電漿科學的展望

Perspectives on Plasmas

--- the fourth state of matter

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Outline

宇宙中大部分的物質處於電漿狀態, 即原子解離成帶正電的離子與帶負電的電子.

電漿所產生的現象廣泛存在, 並造成許許多多有趣的現象. 然而, 大部分的人對電漿的認識是電漿電視.

這個演講將引導大家從電磁學進入電漿科學. 我會介紹電漿的物理特性, 主要的研究領域, 如雷射電漿, 太空與天文電漿, 熱核融合電漿、電漿粒子加速、微粒電漿等;

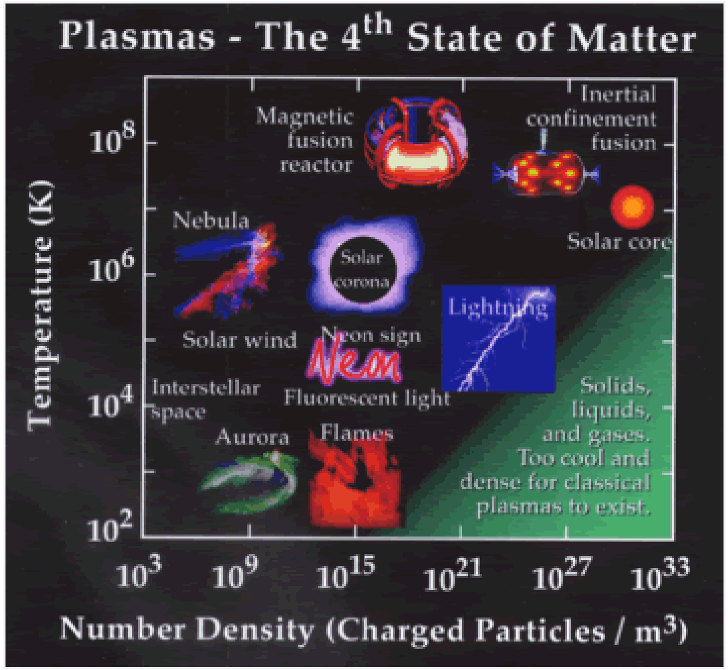
並介紹電漿的應用, 如電漿材料處理, 電漿顯示器.

最後會簡介清華物理的電漿物理研究.

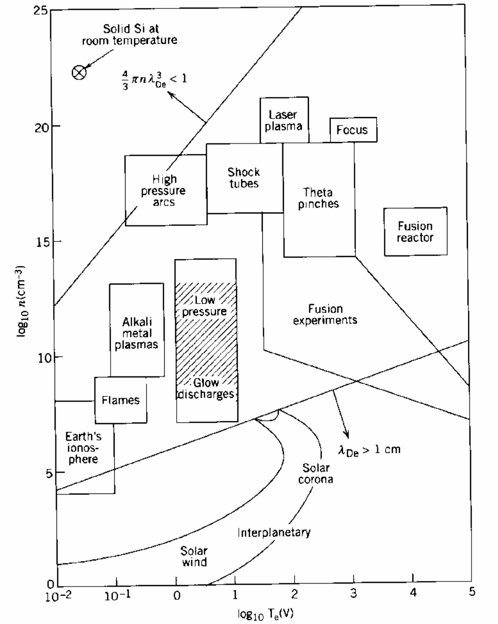
Definition of Plasma

Plasma is a **quasineutral** gas of electrons, ions and neutral particles which exhibits **collective** behavior.

Because of collective behavior, a plasma does not tend to conform to external influences; rather, it often behaves as if it had a mind of its own.



Plasma Classifications

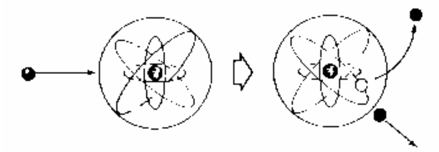


Generation of Plasma

electrons are accelerated by electric field and collide with other particles to induce excitation and ionization.

