# The Electron Cyclotron Maser — Relativity in Action

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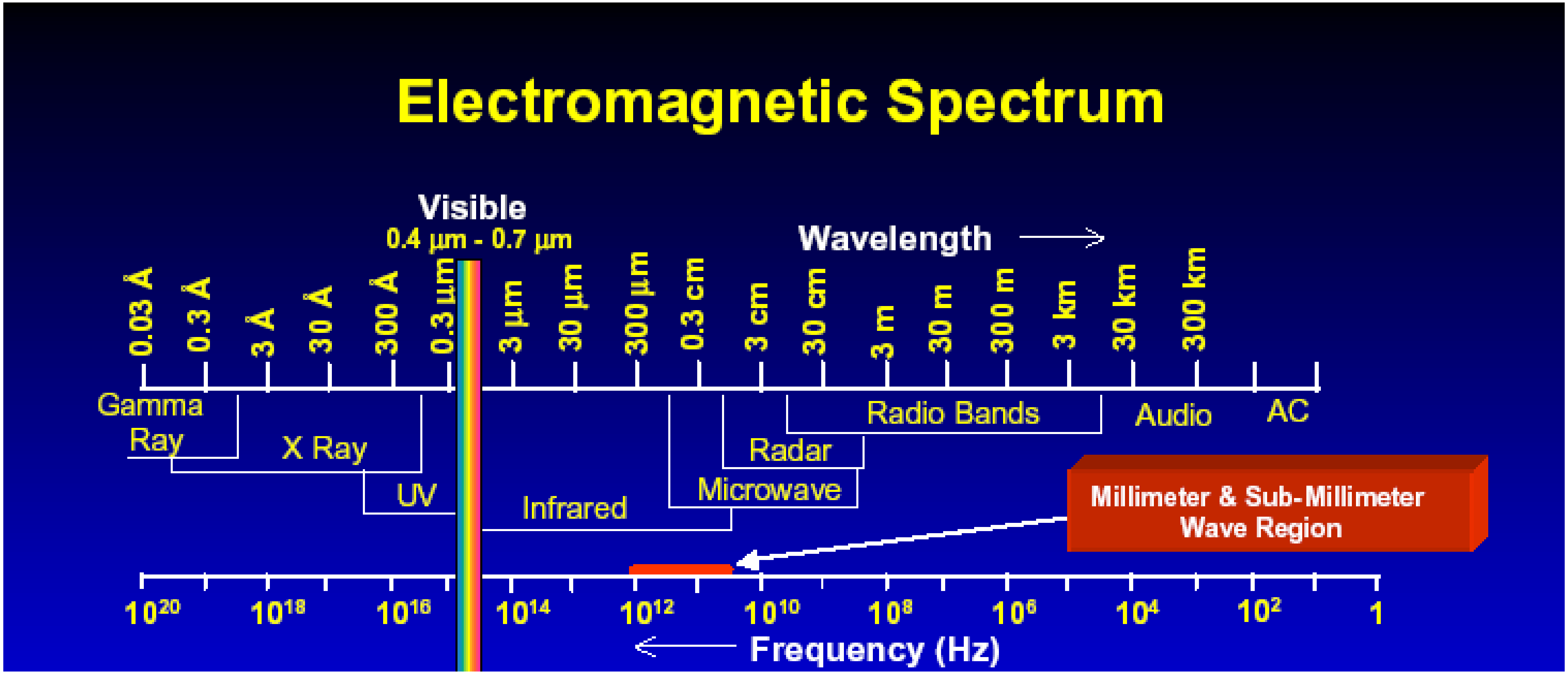
# *Outline*

- Overview of vacuum electronics
- Principle of the electron cyclotron maser (ECM)
- ECM-based devices (gyrotrons)
  - significance and applications
- Mode competition
- Issues at THz
- Summary


Electromagnetic Spectrum
Visible
0.4 µm - 0.7 µm
Wavelength
0.03 Å
0.3 Å
3 Å
30 Å
300 Å
0.3 µm
3 µm
30 µm
300 µm
0.3 cm
3 cm
30 cm
3 m
30 m
300 m
3 km
30 km
300 km
Gamma Ray
X Ray
UV
Infrared
Microwave
Radar
Radio Bands
Audio
AC
Millimeter & Sub-Millimeter Wave Region
10^20
10^18
10^16
10^14
10^12
10^10
10^8
10^6
10^4
10^2
1
Frequency (Hz)

# *Vacuum Electronics for the Generation of Coherent Radiation*

*Microwave tubes*: matured in the 1960s

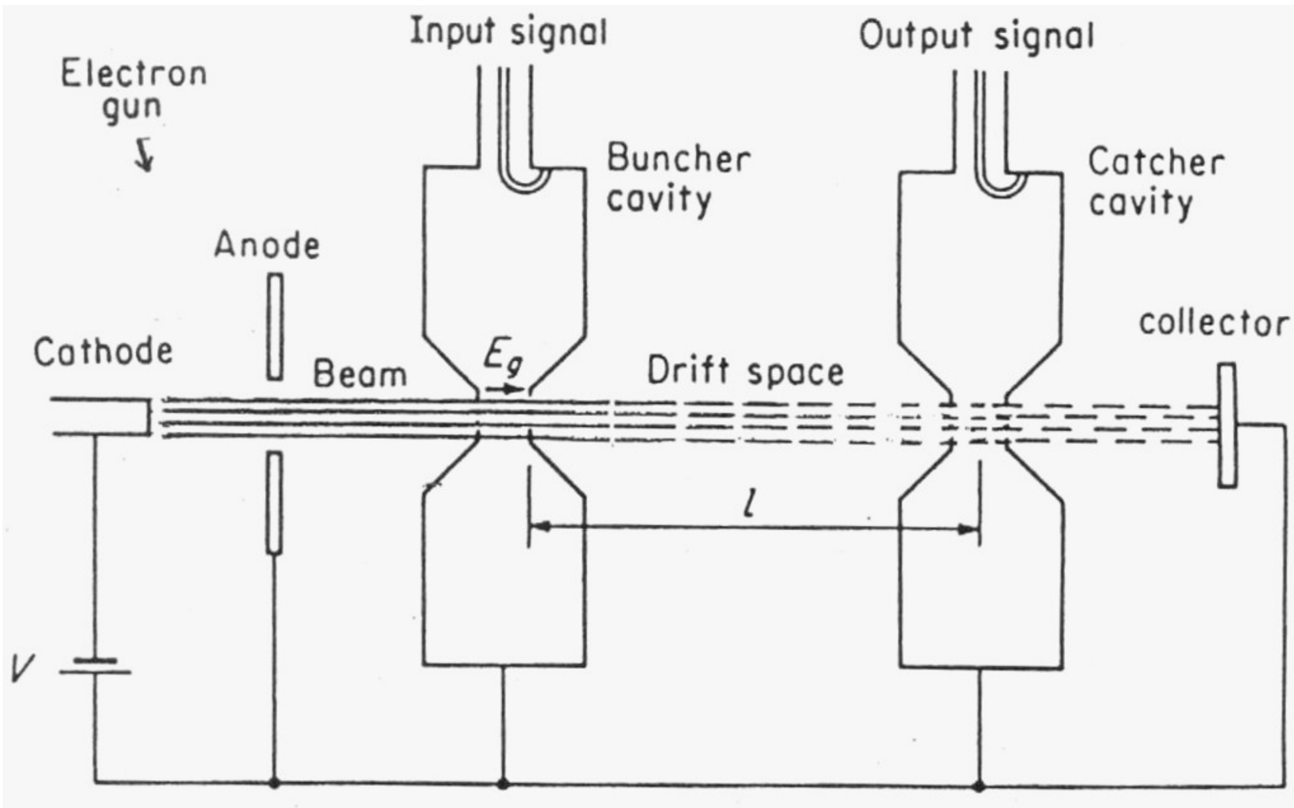
Cornerstones:
1. Magnetron
2. Klystron
3. Traveling Wave Tube (TWT)

*Relativistic electronics*: 1970s – present

Cornerstones:
1. Free Electron Laser (FEL)
2. Electron Cyclotron Maser (ECM)

# 電子流如何產生電磁波

## -以速調管(klystron)為例




直流電子與電磁波作用: $\langle P\rangle_t = \langle I_0 E_0 \cos\omega t\rangle_t = 0$

交流電子與電磁波作用： $\langle P\rangle_t = \langle I_0 \cos\omega t E_0 \cos\omega t\rangle_t = \frac{1}{2} I_0 E_0$

→ 需要一個「群聚」機制, 使電子由直流變交流

# *Comparison between Conventional and Relativistic Electronics*

| | Conventional Microwave Electronics | Relativistic Electronics |
|---|---|---|
| **Examples** | Magnetron, Klystron, TWT | ECM, FEL |
| **Frequency** | $< 10^{11}$ Hz | $10^{10}$ Hz – X-ray |
| **Power** | $< 10^{6}$ W | $10^{4}$ W – $10^{10}$ W |
| **Electron Energy** | $< 10^{5}$ V | $10^{3}$ V – $10^{10}$ V |
| **Beam Current** | $< 10^{2}$ A | 1 A – $10^{6}$ A |
| **Basic Equations** | Circuit equations + Fluid equations | Maxwell equations + Relativistic kinetic eq. |

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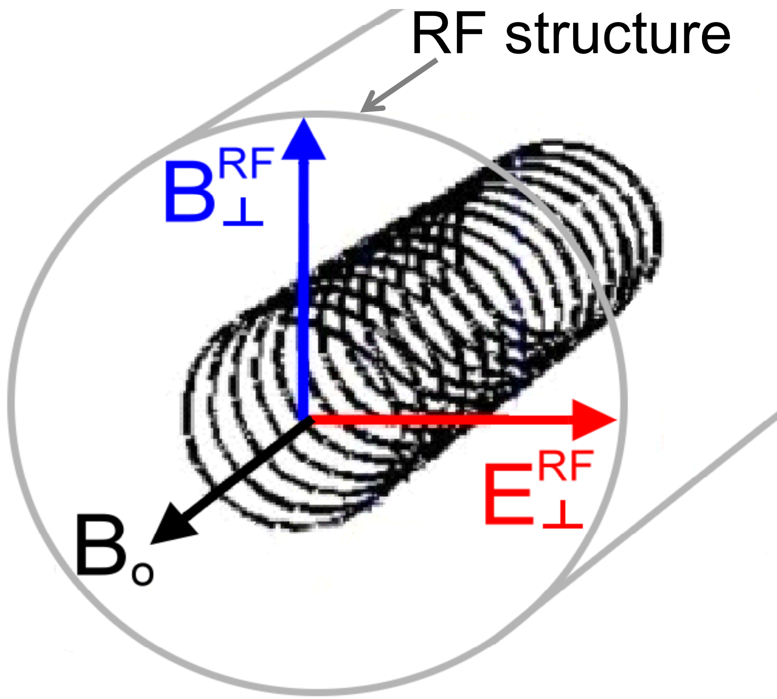
# *Physical Conditions Required for the Generation of Coherent Radiation*

1. A mechanism for the RF fields to bunch a DC electron beam into an AC electron beam.

2. Synchronism between the bunched electrons and the RF fields.

# *Basic Model of the Electron Cyclotron Maser (ECM)**




*Discovered independently by:

R. Q. Twiss, (1958) — classical theory

A. V. Gaponov, (1959) — classical theory

J. Schneider, (1959) — QM theory

R. H. Pantell, (1959) — experiment

# Cyclotron motion in uniform magnetic field

$$\boldsymbol{F} = q\boldsymbol{v} \times \boldsymbol{B}$$

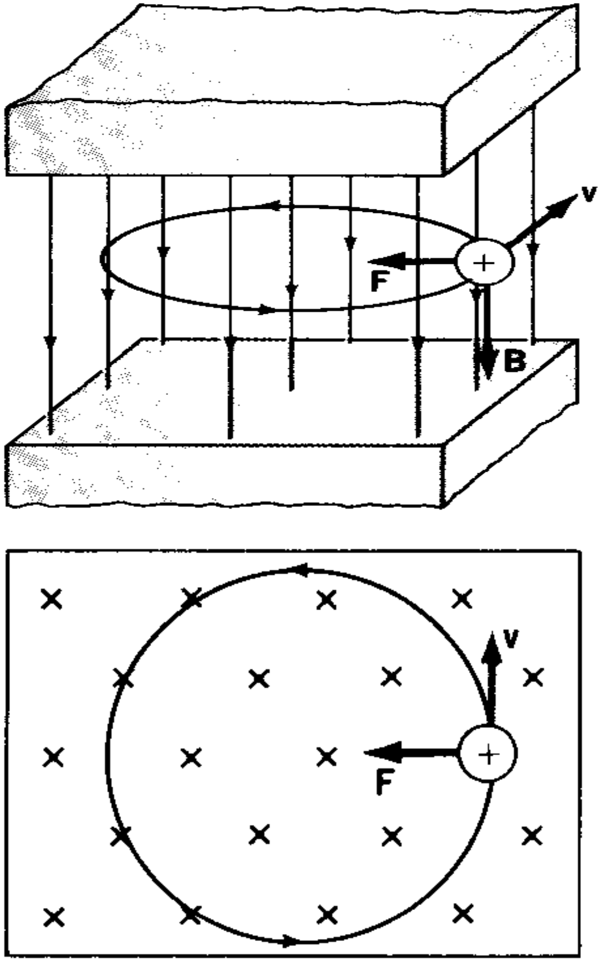
**Non-relativistic cyclotron frequency:**

$$\Omega_c = \frac{qB}{m} \quad \text{(independent of particle energy)}$$

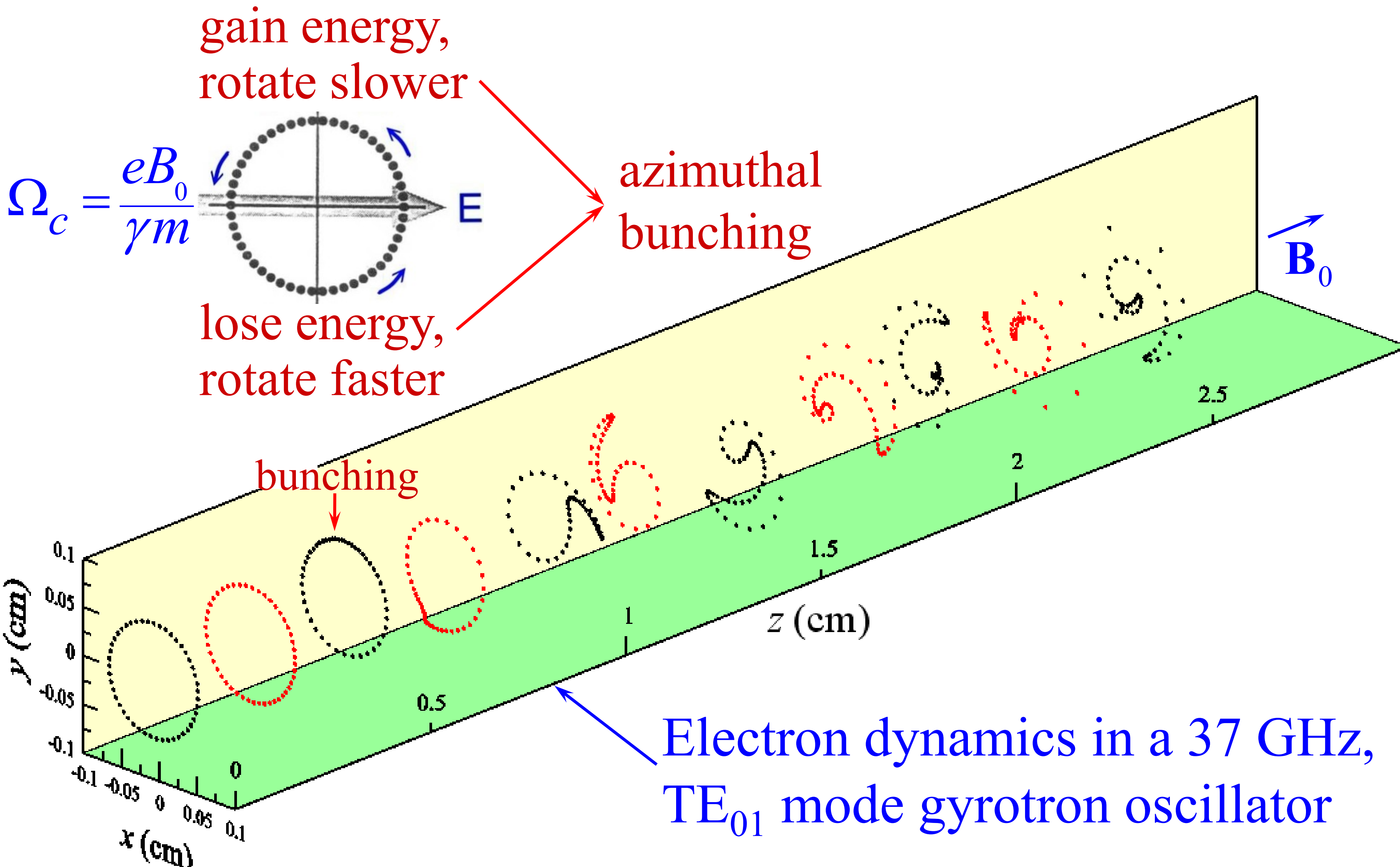
**Relativistic cyclotron frequency:**

$$\Omega_c = \frac{qB}{\gamma m} \quad \text{(depend on particle energy)}$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

