N90-21805

HIGH POWER MILLIMETER WAVE SOURCE DEVELOPMENT PROGRAM

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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

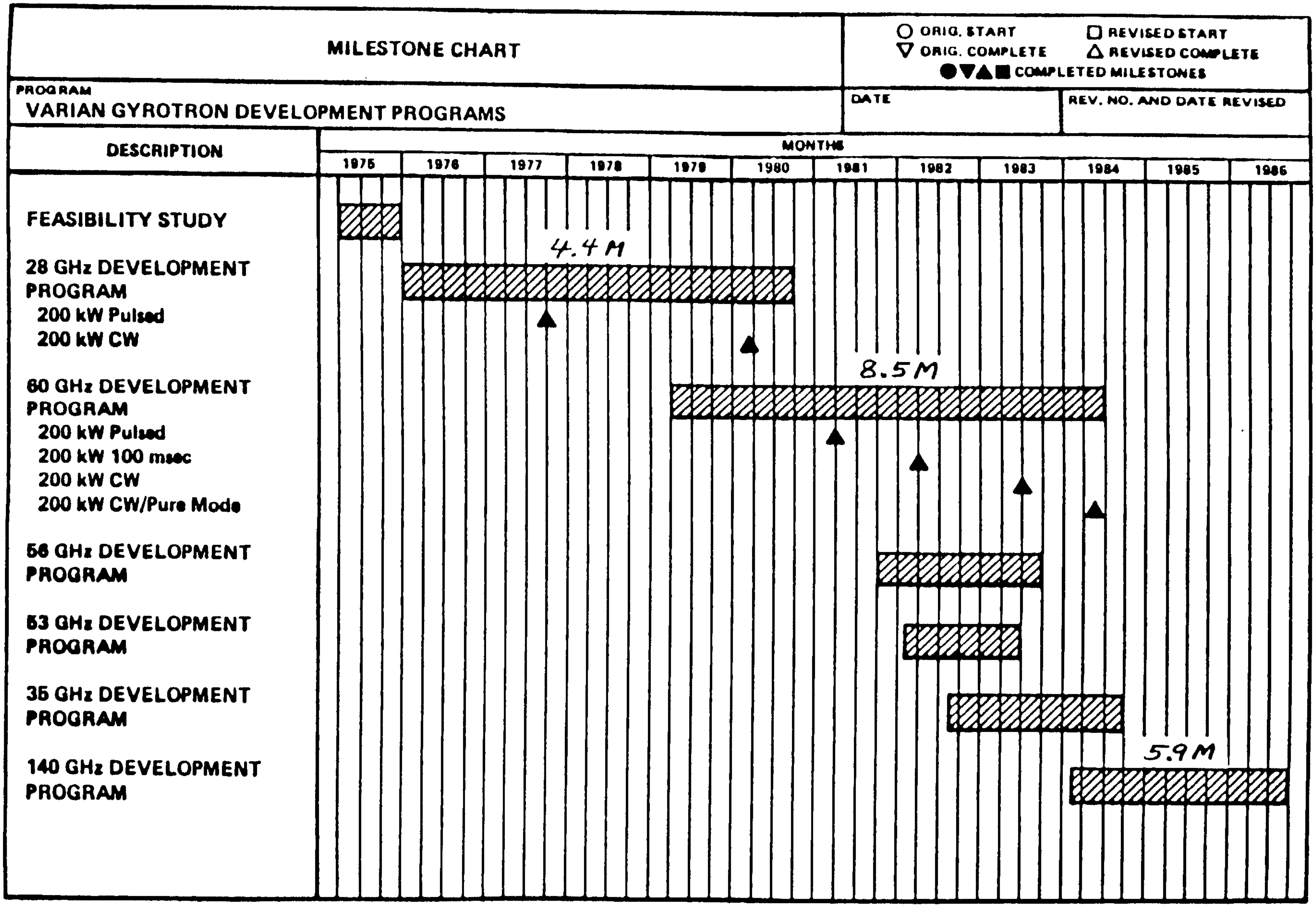
C) POWER TRANSMISSION

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


MILESTONE CHART
ORIG. START
ORIG. COMPLETE
REVISED START
REVISED COMPLETE
COMPLETED MILESTONES
PROGRAM
VARIAN GYROTRON DEVELOPMENT PROGRAMS
DATE
REV. NO. AND DATE REVISED
DESCRIPTION
MONTHS
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
FEASIBILITY STUDY
28 GHz DEVELOPMENT PROGRAM
200 kW Pulsed
200 kW CW
60 GHz DEVELOPMENT PROGRAM
200 kW Pulsed
200 kW 100 msec
200 kW CW
200 kW CW/Pure Mode
56 GHz DEVELOPMENT PROGRAM
53 GHz DEVELOPMENT PROGRAM
35 GHz DEVELOPMENT PROGRAM
140 GHz DEVELOPMENT PROGRAM
4.4 M
8.5 M
5.9 M

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

TASK	INSTITUTION	P.I.	BUDGET 1987	1988	1989
140 GHZ GYR.	VARIAN	JORY/FELCH	1000	1500	2000
140/280 GHZ	MIT	TEMKIN	400	450	?
Q-O 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

<u>ECH SOURCE DEVELOPMENT PROGRAM PLAN</u>

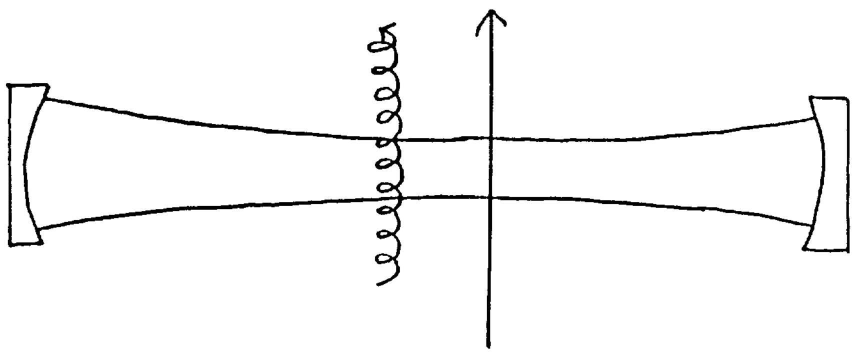
(BASED ON CURRENT FUNDING)

- 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

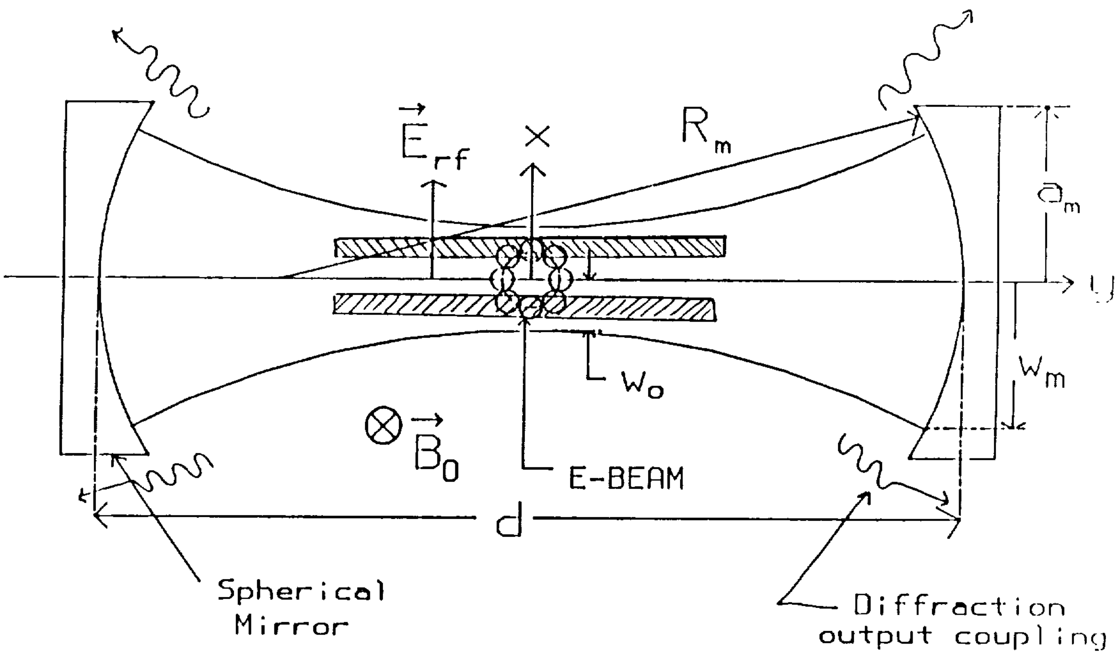
$P > 1$ MW

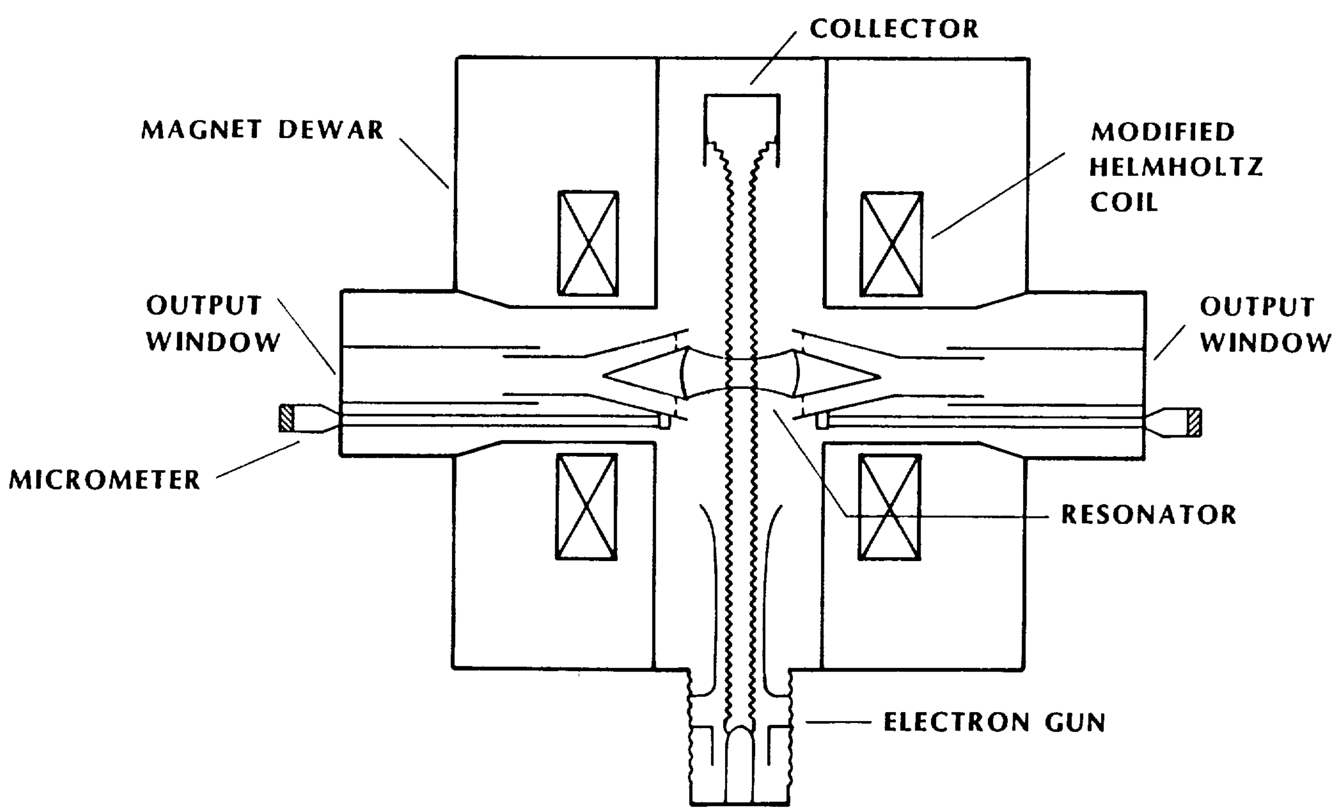
$f = 300$ GHz (Or maybe as high as 600 GHz)

