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OPERATION OF A STEP TUNABLE MEGAWATT GYROTRON*

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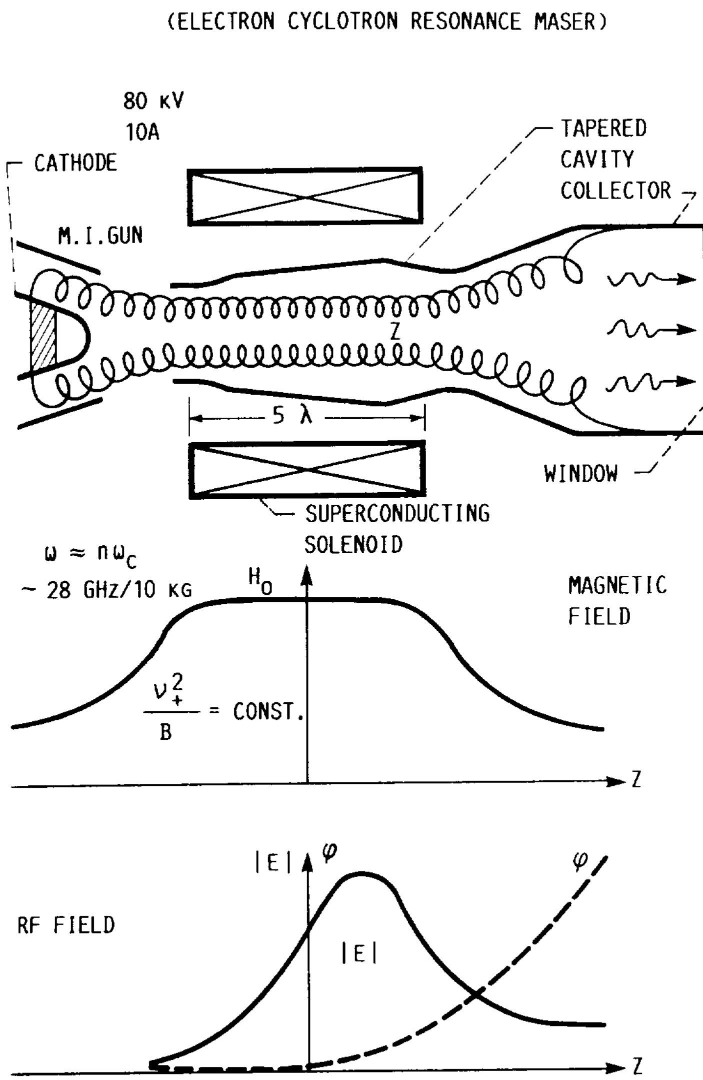
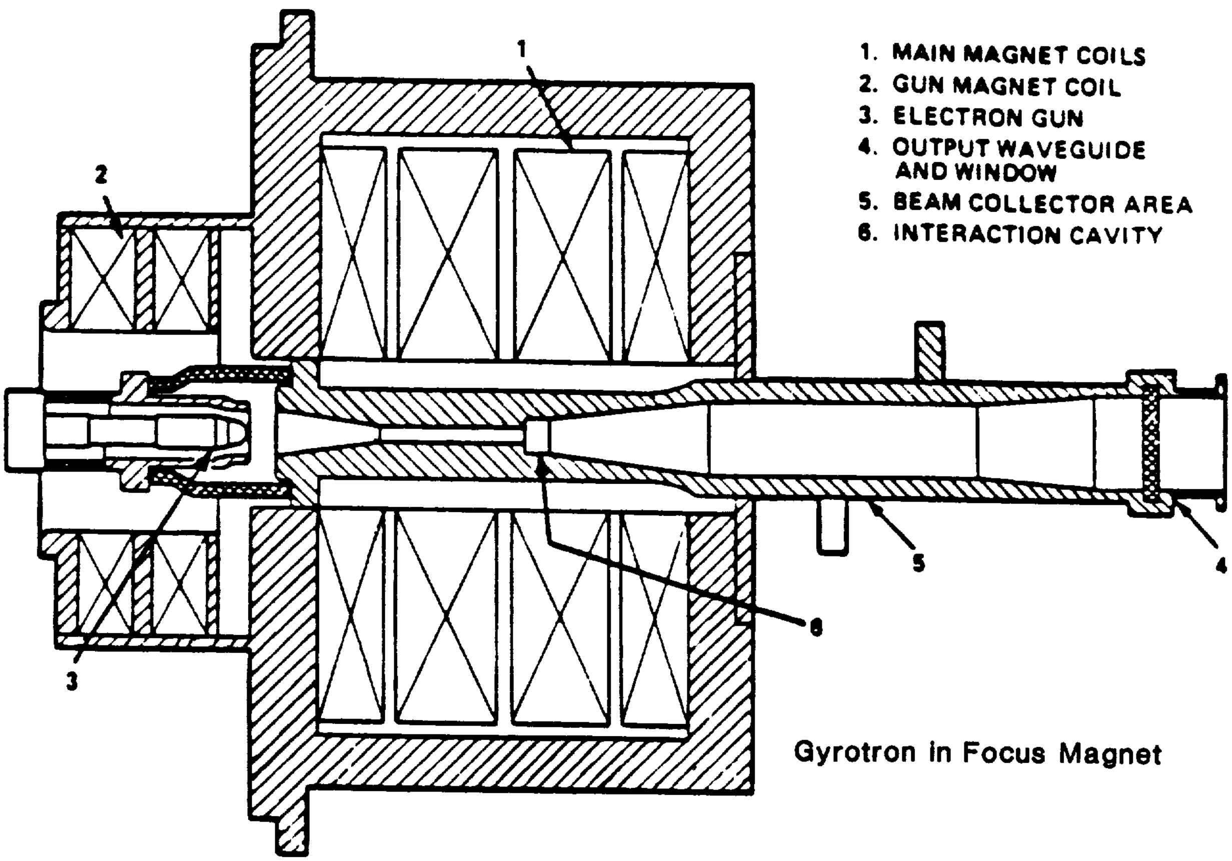