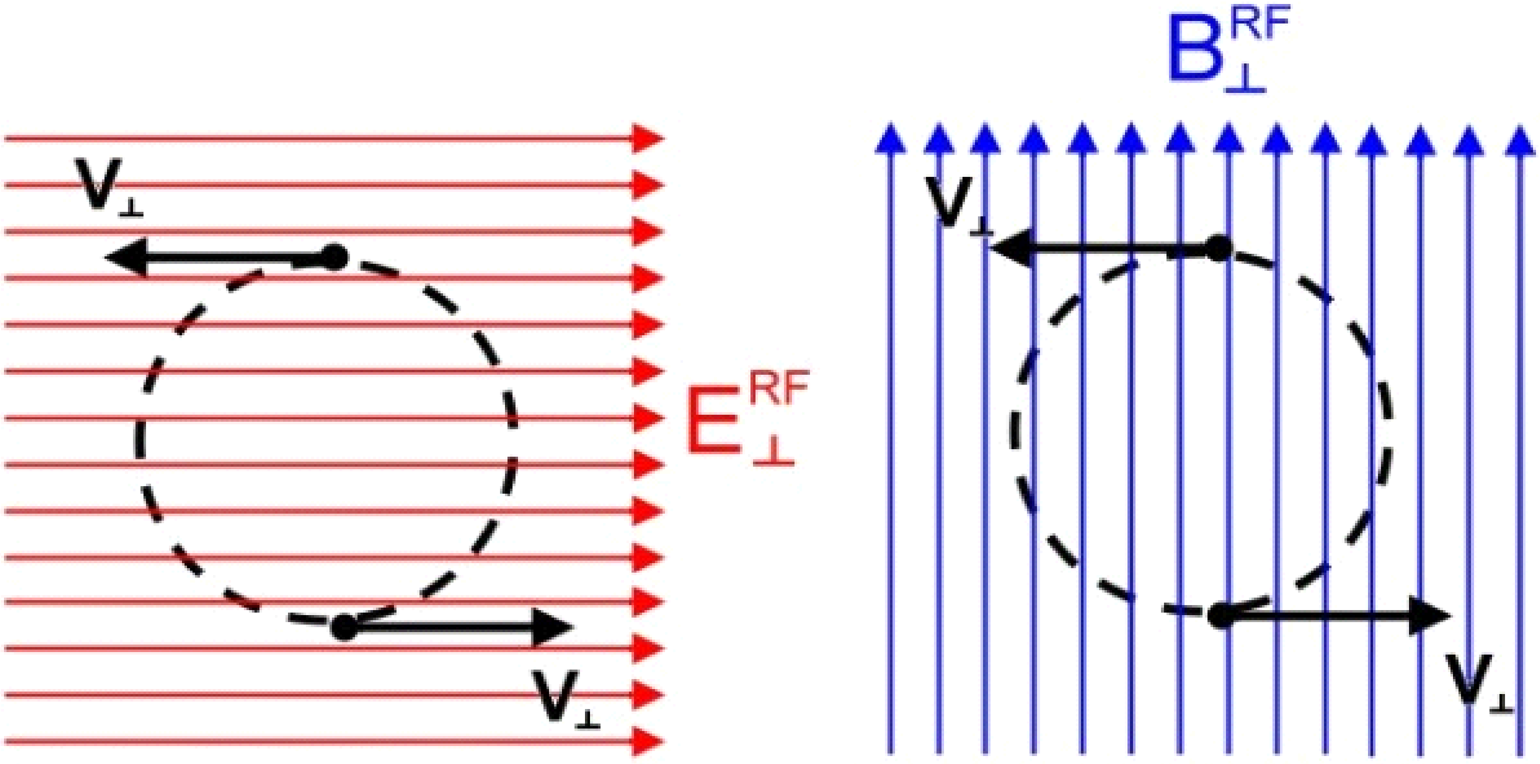


# *Principle of the Electron Cyclotron Maser – a Relativistic Bunching Mechanism*




Electron dynamics in a 37 GHz, $TE_{01}$ mode gyrotron oscillator

# *A Competing Mechanism – Axial Bunching*




Azimuthal bunching due to $e\mathbf{E}_{\perp}^{RF}$ electric force

Axial bunching due to $e\mathbf{v}_{\perp} \times \mathbf{B}_{\perp}^{RF}$ magnetic force

# *Early observations of stimulated cyclotron radiation in **fast-wave** structures*

| year | author(s) | bunching mechanism attributed to |
|---|---|---|
| 1959 | Pantell | axial |
| 1959 | Gaponov | axial |
| 1959 | Gaponov and Zhelznyakov | azimuthal |
| 1964 | Bott | axial |
| 1964 | Hirshfield and Wachtel | azimuthal |
| 1965 | Bott | azimuthal |
| 1966 | Schriever and Johnson | axial |

# *A Physics Issue*

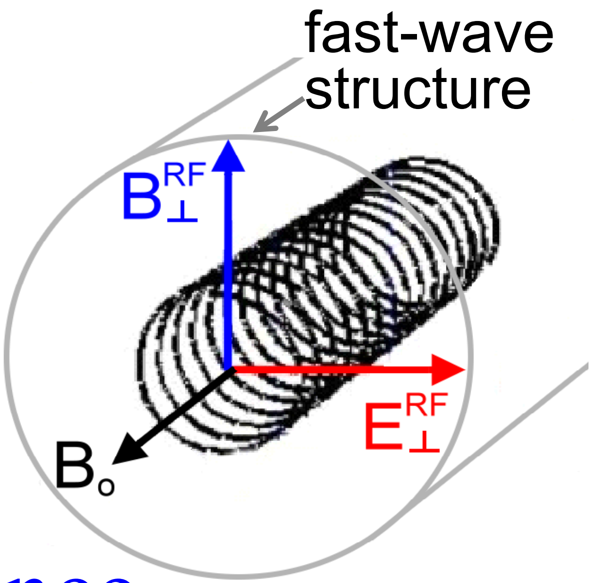
All experiments worked under the same set of conditions:

(1) fast-wave structure

(2) DC magnetic field

(3) spiraling electron beam

(4) electron cyclotron resonance




But there were two interpretations for the observed radiation. Which one was correct?

# *Mechanism Competition*

Azimuthal and axial bunching mechanisms, though simultaneously present, are always in competition such that one partially offsets the other.

Azimuthal bunching dominates,

if $\omega^2 > k_z^2 c^2$ (fast-wave).

Axial bunching dominates,

if $\omega^2 < k_z^2 c^2$ (slow-wave)

Thus, early observations of stimulated cyclotron radiation in fast-wave structures could only be explained by the azimuthal bunching mechanism.

K. R. Chu and J. L. Hirshfield, **Phys. of Fluids 21**, 461 (1978).
K. R. Chu, **Rev. Modern Phys. 76**, 489 (2004), Secs. II & IV.

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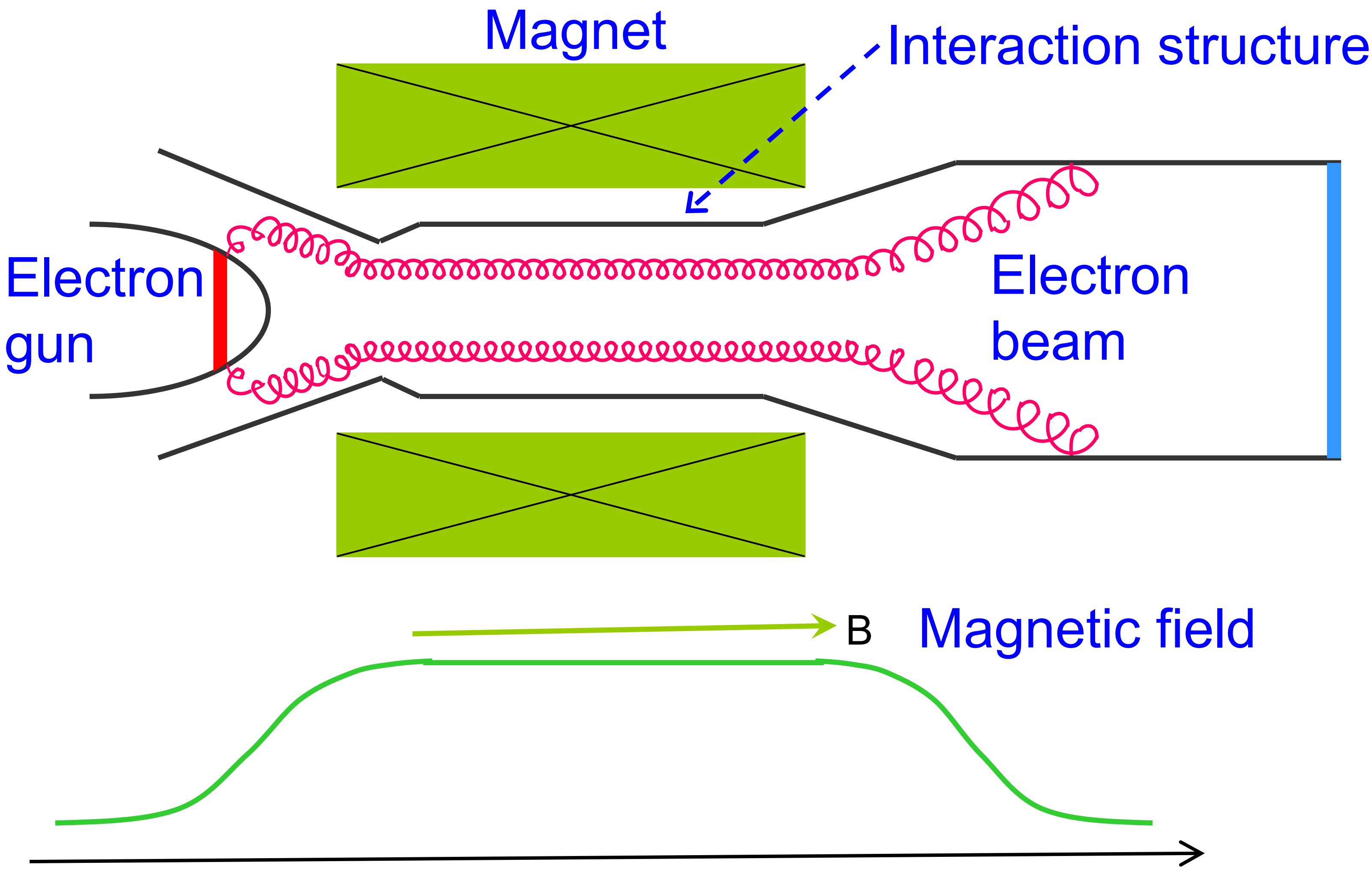
# *ECM-Based Devices (Gyrotrons)*



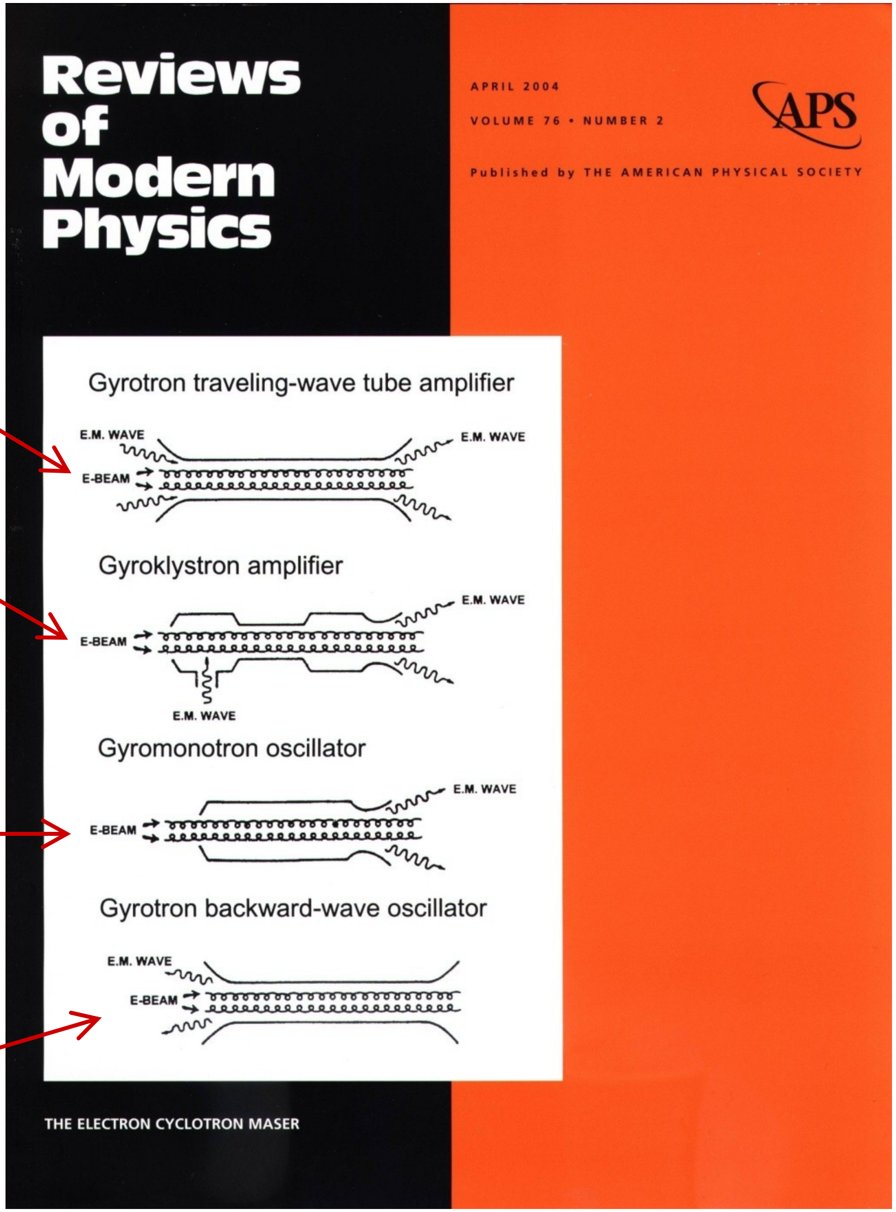
# *Types of ECM-Based Devices*

Phase control
Broad bandwidth
High-resolution space radar

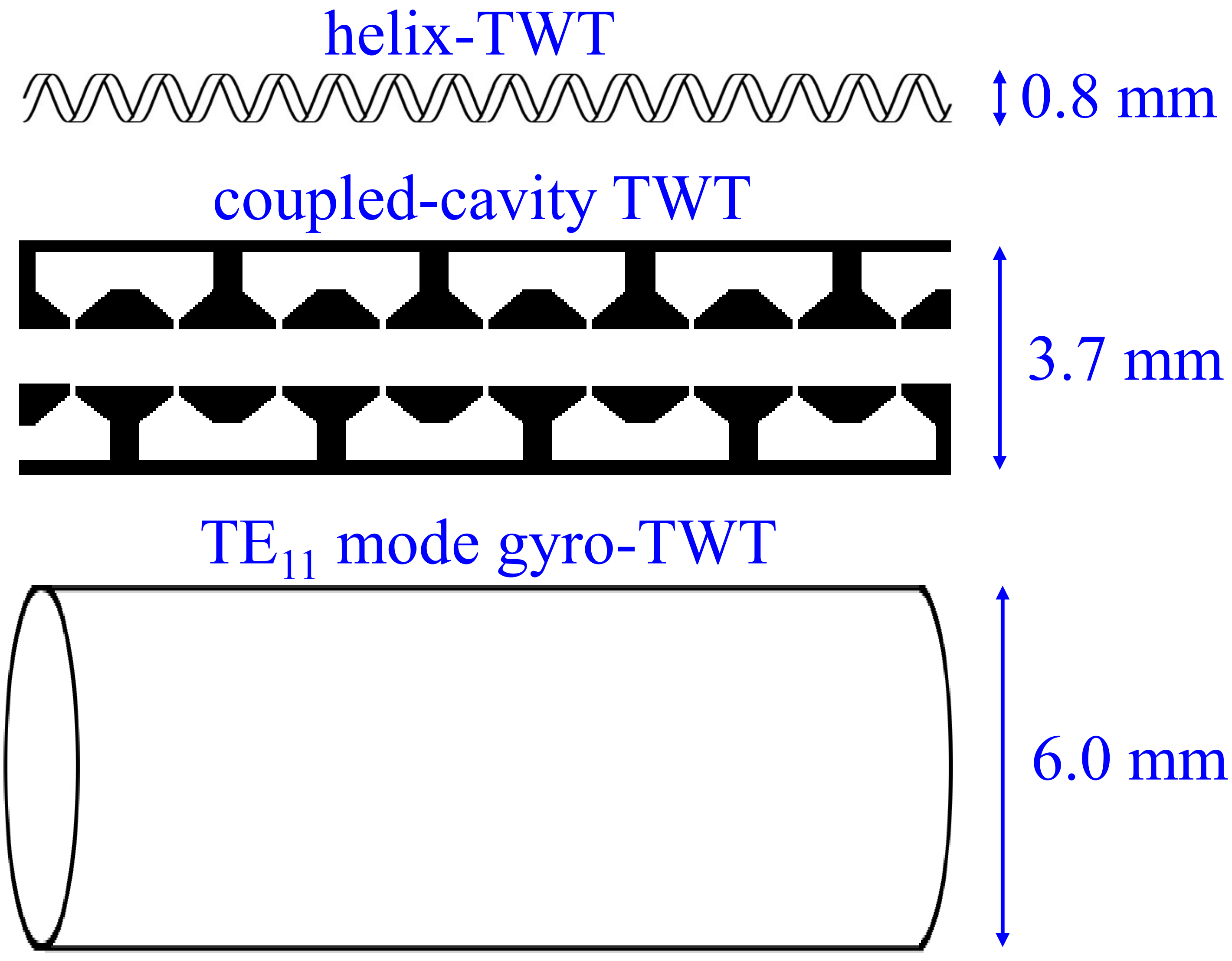
Phase control
Narrow bandwidth
Particle acceleration
Space radar