$\eta \geq 20\%$

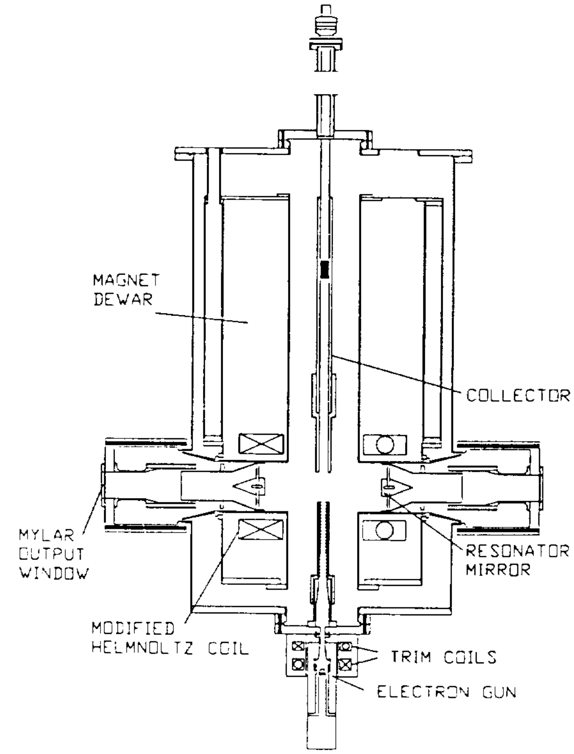
CW (Or at least 3 second) relevant

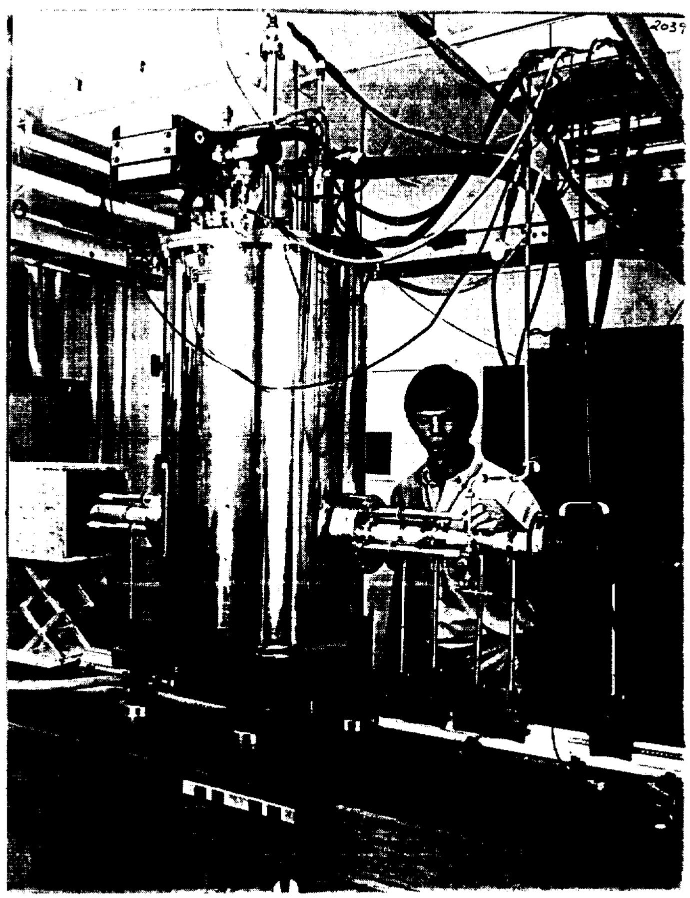
QUASI-OPTICAL RESONATOR CONFIGURATION





NRL QUASI-OPTICAL GYROTRON





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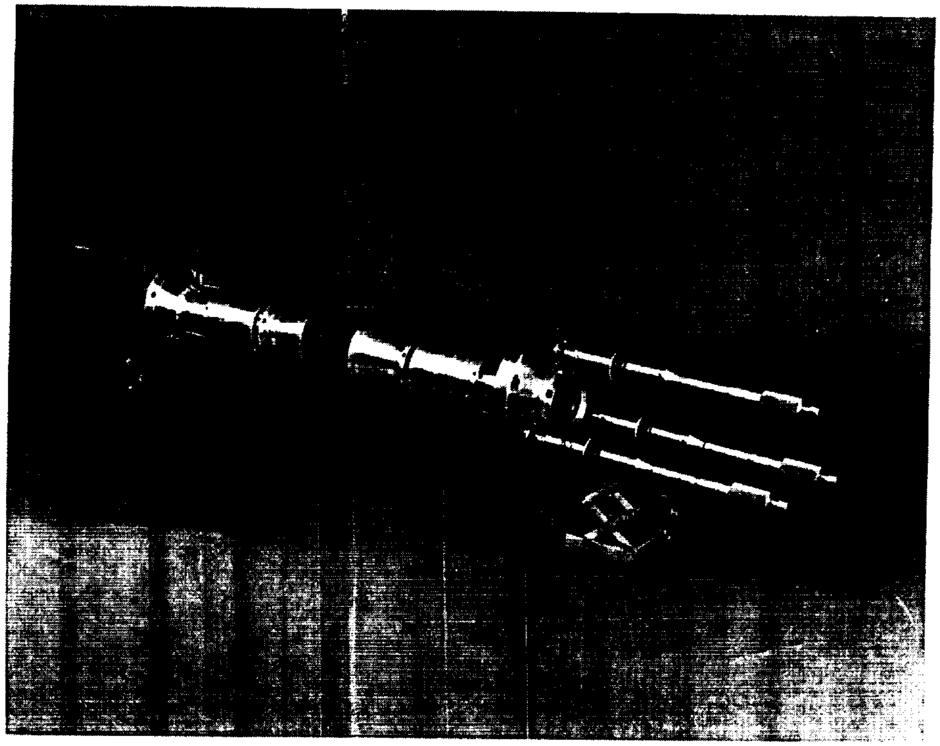

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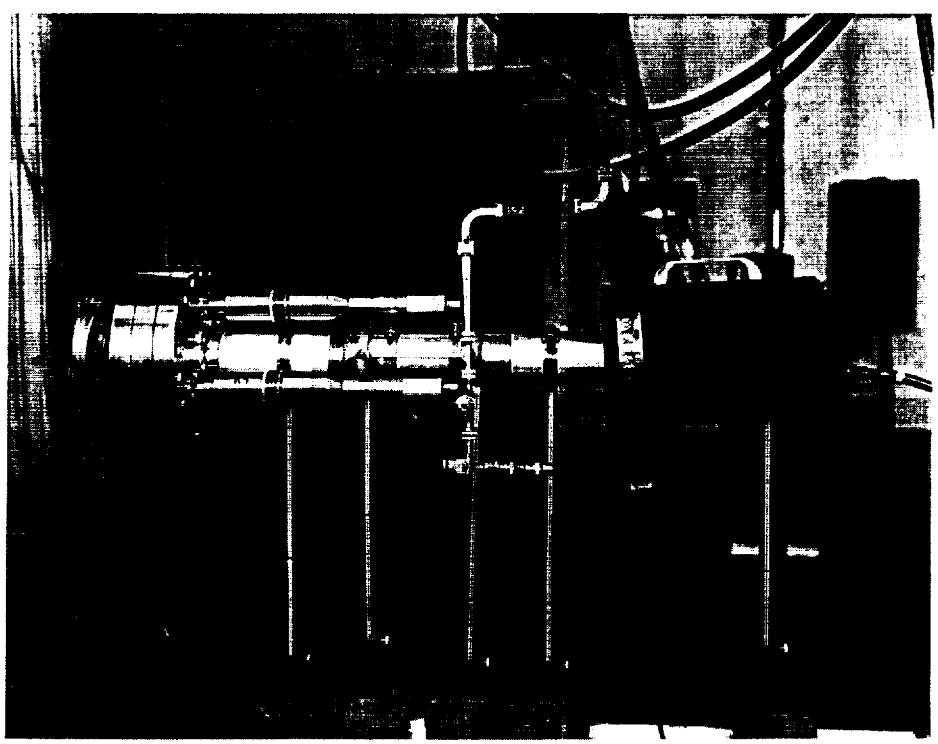

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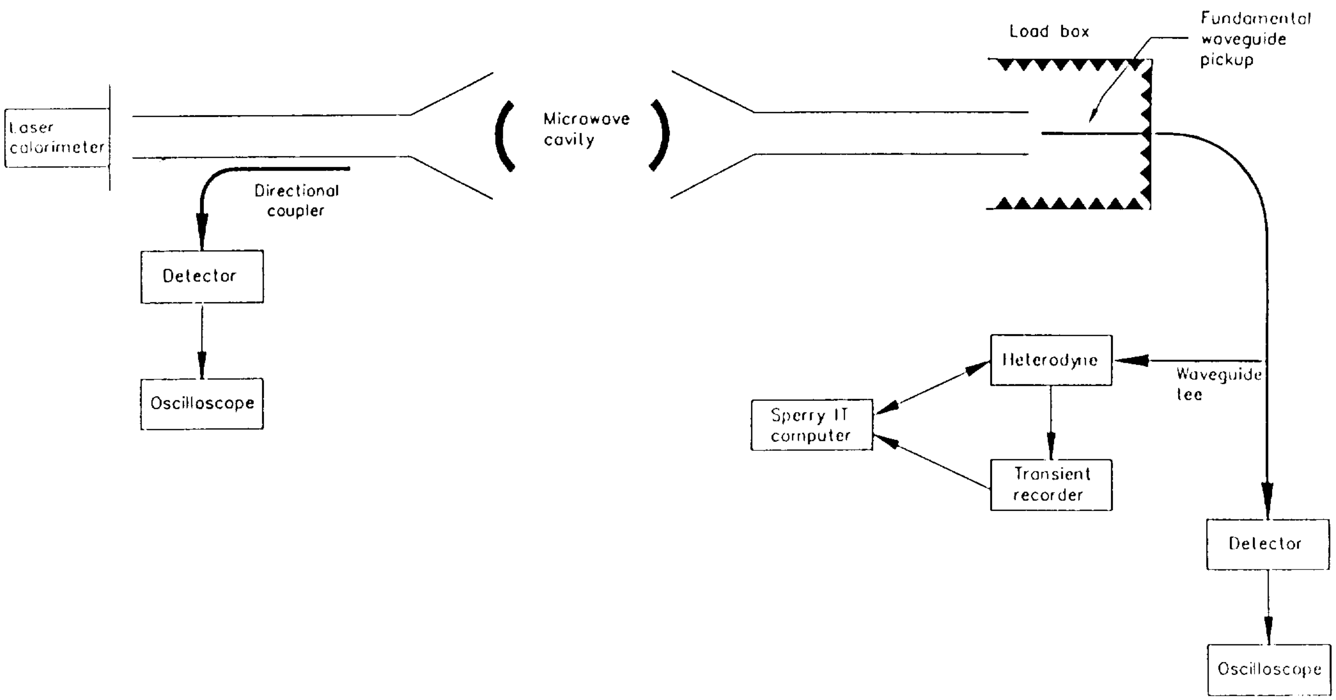
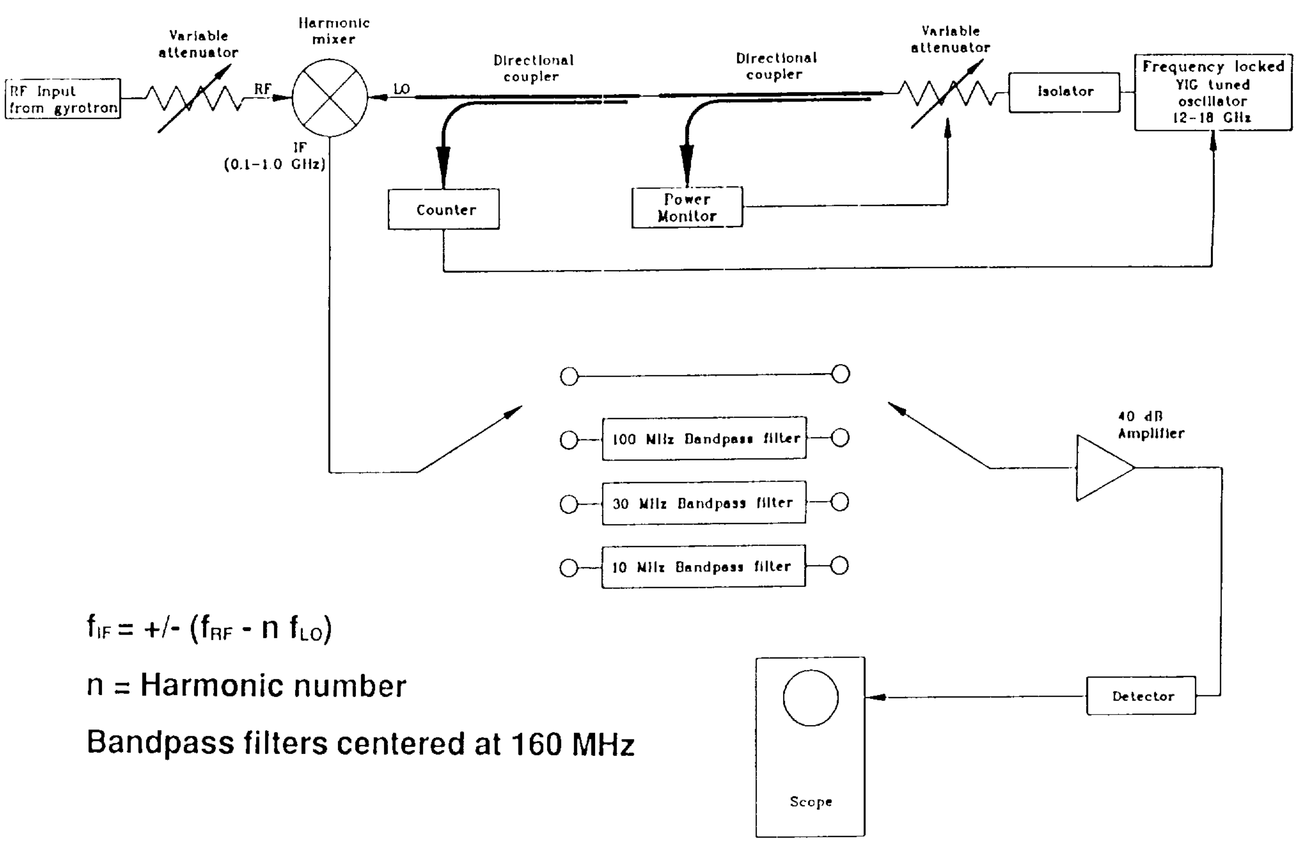
Diagnostic Setup



