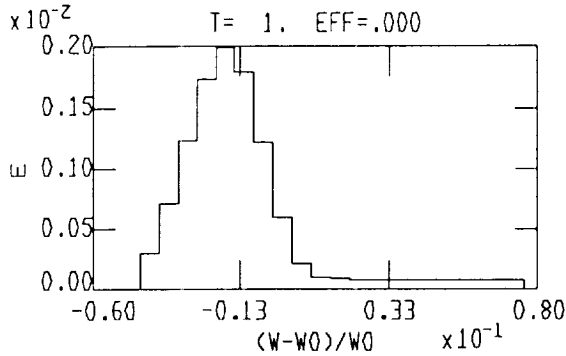
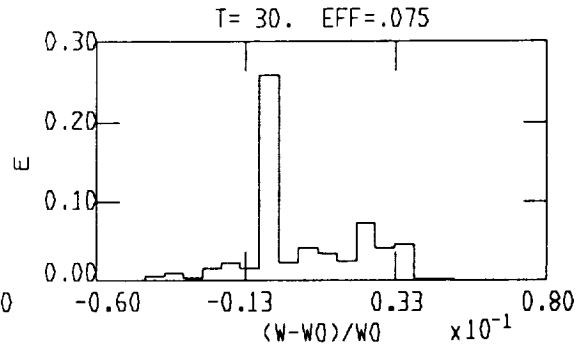
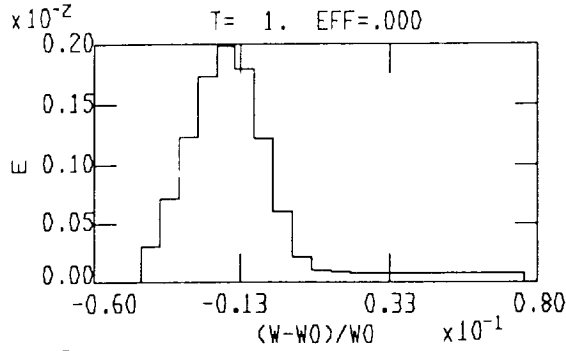
# Magnetic Field Profile



	Q	% Transmitted	% of Total
Loss	5.662e+04	3.415e-01	8.22
Diffraction	5.069e+03	3.814e+00	91.78
Total	4.653e+03	4.155e+00	

OC0= 0.112E+01 DOC= 0.

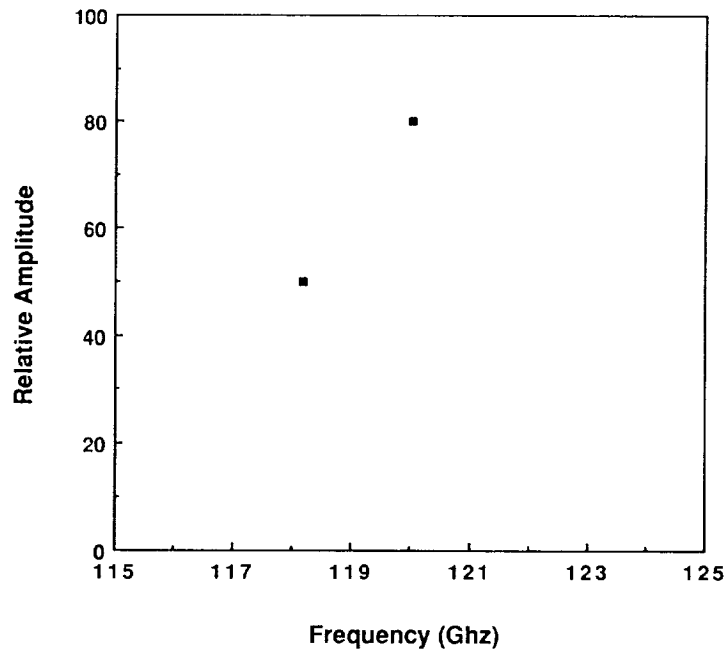
DW= 0.600E-02 IB= 0.999E+01



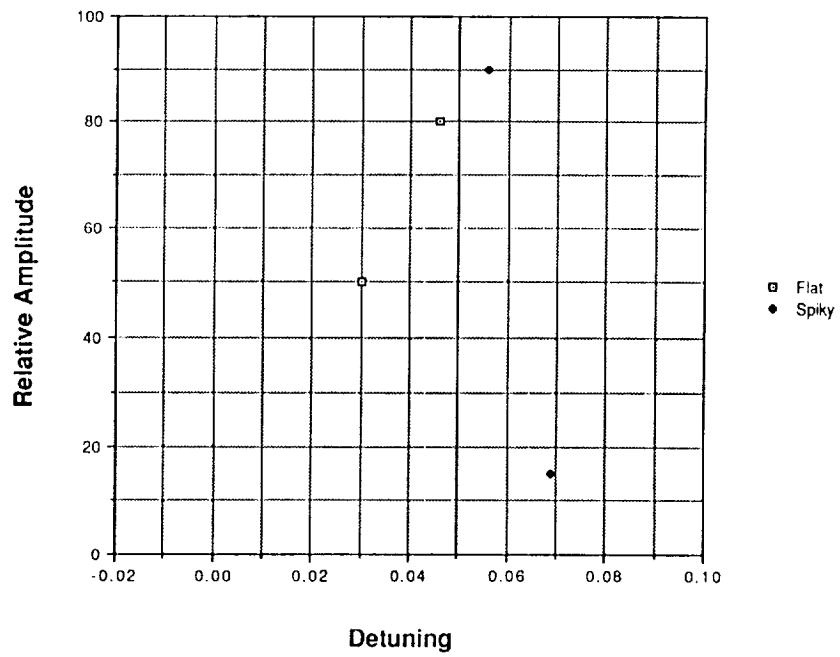
frame # 10:08:06  
203/24/88

SC KR = 0.000

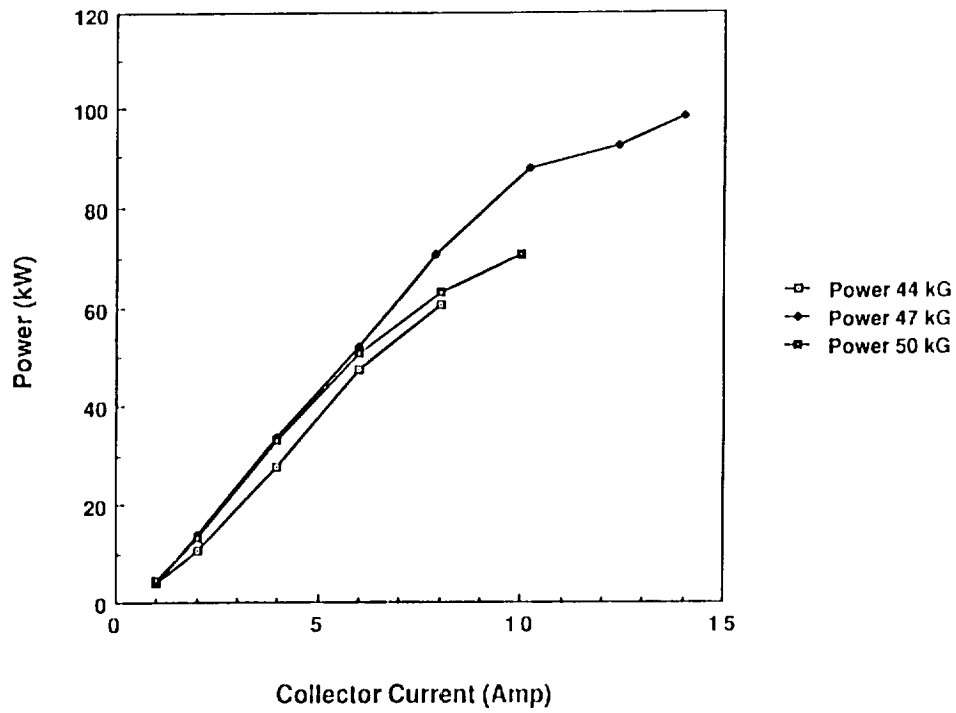
### Mode Spectrum for QOG at 75 kV, 14 Amp and 47 kG



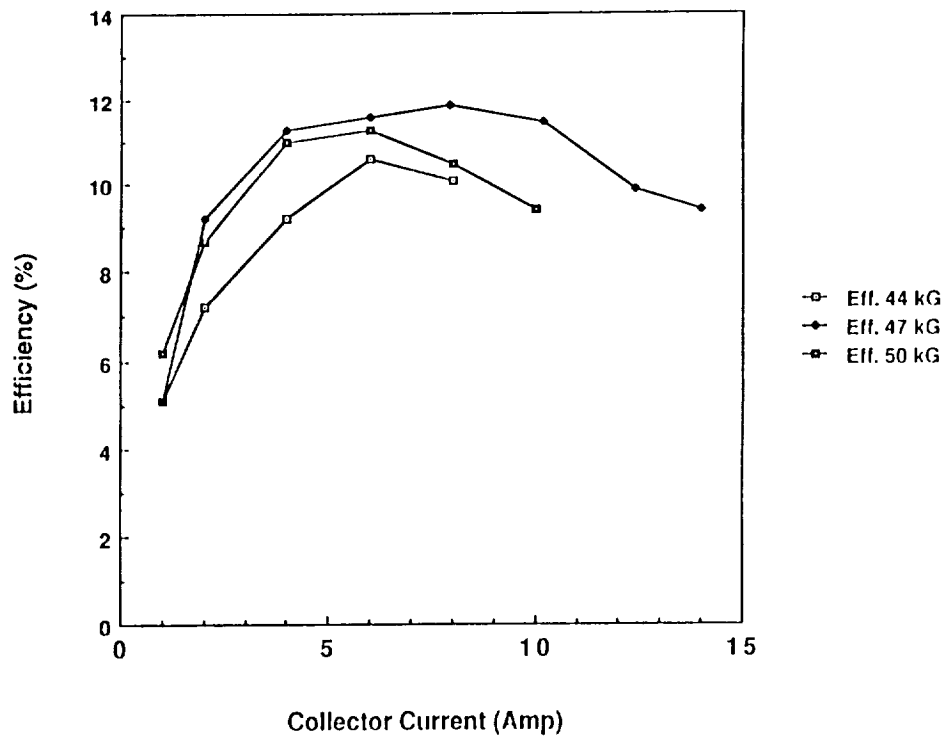
### Mode Spectrum for 75 kV, 14 Amp and 47 kG