High average power
Fusion plasma heating
Industrial processing

Continuous frequency tunability
Not yet exploited



# *Shape and Dimension Comparison of 30 GHz Traveling-Wave Amplifier Circuits*

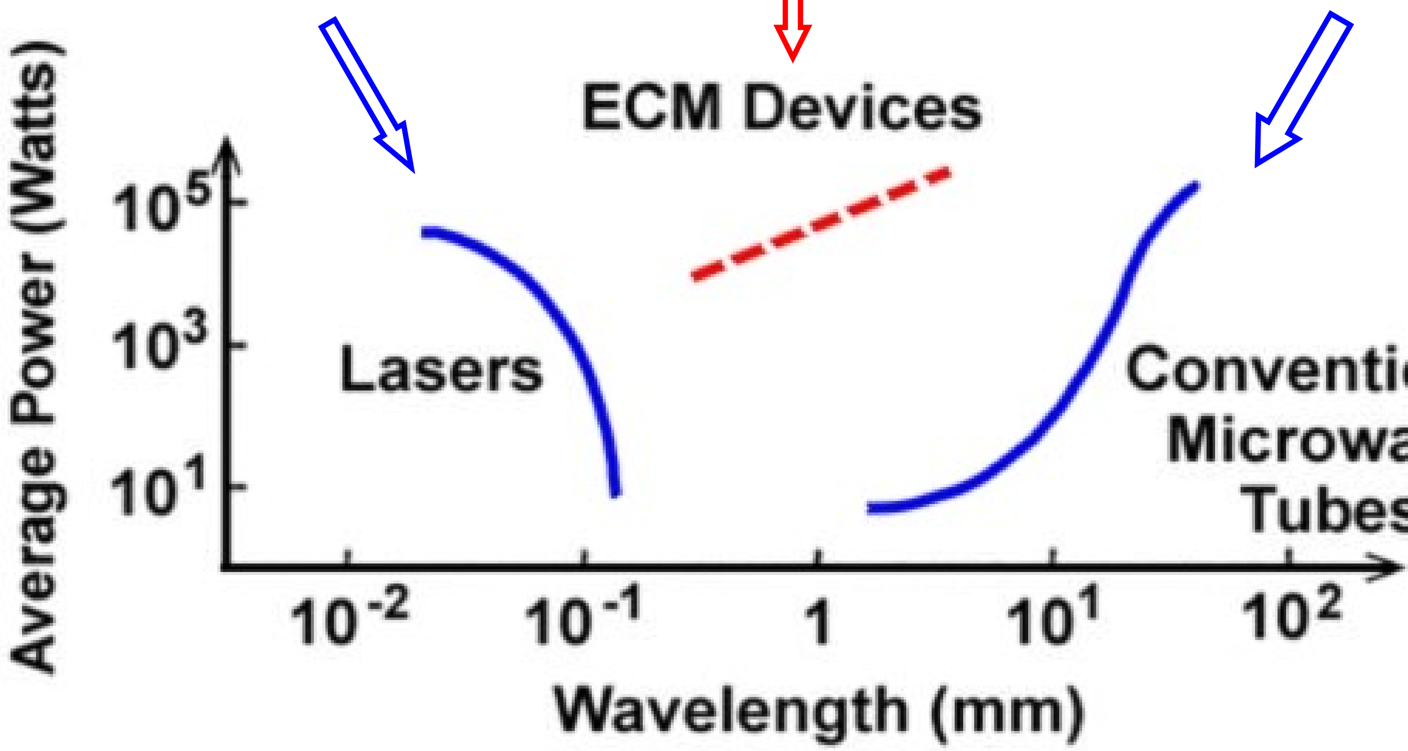


# *Significance of the ECM*

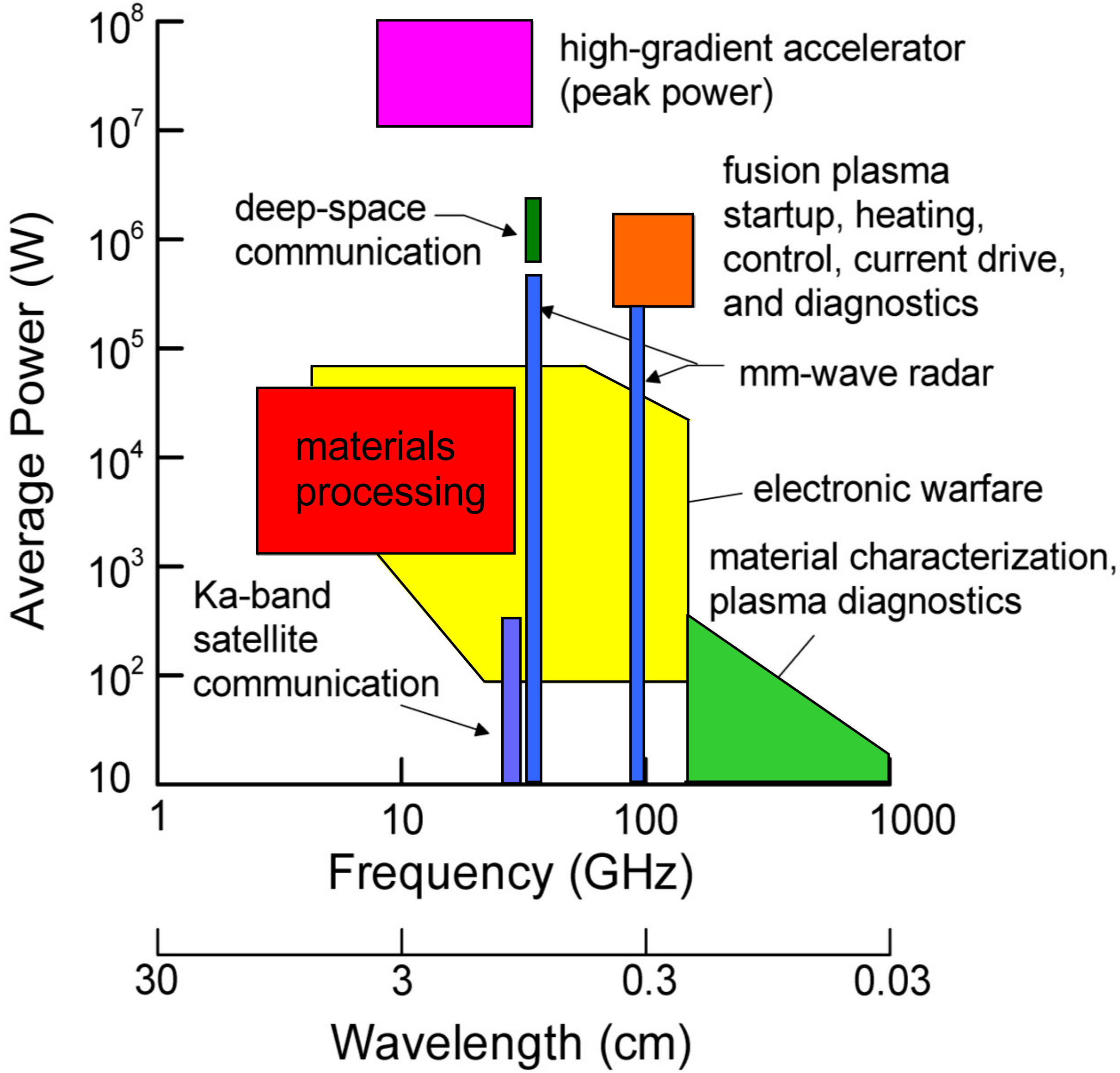
one photon
per excitation,
large interaction
space

multiple photon
per electron,
large interaction
space

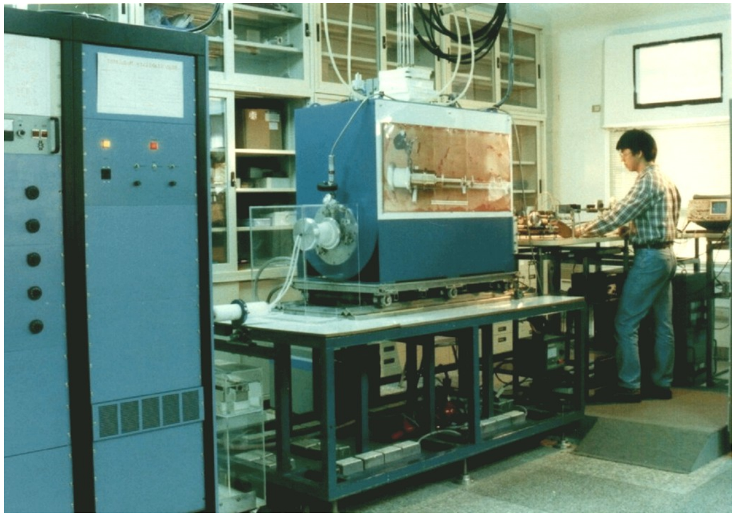
multiple photon
per excitation,
interaction space
~ wavelength

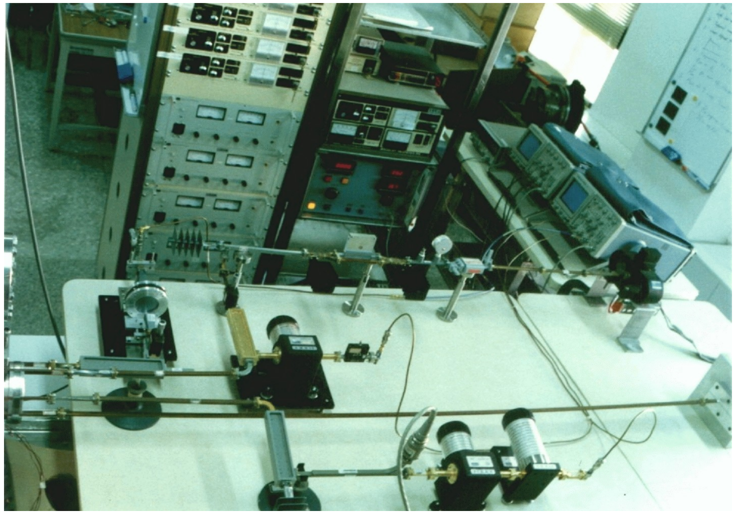


# Current and Potential Applications of High-Power Millimeter/Submillimeter Waves

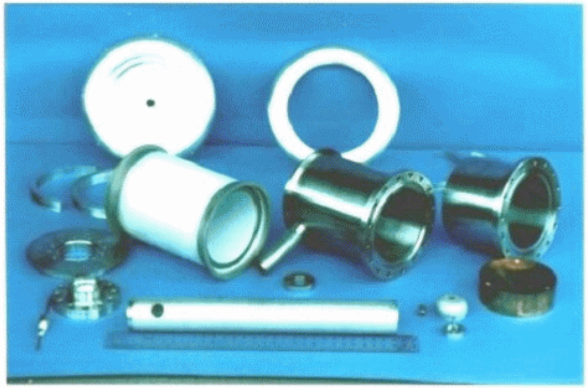


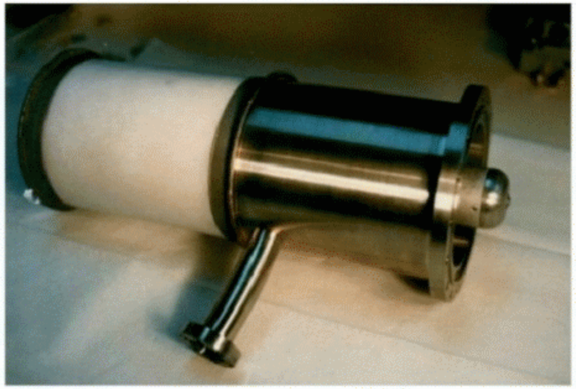
# NTHU High Frequency Electrodynamics Lab

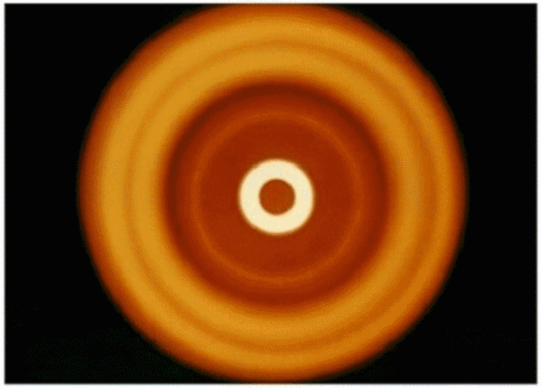




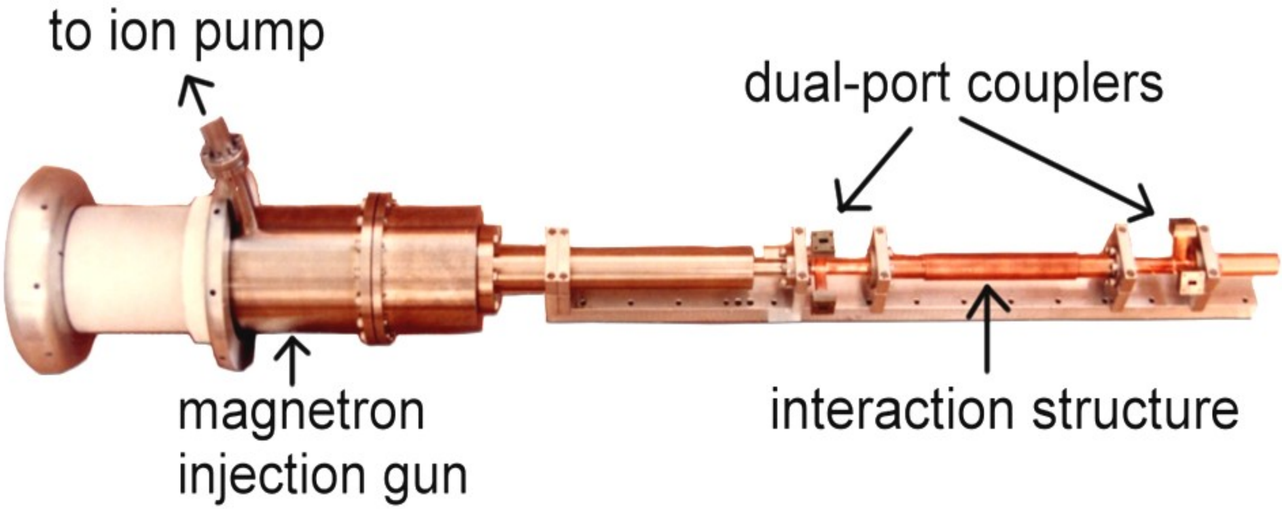
## A single-anode, mechanically tunable magnetron injection gun