*Work supported by the U.S. Department of Energy, Office of Fusion Energy.

GYROTRON FUNDAMENTAL OSCILLATOR
(28 GHz, 200 KW, CW, 80 KV, 8 A, length : 2m, B : 12 KG)



Gyrotron in Focus Magnet

Electrons are emitted from a small annular band on the electron gun or cathode, usually at a high negative voltage.

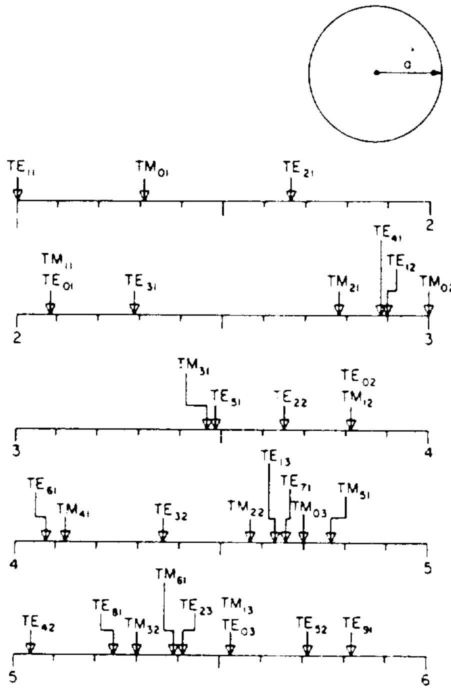


Fig. 5. Normalized modal cutoff frequencies for a circular waveguide.

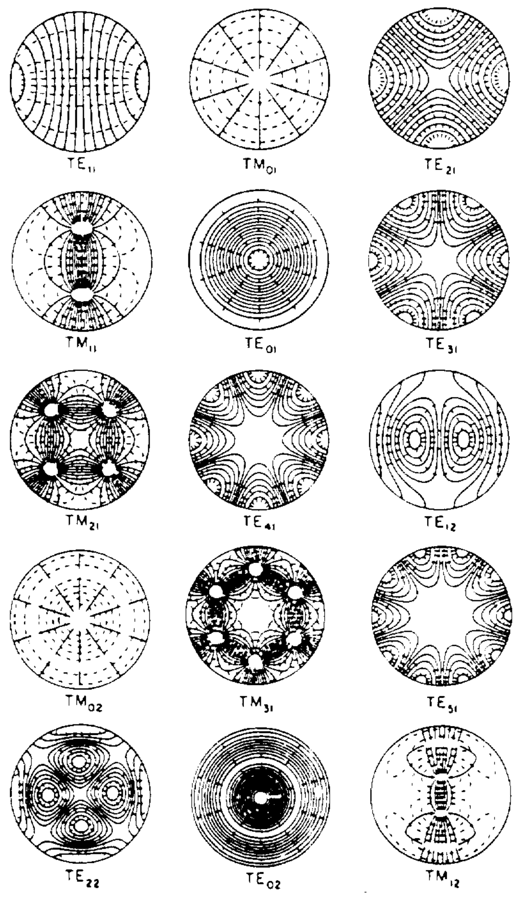


Fig. 6. Transverse modal field distribution for a circular waveguide (first 30 modes).

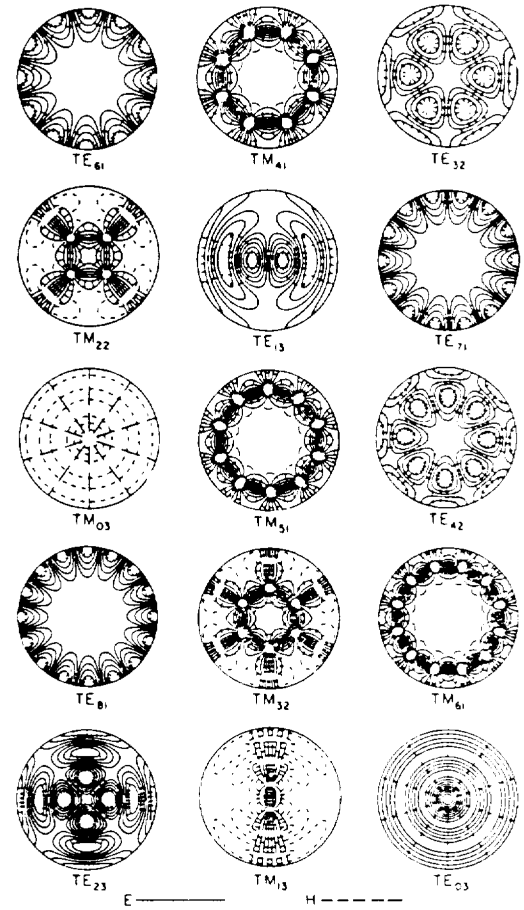


Fig. 6. (*Continued*)