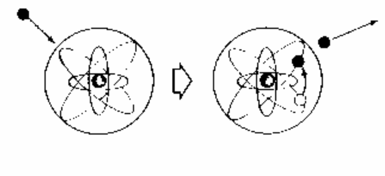
Electron impact ionization:

$$e^- + A \rightarrow 2e^- + A^+$$



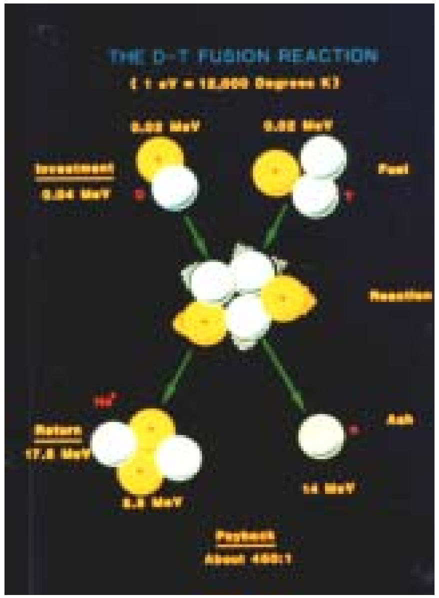
Electron impact excitation

$$e^- + A \rightarrow e^- + A^*$$

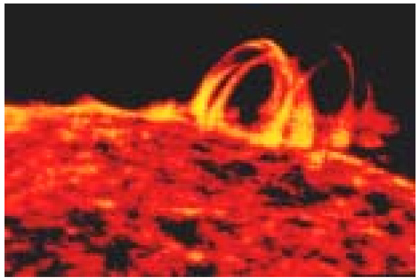


Meanwhile de-excitation and recombination also take place.

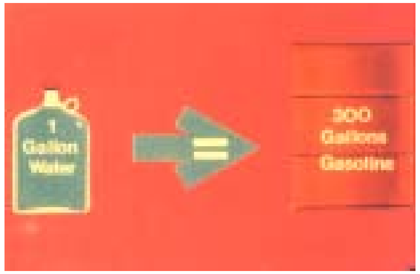
核融合反應



天然的核融合爐：太陽

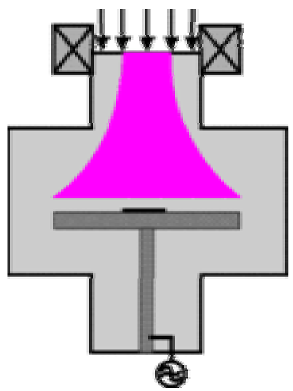


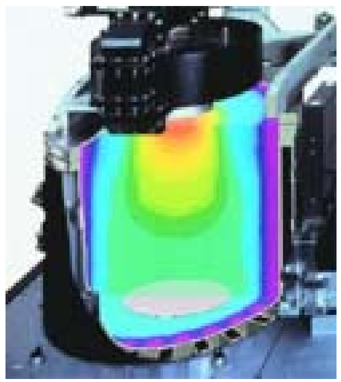
海水 ⟶ 能量



Plasma Generation

(Ex: Electron Cyclotron Resonance)





Maxwell's Equations

In terms of free charges and currents, Maxwell's equations read

$$\nabla \cdot \mathbf{D} = \rho_f \qquad \nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} = \mathbf{J}_f$$

The constitutive relations:

$$\mathbf{P} = \varepsilon_0 \chi_e \mathbf{E}$$

$$\mathbf{M} = \mu_0 \chi_m \mathbf{H}$$

So

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} = \varepsilon_0 (1+\chi_e)\mathbf{E} = \varepsilon \mathbf{E}$$

$$\mathbf{H} = \frac{1}{\mu_0}\mathbf{B} - \mathbf{M} \quad \Rightarrow \quad \mathbf{B} = \mu_0 (1+\chi_m)\mathbf{H} = \mu \mathbf{H}$$

Nonlinear Model for Gyrotron Oscillators

● **Wave modulates the electron beam**

$$\eta = \frac{-1}{\gamma_o - 1}\sum_j \Delta\gamma_j W_j = f(E_o^2;\Delta)$$

where $\Delta\gamma_j = \int_0^L \frac{d\gamma}{dz}dz = \int_0^L \frac{-\vec{P}\cdot\vec{E}}{P_z}dz$

weighting factor W_j, and electron transit angle,

$$\Delta = \left(\omega - k_z v_z - \frac{s\Omega_e}{\gamma}\right)\frac{L}{v_z}$$