Heterodyne Diagnostic

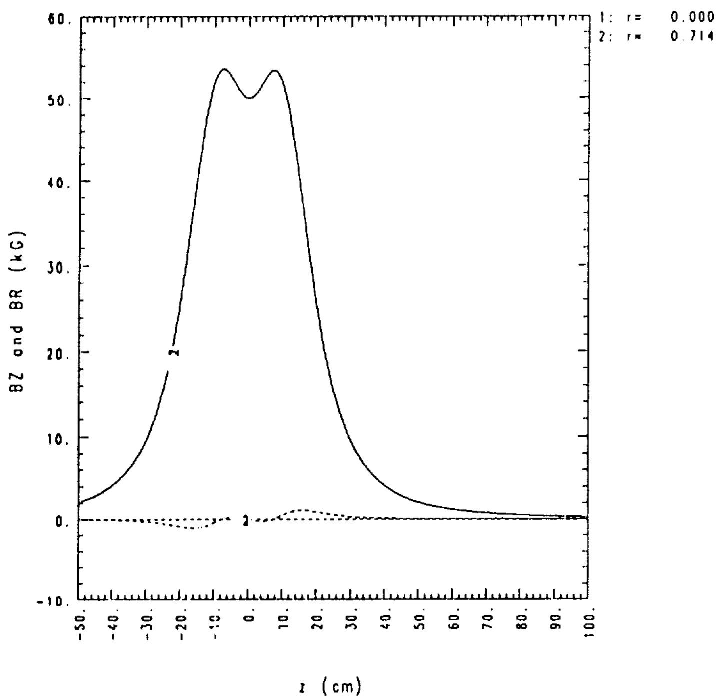


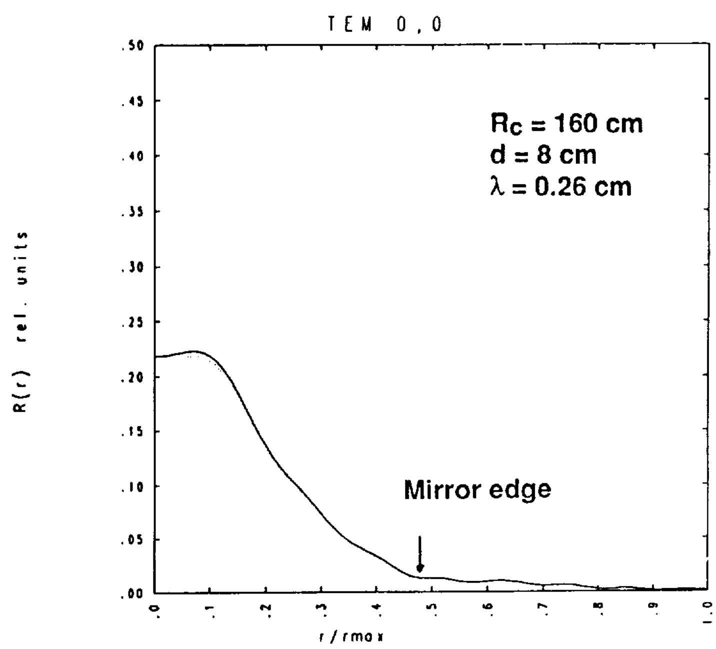
$f_{IF} = +/- (f_{RF} - n\, f_{LO})$

n = Harmonic number

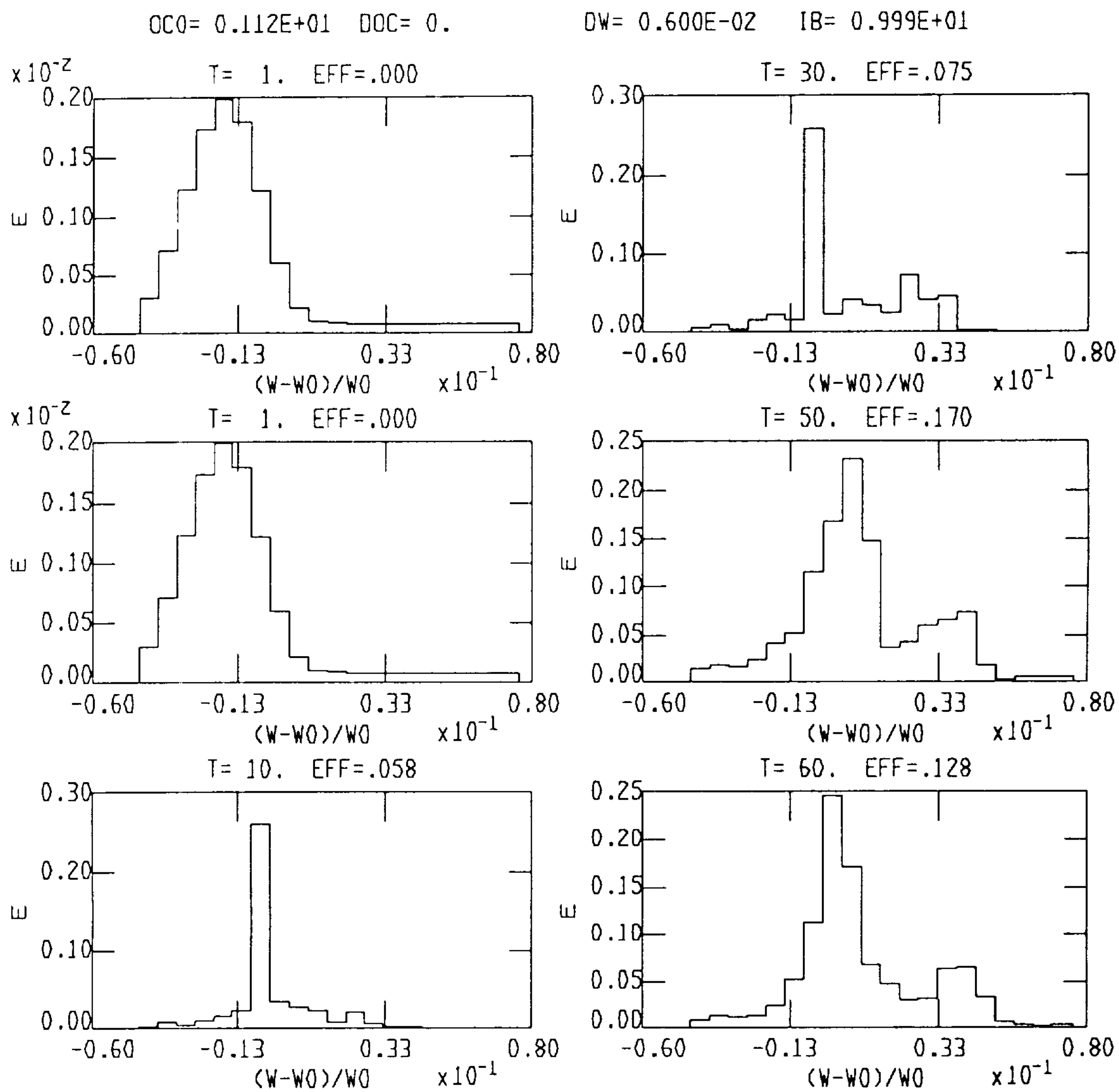
Bandpass filters centered at 160 MHz

Magnetic Field Profile





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

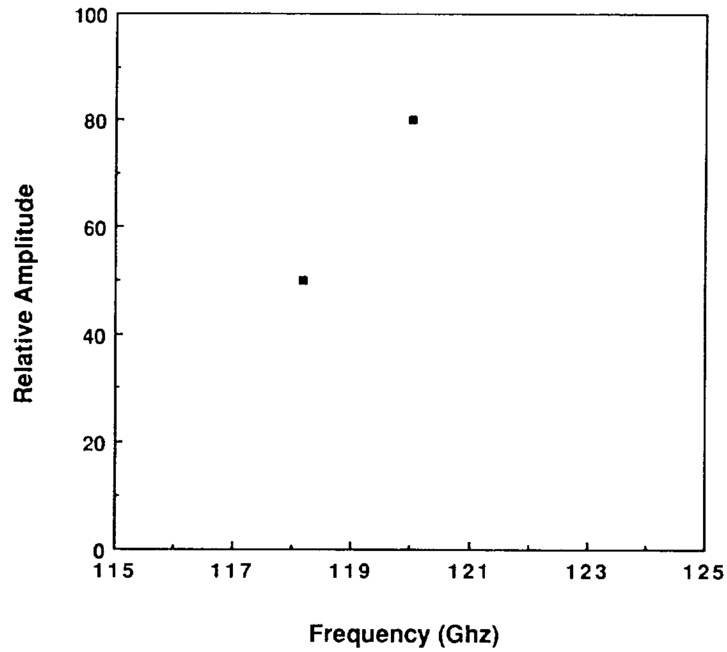


frame #

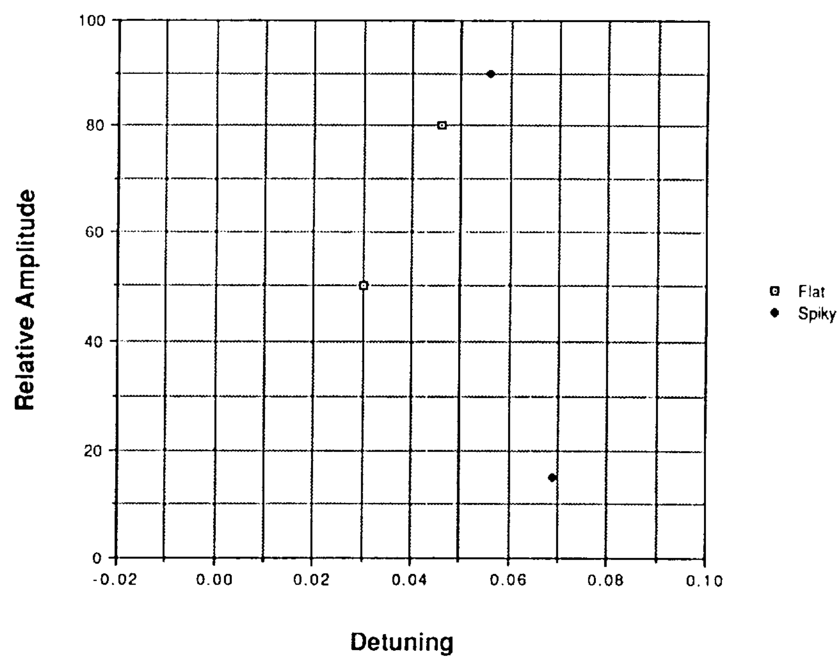
10:08:06
203/24/88

SC KR = 0.000

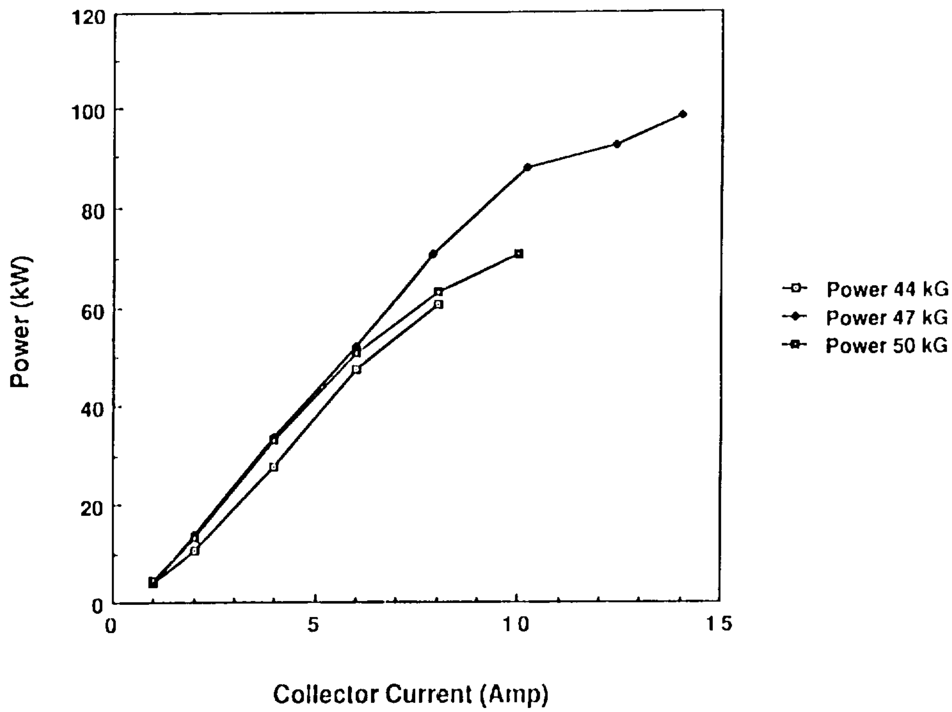
Mode Spectrum for QOG at 75 kV, 14 Amp and 47 kG



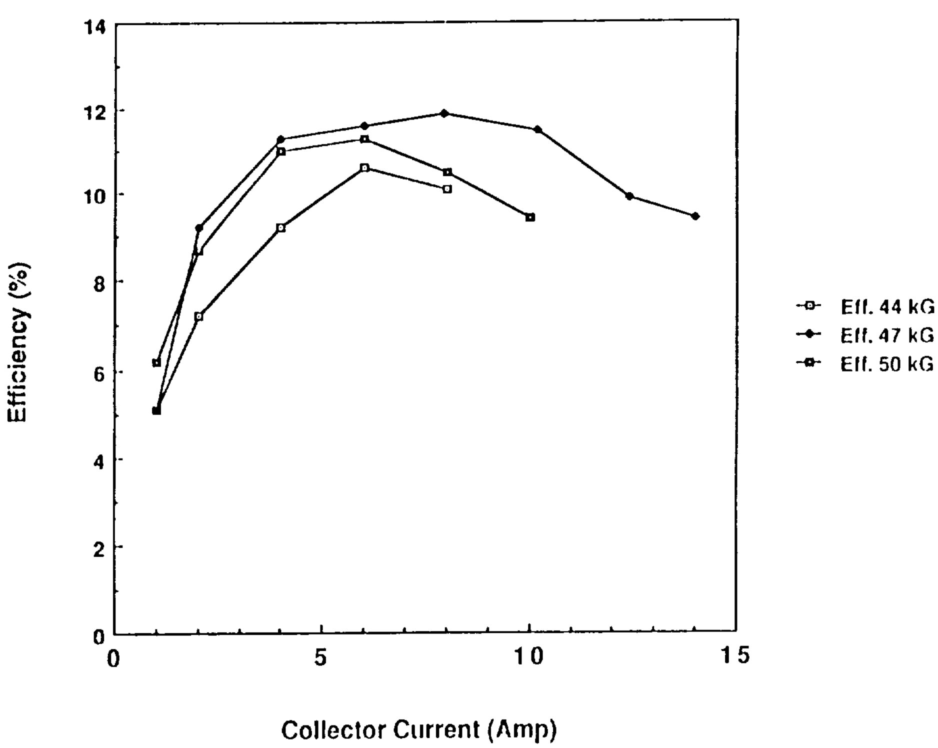
Mode Spectrum for 75 kV, 14 Amp and 47 kG