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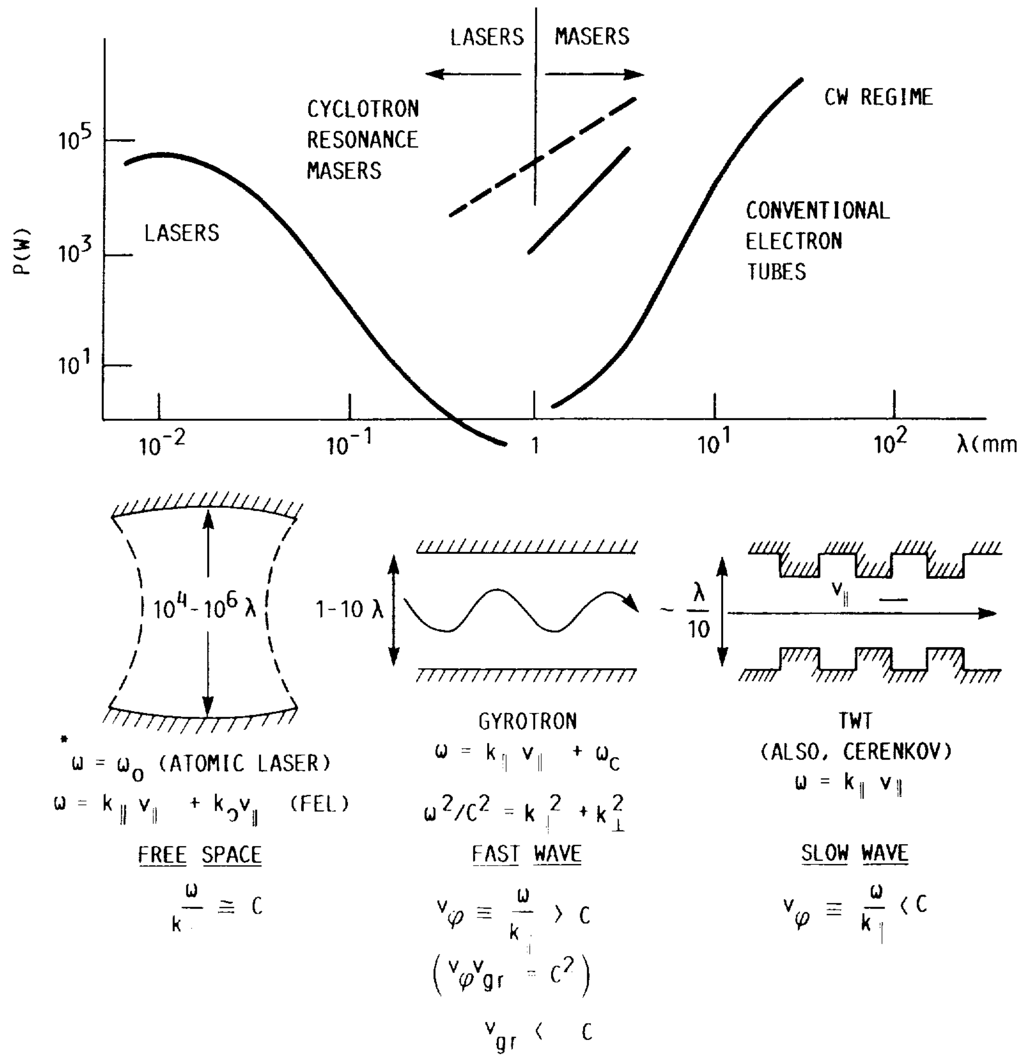
Lee, C.S.; Lee, S.W.; and Chuang, S.L.: Plot of Modal Field Distribution in Rectangular and Circular Waveguides. IEEE Trans. Microwave Theory and Technol., vol. MTT-33, no. 3, Mar. 1985, p. 271.