● **Electron beam generates wav**

$$E_o^2 = \frac{QI_bV_b}{\alpha}\eta = \left(\frac{QP_b}{\alpha_{nm}}\right)\eta$$

where

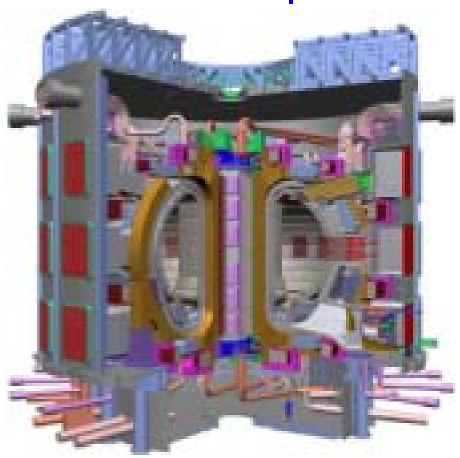
$$\alpha_{nm} = \frac{\mu\pi k^2 a^4 L}{8(\chi'_{nm})^2}\left[1-\left(\frac{n}{\chi'_{nm}}\right)^2\right]J_n^2(\chi'_{nm})$$

and $Q = \frac{\omega_o W}{P_{loss}}$

Research and Applications

國際核融合實驗反應爐: ITER

(International Thermonuclear Experimental Reactor)



合作國家： 歐盟、美、俄、日、中、韓

造價：28億美元

預期完工日期：2015年

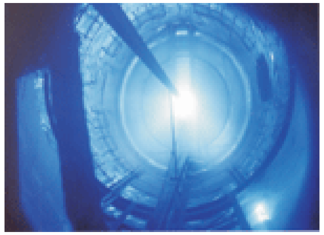
電漿溫度：攝氏1億度

預期產生功率：500 MW

環境電漿

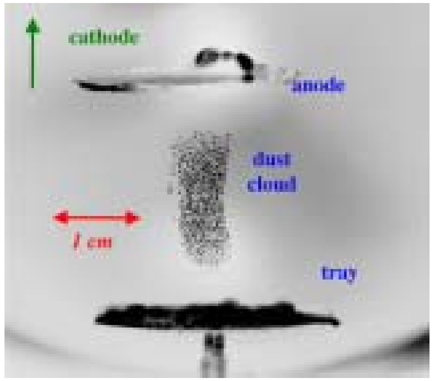
電漿氣化熔融

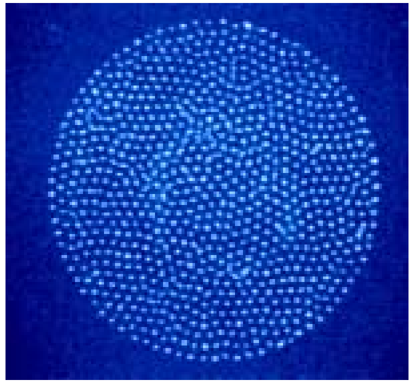
電漿轉化



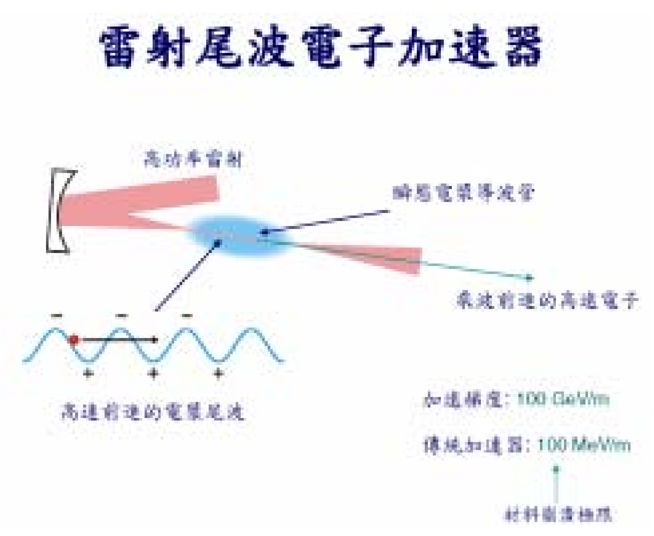
電漿清潔製程

微粒電漿(Dusty Plasma)