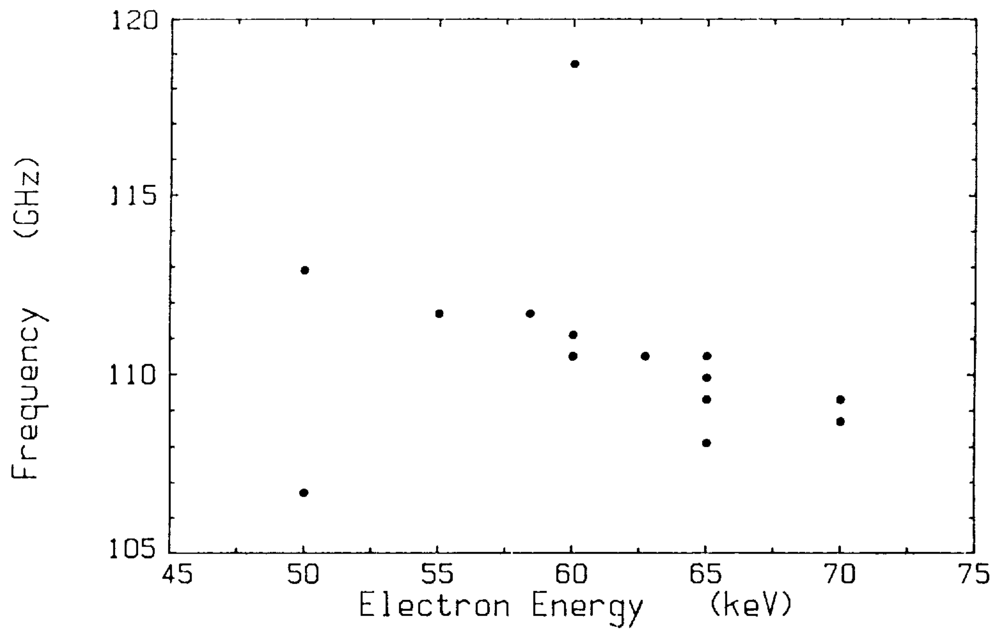


Operation at 75 kV and 20 cm Separation

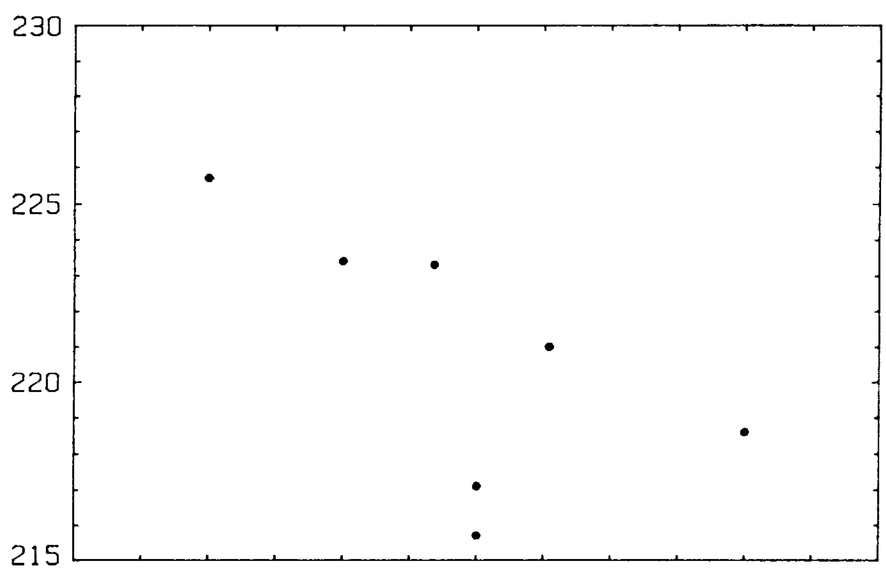


Operation at 75 kV and 20 cm Separation





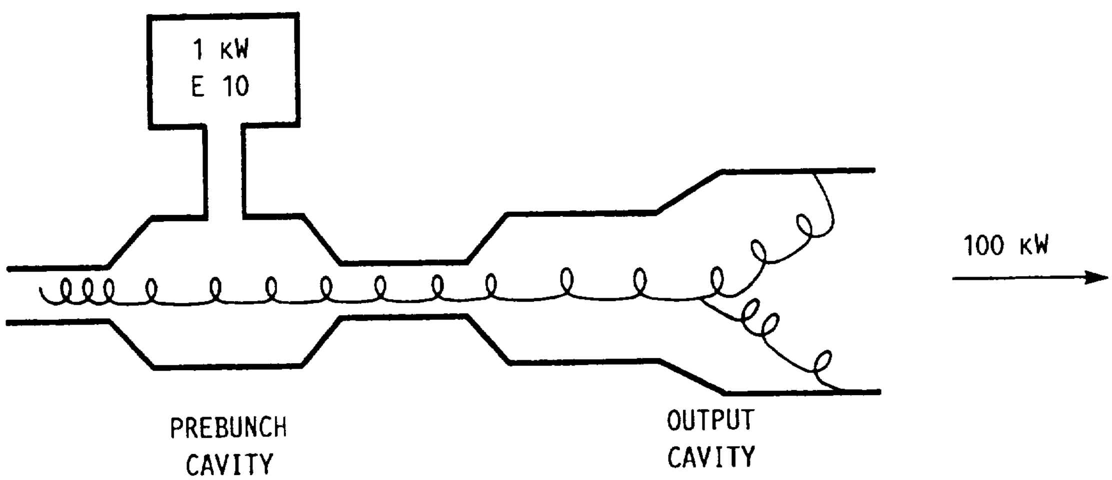
25 cm Mirror Separation



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

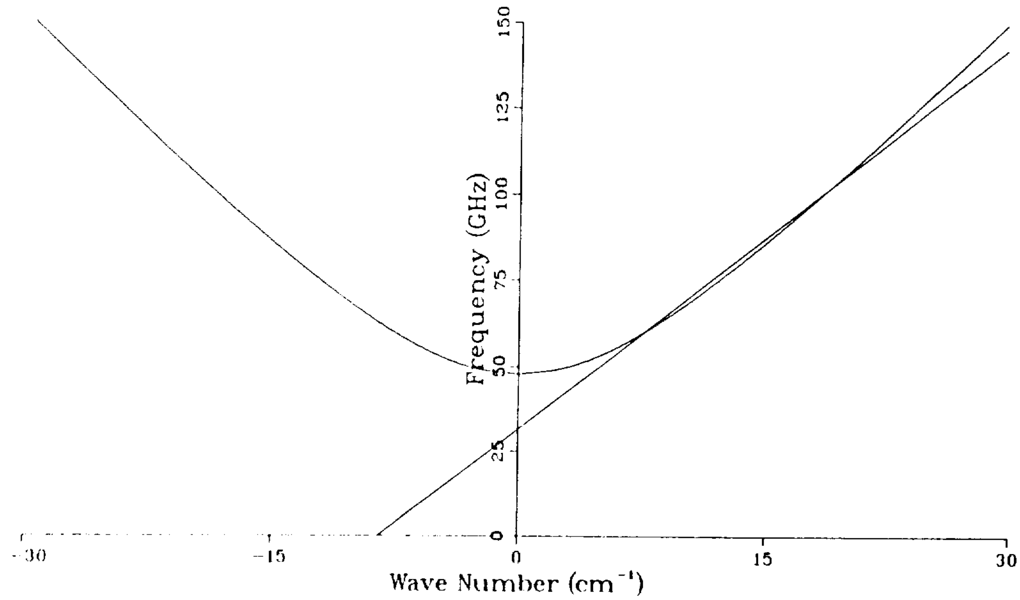
PHASE LOCKED 85 GHz GYROTRON

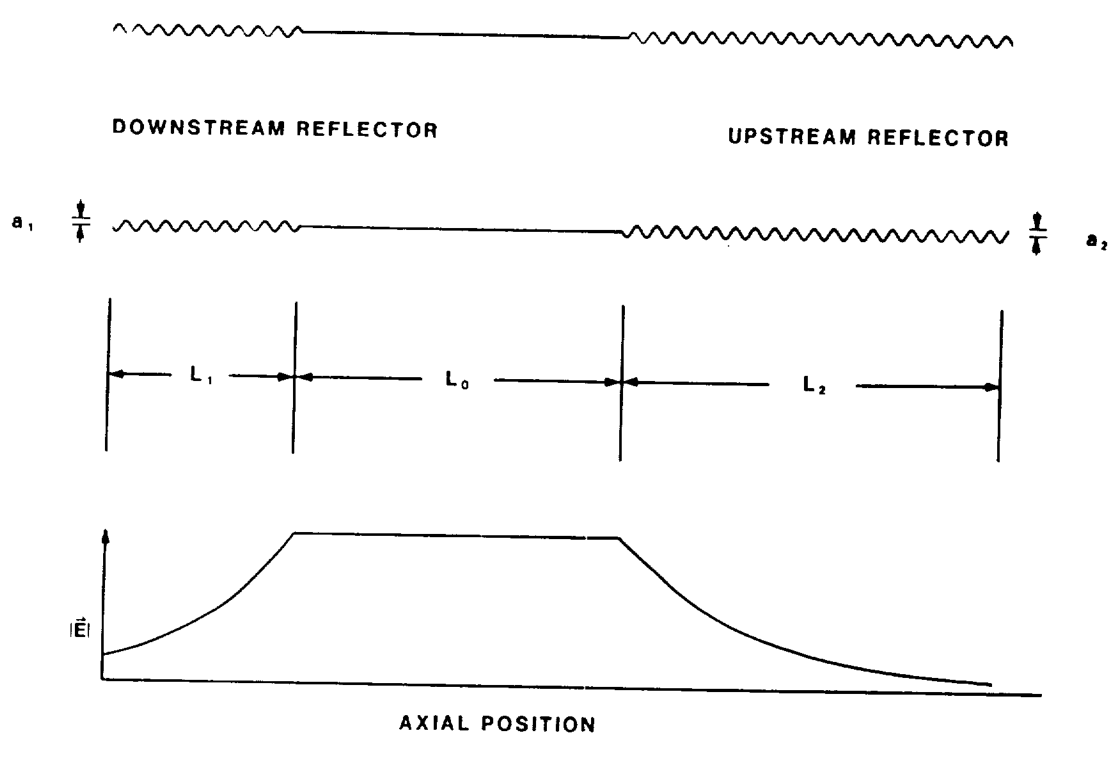


ISSUES

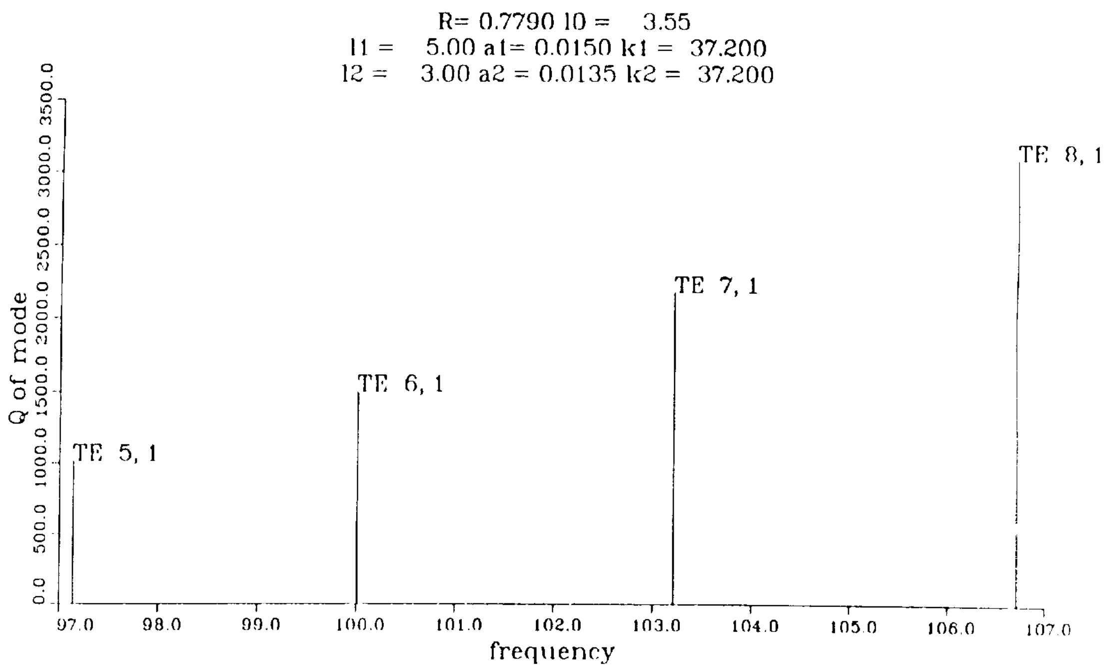
- STABILIZE PREBUNCHING CAVITY
- ISOLATE CAVITIES
- MAXIMIZE LOCKING BANDWIDTH

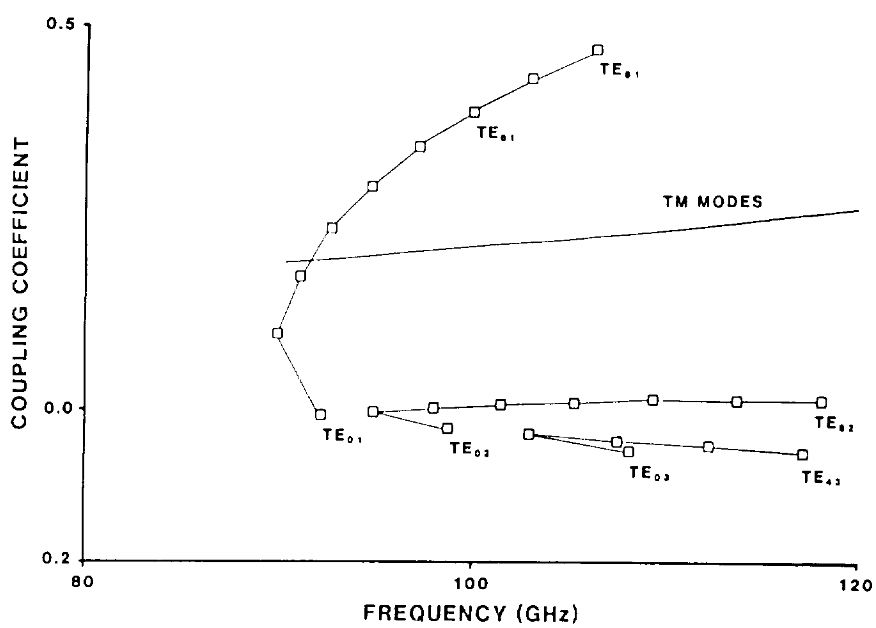
CARM Dispersion Relation

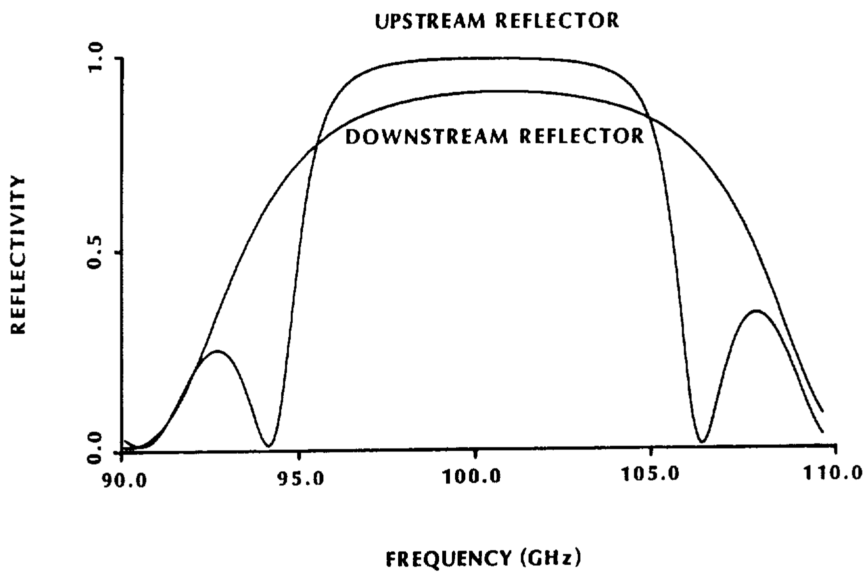




Bragg Cavity Modes







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 μsec
Velocity pitch ratio	0.71
Pitch angle spread limit	2 percent
Energy spread limit	7 percent