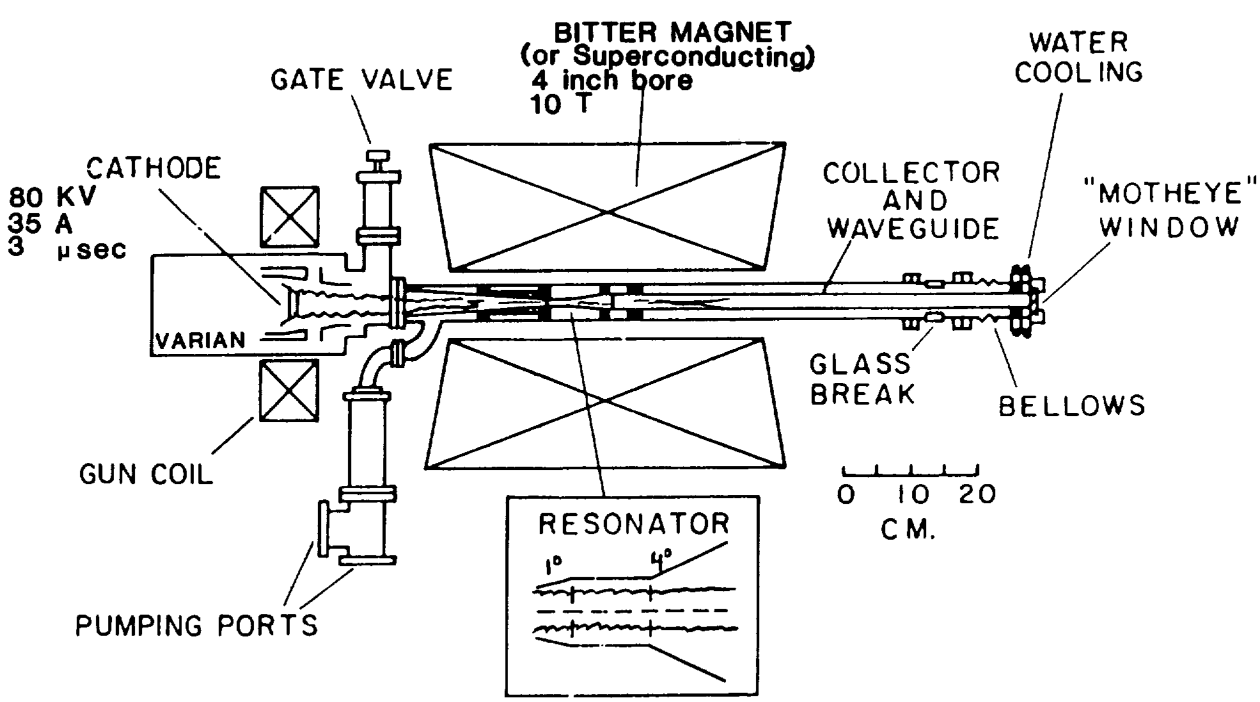

LASERS
MASERS
CYCLOTRON RESONANCE MASERS
CW REGIME
CONVENTIONAL ELECTRON TUBES
LASERS
P(W)
10^5
10^3
10^1
10^{-2}
10^{-1}
1
10^1
10^2
λ(mm)
10^4-10^6 λ
1-10 λ
$\sim \frac{\lambda}{10}$
$v_\parallel$
GYROTRON
TWT
(ALSO, CERENKOV)
*$\omega = \omega_0$ (ATOMIC LASER)
$\omega = k_\parallel v_\parallel + k_\circ v_\parallel$ (FEL)
$\omega = k_\parallel v_\parallel + \omega_c$
$\omega^2/c^2 = k_\parallel^2 + k_\perp^2$
$\omega = k_\parallel v_\parallel$
FREE SPACE
FAST WAVE
SLOW WAVE
$\frac{\omega}{k} \cong c$
$v_\varphi \equiv \frac{\omega}{k_\parallel} > c$
$(v_\varphi v_{gr} = c^2)$
$v_{gr} < c$
$v_\varphi \equiv \frac{\omega}{k_\parallel} < c$

ADVANTAGES OF GYROTRONS

- MODERATE VOLTAGE OPERATION
  BELOW 100 kV. USE EXISTING SUPPLIES.
- INDUSTRIAL TECHNOLOGY BASE
  GOOD FABRICATION EXPERIENCE. RELIABILITY.
- CW OPERATION
  STABLE. BEST CHANCE TO USE A WINDOW.
- MODEST DEVICE SIZE
  LIKELY TO BE LEAST EXPENSIVE APPROACH.
- HIGH EFFICIENCY
  ENERGY RECOVERY NOT REQUIRED.
- SIMPLE DEVICE CONFIGURATION
- BASIC PHYSICS UNDERSTOOD
  EFFICIENCY, FREQUENCY, SPACE CHARGE, INSTABILITIES.