# The NTHU Experimental Gyrotron Traveling-Wave Amplifier

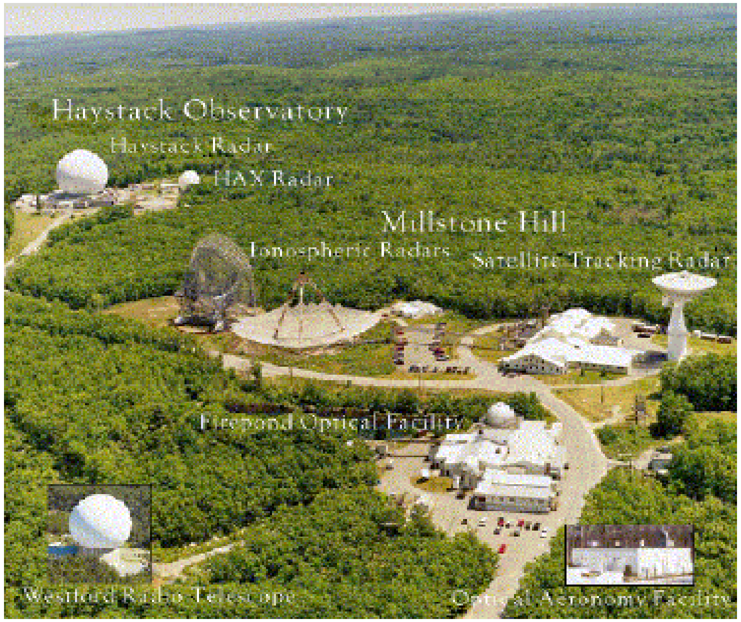



# Comparison of the NTHU Gyro-TWT with the state-of-the-art TWT

| type | peak power | efficiency | gain | bandwidth |
|---|---|---|---|---|
| gyro-TWT | 93 kW | 26.5 % | 70 dB | 8.6 % |
| TWT | 50 kW | 16 % | 40 dB | 6 % |

# *Applications of the Gyro-TWT*

1. Satellite and orbital debris radar measurements:



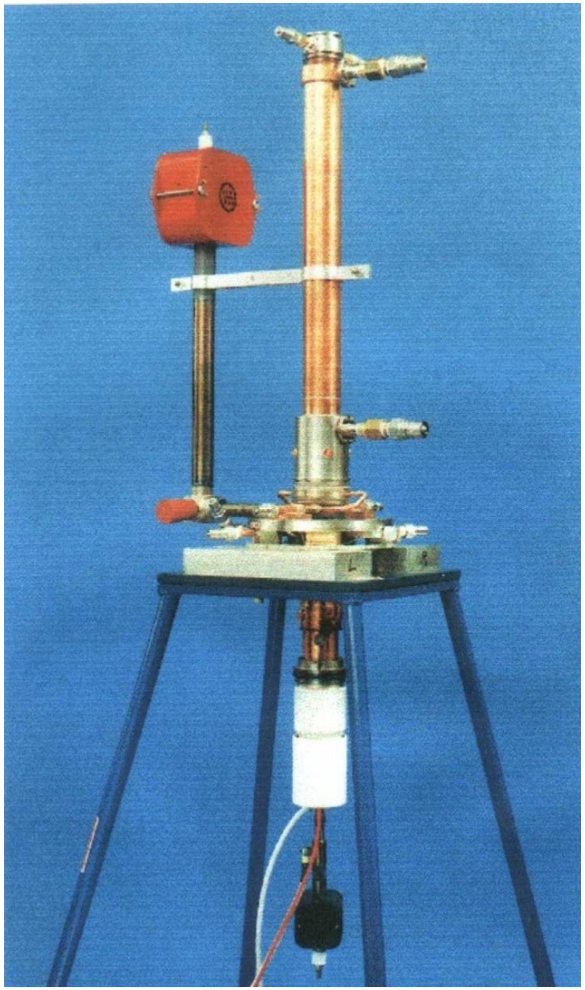

W-band upgrade of the Haystack radar (operated by MIT Lincoln Laboratory)

2. Missile and space object tracking:

Ka-band upgrade of the U. S. Army Kwajalein Atoll radar complex (operated by MIT Lincoln Laboratory)

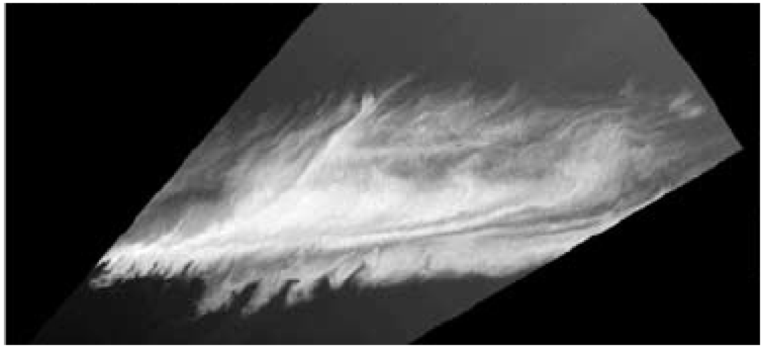
# *Gyroklystron and Applications*

94GHz, 100kW Gyroklystron, Naval Research Laboratory

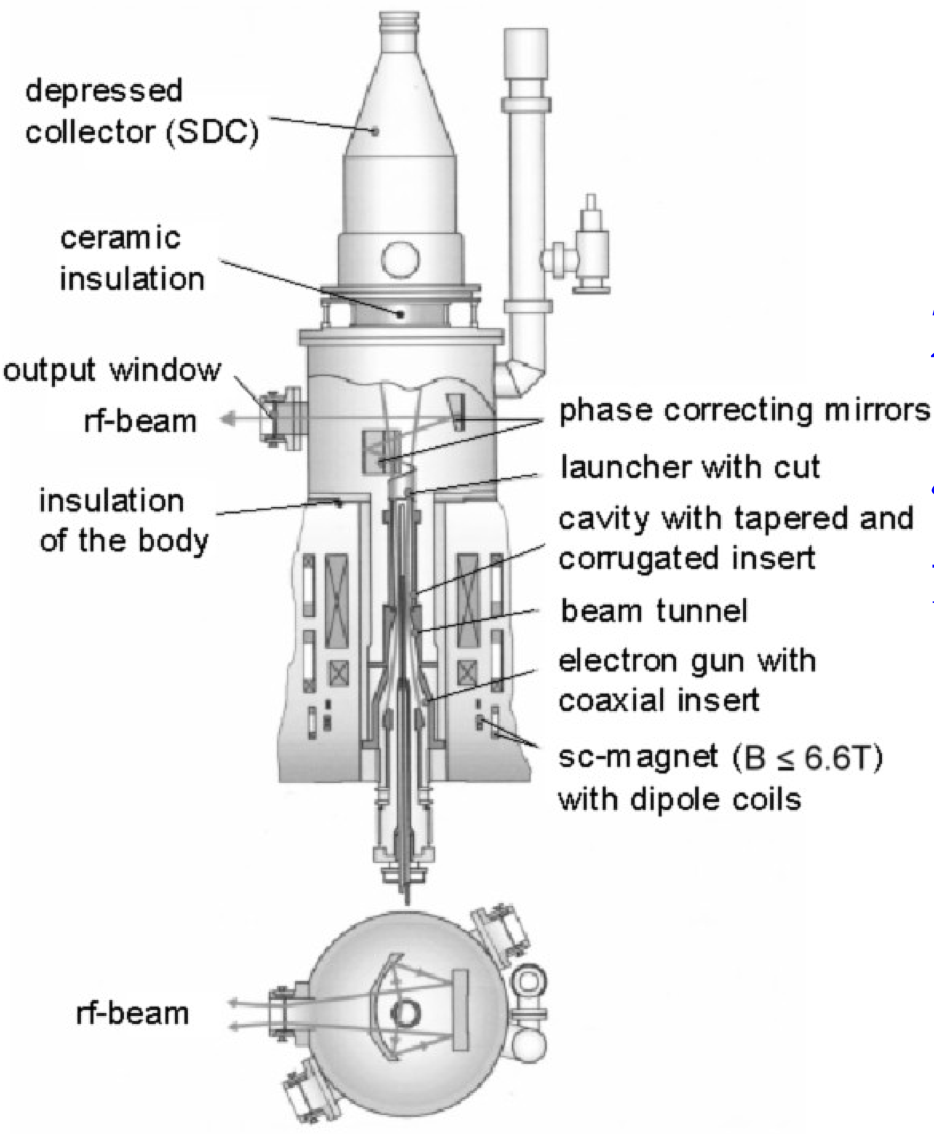


W-band Advanced Radar for Low Observable Control (WARLOC)