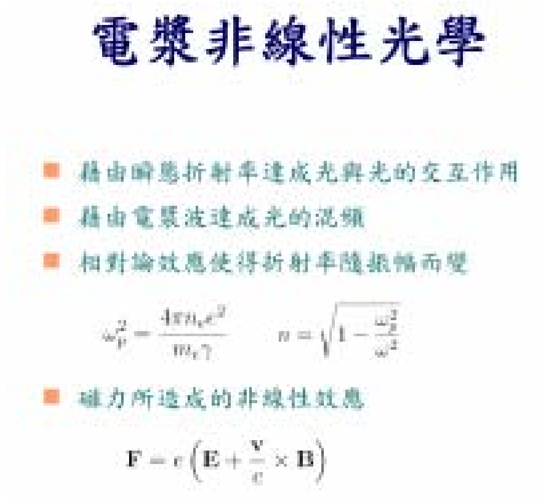




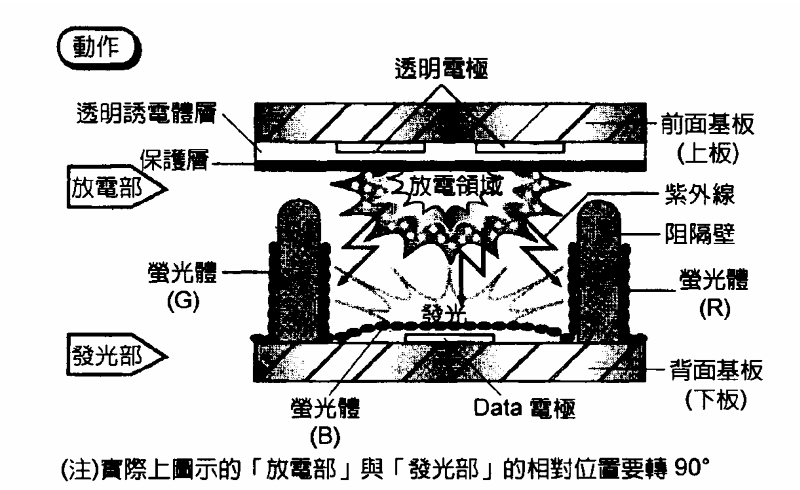
雷射電漿(Laser Plasma)



雷射電漿(Laser Plasma)



Plasma Display Panel (PDP)



High Frequency and Plasma Lab

by Prof. C.S. Kuo

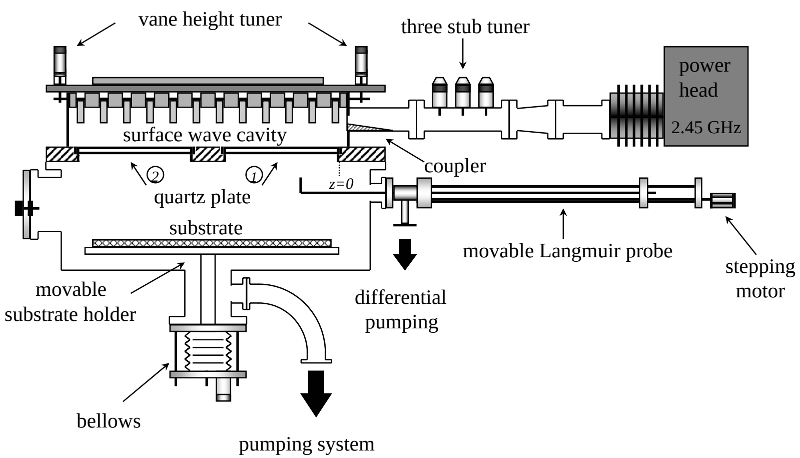
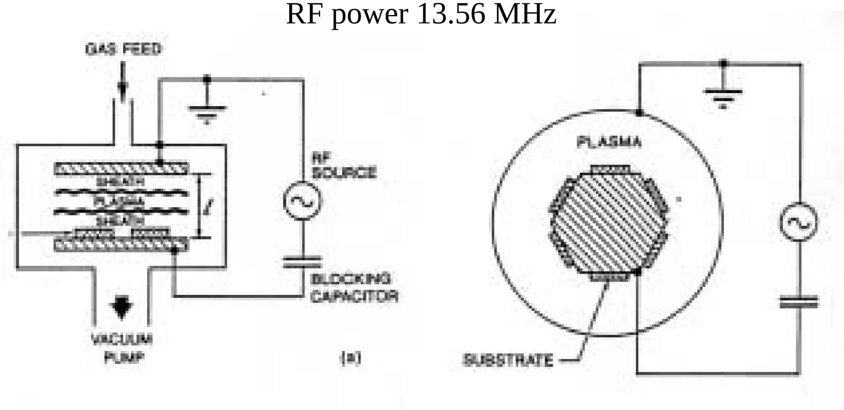