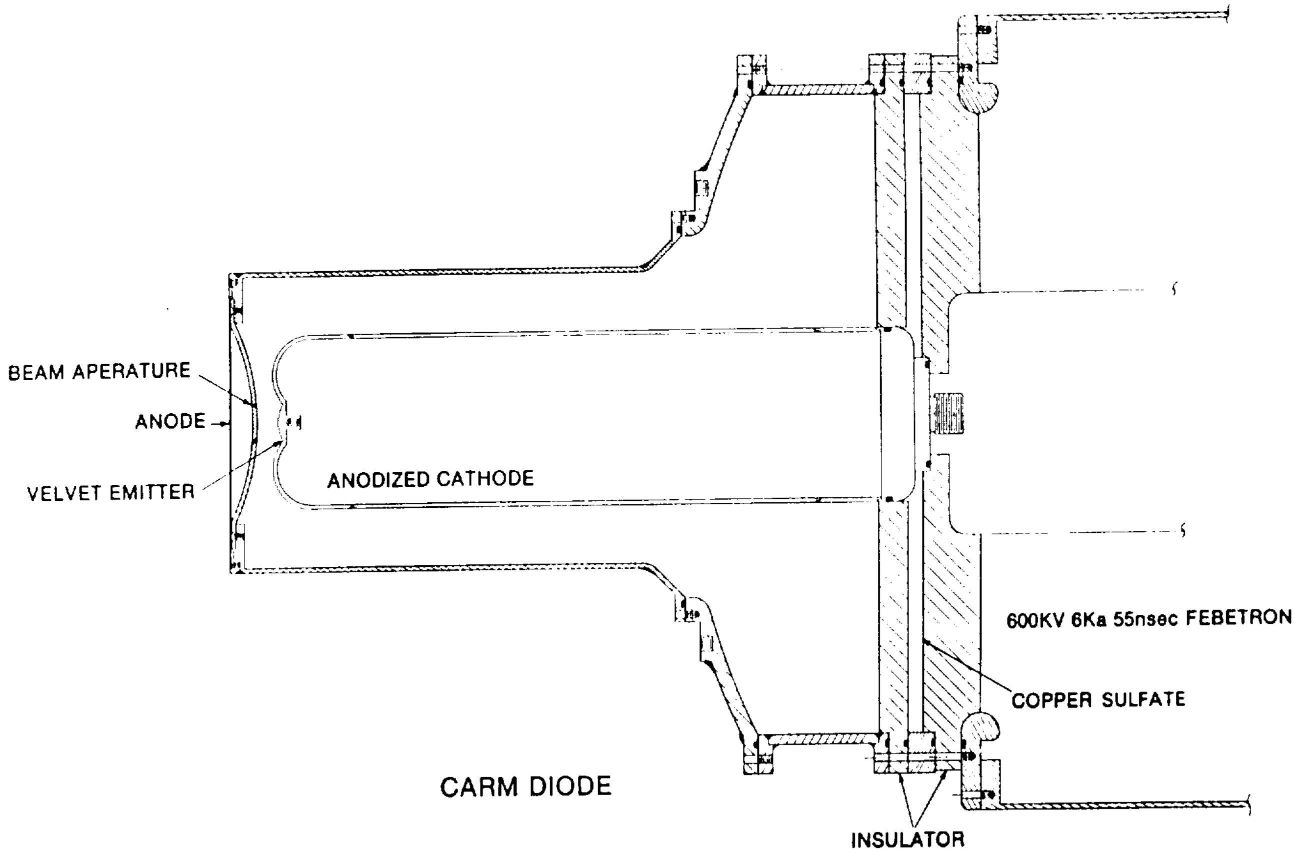
Resonator

Cavity type	circular wave guide
Reflector type	Bragg reflector
Output reflectivity	92 percent
Operating mode	TE_{14} (volume mode)
Wave group velocity	0.97c
Cavity length	~ 10 cm
Cavity diameter	1.8 cm
Ohmic heating	3 kW/cm^2

Magnet

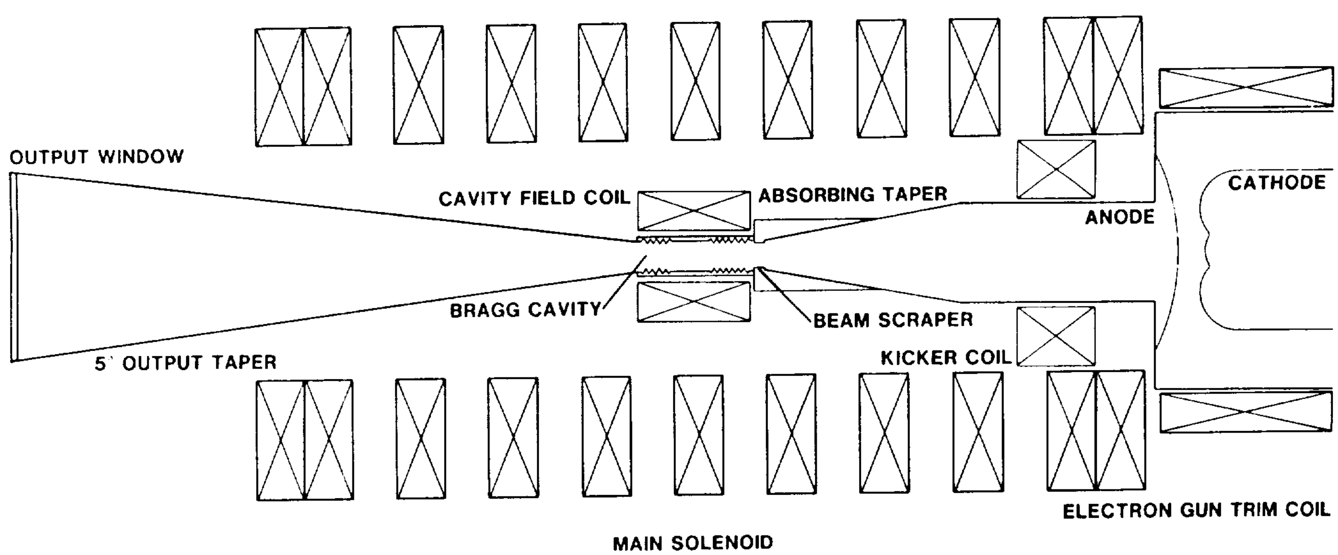
Magnet type	superconducting
Cavity magnetic field	~ 55 kG

Predicted efficiency	20 to 40 percent
Predicted output power	10 MW



BEAM APERATURE
ANODE
VELVET EMITTER
ANODIZED CATHODE
600KV 6Ka 55nsec FEBETRON
COPPER SULFATE
INSULATOR

CARM DIODE



OUTPUT WINDOW
CAVITY FIELD COIL
ABSORBING TAPER
CATHODE
ANODE
BRAGG CAVITY
BEAM SCRAPER
KICKER COIL
5° OUTPUT TAPER
ELECTRON GUN TRIM COIL
MAIN SOLENOID

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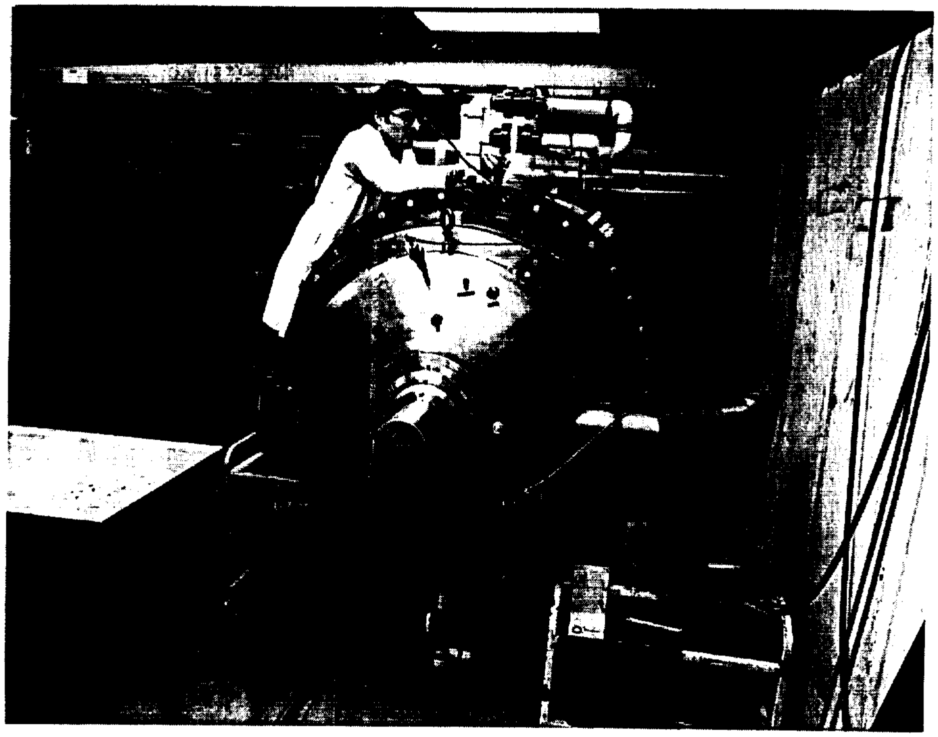

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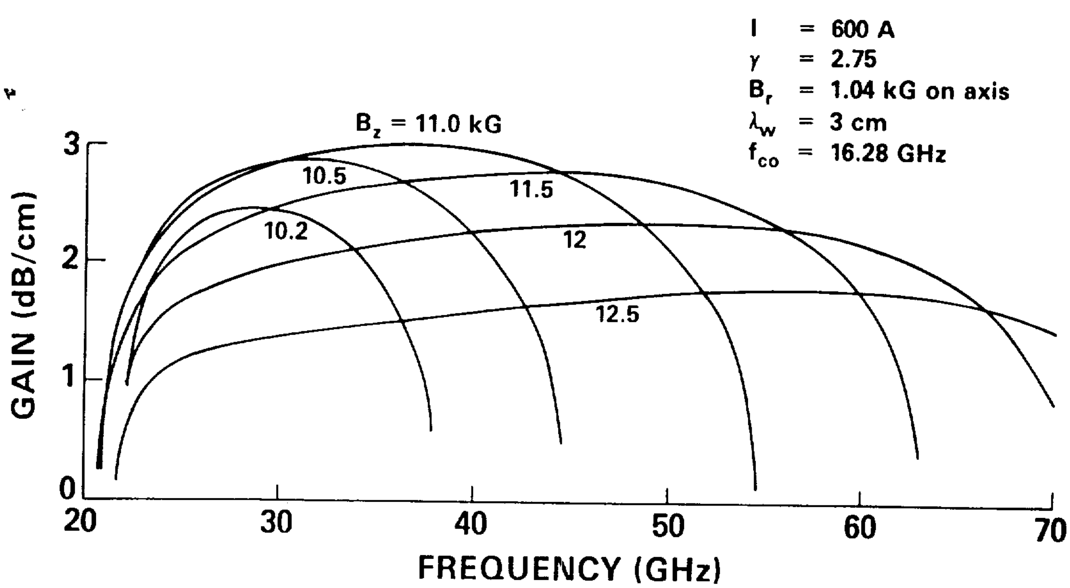
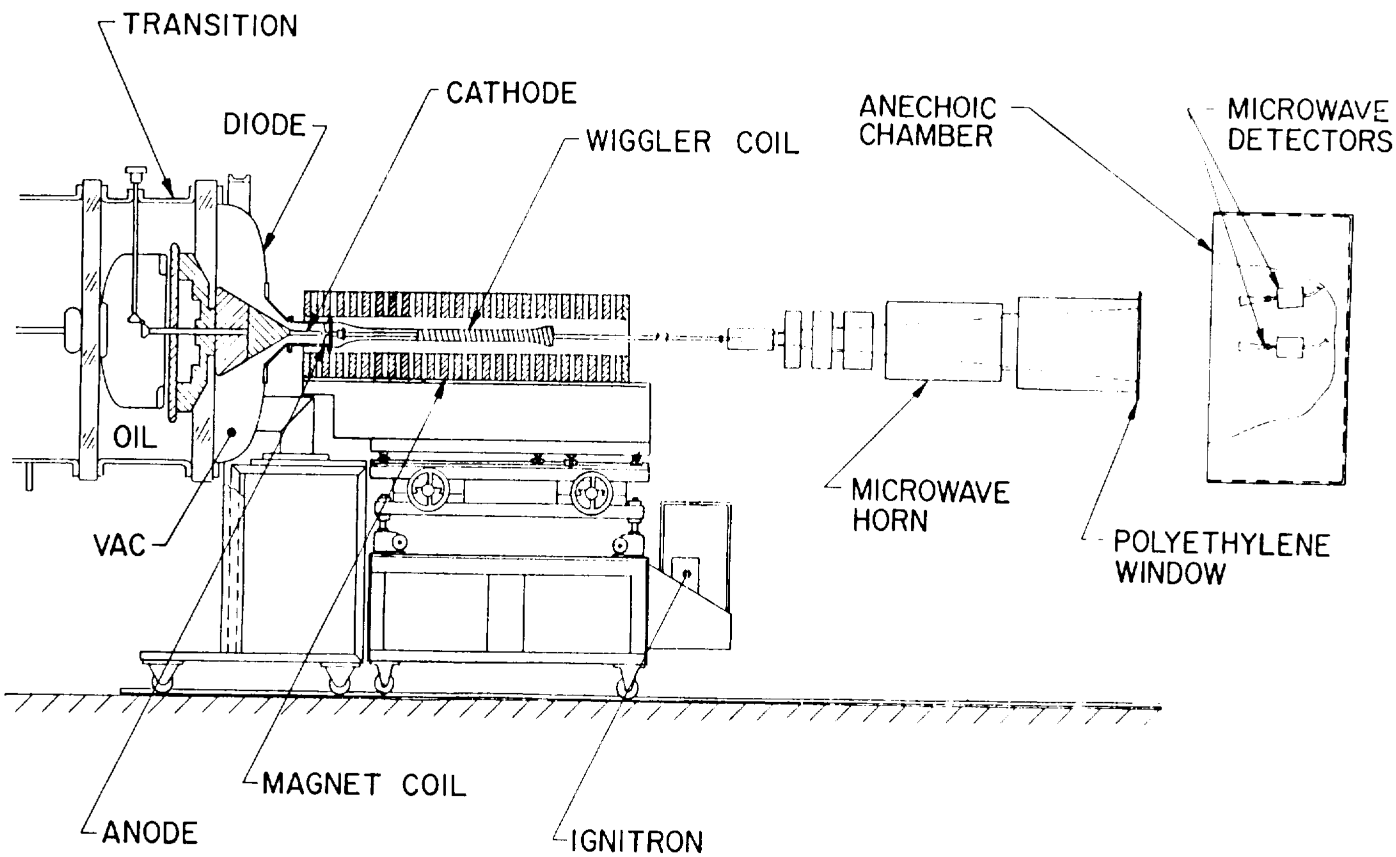
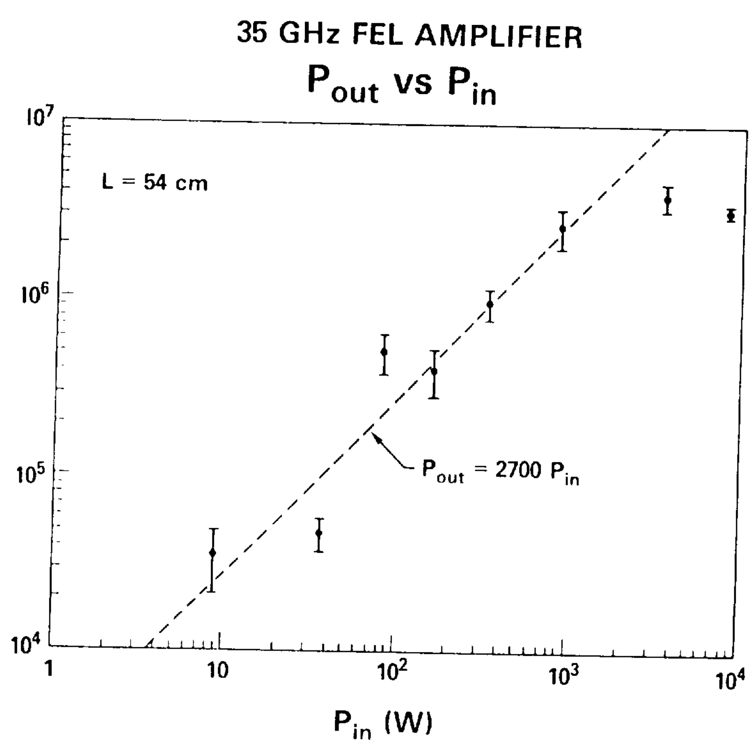
35-GHz FEL AMPLIFIER