Radar image of cloud from the WARLOC

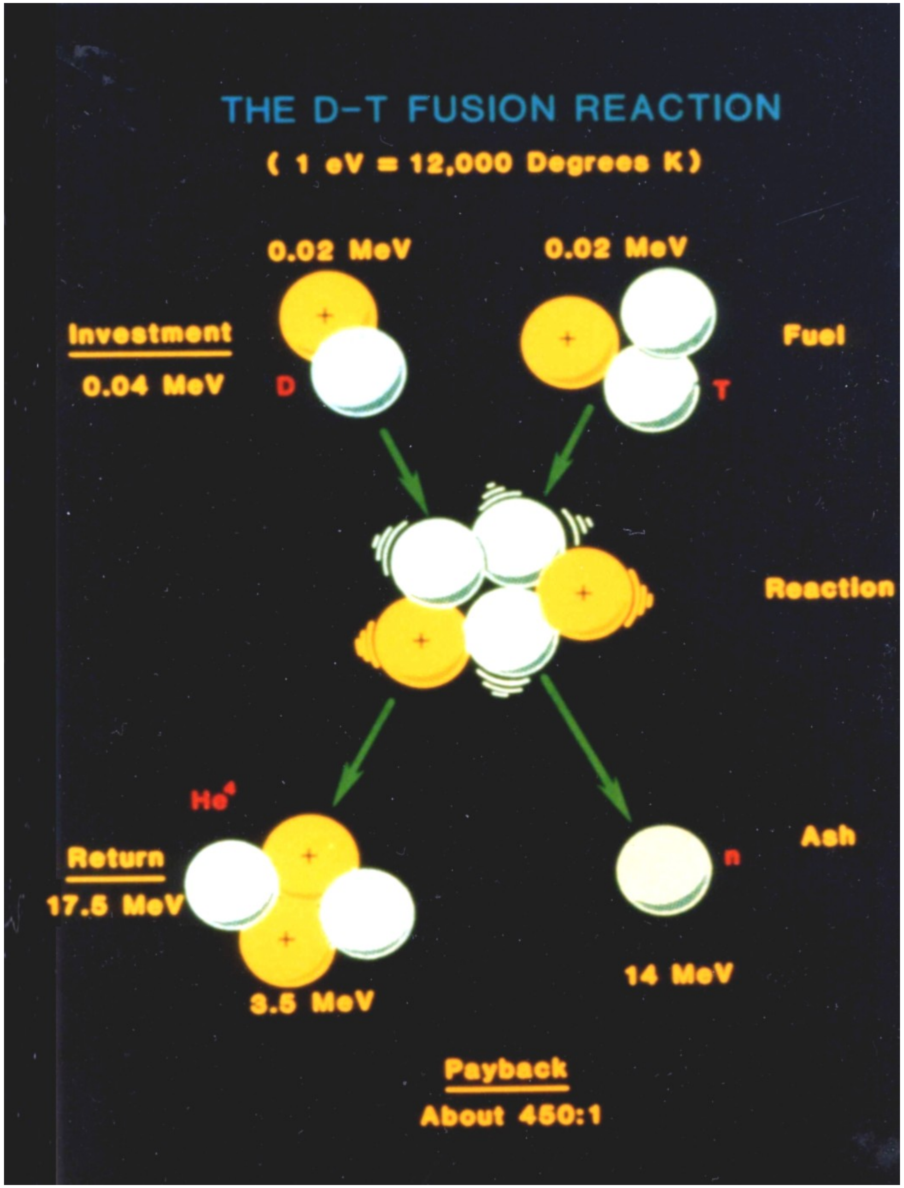


# *The Gyromonotron Oscillator*

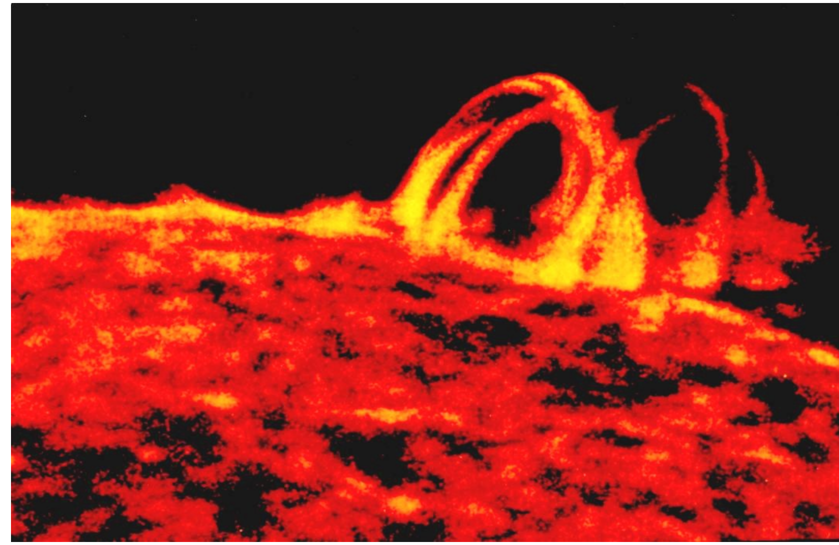



165 GHz, $TE_{31,17}$ mode, 2.2 MW coaxial gyromonotron for fusion plasma heating *(Piosczyk et al.,2002)*

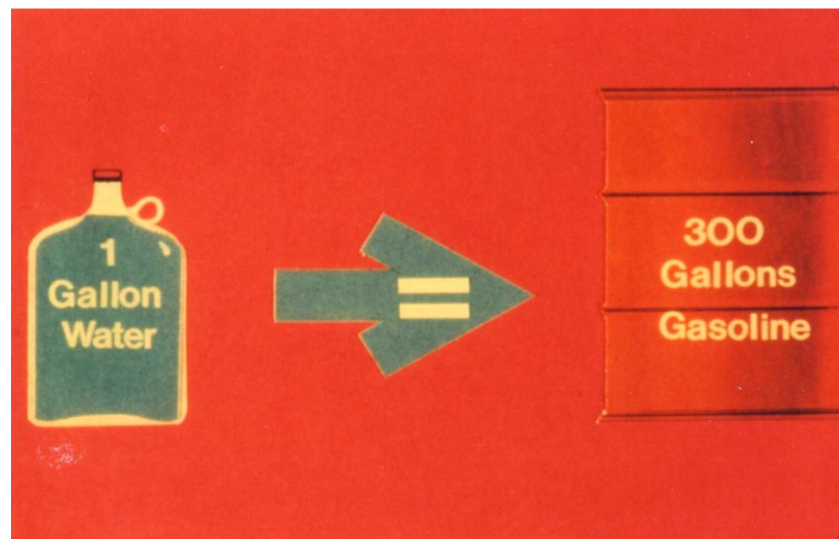
# D-T fusion reaction



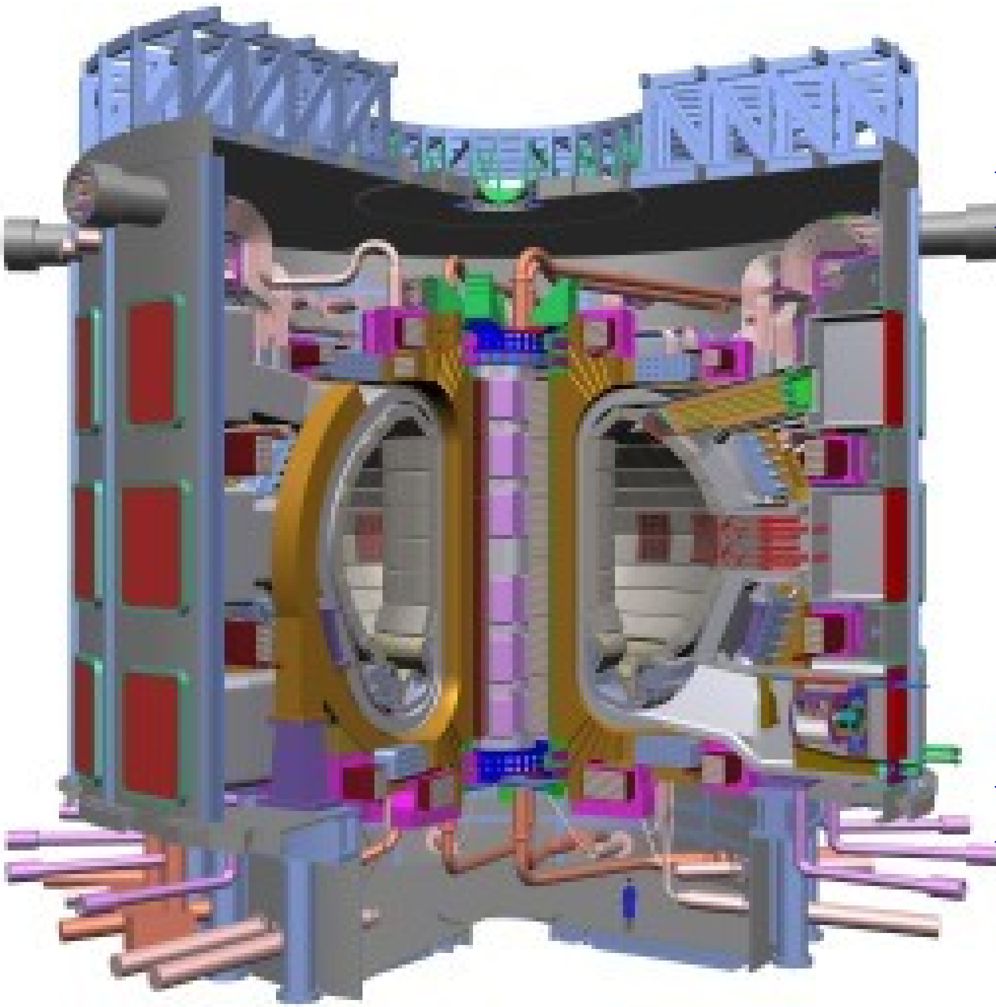

# Nature's fusion reactor: Sun



## Sea water ⟶ Energy



# *Application of the Gyromonotron: Fusion plasma heating*



## ITER Tokamak

Participants: EU, USA, Russia, Japan, China, Korea

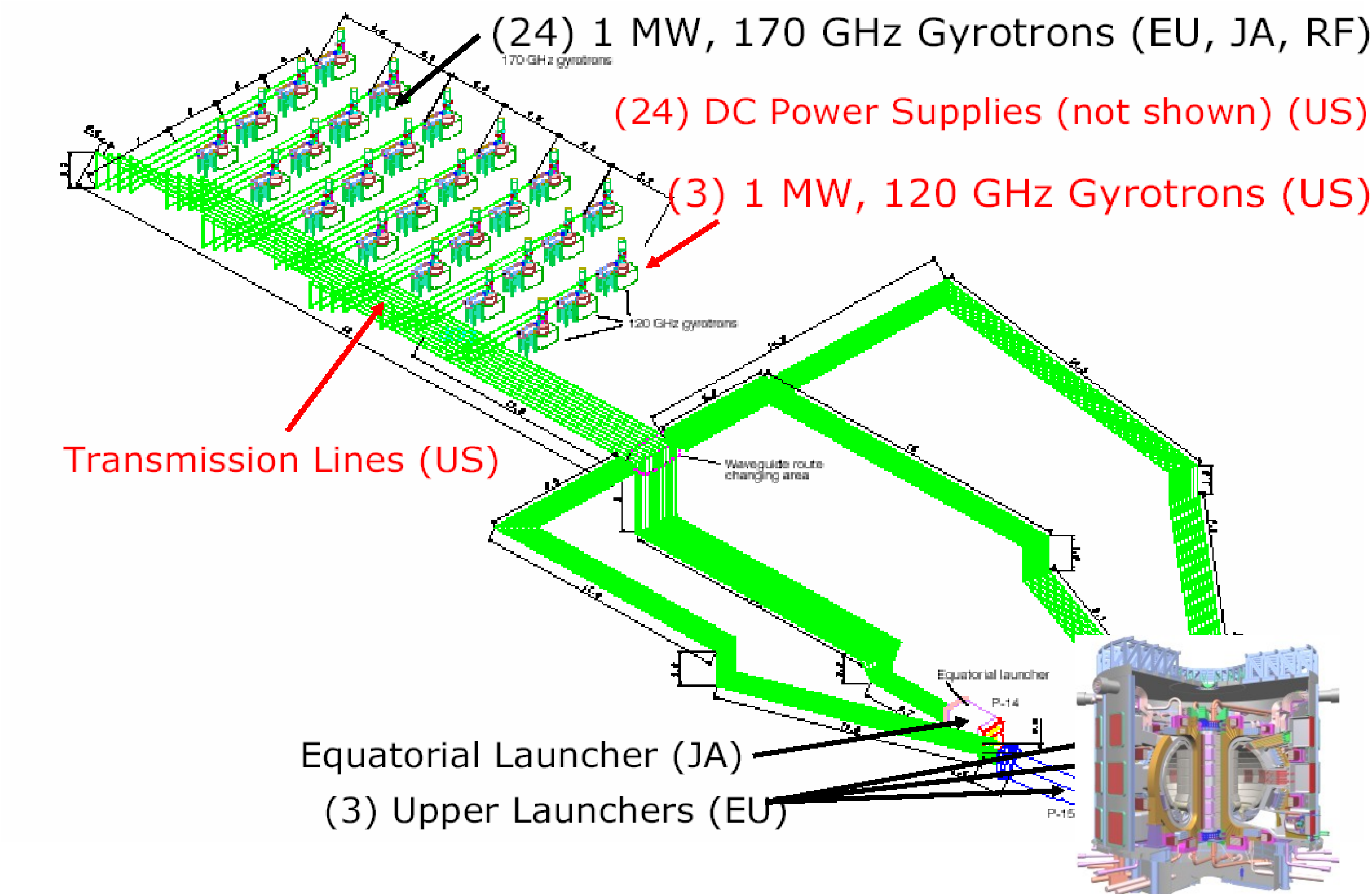
Cost: US$15 Billion

Completion date: 2015

Plasma temp: $10^8$ K

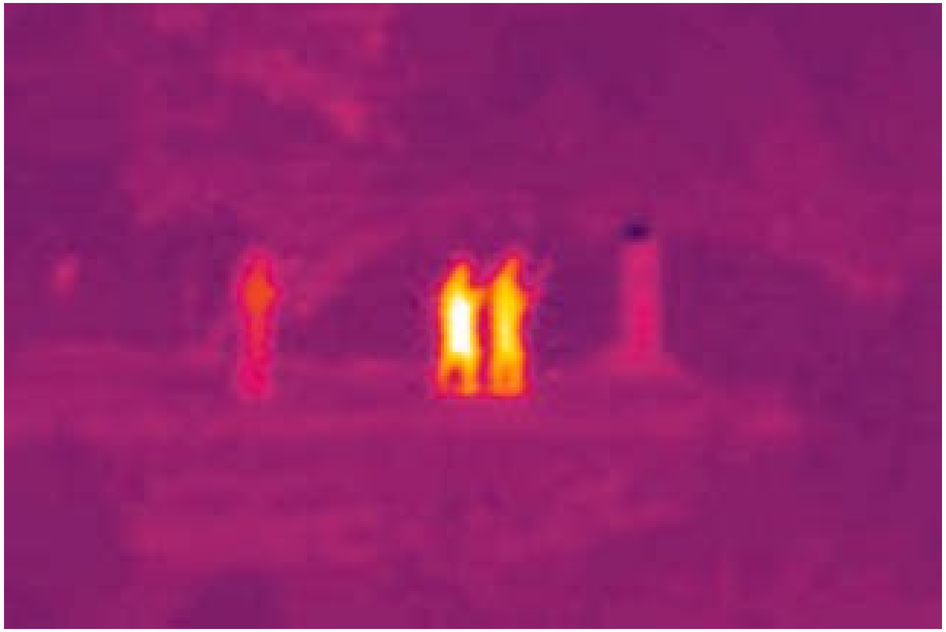
Output power: 500 MW

# ITER Plasma Heating System

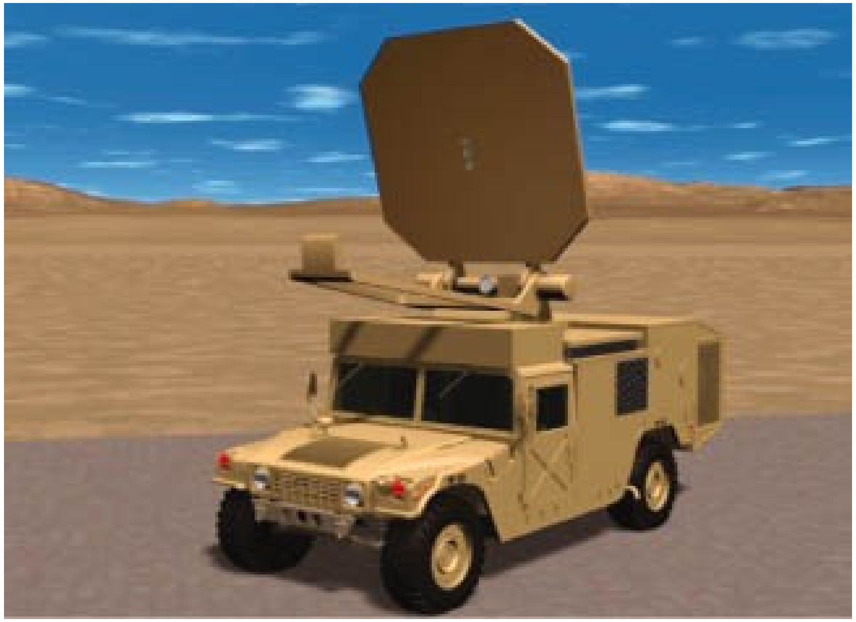



R. Vernon *et al.,* in the 16th ANS Meeting on the Technology of Fusion Energy, Madison, Wisconsin, 2004

# *Application of the Gyromonotron*: Active Denial Technology



**Infrared image of silhouette targets**



**Vehicle-mounted ADT concept**

# *Application of the Gyromonotron*: materials characterization, plasma wave scattering, and electron spin resonances, etc.

Research Center for Development of Far-Infrared Region
University of Fukui, Japan

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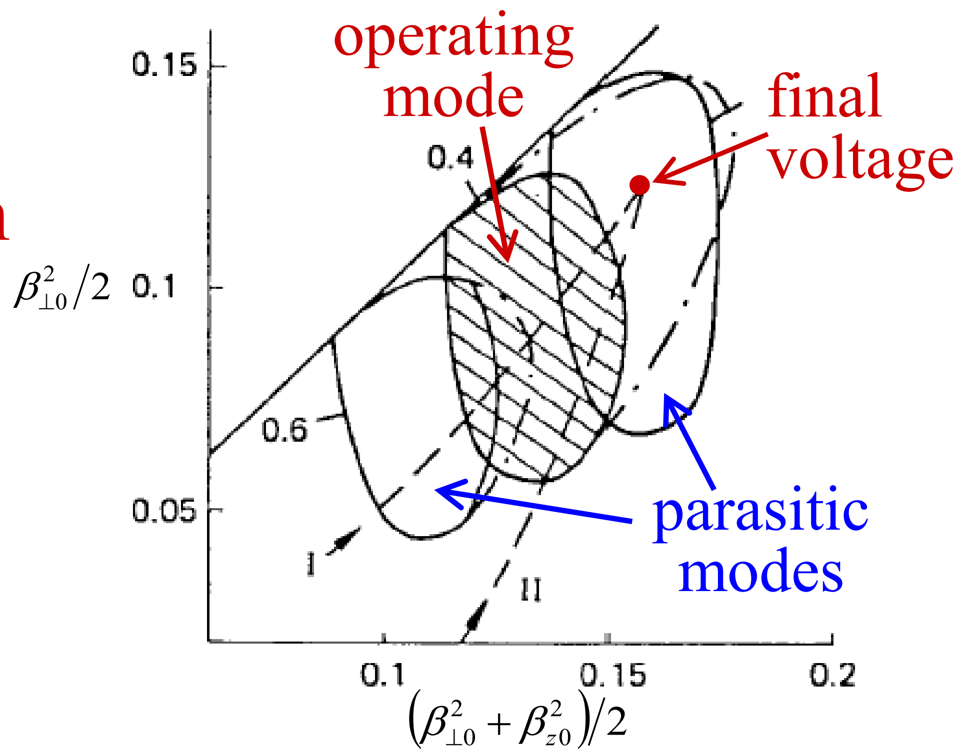
# Mode Competition in the Gyromonotron

"One should find such a start-up scenario which will provide the initial excitation of the desired mode, which, being excited, will suppress all parasites."

G. S. Nusinovich, IEEE Trans. **Plasma Sci**. **27**, 313 (1998)



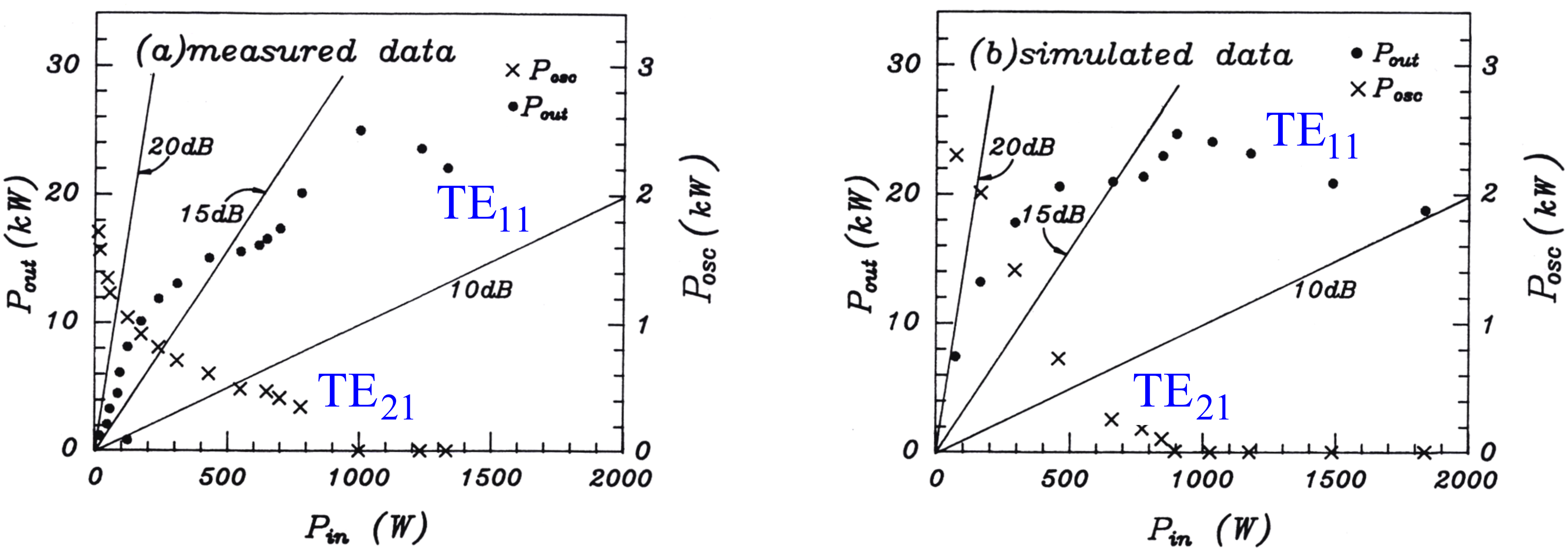

"The desired mode must be excited before unwanted modes are excited as the gun voltage is raised to its steady-state value."

K. E. Kreischer and R. J. Temkin, **Phys. Rev. Lett**. **59**, 547 (1987).

# *Mode Competition in the Gyro-TWT*

"Beam perturbations associated with one mode will appear as deleterious velocity and energy spreads to another mode of different frequency and field profile."