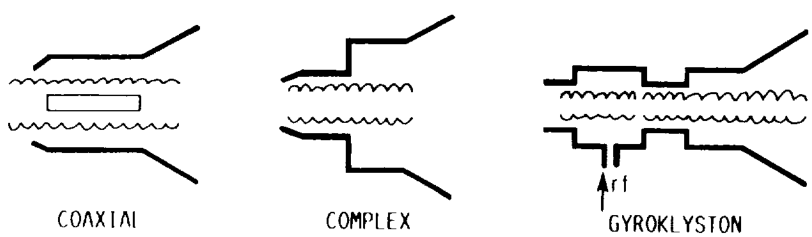
SCHEMATIC OF EXPERIMENT

(MIT Gyrotron by K. Kreischer & R. Temkin)



MW GOALS

- EXTRAPOLATE 200 kW RESULTS TO MW POWER LEVELS
  - SINGLE CAVITY WITH ISOLATED, ASYMMETRIC MODE
- DETERMINE IF FOLLOWING ARE POSSIBLE:
  - SINGLE MODE EMISSION IN HIGHLY OVERMODED CAVITY
  - BEAM PROPAGATION NEAR I_{MAX}
  - BEAM-rf SEPARATION AFTER CAVITY
  - CONVERSION TO POLARIZED, GAUSSIAN BEAM
- STUDY ADVANCED CAVITY CONCEPTS
  - COAXIAL CAVITY
  - COMPLEX CAVITY
  - GYROKLYSTONS
- DEVELOP PHYSICS BASE FOR NEXT GENERATION OF GYROTRONS
  - 5-10 MW AT 140 GHz
  - 1 MW AT 280 GHz FOR CIT



GYROTRON DESIGN THEORY

- Linear theory: Starting current
- Nonlinear theory: Efficiency $\eta_\perp(F,\mu)$
  - F=normalized rf field amplitude
  - μ=normalized length
- Cavity ohmic losses sets upper limit on F
- Energy balance equation:

$$Q=4\pi\left(\frac{L}{\lambda}\right)^2$$

- Combining these equations yields:

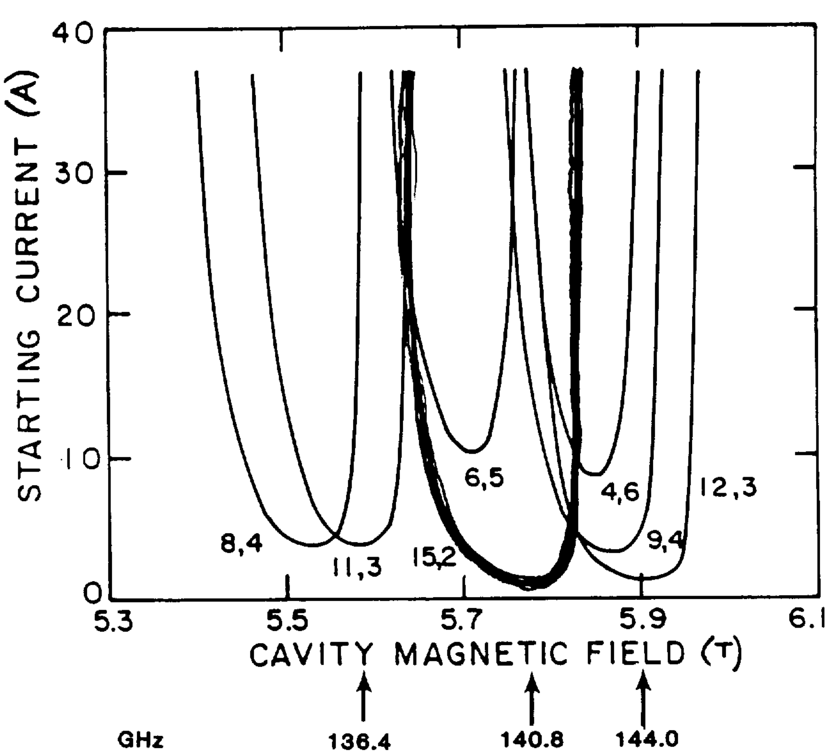
$$(\nu_{mp}^2 - m^2) = \frac{2470\mu\beta_{\|}P(\mathrm{MW})\nu^{2.5}(\mathrm{GHz})}{\beta_\perp^2\rho_{ohm}(\mathrm{W/m^2})}$$

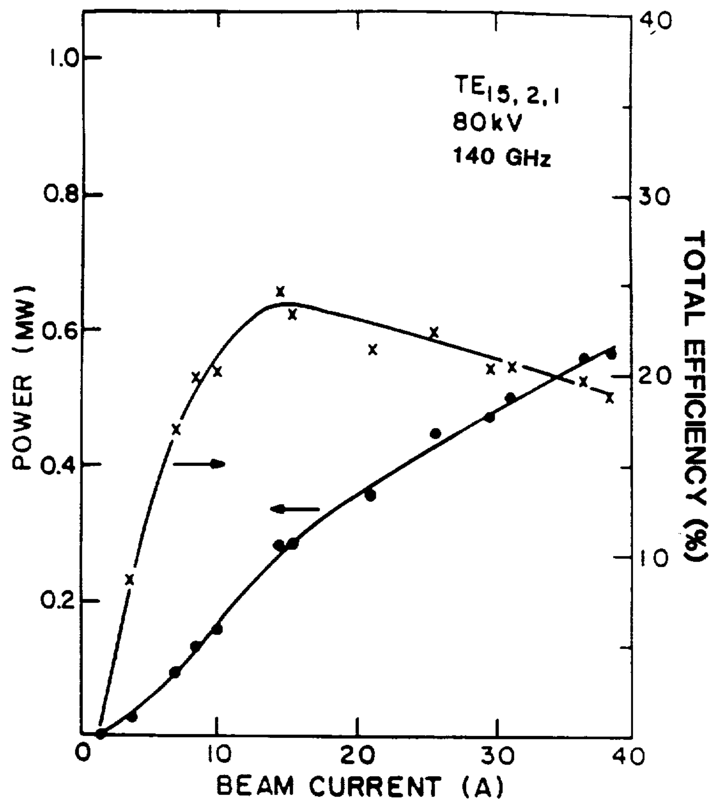
where cavity diameter $D/\lambda = \nu_{mp}/\pi$