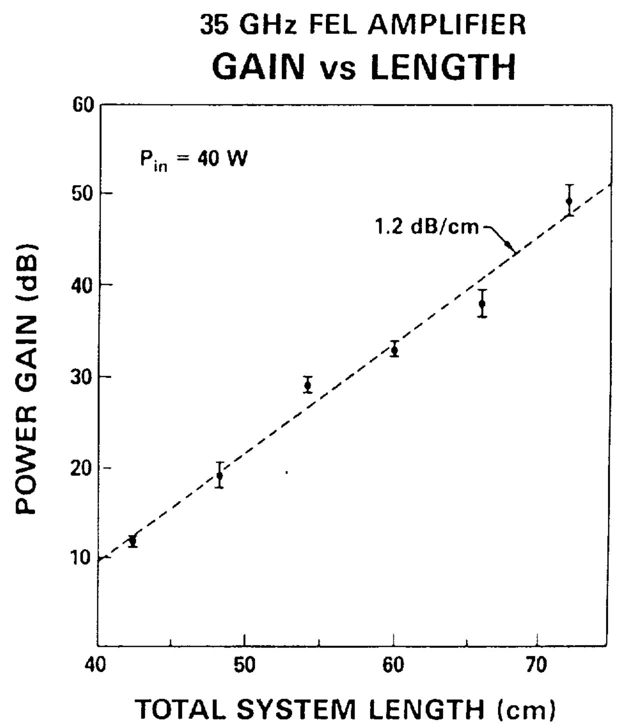
THEORETICAL GROWTH CURVES

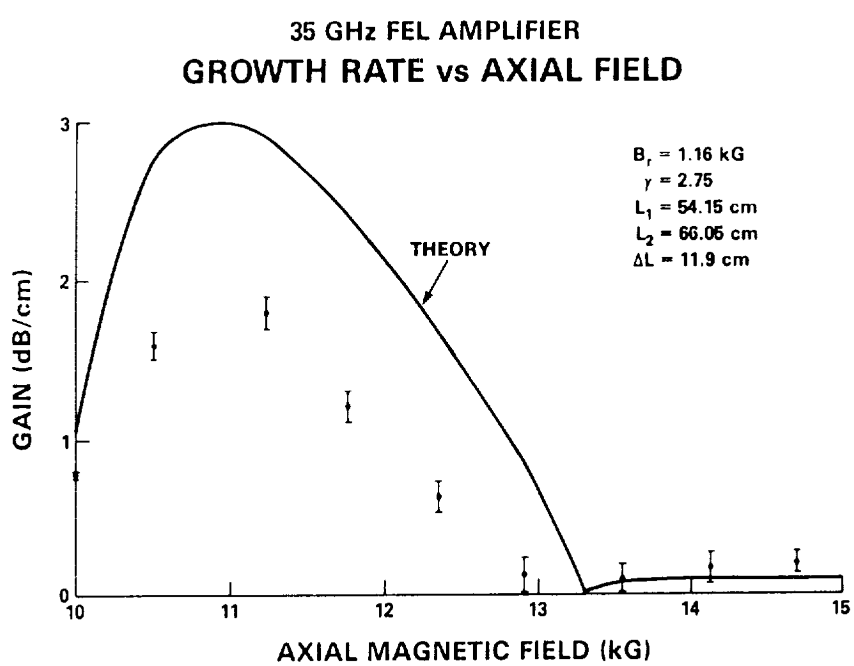




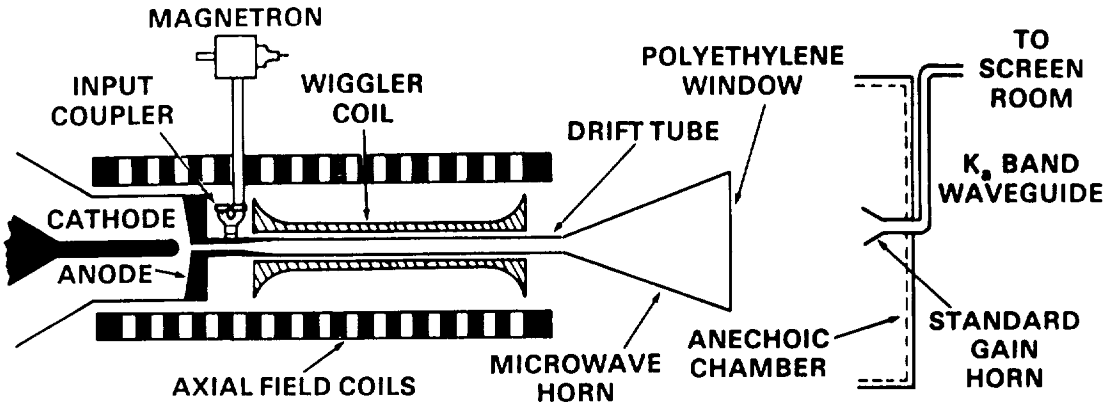
N.R.L. F.E.L. EXPERIMENT



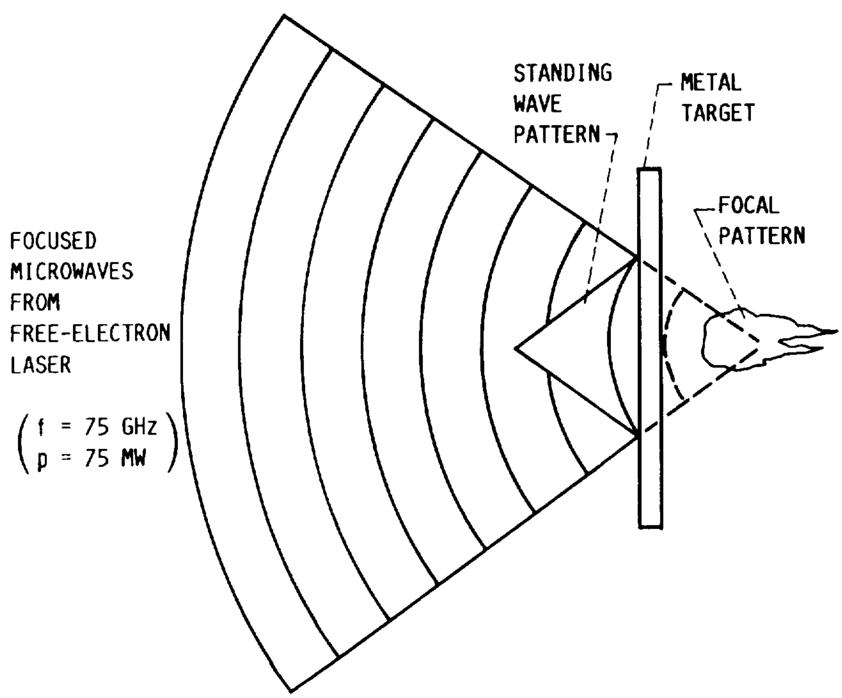

35 GHz FEL AMPLIFIER
GAIN vs LENGTH
P_{in} = 40 W
1.2 dB/cm
POWER GAIN (dB)
TOTAL SYSTEM LENGTH (cm)
60
50
40
30
20
10
40
50
60
70


35 GHz FEL AMPLIFIER
GROWTH RATE vs AXIAL FIELD
B_r = 1.16 kG
γ = 2.75
L_1 = 54.15 cm
L_2 = 66.05 cm
ΔL = 11.9 cm
THEORY
GAIN (dB/cm)
AXIAL MAGNETIC FIELD (kG)
3
2
1
0
10
11
12
13
14
15

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_2 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

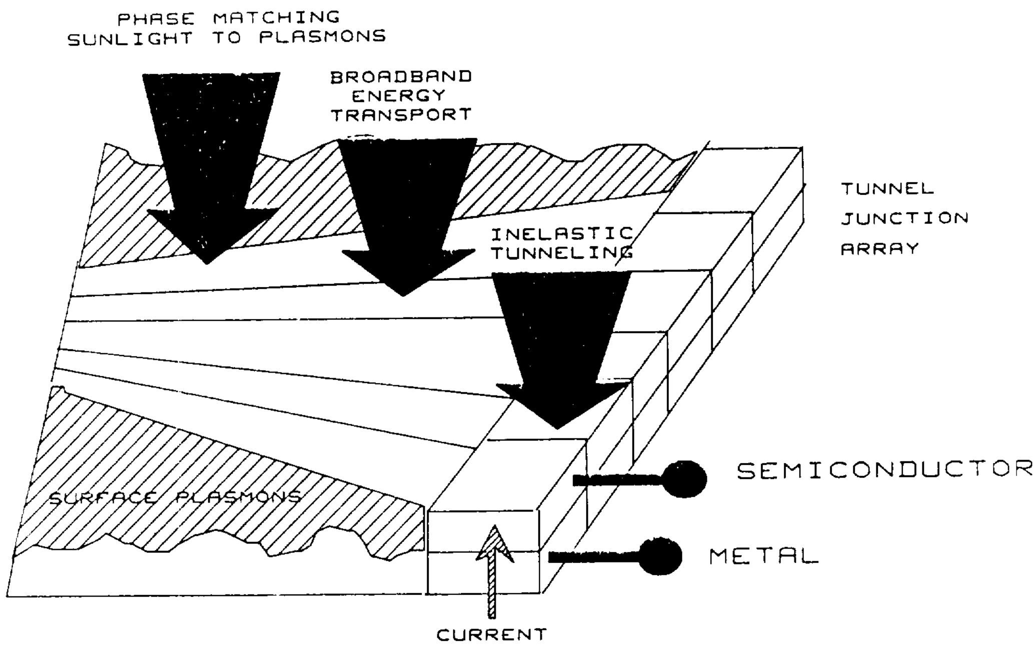
Plasmon-assisted inelastic electron tunneling

Photon ⇝ (junction) plasmon →

→ energetic e^- →

→ Tunneling across a barrier

EXTRACTING POWER FROM
SURFACE PLASMA OSCILLATIONS



from –
L. Anderson (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.

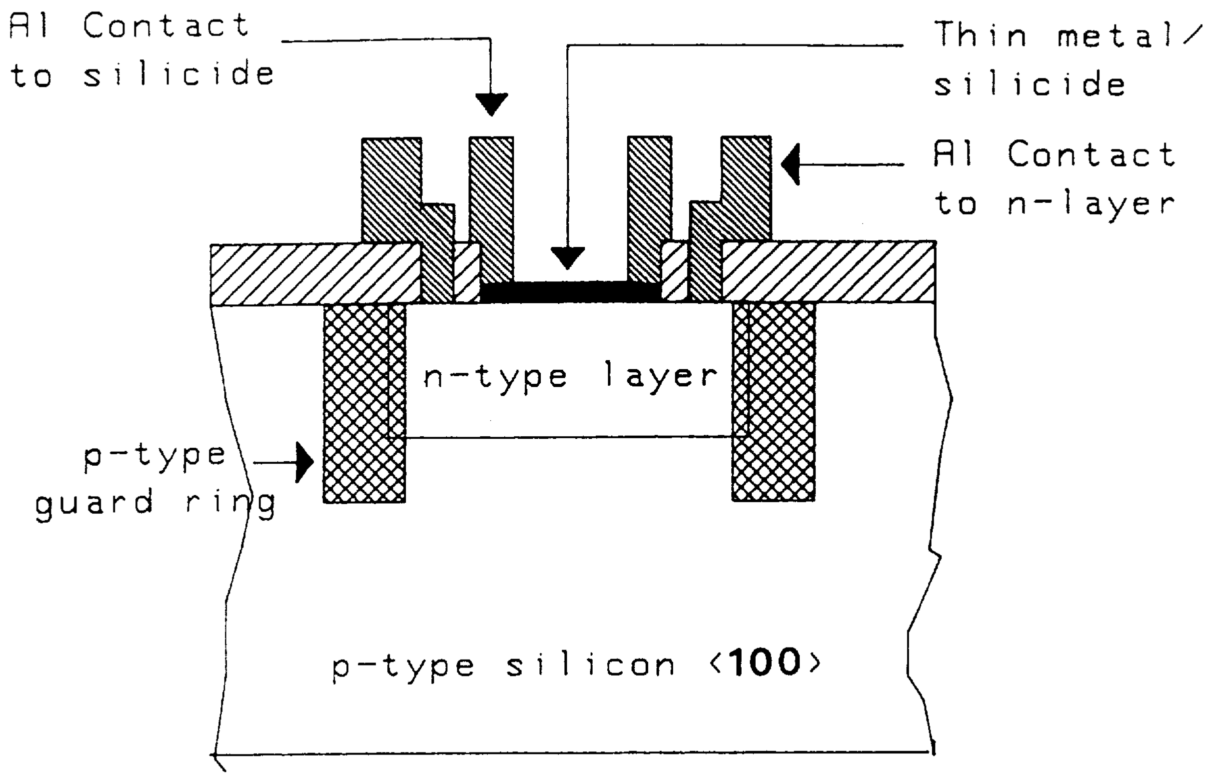
(II) CONTACT METAL (AL) THICKNESS OF 1 UM.