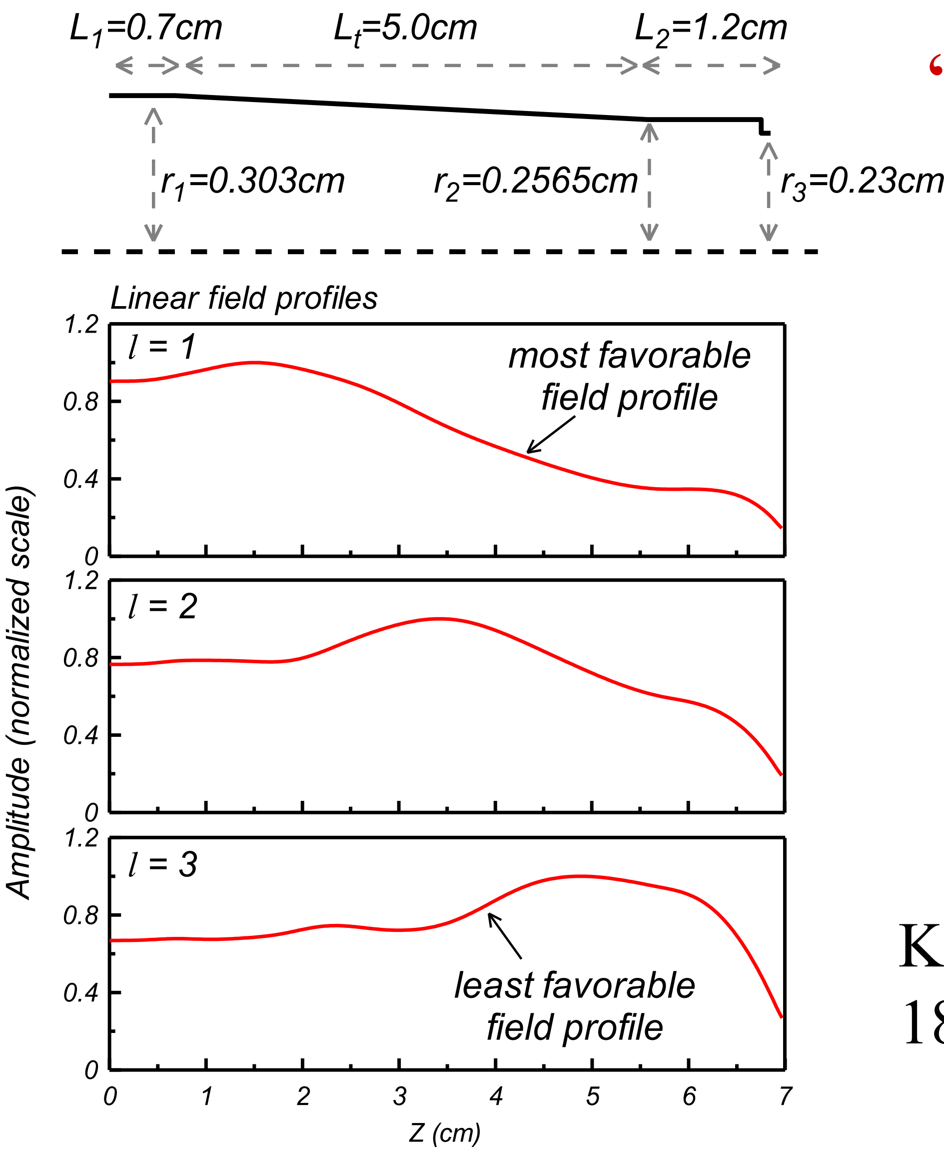
$P_{out}$ (TE$_{11}$) & $P_{osc}$ (TE$_{21}$) vs $P_{in}$




L. R. Barnett *et al.*, **Phys. Rev. Lett.** 63, 1062-1065 (1989)

K. R. Chu," **Rev. Modern Phys. 76**, 489 (2004), Sec. VI.

# Mode Competition in the Gyro-BWO

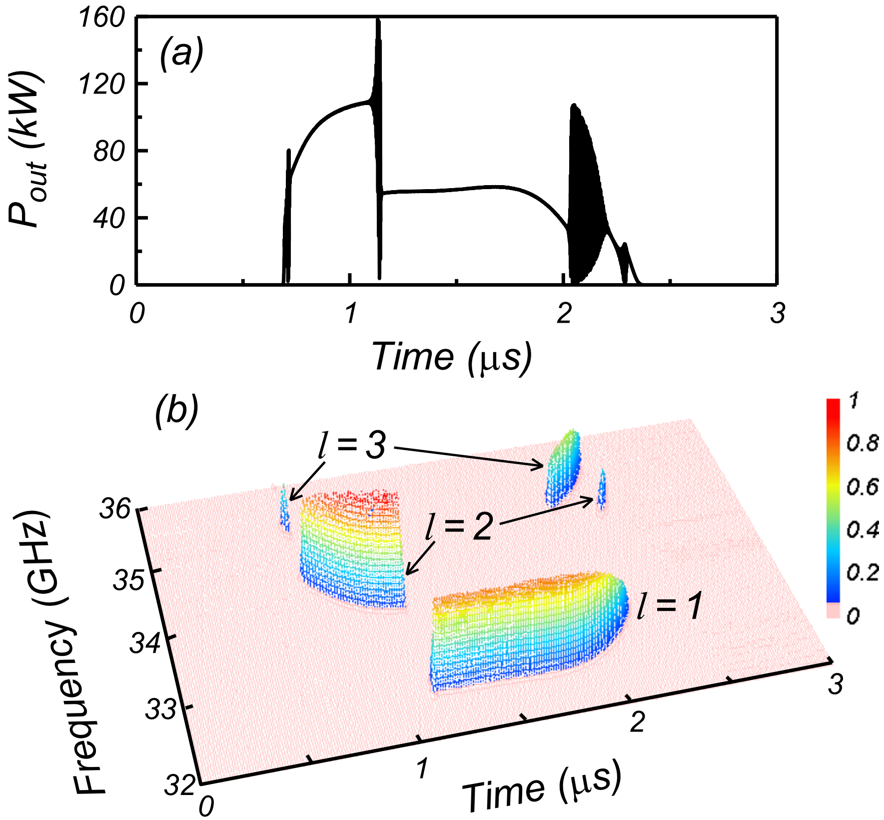



"Asymmetry of field profiles plays a dominant role in mode competition. A mode with a favorable field profile will suppress another mode with a less favorable field profile."

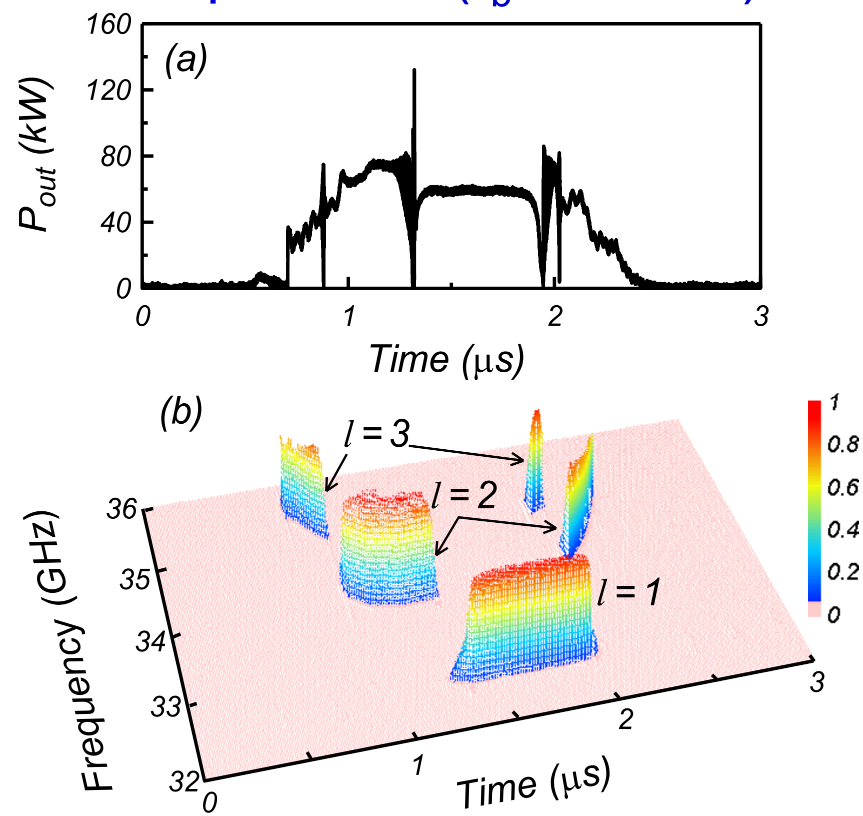
K. F. Pao *et al*., **Phys. Rev. Lett. 95**, 185101 (2005).

# *Mode Competition in the Gyro-BWO*

Particle simulation ($I_b$ = 4.8 A)




Experiment ($I_b$ = 4.88 A)




K. F. Pao, T. H. Chang, C. T. Fan, S. H. Chen, C. F. Yu, and K. R. Chu, Phys. Rev. Lett. 95, 185101 (2005).

- The latest-starting, lowest-order $l$ = 1 mode eventually dominates.

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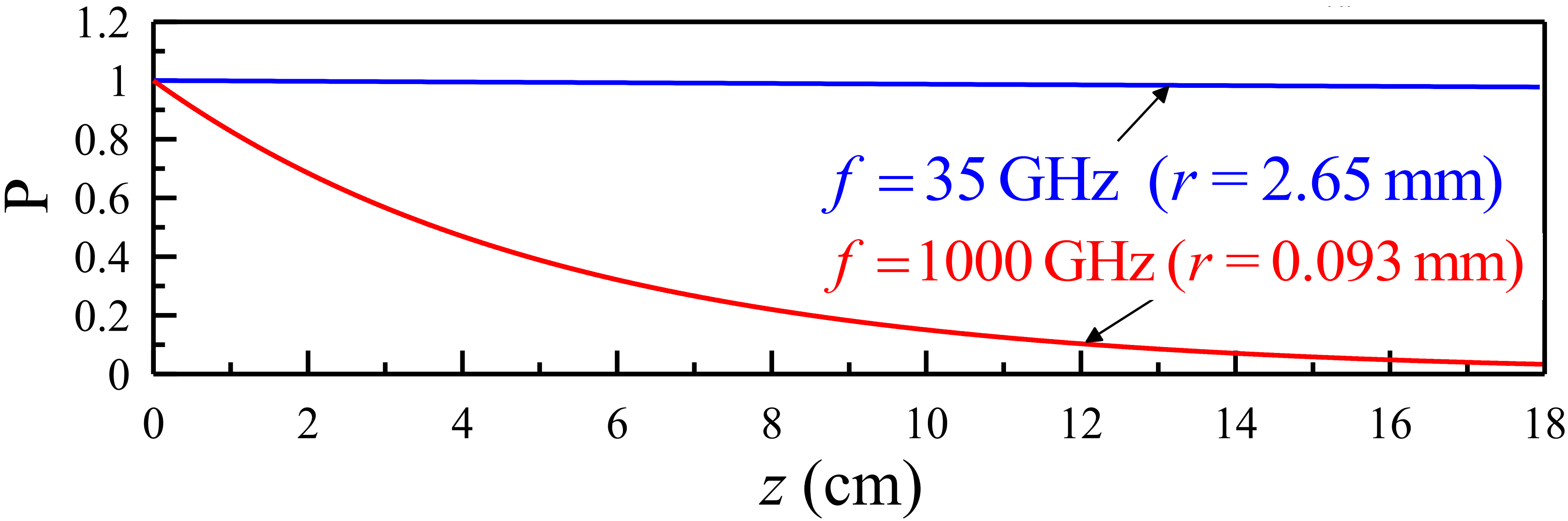
# *Issues at THz: Heavy Wall Losses*

## $TE_{01}$ mode attentuation in copper waveguides ($f = 1.06 \times$ cutoff frequency)




➔ Higher order modes are preferable.

Many applications require a broad tuning range.

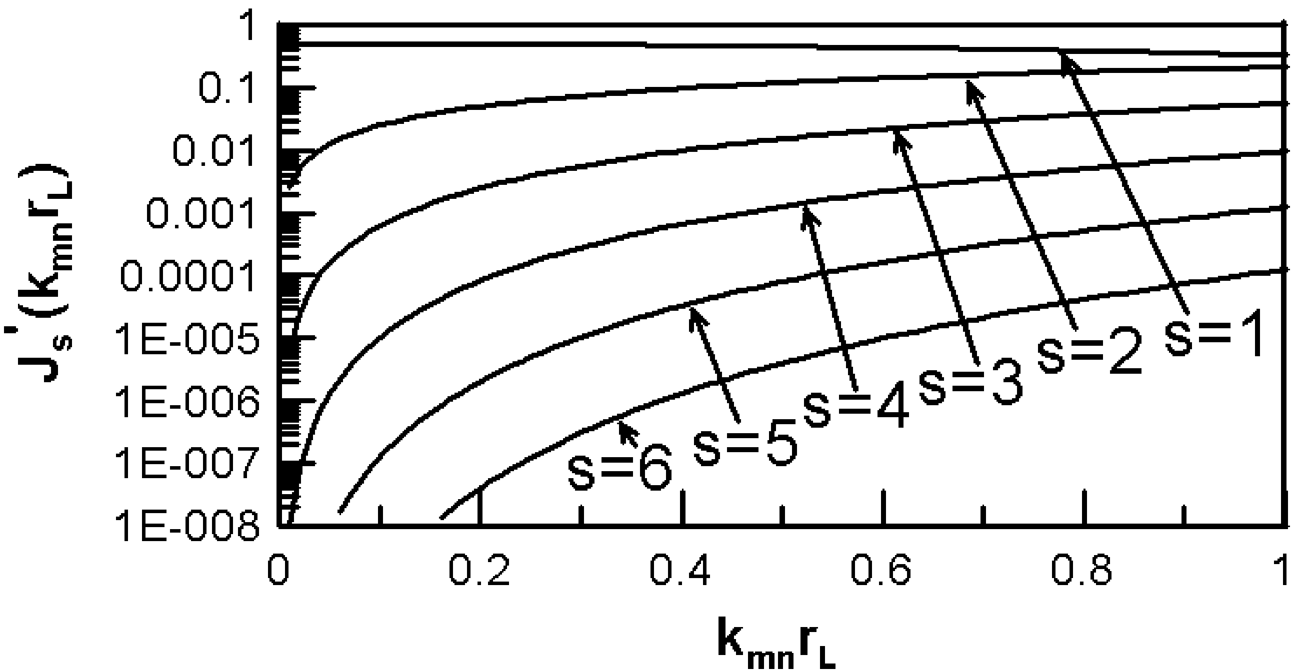
➔ Higher order modes are unaviodable.

# *Issues at THz: High B-field*

Up to 40 T is required for fundamental cyclotron harmonic interaction ($s$ =1)

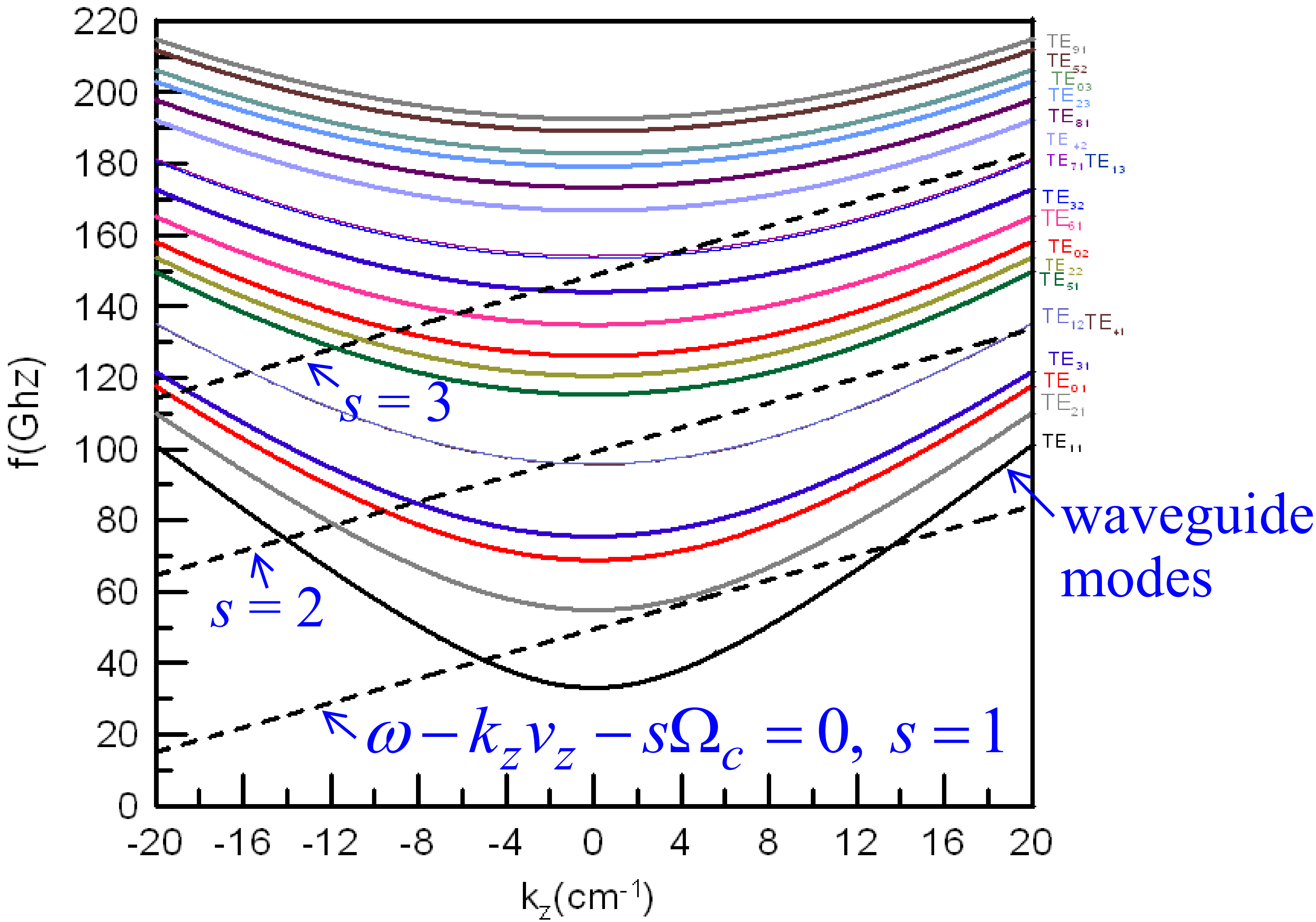
➔ $s$>1 harmonic interaction is preferable.