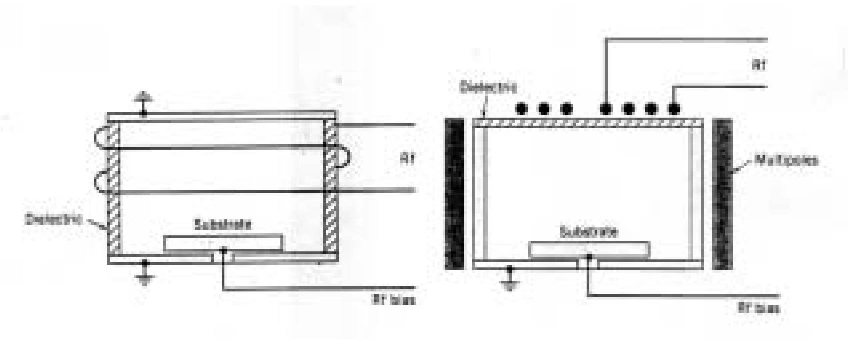
Fig.1

RF Capacitively Coupled Plasma

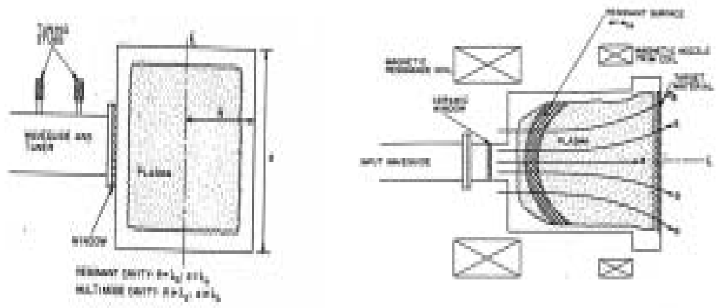
RF power 13.56 MHz



RF Inductively Coupled Plasma



Microwave Plasma Source

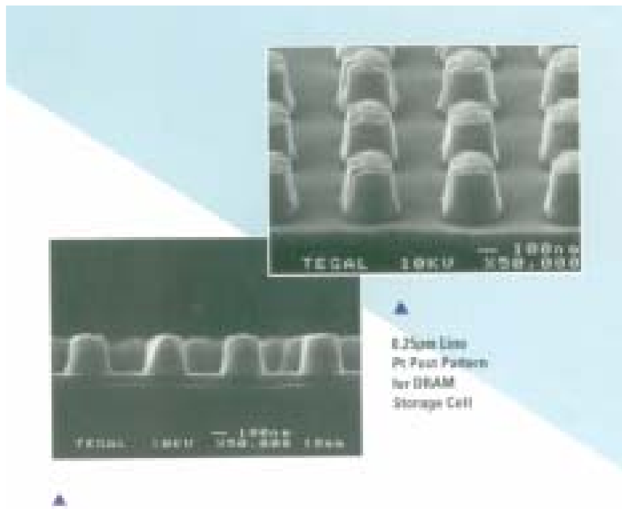


Power source frequency=2.45 GHz

He plasma

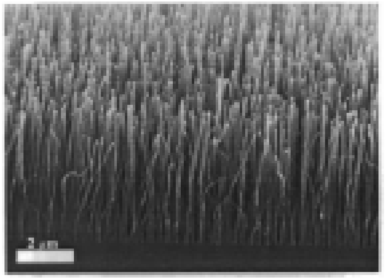
Ar plasma

Plasma etching processing

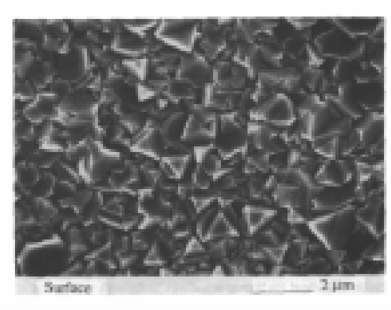


Plasma Processing