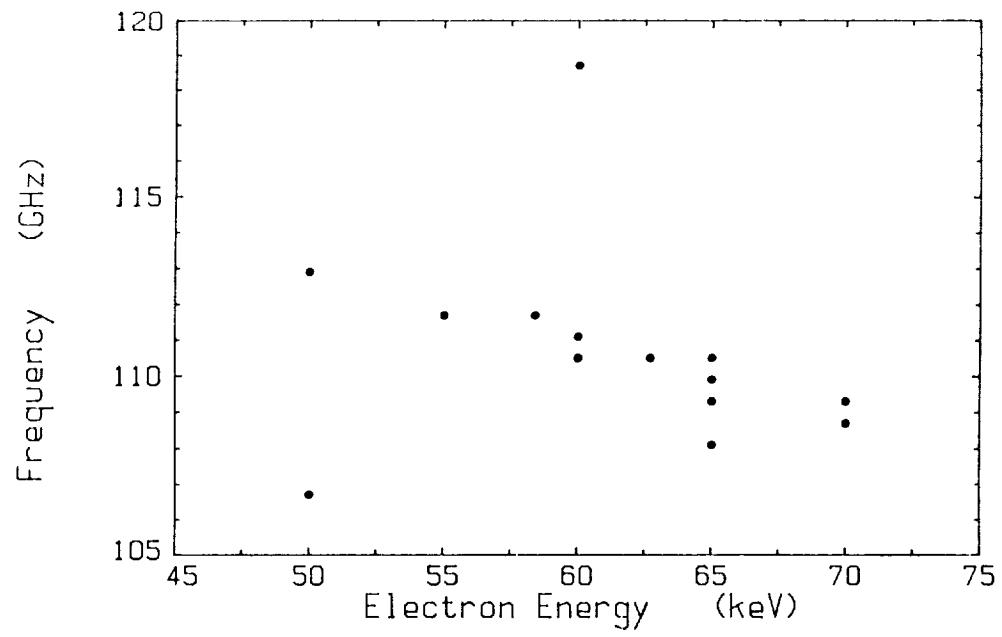


### Operation at 75 kV and 20 cm Separation

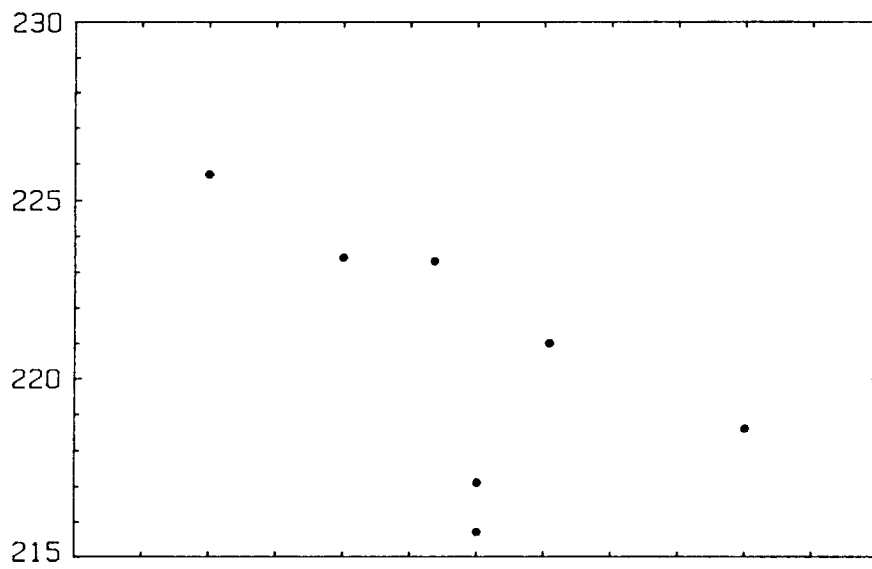


### Operation at 75 kV and 20 cm Separation





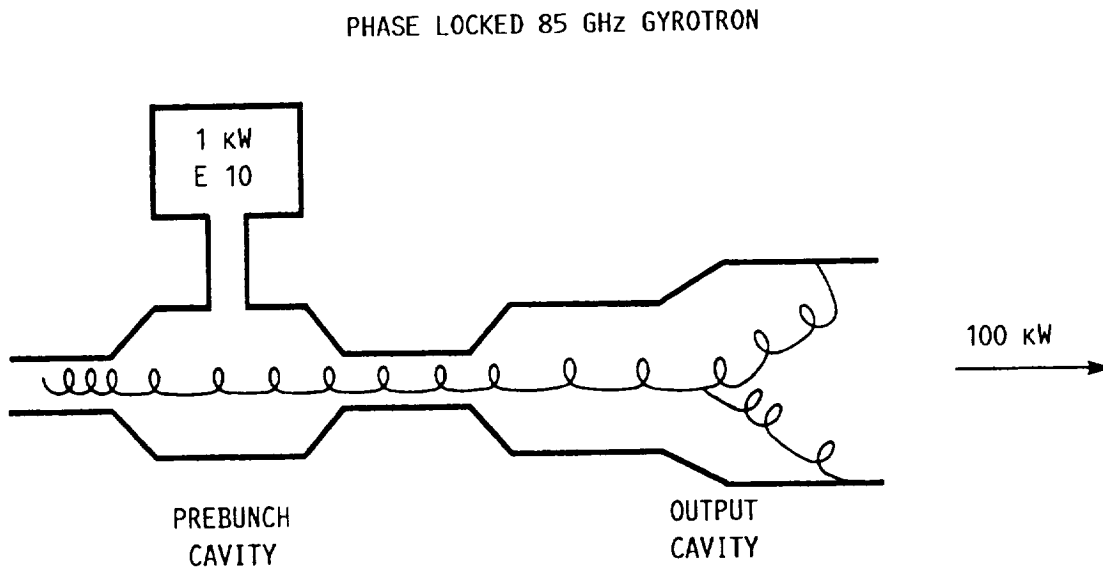
25 cm Mirror Separation





## FUTURE PLANS

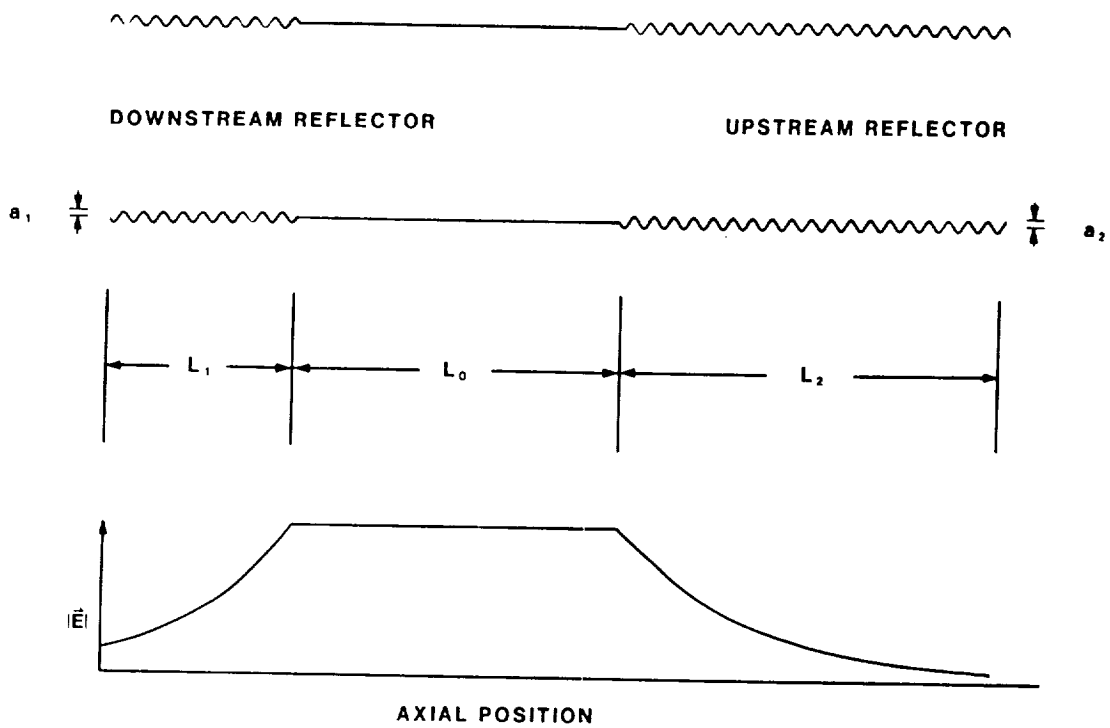
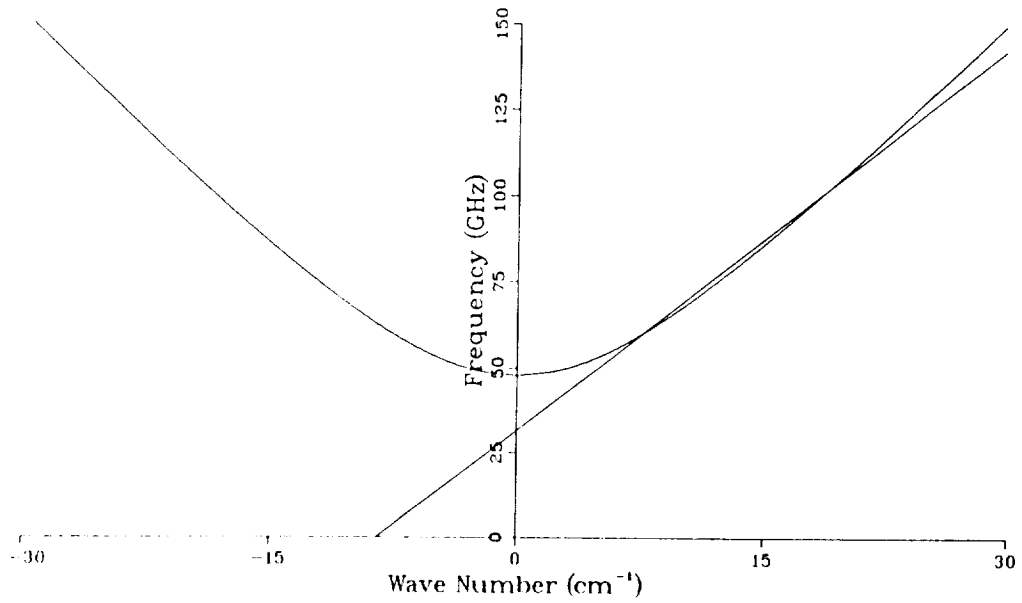
- INSTALL 80 KEV, 35A VUW8144 (MIT) ELECTRON GUN
- MODE CONTROL BY MODE LOCKING AND BY STRUCTURED MIRRORS
- HARMONIC OPERATION
- ACHIEVE  $P = 1$  MW WITH USE OF A 6 MW SHEET BEAM ELECTRON GUN