Interaction strength: $H_{sm} = J_{s-m}^{2}(k_{mn}r_c)J_s^{'2}(k_{mn}r_L)$



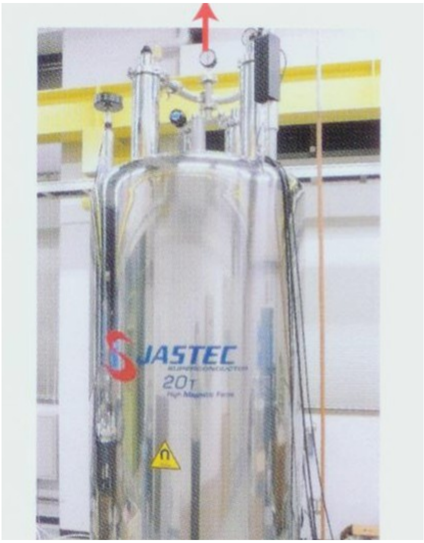

➔ Can $s$>1 modes compete with $s$ =1 mode?

# *Beam-Wave Resonance Chart*

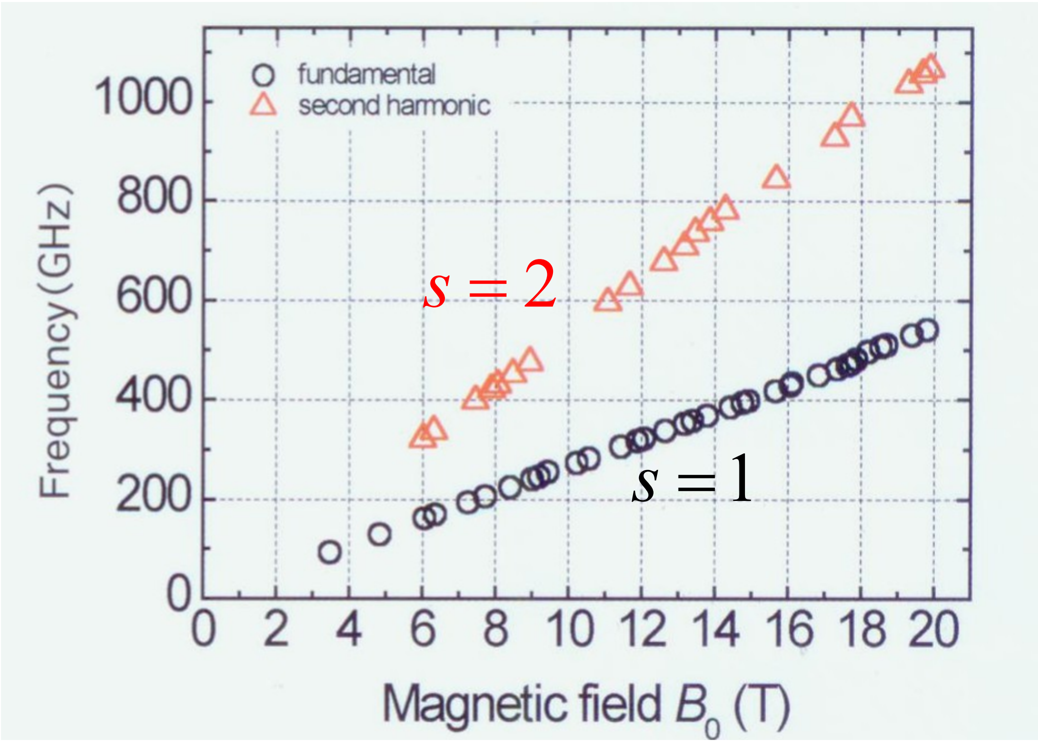


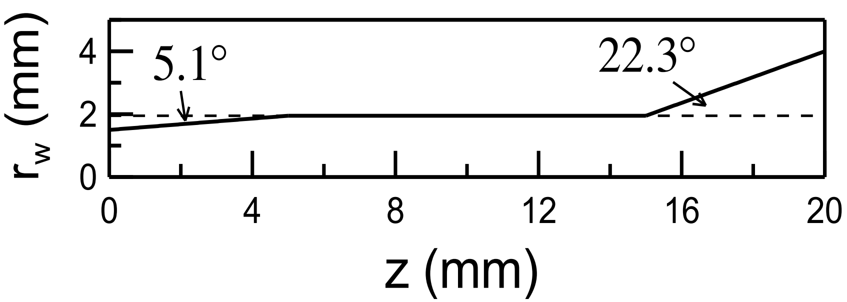
# *The Fukui 2nd Harmonic THz Gyrotron*

~100 W THz wave




CW gyrotron in a 20 T SC magnet




$I_b$ (max): 1 A

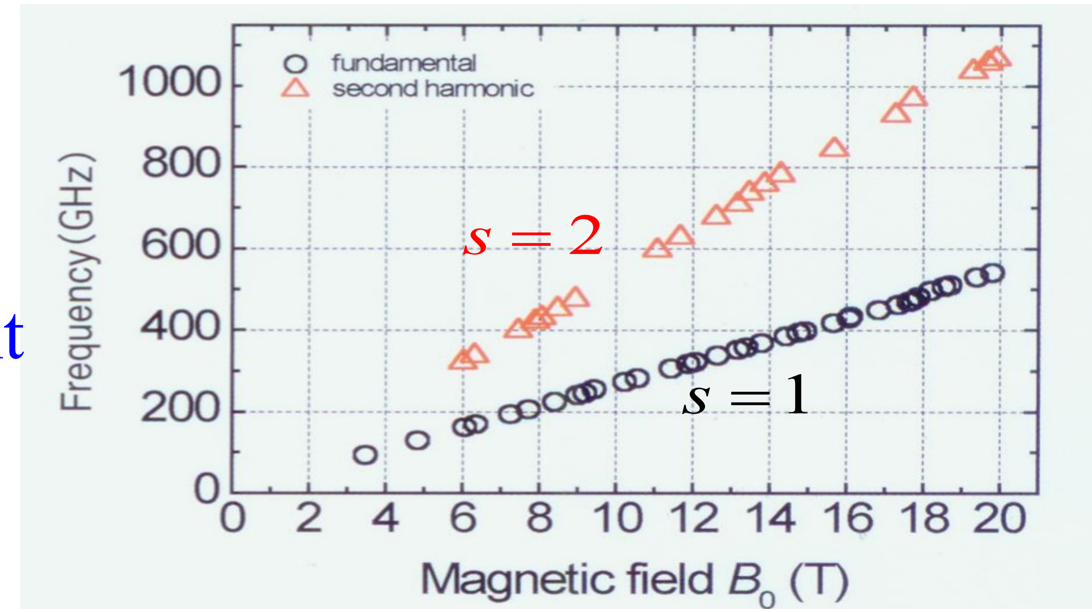
$V_b$: 30 kV

α: 1.1

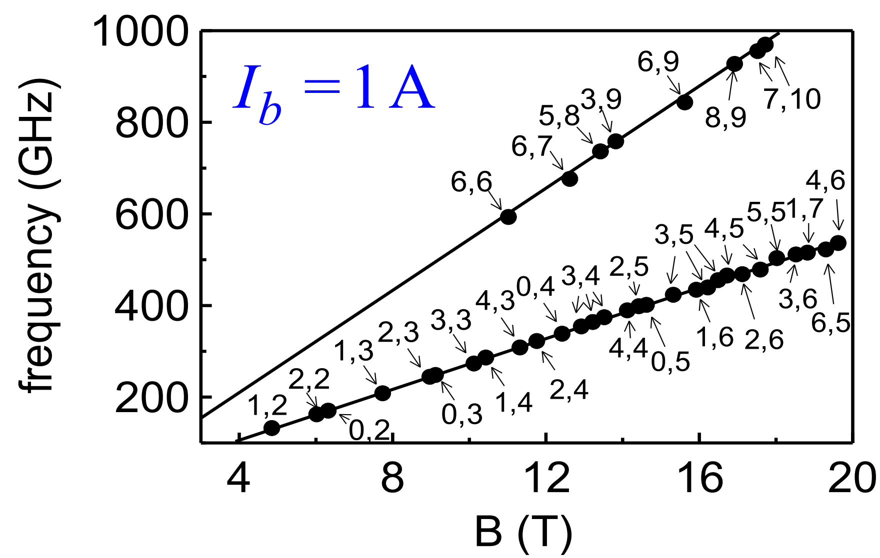
$\Delta v_z/v_z$: ~10%

# *Particle Simulation of the Fukui Experiment*

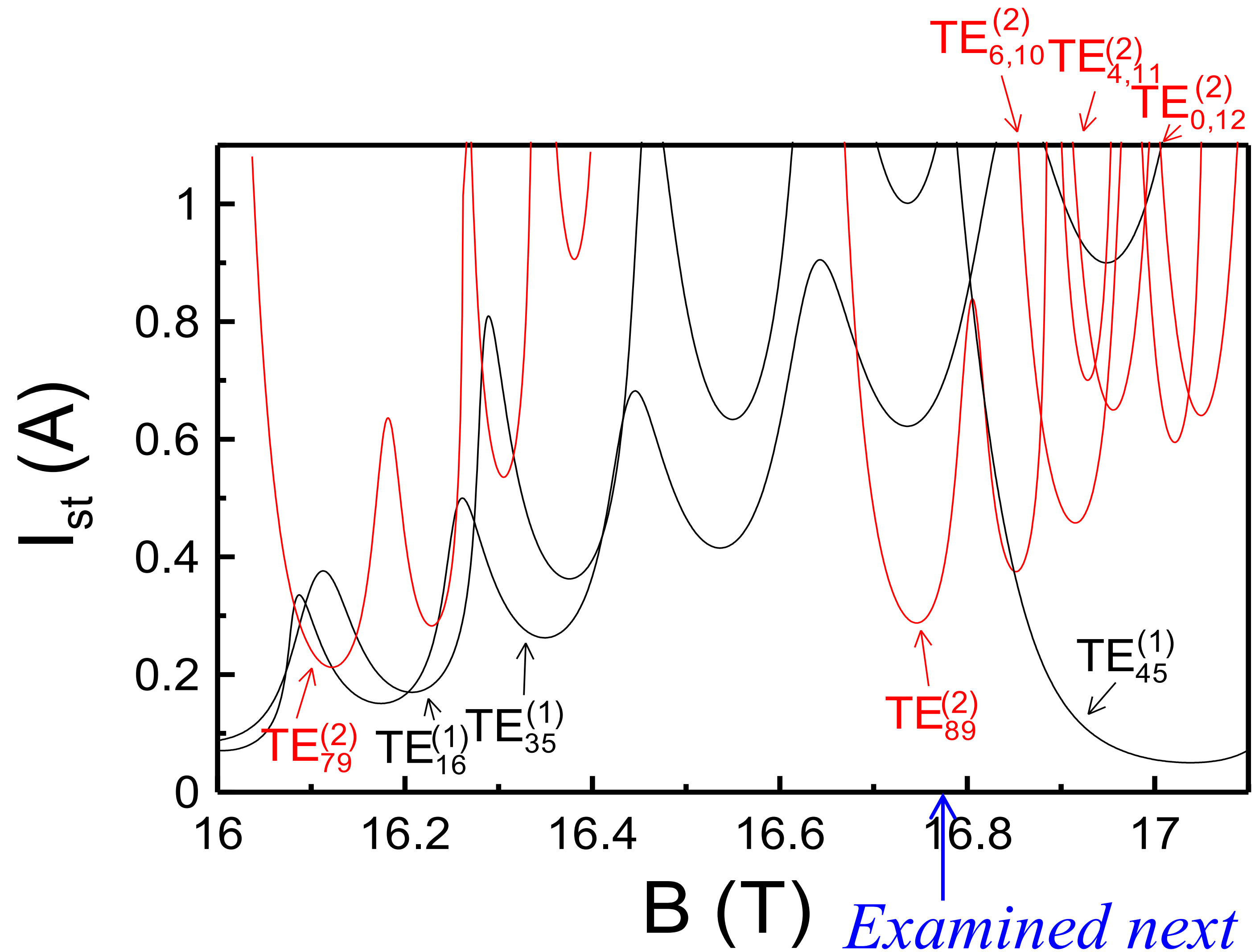
Experiment




Multi-mode, particle-in-cell simulation

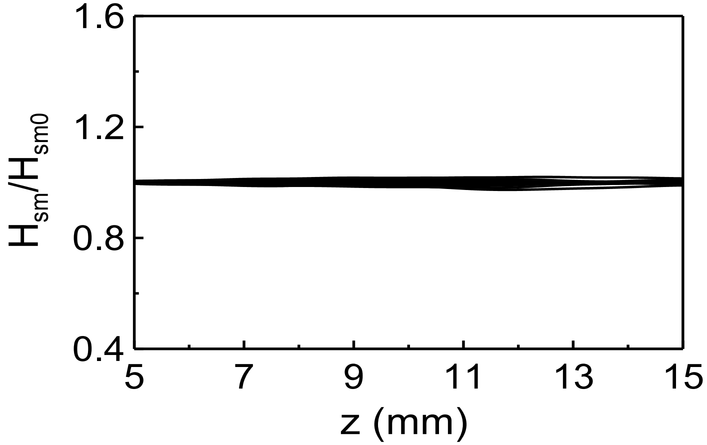


# *$I_{st}$ vs B-Field for the Fukui Experiment (in the range of 16-17 T)*

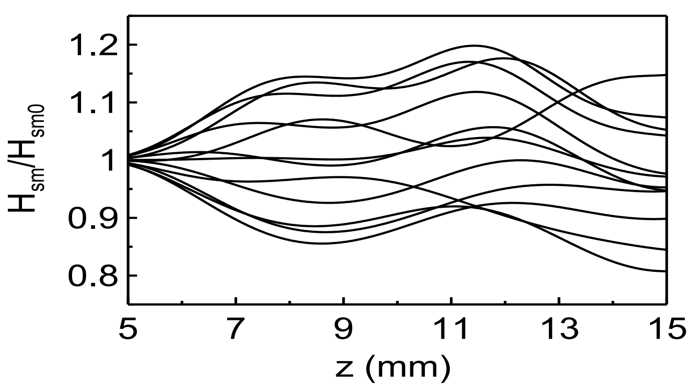


# *Harmonic Mode Competition*
## *– governing mechanism and general trend*

(a) $s = 1$




(b) $s = 2$




**$s$ = 1 interaction:**

Coupling strength ($H_{sm}$) almost unchanged throughout the interaction.