- Others: Maximum Current
  - Beam Mirroring
  - Space Charge
  - Beam Thickness
  - Voltage Depression

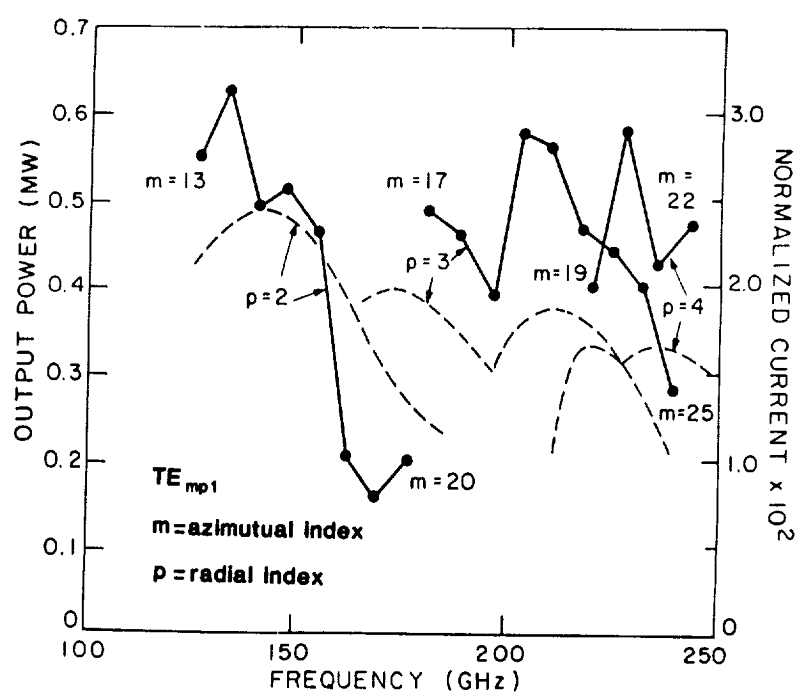
1 MW DESIGN PARAMETERS

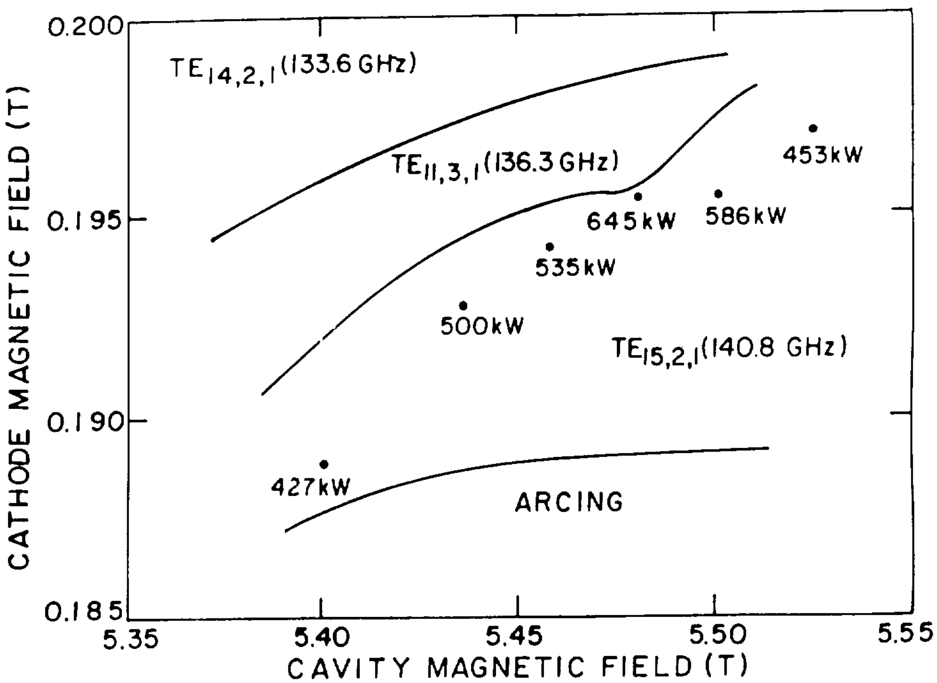
	140 GHz	280 GHz
Current(A)	35	42
Voltage(kV)	80	80
η_T(%)	36	30
Velocity ratio	1.93	2.0
Beam radius(cm)	0.53	1.4
Cavity radius(cm)	0.75	1.7
Cavity length(L/λ)	6.0	7.1
Diffractive Q	450	630
Magnetic compression	30	40
Cavity current density(A/cm^2)	384	510
Beam thickness(r_L)	3.85	3.2
Voltage depression(%)	4.0	2.6
Emitter radius(cm)	2.89	8.9
Mode	$TE_{15,2,1}$	$TE_{80,4,1}$
Mode separation(GHz)	7.2	3.0