### ISSUES

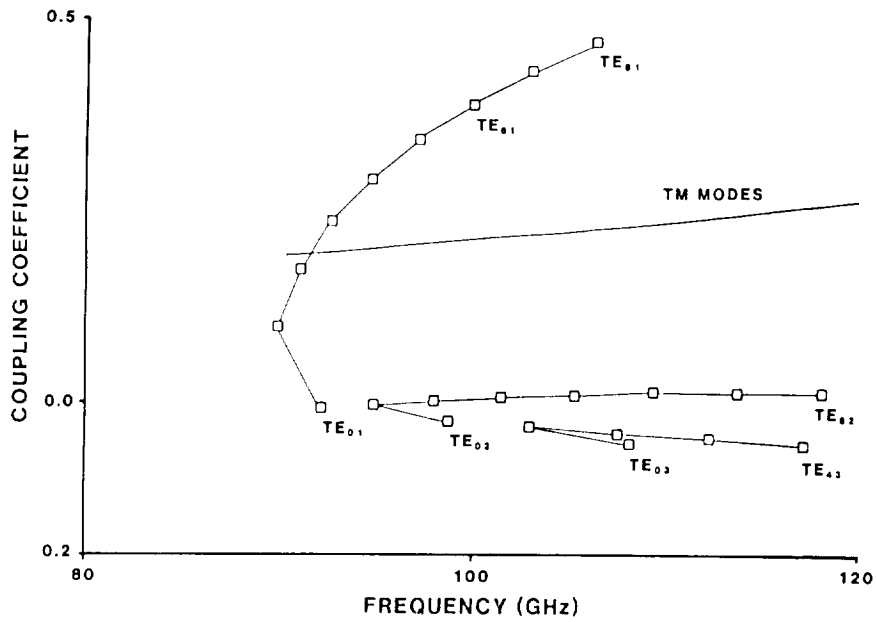
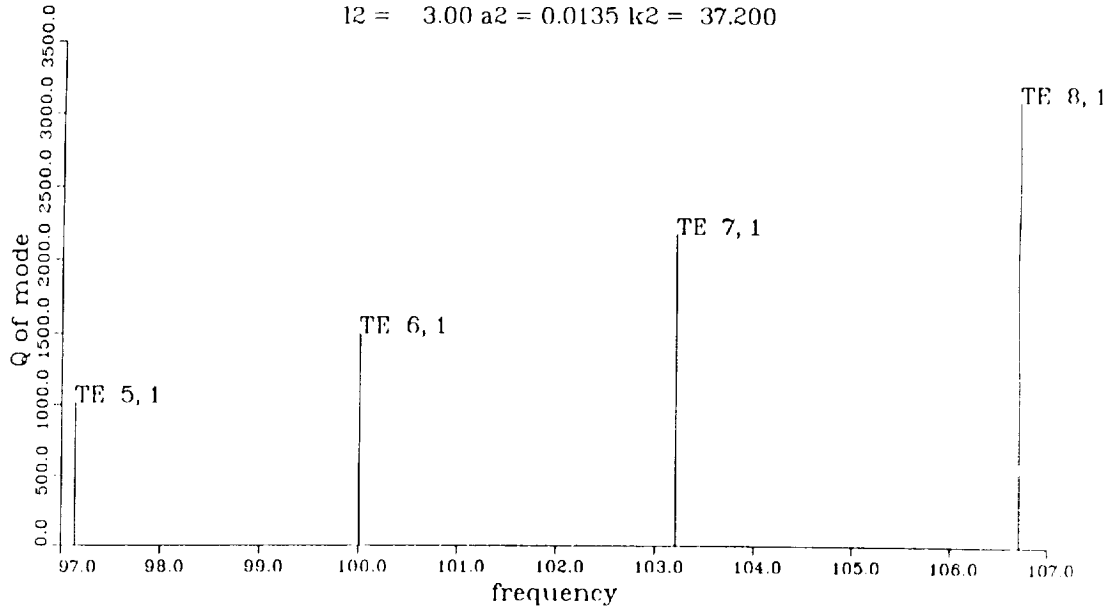
- STABILIZE PREBUNCHING CAVITY
- ISOLATE CAVITIES
- MAXIMIZE LOCKING BANDWIDTH

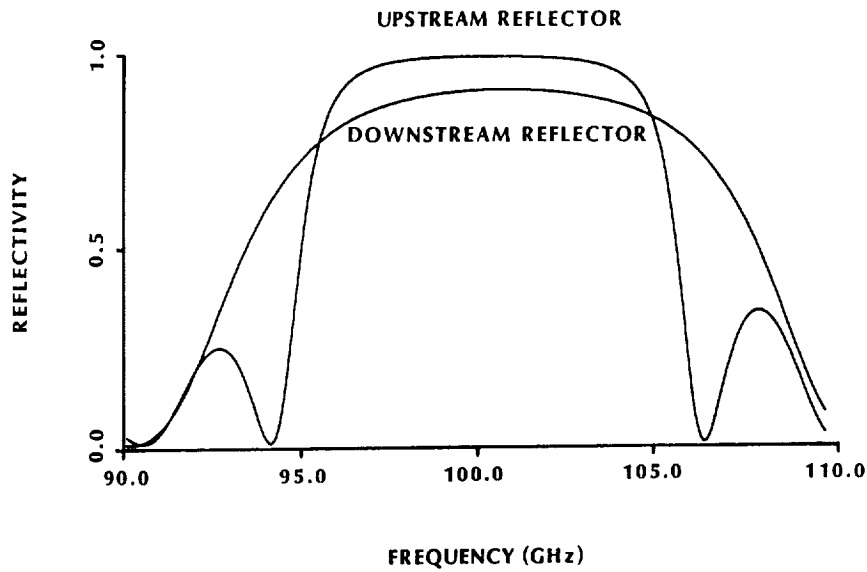
# CARM Dispersion Relation



# Bragg Cavity Modes

$R = 0.7790$   $l_0 = 3.55$   
 $l_1 = 5.00$   $a_1 = 0.0150$   $k_1 = 37.200$   
 $l_2 = 3.00$   $a_2 = 0.0135$   $k_2 = 37.200$





PRELIMINARY DESIGN PARAMETERS OF 250 GHz LONG PULSE CARM EXPERIMENT

Electron Beam

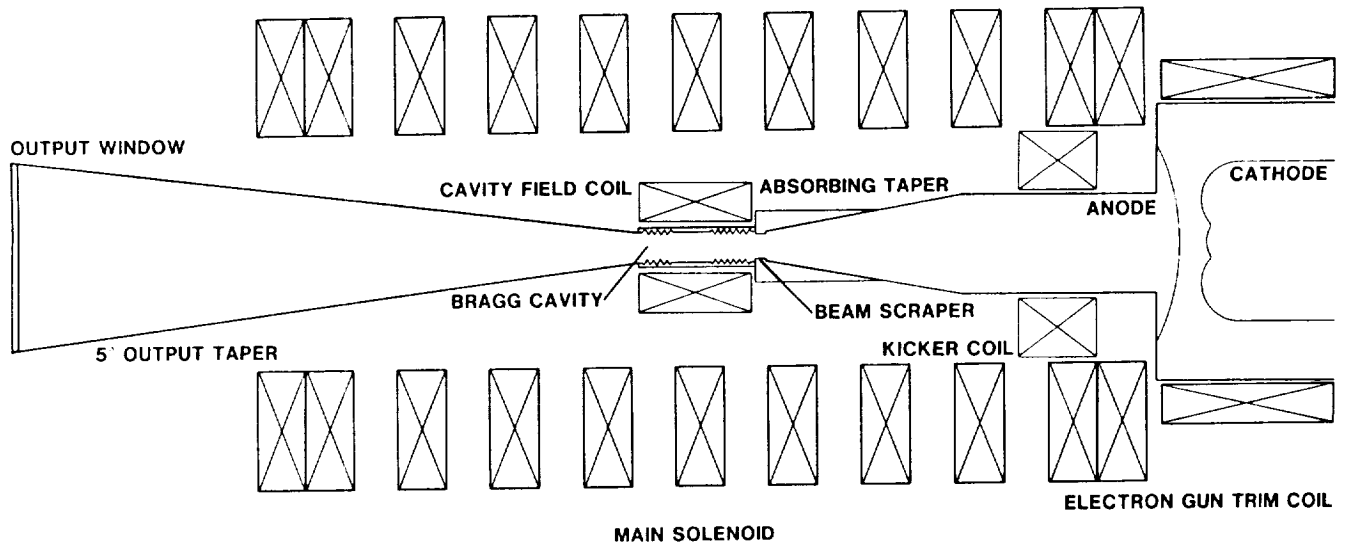
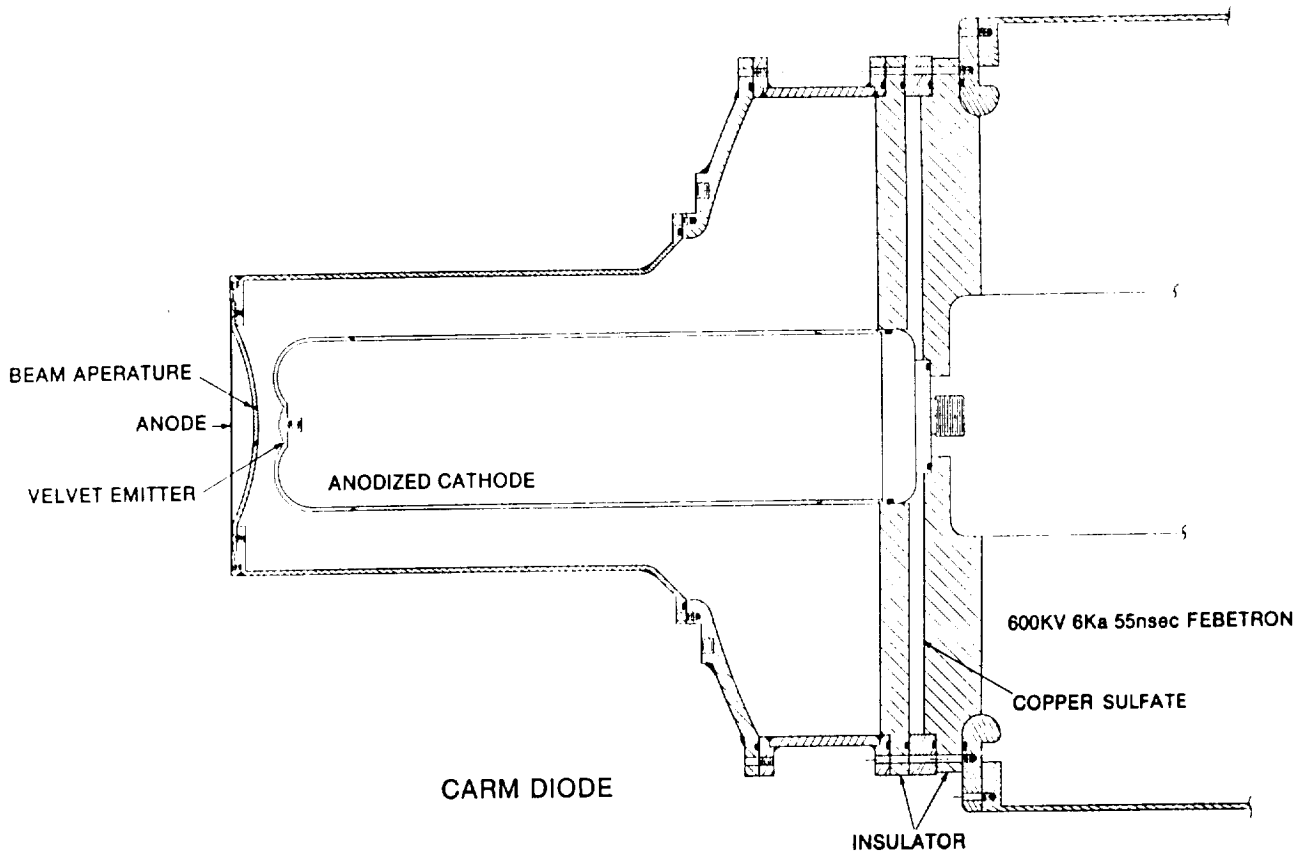
Gun type	temperature-limited MIG
Beam cross section	annular
Beam diameter	1.1 cm
Beam voltage	500 kV
Beam current	100 amp max
Pulse width	1 $\mu$ sec
Velocity pitch ratio	0.71
Pitch angle spread limit	2 percent
Energy spread limit	7 percent