Carbon nano tubes



Growth of diamond



High Frequency Electrodynamics Lab

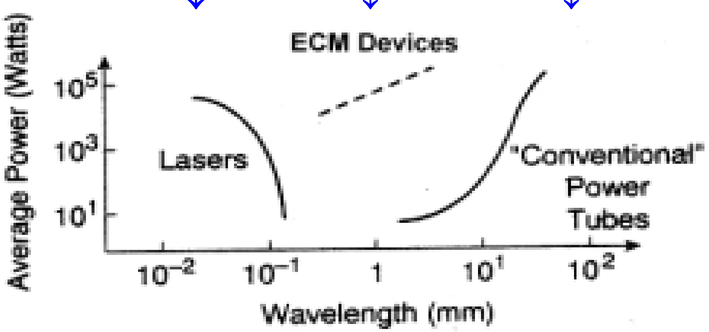
(i) Nonstationary and Chaotic Behavior of the Electron Cyclotron Maser

Significance of the ECM

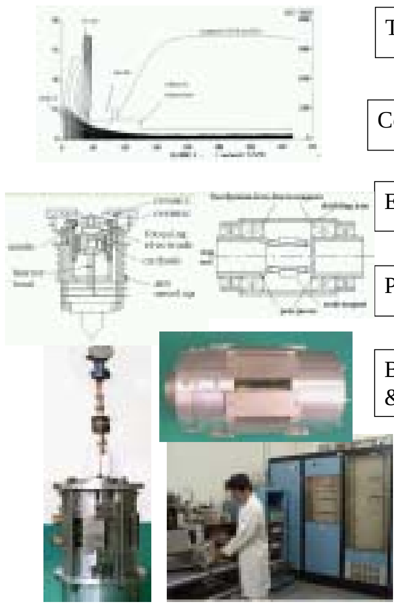
~~one photon per excitation,~~ | multiple-photon per electron, | multiple photon per electron,

large interaction space | large interaction space | ~~interaction space ~ wavelength~~