**$s$ = 2 interaction :**

In the nonlinear regime,

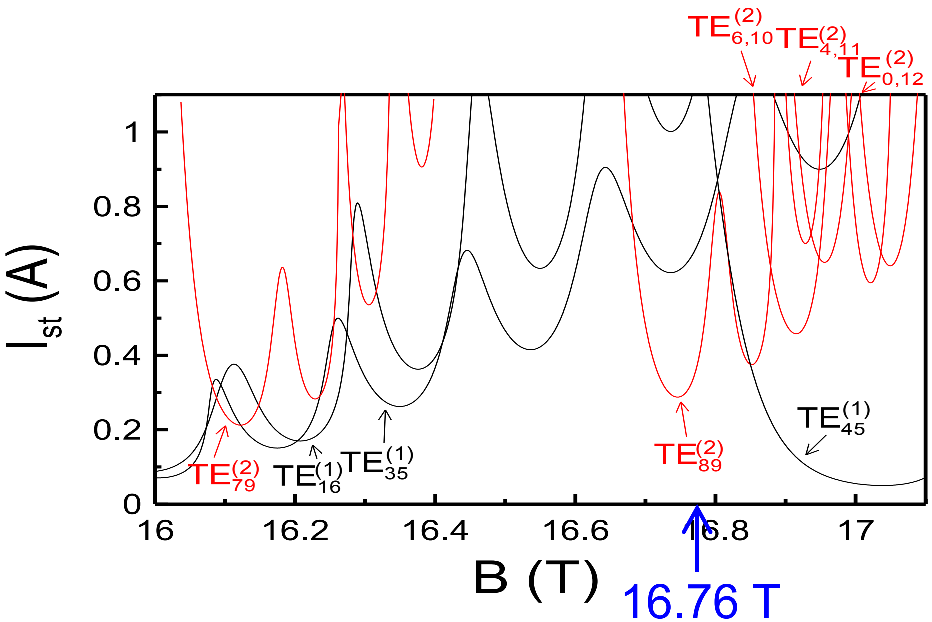
$H_{sm}$ { increases for energy-gaining electrons; decreases for energy-losing electrons }

$\Rightarrow$ unfavorable for competition

Governing mechanism: Nonlinear variation of $H_{sm}$

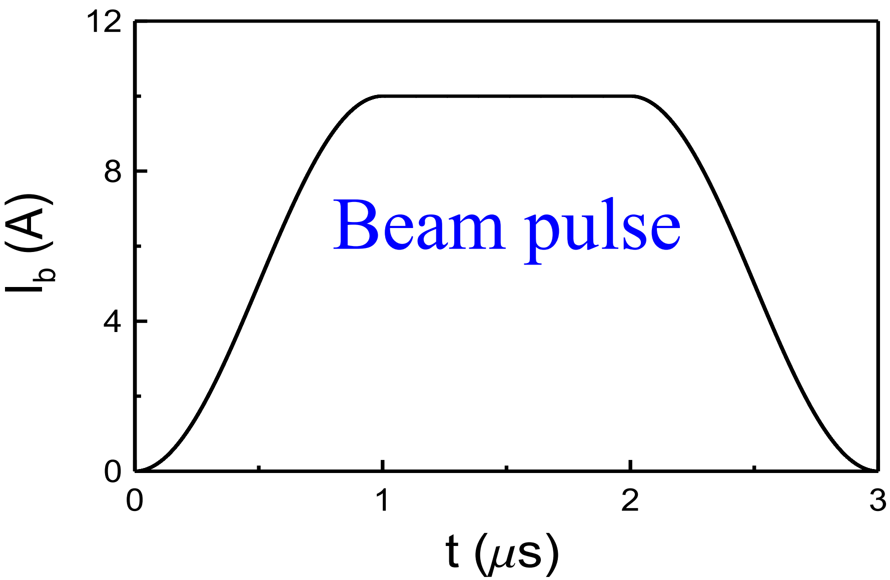
General trend: $s$ =1 mode suppresses $s$>1 modes.

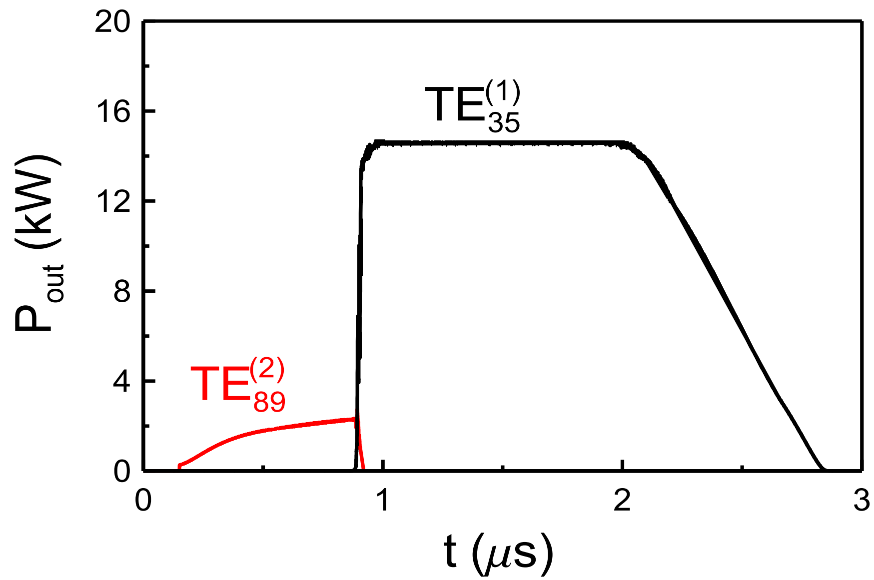
# *Competition between the* $TE_{35}^{(1)}$ *and* $TE_{89}^{(2)}$ *Modes*




The $TE_{89}^{(2)}$ mode, though excited first, is eventually suppressed by the $TE_{35}^{(1)}$ mode.

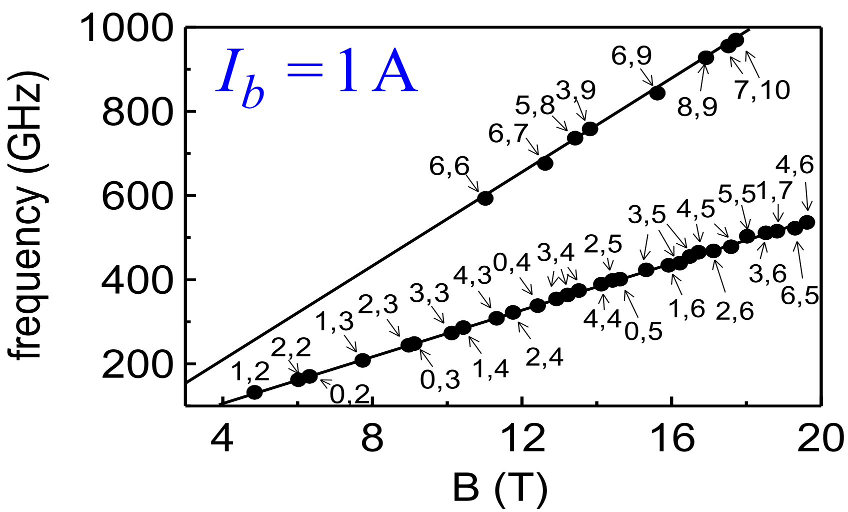
Two-mode simulation:

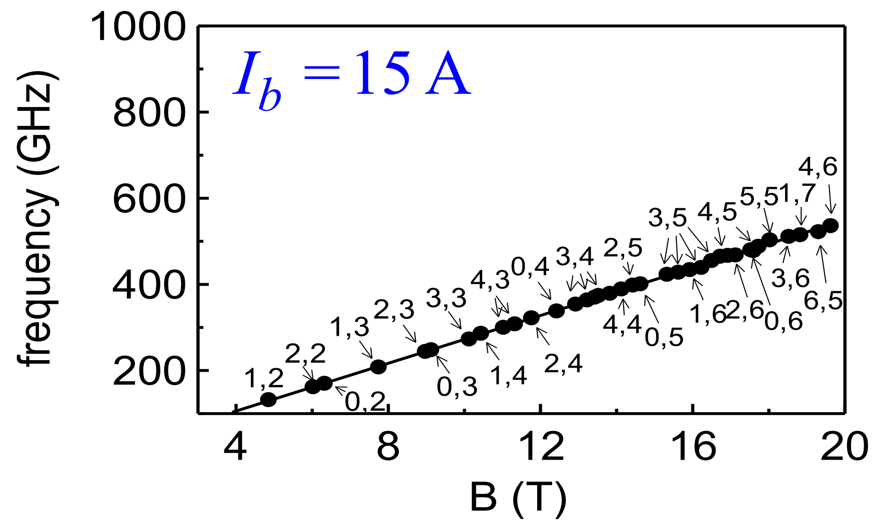


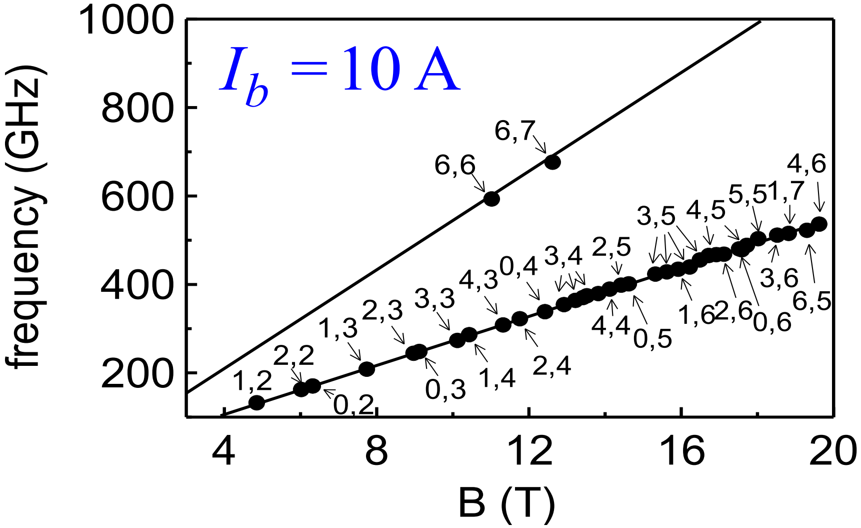



# *Simulated Mode Charts*

## *– verification of the governing mechanism and general trend*




More and more $s = 2$ modes get suppressed as $I_b$ rises above $I_{st}$ of more and more $s = 1$ modes.

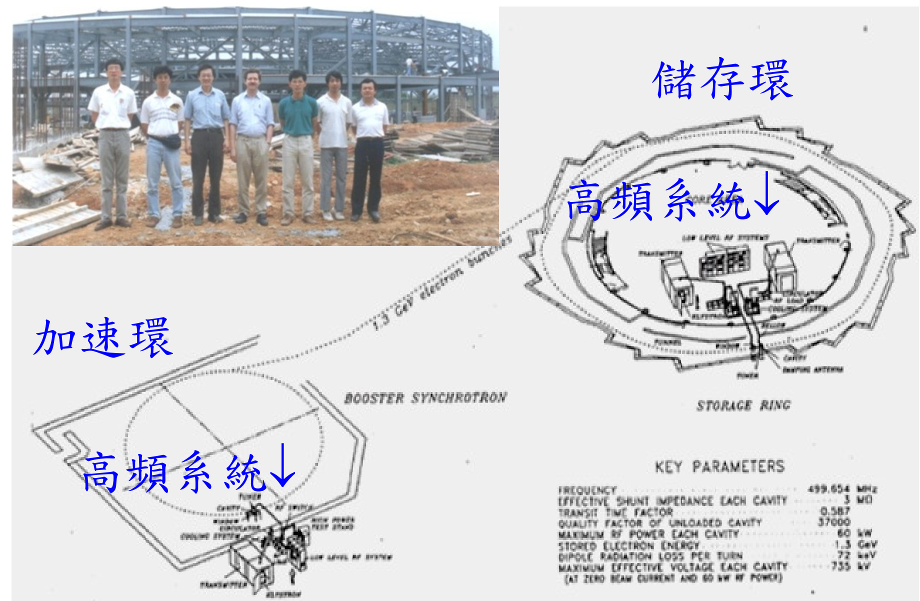
# *Summary*

- ECM-based devices provide unique radiation sources in the mm wave regime for a variety of applications.

- They are also intriguing nonlinear systems, understanding of which is key to the realization of the full potential of this class of devices.

# 同步輻射研究中心

## （位於新竹科學園區）

# 高頻系統

60 kW速調管

高頻控制系統

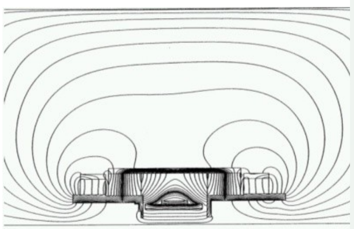
電源供應器

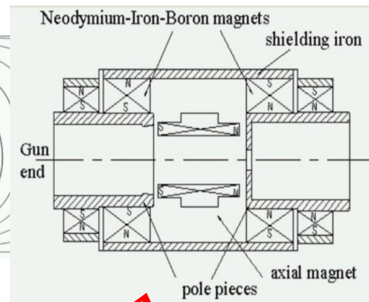
同軸傳輸線

冷卻系統

微波循環器

# *Engineering and Fabrication of Microwave Tubes*








**CAD**

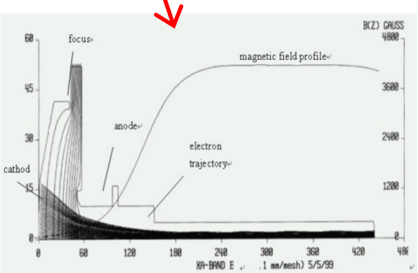
**Engineering Drawing**

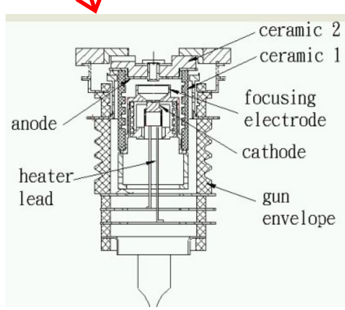
**Precision Machining**

**Brazing**

**Tube Assembly**

**Hot Test**



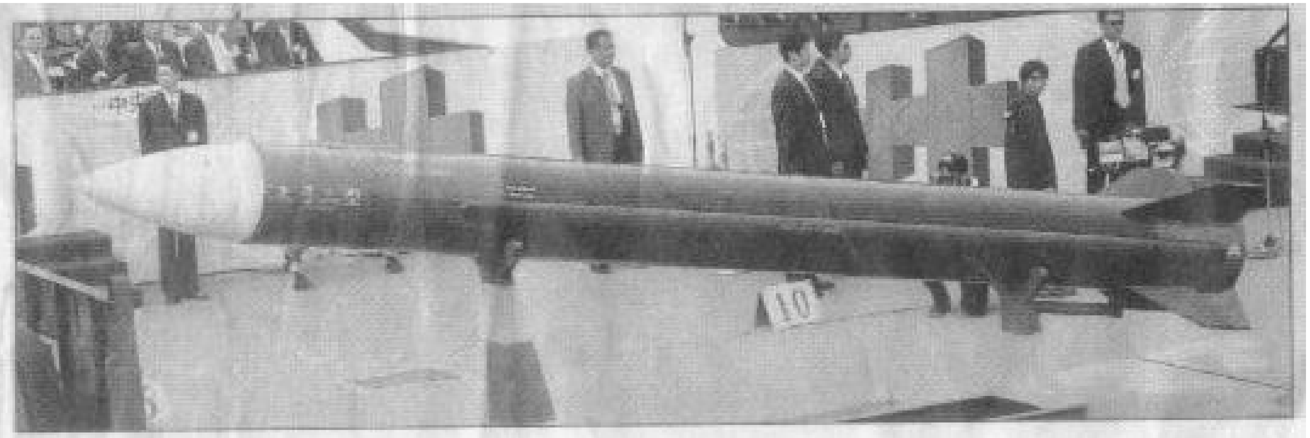




High voltage, high vacuum, high precision, high temperature

中華民國96年12月9日／星期日
24 E-mail：jb@mail.chinatimes.com.tw
焦點新聞 A2
中國時報 CHINA TIMES

雄二E
雄風三
天弓三

# 兩位王博士救回「新三彈」



# “University Training of Tube Engineers in the US and broad,” plenary paper presented at IVEC, 2006 by Dr. G. Caryotakis, Head, Klystron Department, SLAC

## University Training in Vacuum Electronics (Europe and Asia)

| | Japan | Germany | France | UK | China | Korea | Taiwan | India | Russia | Israel |
|---|---|---|---|---|---|---|---|---|---|---|
| Are Vacuum Electronics courses offered? | YES (as part of plasma science) | YES U of Karlsruhe | NO Graduate Courses | YES | YES | YES | YES | YES | YES | YES |
| Practical training university facilities? | SOME EXP. FACILITIES | YES | No | YES | YES | YES | YES | YES | YES | SOME |
| Adequate employment? | NO | Thales at Ulm. But most go to Solid State | Few industrial jobs Research labs | SOME | YES | YES | YES | | Low salaries | FEW IN MW INDUSTRY |
| Interaction with industry? | SOME INTERACTION | Only via professional Societies | No | YES | YES | YES | YES | | Somewhat | “LOW LEVEL ” |
| How many PhD degrees last year? | 10 | 5 | 2 | 5 | 30-50 | 4 | 1 | 5 | 10 | 5 |
| Overall rank (Highly subjective) | 7 | 9 | 10 | 8 | 1 | 2 | 3 | 5 | 6 | 4 |

Survey Results –Countries in Order of Descending GDP

# Thank you