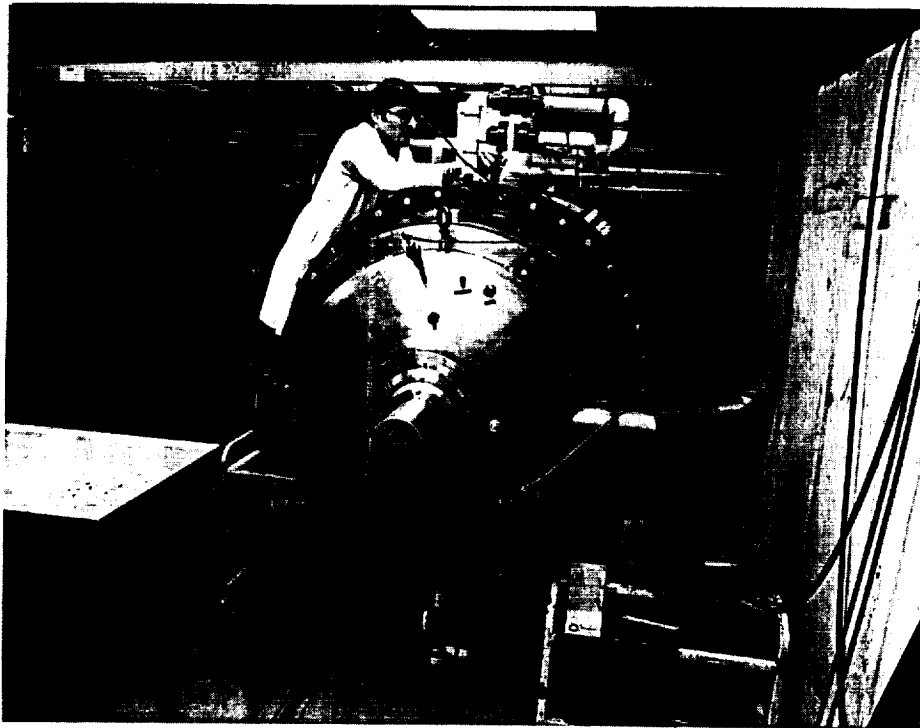
Resonator

Cavity type	circular wave guide
Reflector type	Bragg reflector
Output reflectivity	92 percent
Operating mode	TE <sub>14</sub> (volume mode)
Wave group velocity	0.97c
Cavity length	~ 10 cm
Cavity diameter	1.8 cm
Ohmic heating	3 kW/cm <sup>2</sup>

Magnet

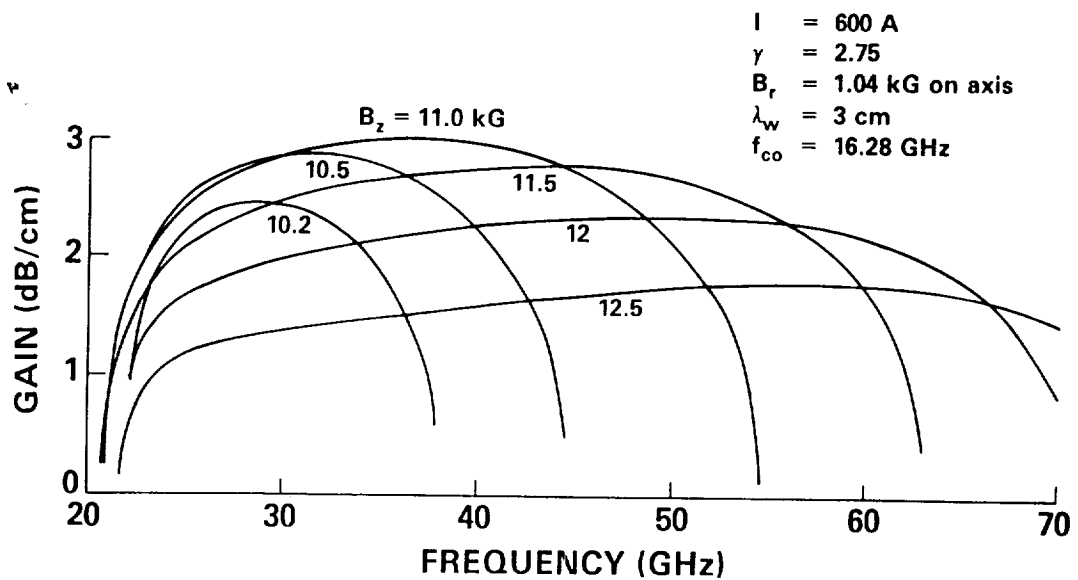
Magnet type	superconducting
Cavity magnetic field	~ 55 kG
Predicted efficiency	20 to 40 percent
Predicted output power	10 MW

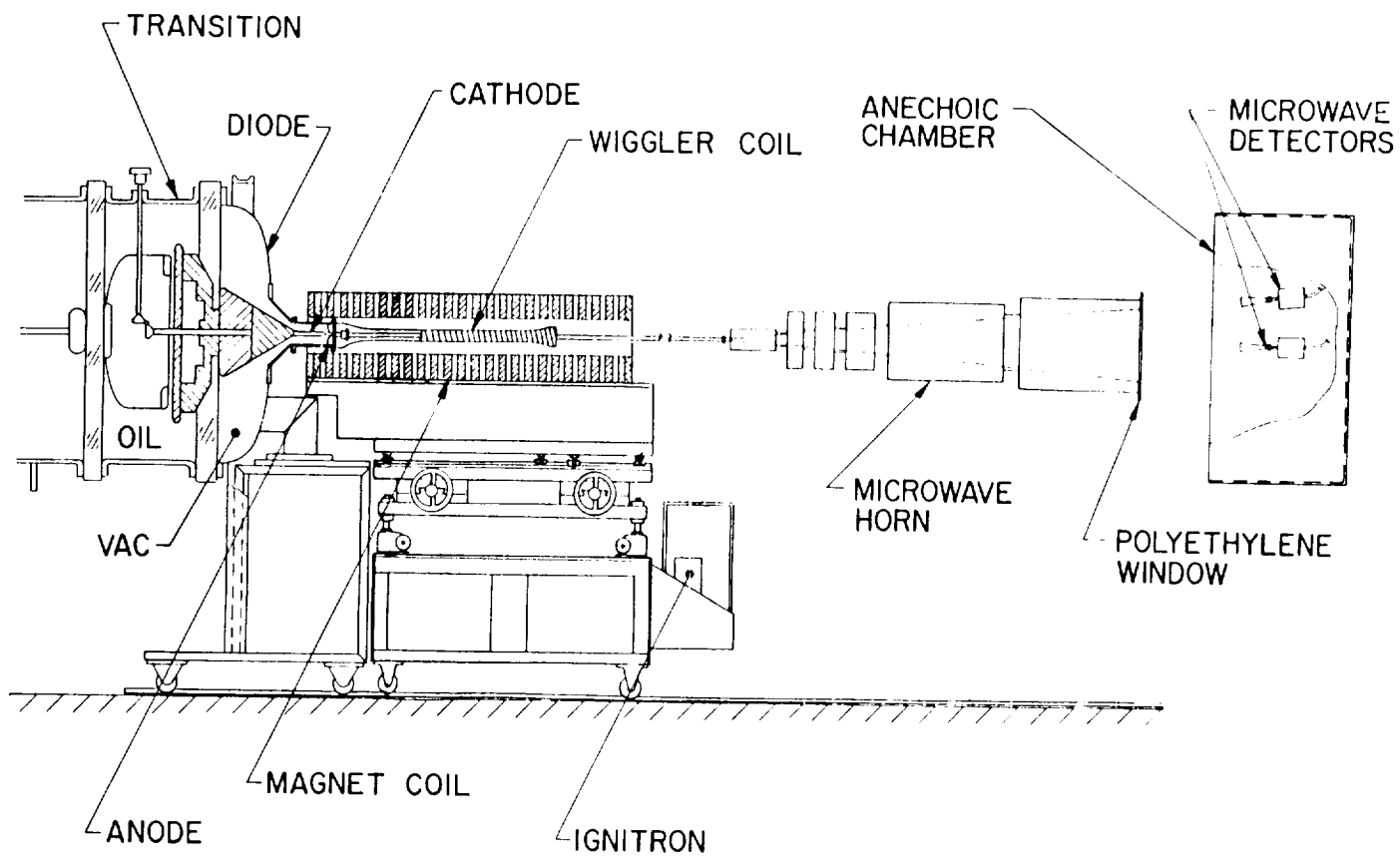




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### 35-GHz FEL AMPLIFIER THEORETICAL GROWTH CURVES