(III) THE DIFFUSED N-TYPE LAYER FORMING THE ACTIVE DEVICE WAS 1 UM DEEP.

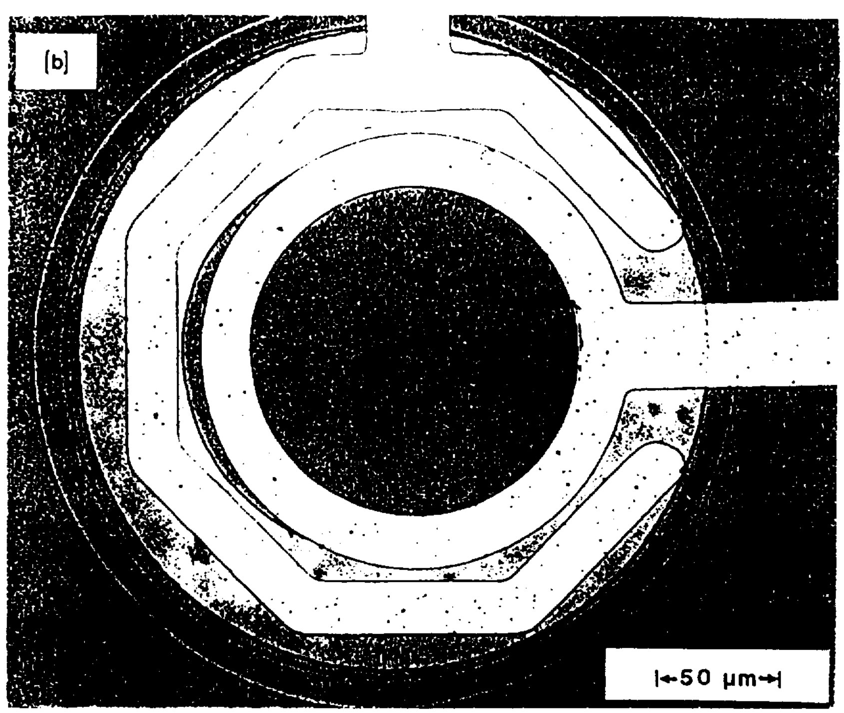
(IV) THE P-TYPE GUARD RING FOR THE GUARD RING SCHOTTKY DIODE WAS 1.5 UM DEEP.

(V) THE DOPING CONCENTRATION OF THE N-TYPE LAYER WAS CLOSED TO THE SOLID SOLUBILITY LIMIT FOR PHOSPHOROUS IN SILICON 1 X 1020 CM-3.

(VI) THE SUBSTRATE WAS HIGH RESISTIVITY P-TYPE <100> SILICON.



(a) CROSS SECTION



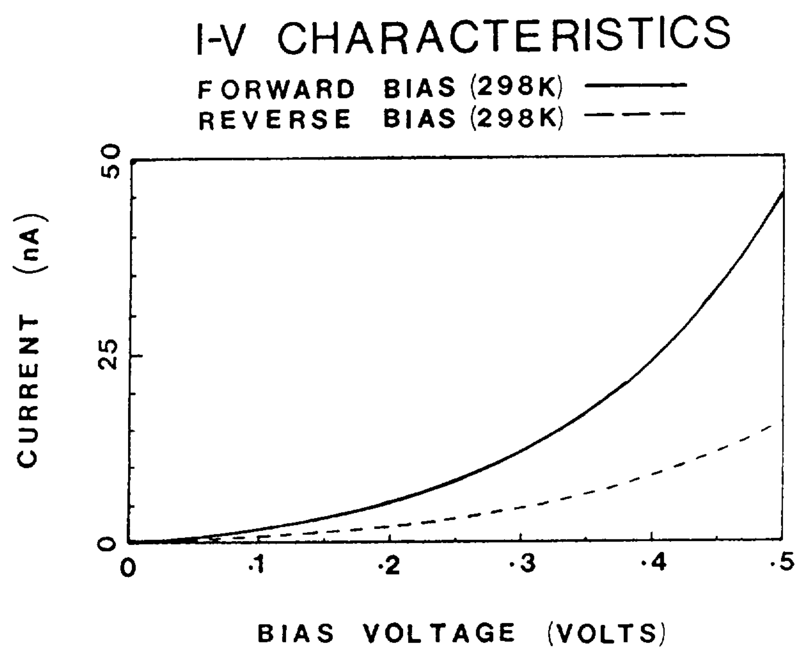
(b) TOP VIEW

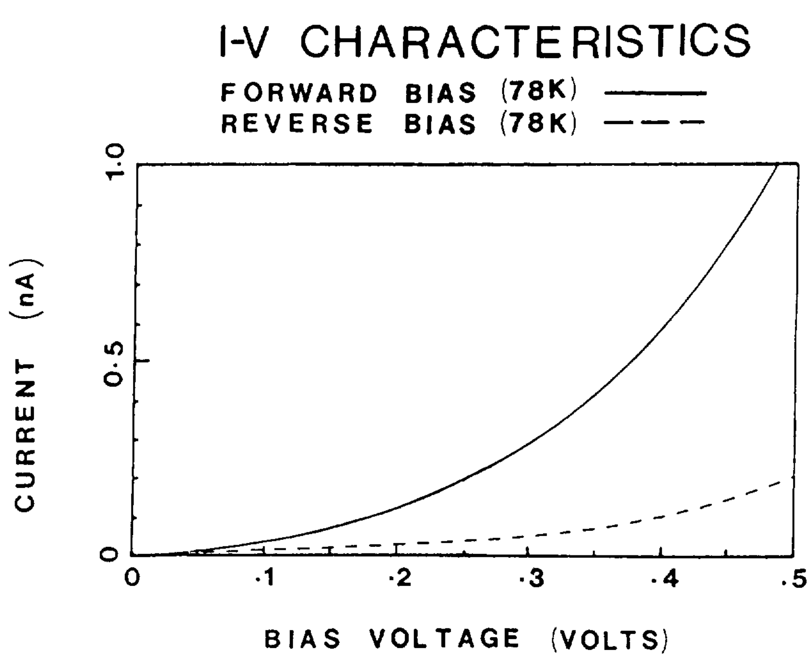
OPTICAL DETECTOR STRUCTURE

DEVICE CHARACTERIZATION

- I - V MEASUREMENTS
- C - V MEASUREMENTS
- SHEET RESISTANCE MEASUREMENTS
- INCLUDING RTA OF WSi_2

- OPTICAL RESPONSE
  - VISIBLE
  - FAR-INFRARED





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

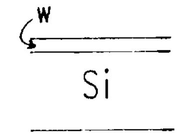
- GOOD ADHESION PROPERTIES
- HIGH TEMPERATURE STABILITY
- LOW RESISTIVITY
- SUITABLE FOR GROWING AN INSULATING LAYER BY OXIDATION

SAMPLE PREPARATION

DEPOSITION OF TUNGSTEN

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

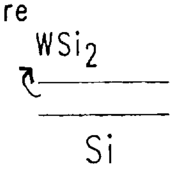
Film Thickness	20 nm.
Uniformity	1 nm.

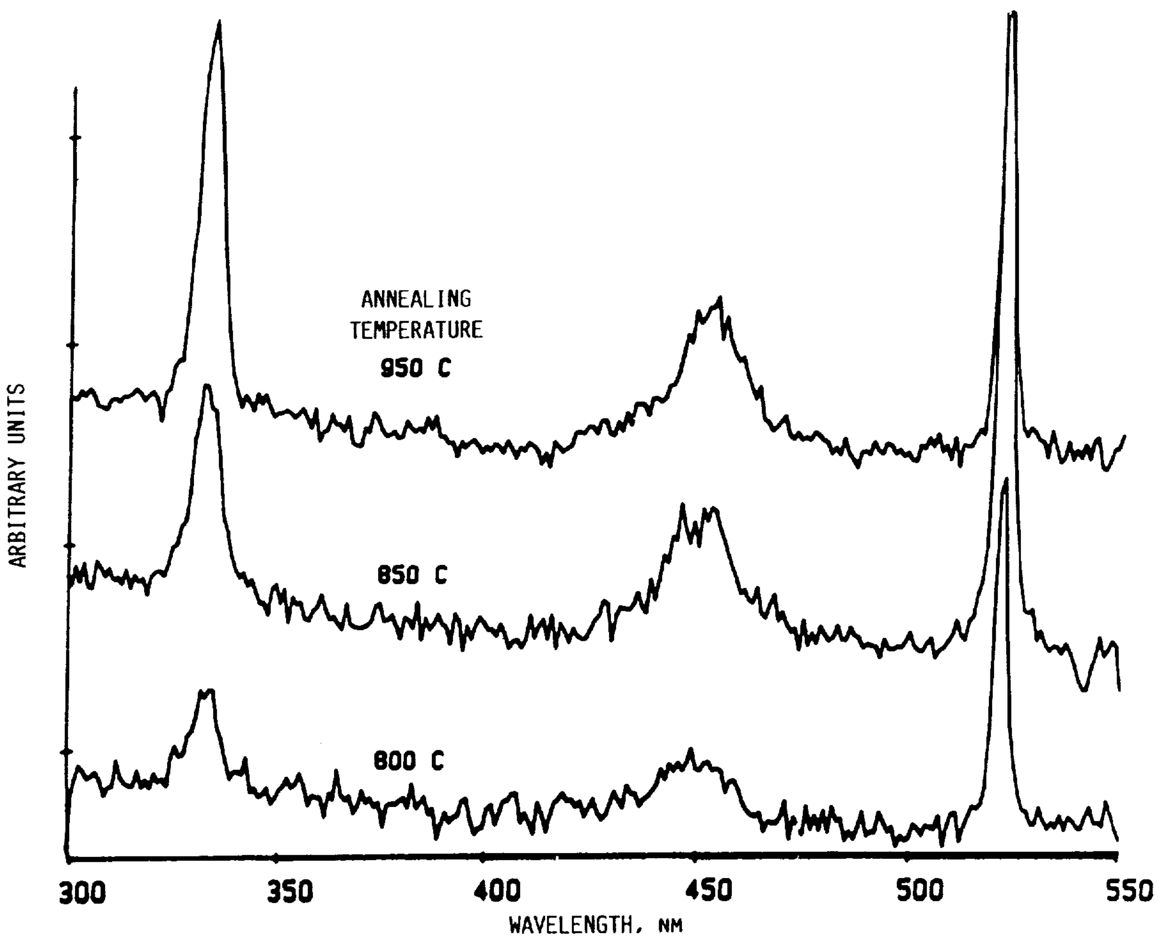


FORMATION OF TUNGSTEN SILICIDE

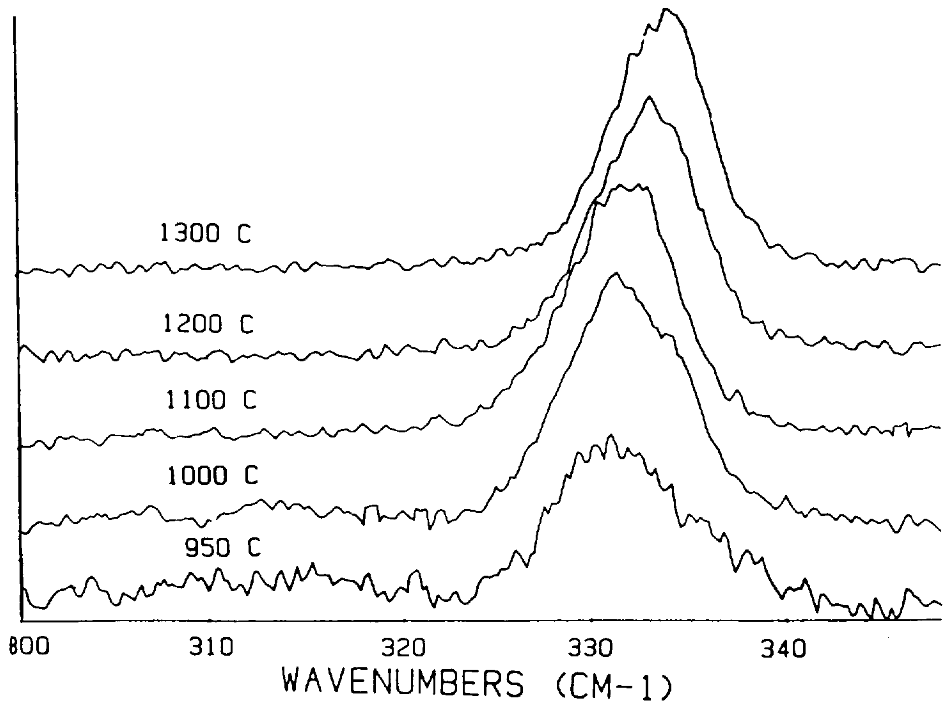
Rapid Thermal Annealing in 10% H_2 and 90% Ar Atmosphere