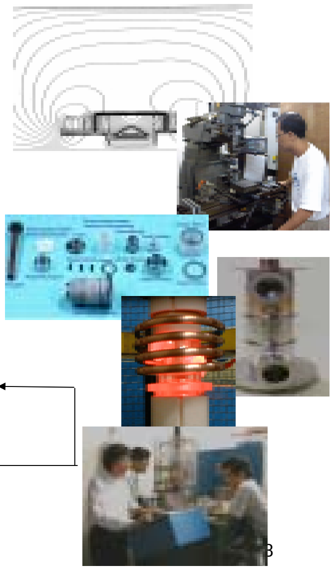
↓ ↓ ↓



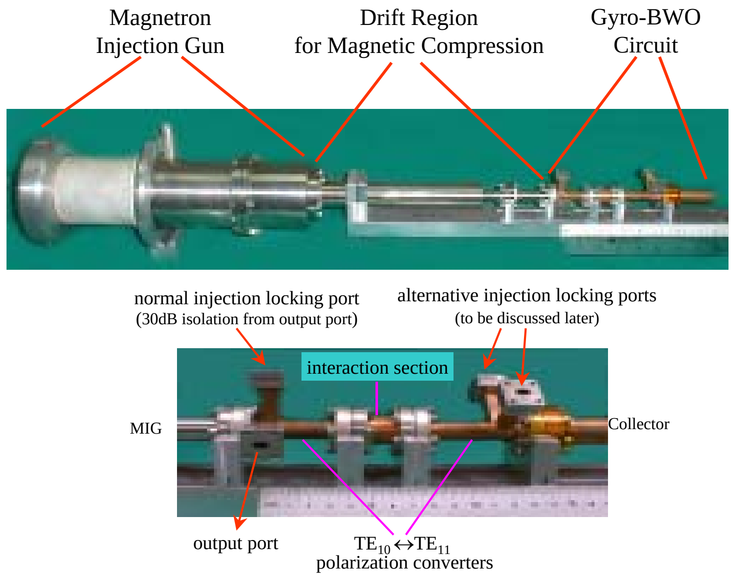
Micro/mm-wave Sources Design & Fabrication



Theoretical design
↓
Computer simulation
↓
Engineering drawing
↓
Precision machining
↓
Brazing in vacuum & RF furnace
↓
Hot test
↓
Final system

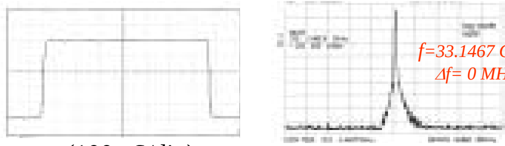


Gyrotron Experimental Setup



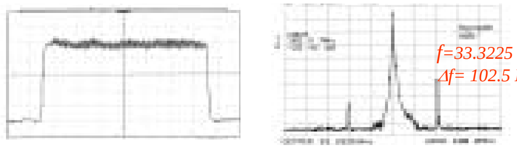
Gyro-monotron pulse shape and spectrogram at different beam currents (I)

(a) Stationary,
I_b=50mA



t (100 nS/div)

(b) Nonstationary,
I_b=1300mA
(self-modulation)



t (100 nS/div)

(c) Nonstationary,
I_b=1600mA
(self-modulation)

t (100 nS/div)

Gyro-monotron pulse shape and spectrogram at different beam currents (II)

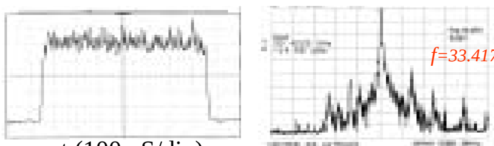
(d) Nonstationary,
I_b=1700mA
(period doubling)

t (100 nS/div)

(e) Nonstationary,
I_b=1800mA
(period tripling)

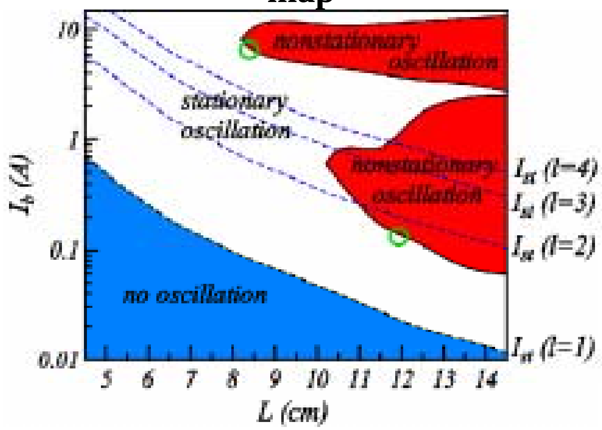
t (100 nS/div)

(f) Nonstationary,
I_b=2000mA
(chaotic)