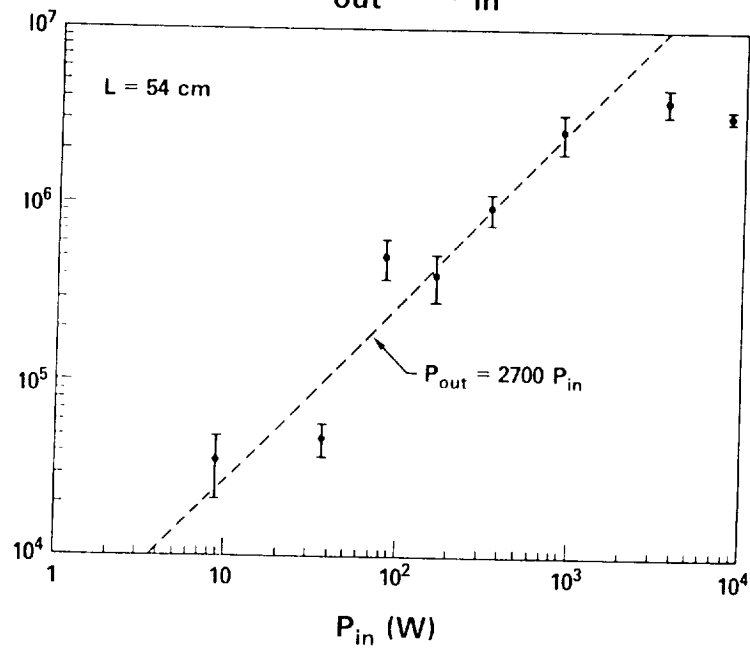




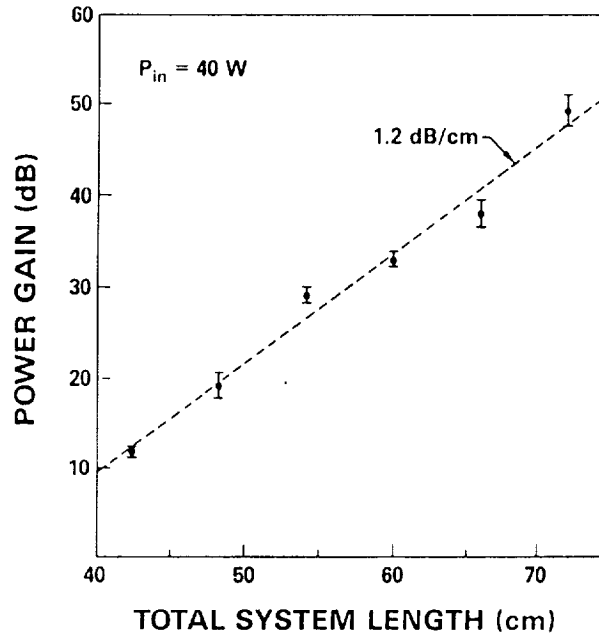
N.R.L. F.E.L. EXPERIMENT

35 GHz FEL AMPLIFIER

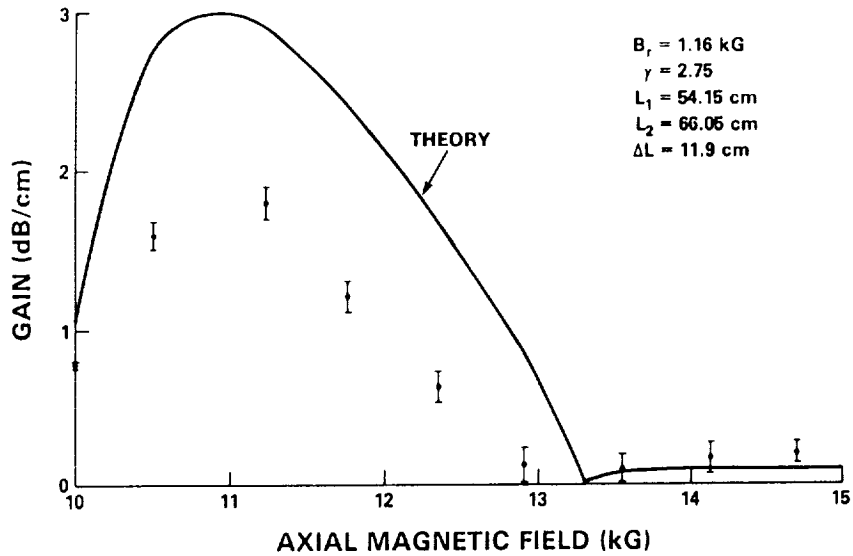
$P_{out}$  vs  $P_{in}$



### 35 GHz FEL AMPLIFIER GAIN vs LENGTH

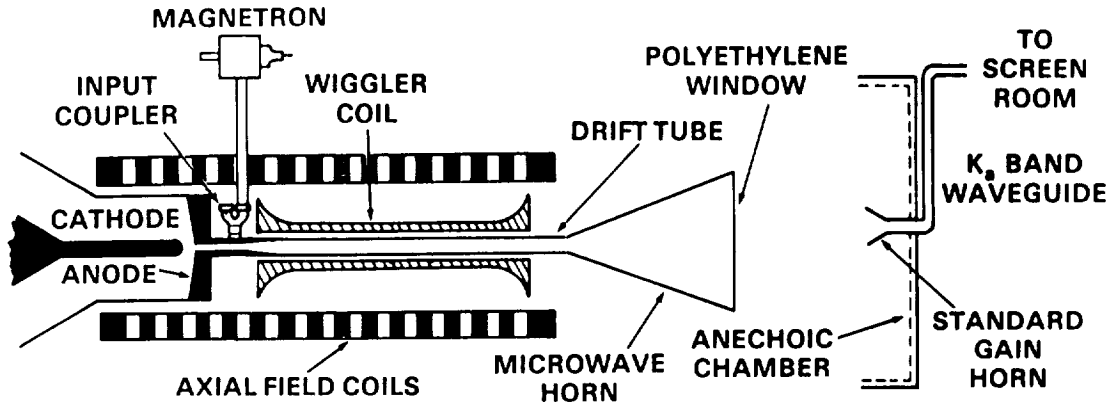


### 35 GHz FEL AMPLIFIER GROWTH RATE vs AXIAL FIELD

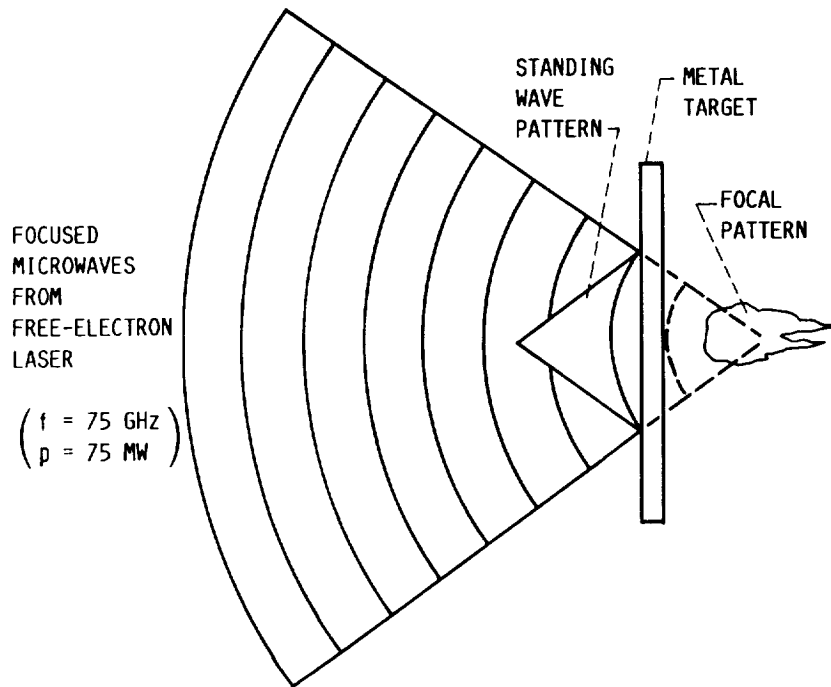




# VEBA MILLIMETER-WAVE FEL AMPLIFIER CONFIGURATION



## MICROWAVE-PRODUCED ATMOSPHERIC PRESSURE AIR BREAKDOWN





**RECTIFYING DEVICES FOR ENERGY CONVERSION: TUNGSTEN SILICIDE  
SCHOTTKY BARRIER DIODES AT 10.6 MICRONS\***

Howard E. Jackson and Joseph T. Boyd  
University of Cincinnati  
Cincinnati, Ohio 45204

**AN OUTLINE**

MOTIVATION

BRIEFLY REVIEW THE PHYSICAL PROCESS

COMMENTS ON DESIGN

CHARACTERIZATION - INCLUDING

- A BRIEF ASIDE ON WSi<sub>2</sub> CHARACTERIZATION
- DEVICE RESPONSE IN THE FAR-INFRARED

CURRENT STATUS

RECOMMENDATIONS FOR FUTURE EFFORTS

**OBJECTIVE**

MAXIMUM IRRADIATION FROM THE EARTH IS  
IN THE 8 - 14 MICRON RANGE.

THIS CORRESPONDS TO A PHOTON ENERGY  
RANGE FROM .155 eV TO .0866 eV.

USE:

POWERING SATELLITES.

ADVANTAGE:

NO TRACKING MECHANISM REQUIRED.

ABLE TO GENERATE POWER AT ALL TIMES AND  
POSITIONS OF ORBIT.

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\*Work supported by NASA Lewis Research Center grant  
NAG3-583.

## ENERGY BANDGAPS OF SEMICONDUCTORS

SILICON (Si)	1.12 eV
GERMANIUM (Ge)	0.7 eV
GALLIUM ARSENIDE (GaAs)	1.4 eV
GALLIUM PHOSPHIDE (GaP)	2.3 eV
INDIUM ARSENIDE (InAs)	0.4 eV
INDIUM PHOSPHIDE (InP)	1.3 eV
INDIUM ANTIMONIDE (InSb)	0.2 eV
CADMIUM SULPHIDE (CdS)	2.6 eV
LEAD SULPHIDE (PbS)	0.4 eV
LEAD SELENIDE (PbSe)	0.3 eV
MERCURY CADMIUM	
TELLURIDE ( $Hg_{1-x}Cd_xTe$ )	
x=0	-0.142 eV
x=1	1.49 eV

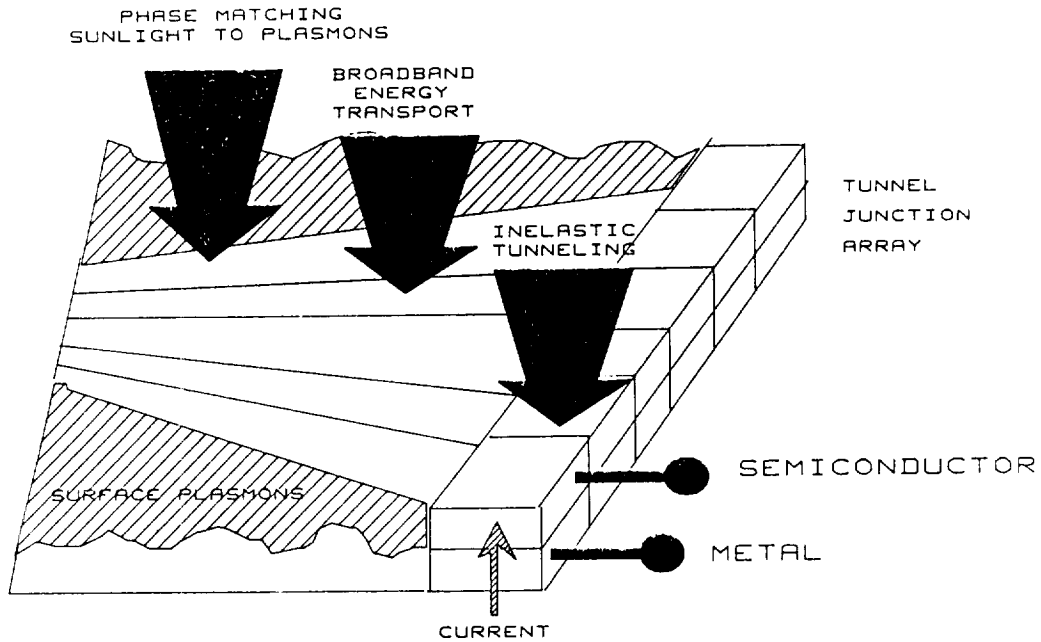
## PLASMON-ASSISTED INELASTIC ELECTRON TUNNELING

PHOTON  (JUNCTION) PLASMON 

 ENERGETIC  $e^-$  

 TUNNELING ACROSS A BARRIER

# EXTRACTING POWER FROM SURFACE PLASMA OSCILLATIONS



*From -  
L. Anselmo (NASA)*

## COMMENTS ON DESIGN

### MAXIMIZE COUPLING OF EM WAVES TO SPO

- (I) THIN METAL FILM
- (II) HIGH PLASMA OSCILLATION FREQUENCY
- (III) LOW RESISTIVITY METAL
- (IV) LOW REFLECTIVITY METAL

### MAXIMIZE TUNNELING CURRENT

- (I) HIGH DOPING CONCENTRATION
- (II) LOW EFFECTIVE BARRIER
- (III) LOW TEMPERATURE OPERATION

### MAXIMIZE RESPONSE TIME

- (I) LOW RESISTANCE & CAPACITANCE
- (II) HIGH ELECTRON MOBILITY

(I) TUNGSTEN SILICIDE THICKNESS OF 200 TO 300 ANGSTROMS.