Time	90s/20s
Thickness	50 nm.
Stoichiometry	$WSi_{1.4}$ (RBS)
Temperature	800C –





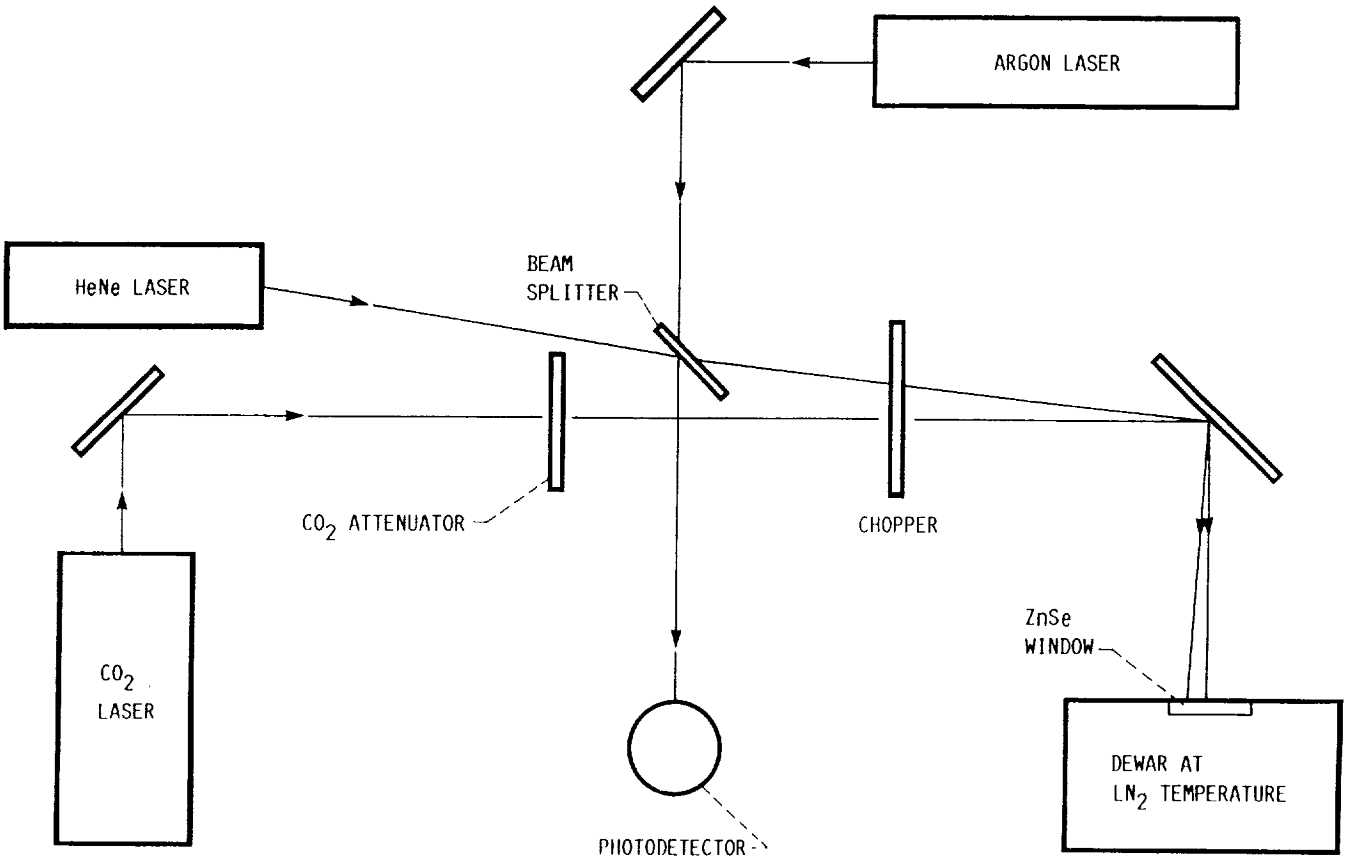
RESPONSIVITY OF TUNGSTEN DIODE



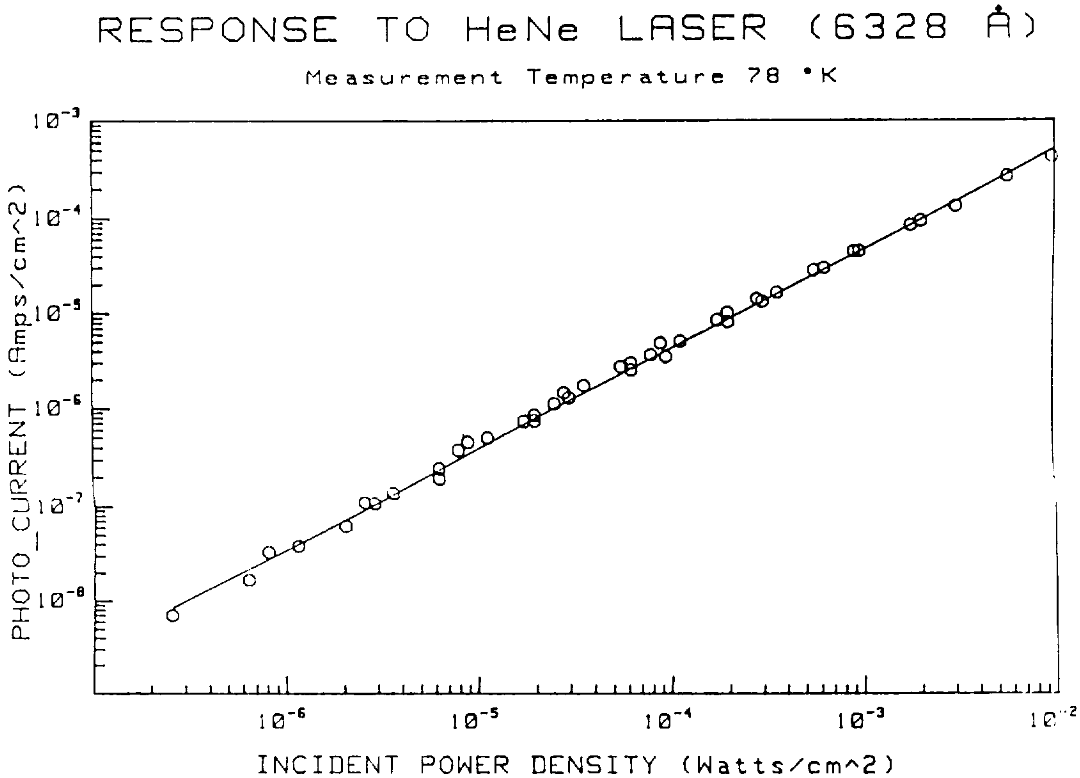
Raman spectra of rapid thermal annealed tungsten silicide

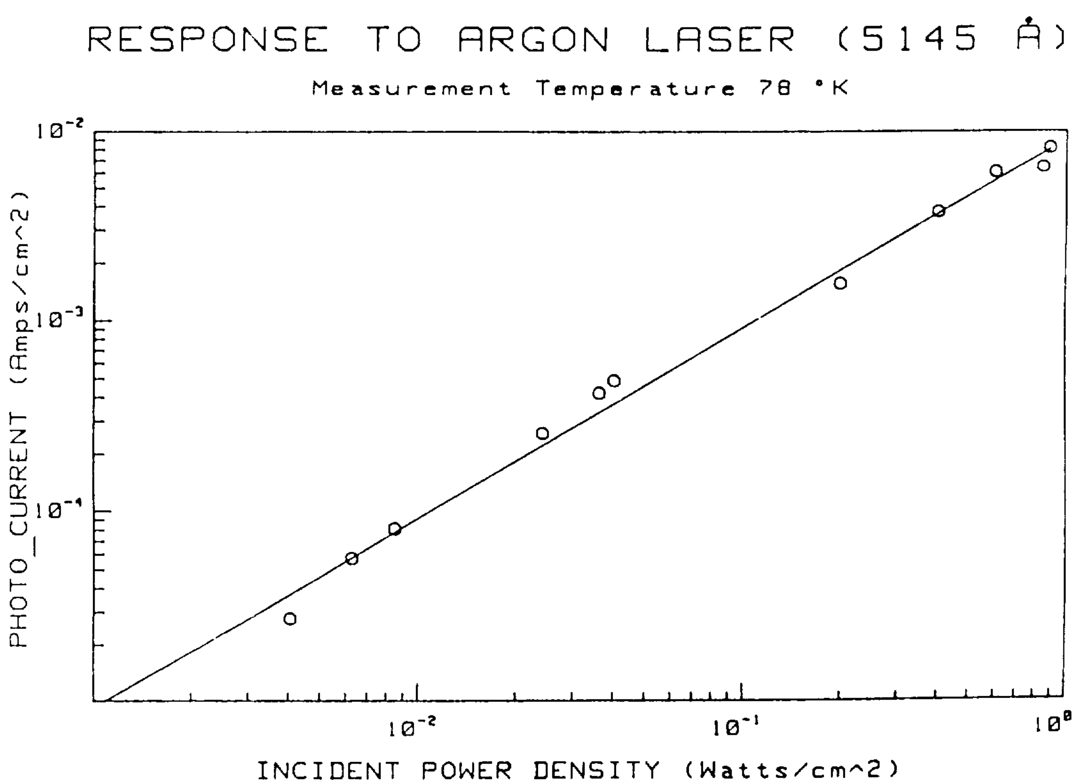
Properties of tungsten silicide films rapid thermally annealed at different temperatures

Material	RTA temp C	Sheet Resistance	Intensity of 332cm−1 Raman line	Peak Positon of 332cm−1 line	FWHM (cm−1)	Ratio of Area under 332cm−1 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**

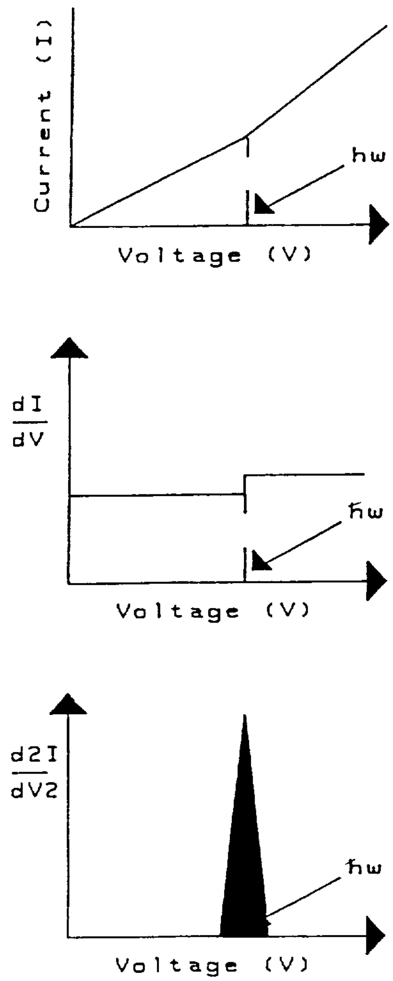


SETUP FOR DIODE TESTING


RESPONSE TO HeNe LASER (6328 Å)
Measurement Temperature 78 °K
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
PHOTO_CURRENT (Amps/cm^2)
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
INCIDENT POWER DENSITY (Watts/cm^2)

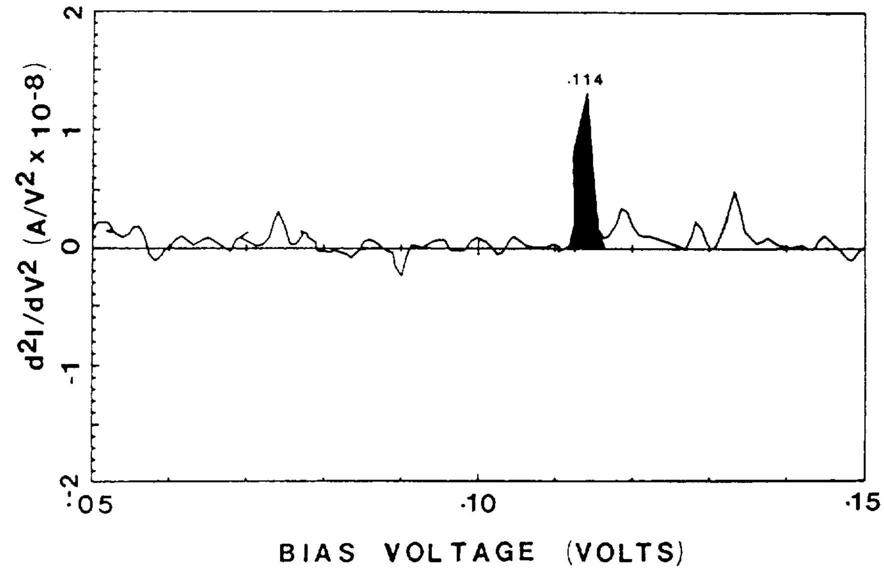

RESPONSE TO ARGON LASER (5145 Å)
Measurement Temperature 78 °K
10^{-2}
10^{-3}
10^{-4}
PHOTO_CURRENT (Amps/cm^2)
10^{-2}
10^{-1}
10^{0}
INCIDENT POWER DENSITY (Watts/cm^2)

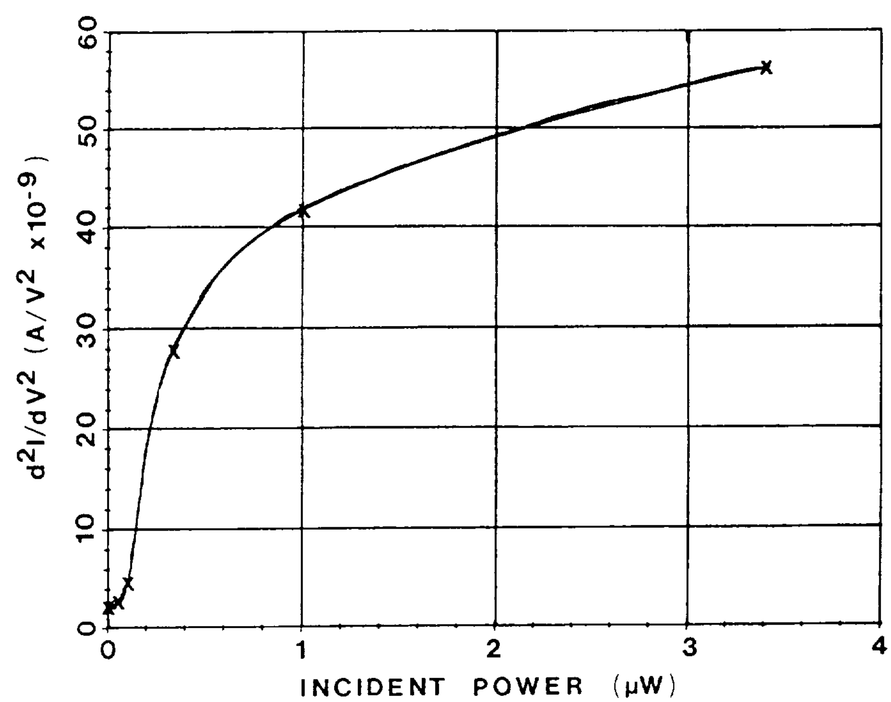
C-3



THEORETICAL RESPONSIVITY CURVES

Second Harmonic Response





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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NASA Lewis Research Center
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

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.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Rectenna; Gyrotron; Free electron laser; Inflatable antenna; Solar pumped laser	Unclassified – Unlimited Subject Category 20

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