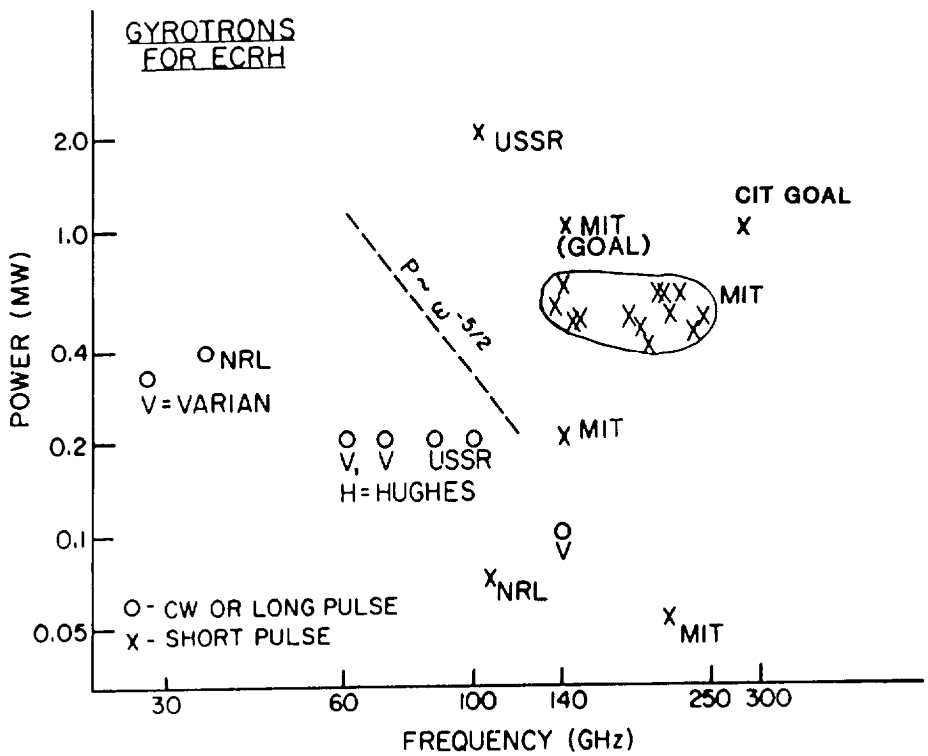


STEP TUNING
(Experimental Results)





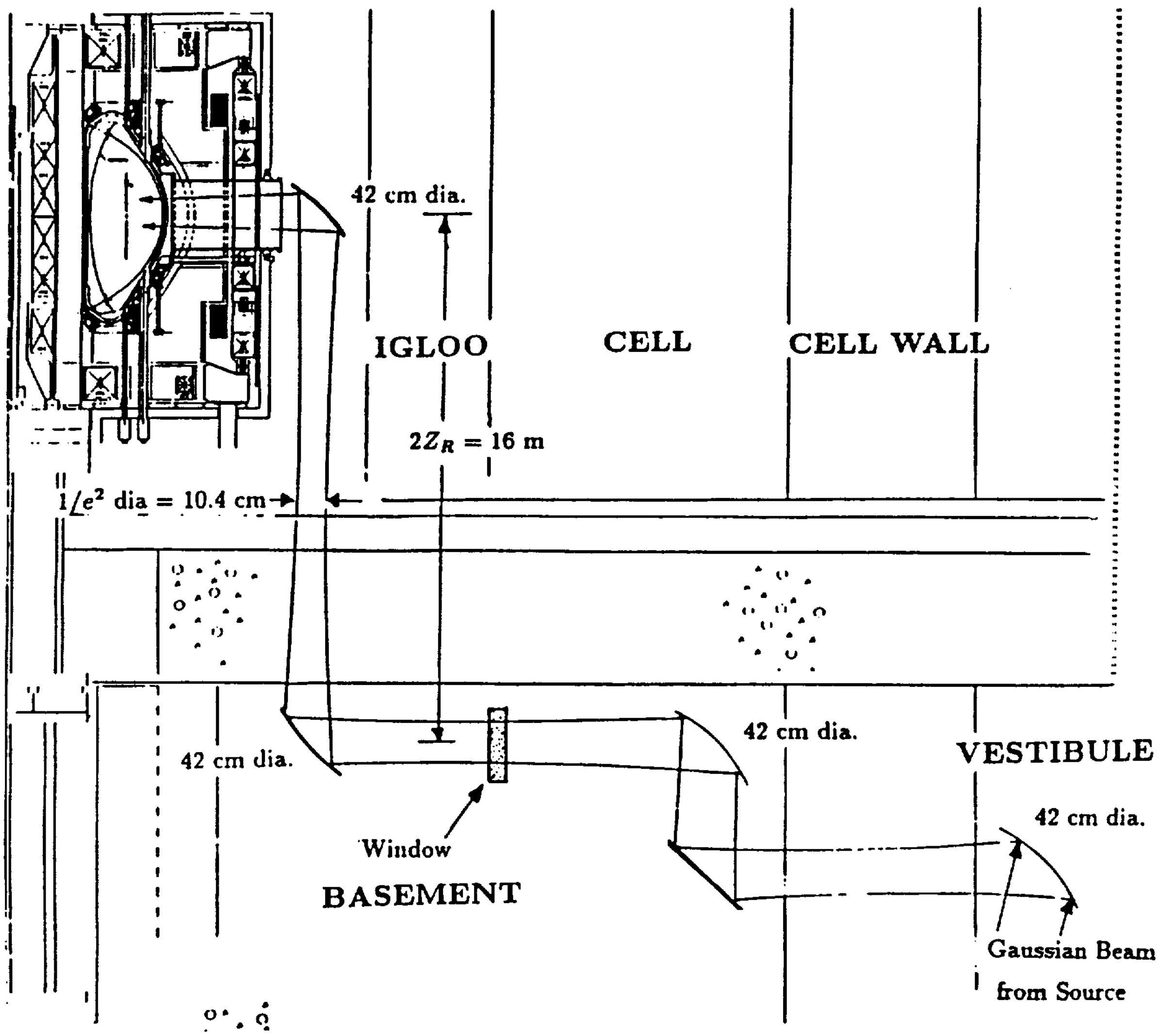
CATHODE MAGNETIC FIELD (T)
0.200
0.195
0.190
0.185
TE14,2,1 (133.6 GHz)
TE11,3,1 (136.3 GHz)
TE15,2,1 (140.8 GHz)
453kW
645kW
586kW
535kW
500kW
427kW
ARCING
5.35
5.40
5.45
5.50
5.55
CAVITY MAGNETIC FIELD (T)