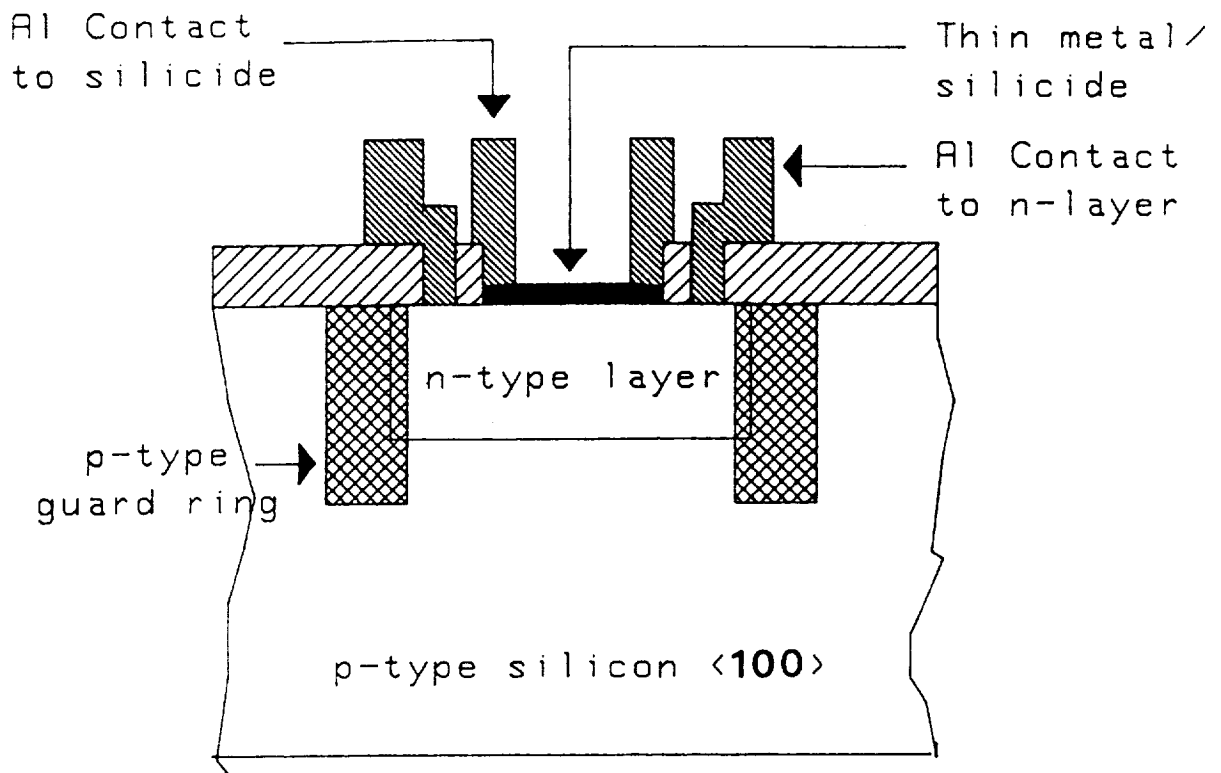
(II) CONTACT METAL (AL) THICKNESS OF 1  $\mu\text{m}$ .

(III) THE DIFFUSED N-TYPE LAYER FORMING THE ACTIVE DEVICE WAS 1  $\mu\text{m}$  DEEP.

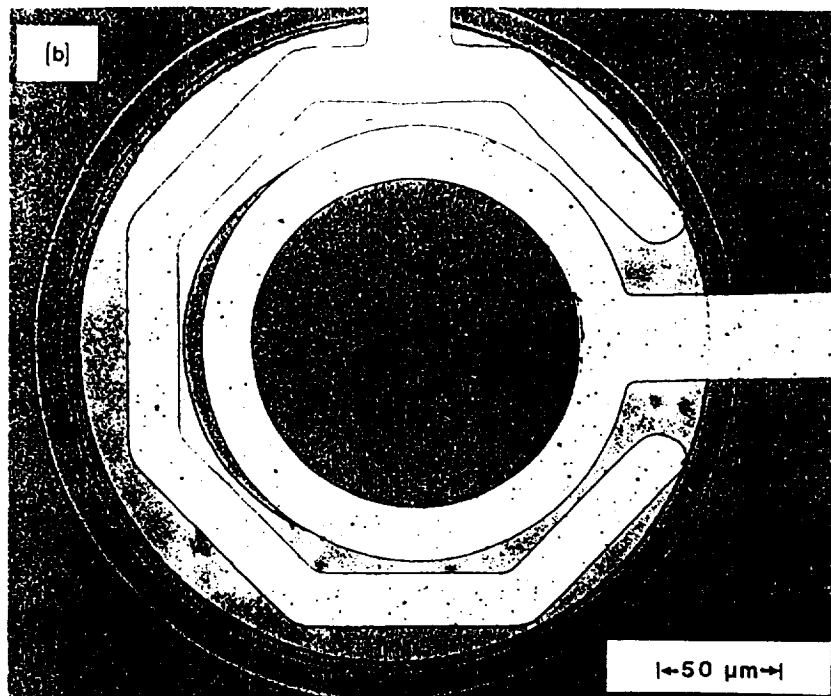
(IV) THE P-TYPE GUARD RING FOR THE GUARD RING SCHOTTKY DIODE WAS 1.5  $\mu\text{m}$  DEEP.

(V) THE DOPING CONCENTRATION OF THE N-TYPE LAYER WAS CLOSED TO THE SOLID SOLUBILITY LIMIT FOR PHOSPHOROUS IN SILICON  $1 \times 10^{20} \text{ cm}^{-3}$ .

(VI) THE SUBSTRATE WAS HIGH RESISTIVITY P-TYPE  $\langle 100 \rangle$  SILICON.



(a) CROSS SECTION



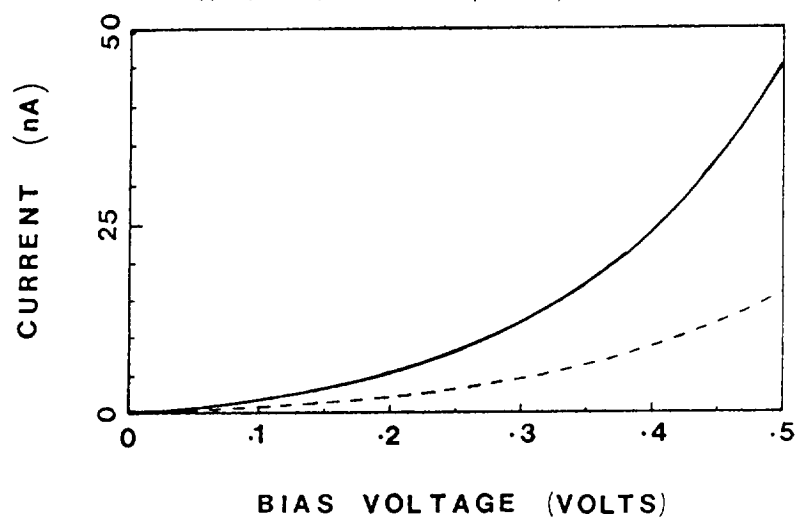
(b) TOP VIEW  
OPTICAL DETECTOR STRUCTURE

## DEVICE CHARACTERIZATION

- I - V MEASUREMENTS
- C - V MEASUREMENTS
- SHEET RESISTANCE MEASUREMENTS
- INCLUDING RTA OF WSi<sub>2</sub>
- OPTICAL RESPONSE
- VISIBLE
- FAR-INFRARED

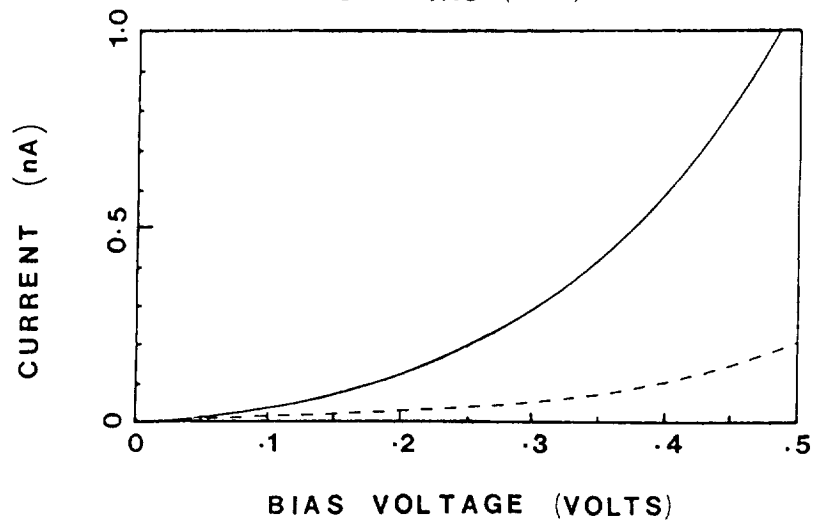
### I-V CHARACTERISTICS

FORWARD BIAS (298K) ———  
REVERSE BIAS (298K) - - - -



### I-V CHARACTERISTICS

FORWARD BIAS (78K) ———  
REVERSE BIAS (78K) - - - -



\* UTILITY OF THE SILICIDE AS  
A GATE AND INTERCONNECT MATERIAL  
FOR VLSI

- GOOD ADHESION PROPERTIES
- HIGH TEMPERATURE STABILITY
- LOW RESISTIVITY
- SUITABLE FOR GROWING AN INSULATING LAYER BY OXIDATION

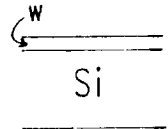
SAMPLE PREPARATION

DEPOSITION OF TUNGSTEN

Magnetron Sputtered at a base pressure  
of  $10^{-7}$  Torr.

Film Thickness 20 nm.

Uniformity 1 nm.



FORMATION OF TUNGSTEN SILICIDE

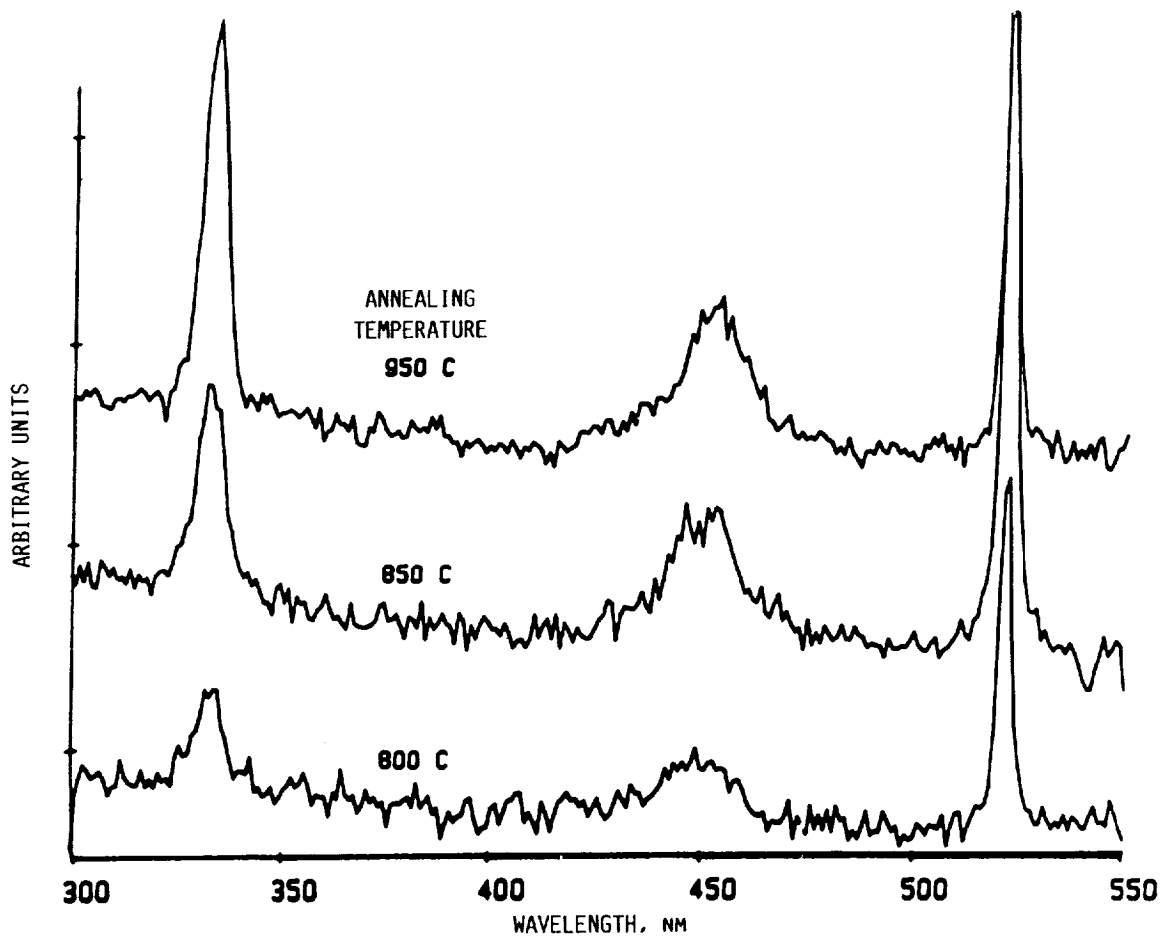
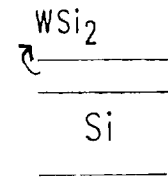
Rapid Thermal Annealing in  
10% H<sub>2</sub> and 90% Ar Atmosphere

Time 90s/20s

Thickness 50 nm.

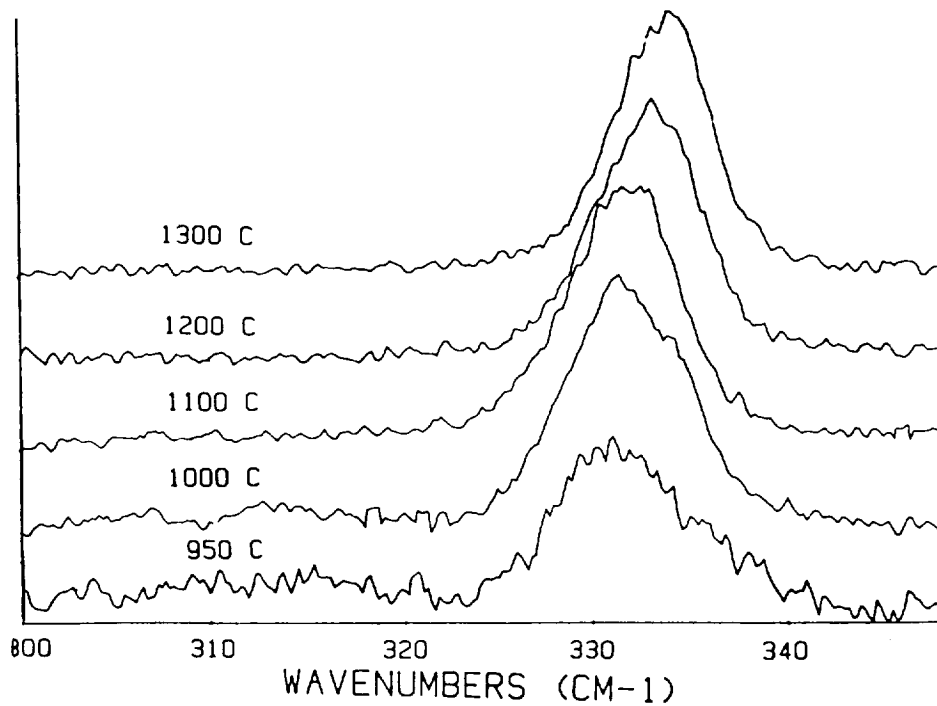
Stoichiometry WSi<sub>1.4</sub> (RBS)

Temperature 800C -



RESPONSIVITY OF TUNGSTEN DIODE

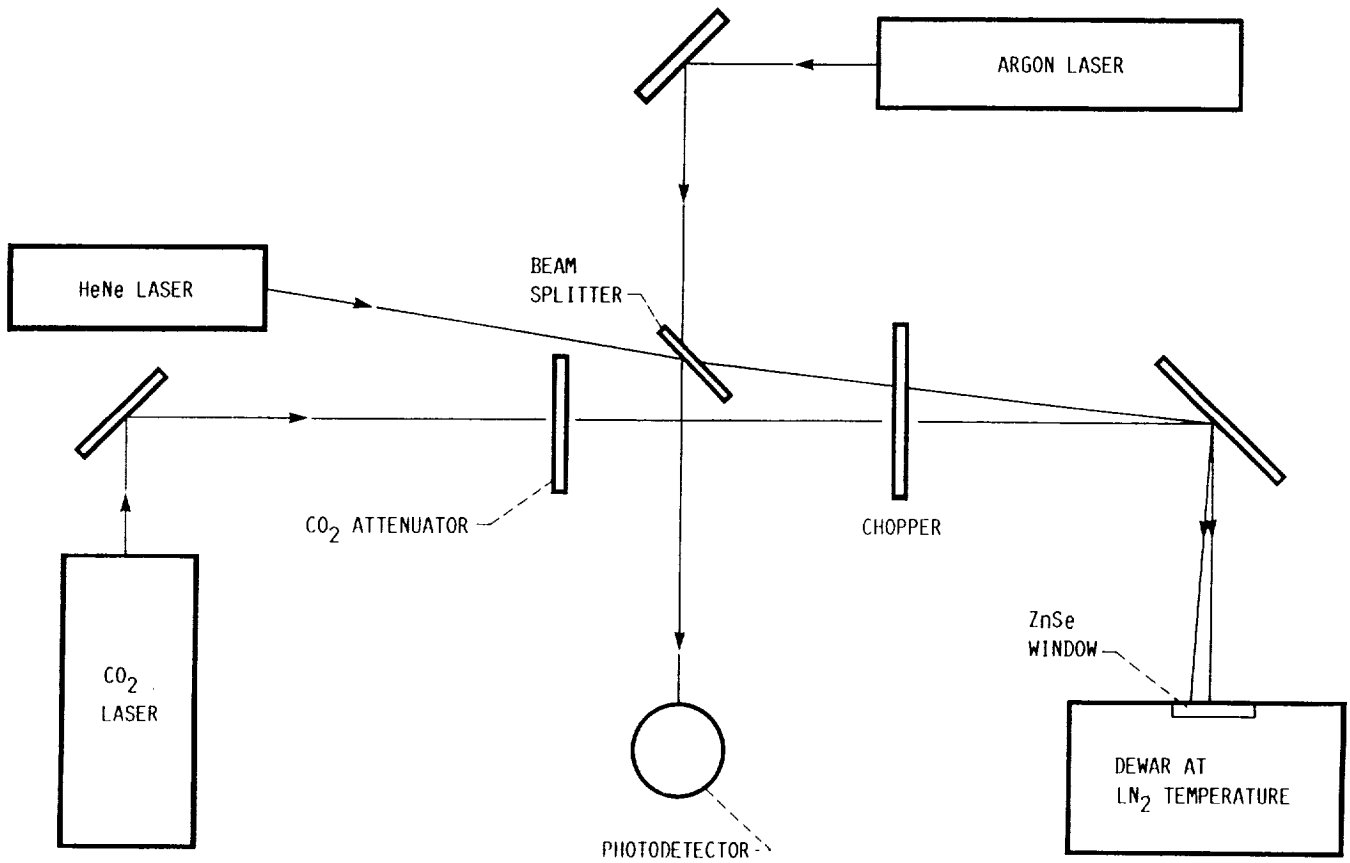




Raman spectra of rapid thermal annealed tungsten silicide

Properties of tungsten silicide films rapid thermally annealed at different temperatures

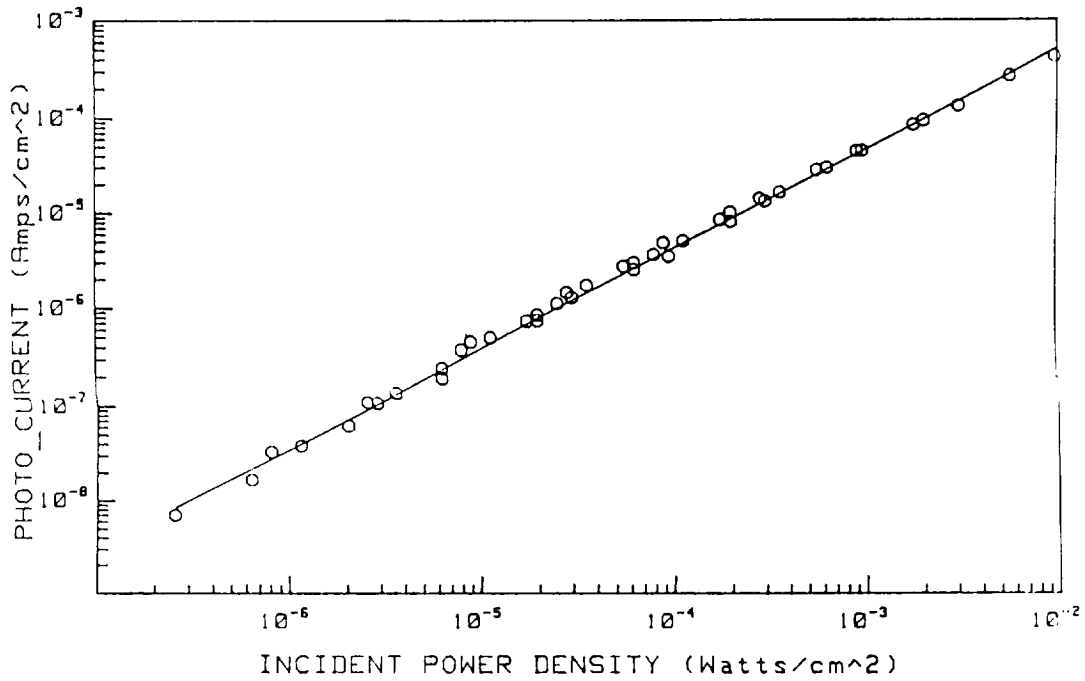
Material	RTA temp C	Sheet Resistance	Intensity of 332cm <sup>-1</sup> Raman line	Peak Position of 332cm <sup>-1</sup> line	FWHM (cm <sup>-1</sup> )	Ratio of Area under 332cm <sup>-1</sup> Peak
W	---	68.34	---	---	---	---
WSi2	950	30.9	31.7	331.0	8.7	1.0
WSi2	1000	24.5	86.6	332.0	7.6	1.19
WSi2	1100	20.7	93.3	334.1	6.4	1.31
WSi2	1200	24.2	105.7	333.7	6.1	1.21
WSi2	1300	314.6	128.6	334.0	5.9	1.25