GYROTRONS FOR ECRH
POWER (MW)
2.0
1.0
0.4
0.2
0.1
0.05
X USSR
CIT GOAL
X
X MIT (GOAL)
MIT
P ~ ω -5/2
O NRL
O
V=VARIAN
X MIT
V, V USSR
H=HUGHES
V
X NRL
X MIT
O - CW OR LONG PULSE
X - SHORT PULSE
30
60
100
140
250
300
FREQUENCY (GHz)

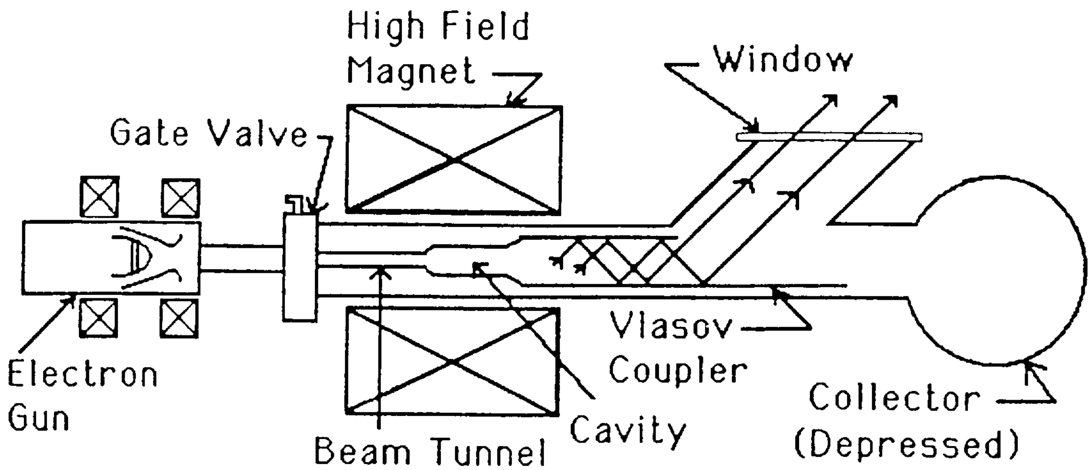
COMPACT IGNITION TOKAMAK (10 MW, 280 GHz, CW)

P. Woskov, ECH/CIT, 1987 (MIT)



Possible CIT 280 GHz Optical Transmission Line

GYROTRON WITH QUASI-OPTICAL OUTPUT COUPLER



120 GHz Designs

(1 MW, 10 MW Gyrotrons)

Power(MW)	1.0	10.0
Current(A)	29	240
Voltage(kV)	80	90
η_T(%)	43	46
Velocity Ratio	2.0	2.5
Wall Loading(kW/cm^2)	1.6	2.0
Beam Radius(cm)	0.62	1.8
Cavity Radius(cm)	0.88	1.87
Maximum Current(A)	62	560
Cathode Current Density(A/cm^2)	5	10
Beam Thickness(mm)	0.21	0.30
Cavity Length(cm)	1.33	0.98
Diffractive Q	370	193
Voltage Depression (%)	**3.5**	**8.4**
J_s(A/cm^2)	**1150**	**1250**
J(A/cm^2)	**350**	**700**