SETUP FOR DIODE TESTING

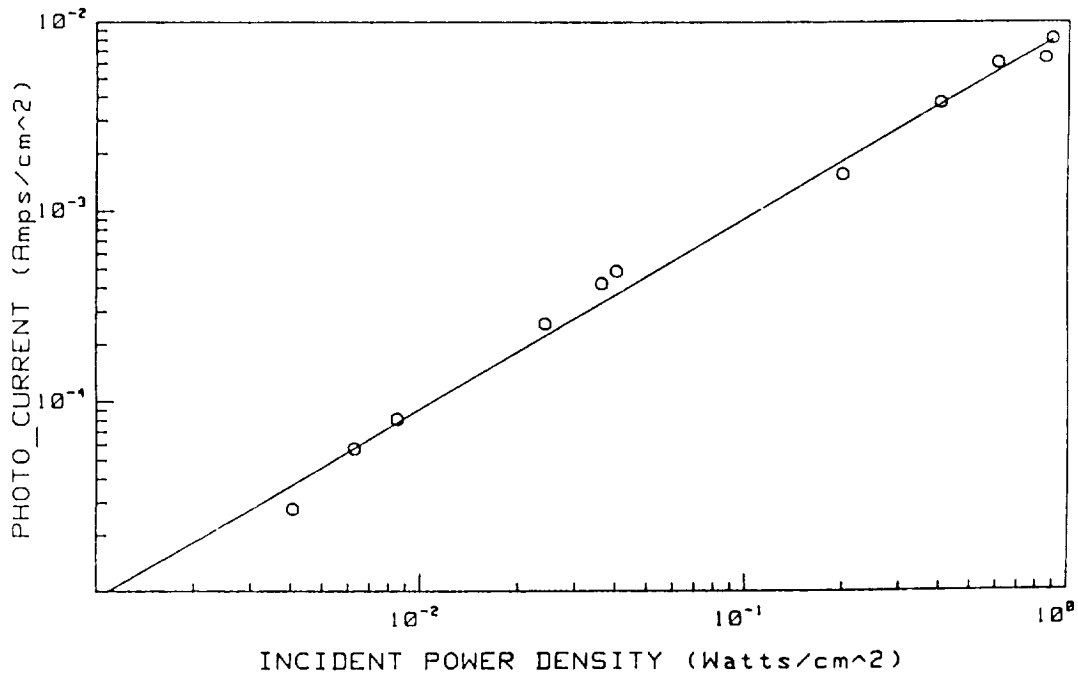
# RESPONSE TO HeNe LASER (6328 Å)

Measurement Temperature 78 °K



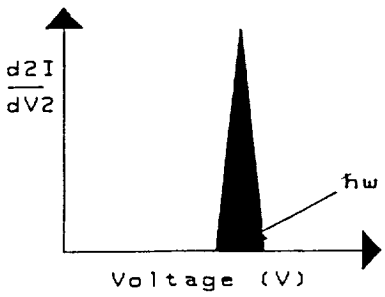
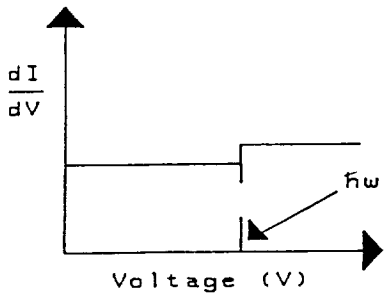
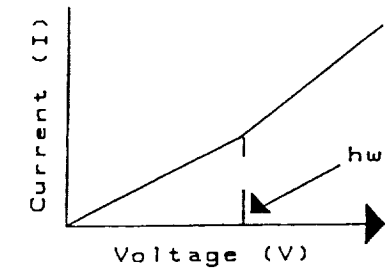
# RESPONSE TO ARGON LASER (5145 Å)

Measurement Temperature 78 °K

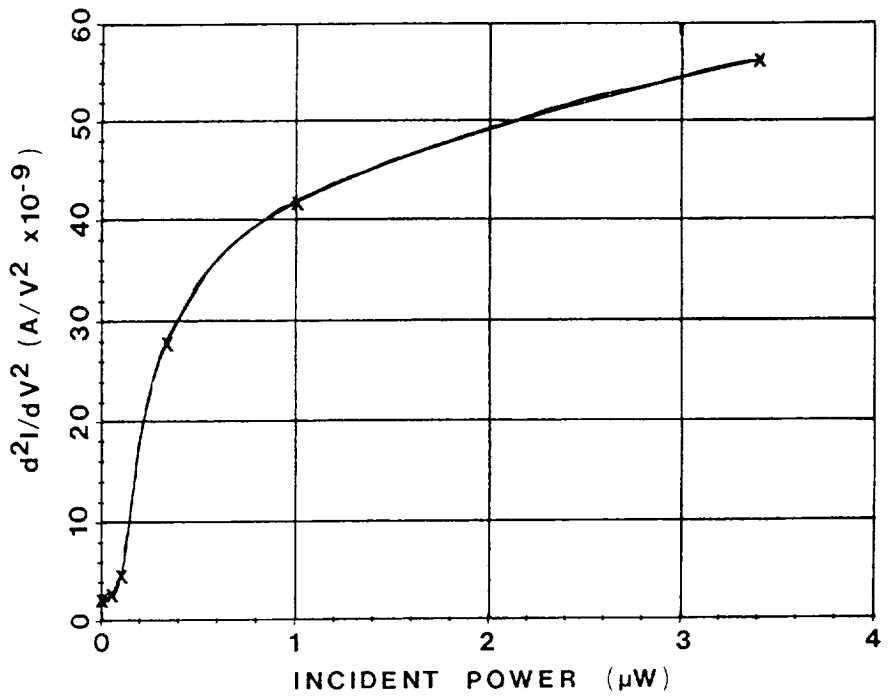
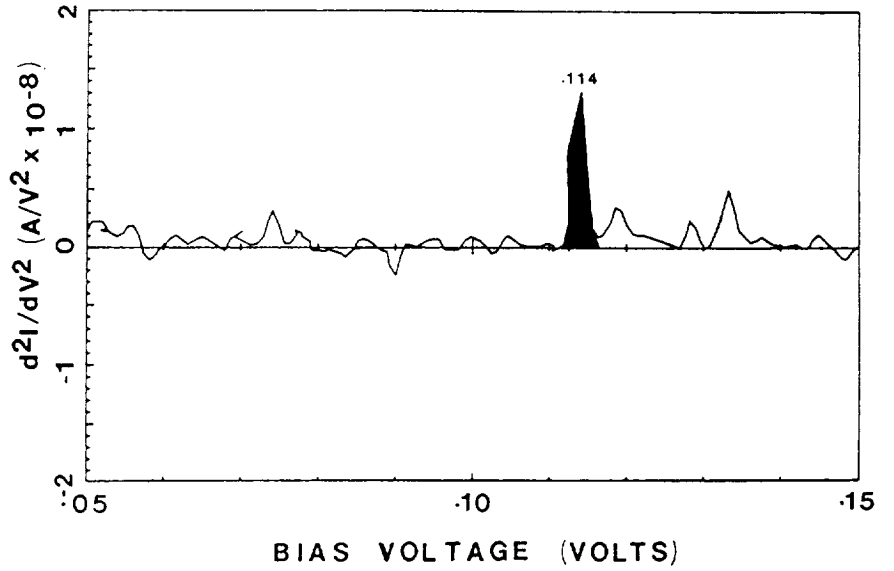


C-3

# Second Harmonic Response



THEORETICAL RESPONSIVITY CURVES



## SUMMARY

- \* DESIGNED AND FABRICATED A  
TUNGSTEN SILICIDE SCHOTTKY  
BARRIER DIODE
- \* A RTA SILICIDE PROCESS WAS  
INVESTIGATED
- \* ELECTRICAL CHARACTERIZATION WAS  
CARRIED OUT
- \*\* DEMONSTRATED RESPONSE TO OPTICAL  
RADIATION AT A WAVELENGTH OF  
10.6 MICRONS
- \* FUTURE DIRECTIONS IDENTIFIED.

## FUTURE EFFORTS

- \* OPTICAL RESPONSE OF PRESENT  
SMALL STRUCTURES
- \* FABRICATION AND CHARACTERIZATION  
OF SUB-MICRON STRUCTURES
- \* DEVELOP ELECTRODE/ANTENNA  
STRUCTURES
- \* OPTICAL RESPONSE AND QUANTUM  
EFFICIENCY OF ARRAYS OF  
SUB-MICRON STRUCTURES.



## CONCLUSIONS

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Cleveland, Ohio 44135

The free-space power transmission concept has been demonstrated. Several prototype systems and components have been developed and successfully tested at 2.45 GHz. Extensive studies have determined the applicability of this concept to missions such as the SPS, the Canadian SHARP, and the CO-OPS Program.

The applicability or practicality of this concept could only be determined by its competitiveness over more conventional techniques of power generation in space (solar and nuclear). In most NASA and DOD scenarios, the separation distance between the transmitter and receiver ranges from a few tens to several thousand kilometers. Because of mass constraints, antenna sizes should be kept to a minimum, forcing the system to operate at higher frequencies and, consequently, to attain a high-power interception efficiency. To remain competitive, this kind of system should operate at frequencies above 100 GHz.

No system above 2.45 GHz has been developed. A prototype system operating at 35 GHz seems to be the next logical step, since technology is already available at that frequency. Technology at 100 GHz and above seem to be feasible, but not available in the immediate future. Development of antenna, RF-power-generation, and rectenna technology is necessary for working systems at these frequencies.

A substantial effort in these areas is being sponsored by the Government, the military, academia, and industry. Although this effort is not directed toward the development of a free-space power transmission system, the outcome of these programs is applicable to beam power technology. A combined effort of all the parties involved should contribute to an early and cost-effective development of such technology.

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15. Supplementary Notes					
16. Abstract <p>NASA Lewis Research Center organized a workshop on technology availability for free-space power transmission (beam power). This document contains a collection of viewgraph presentations that describes the effort by academia, industry and our national laboratories in the area of high-frequency, high-power technology applicable to free-space power transmission systems. The areas covered were rectenna technology, high-frequency, high-power generation (gyrotrons, solar pumped lasers, and free electron lasers), and antenna technology. This workshop took place on March 29-30, 1988, at NASA Lewis Research Center.</p>					
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