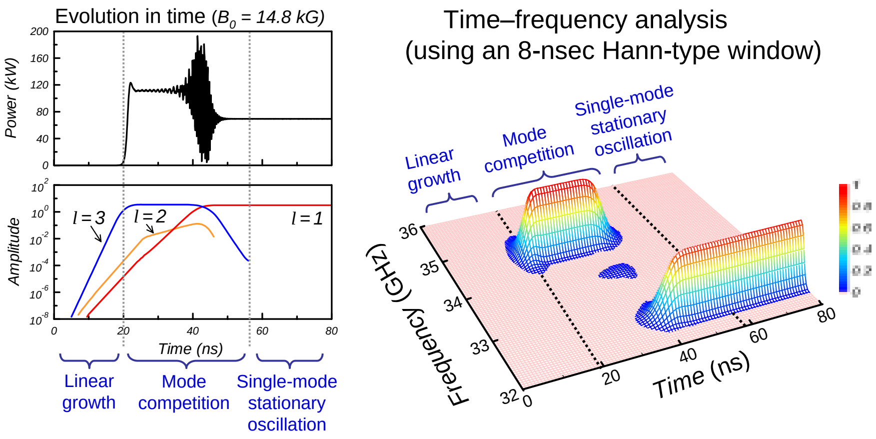
t (100 nS/div)

Single-mode self-modulation --- stability map



No correlation between onset current of nonstationary oscillation and the calculated start-oscillation current of high order axial modes.

Multi-Mode Competition at I_b = 5 A
(PIC Simulation)



- The fast-growing, well-established l = 3 mode is subsequently suppressed by the later-starting, slower-growing l =1 mode.

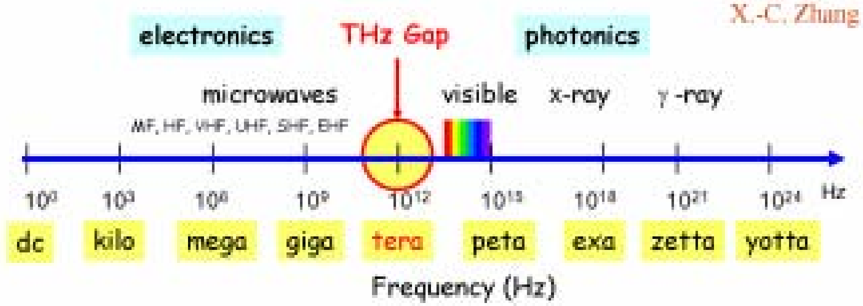
High Frequency Electrodynamics Lab

(ii) Millimeter-Wave and THz Devices, and Their Applications

T-Ray: Next frontier in Science and Technology

Terahertz wave (or T-ray), which is electromagnetic radiation in a frequency interval from 0.1 to 10 THz, lies a frequency range with rich science but limited technology.

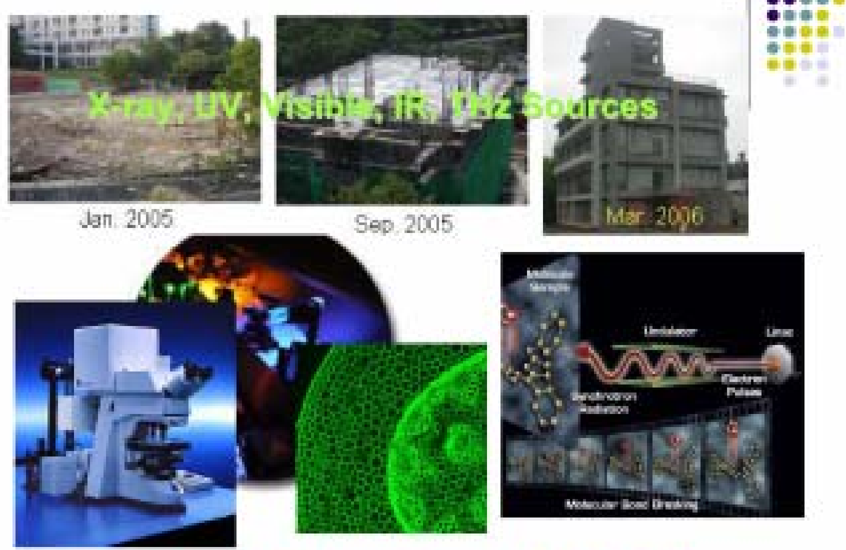
Courtesy of X.-C. Zhang



1 THz ~ 1 ps ~ 300 μm ~ 33 cm^{-1} ~ 4.1 meV ~ 47.6 °K

NCTU

NTHU Relativistic Photonics Research Laboratory



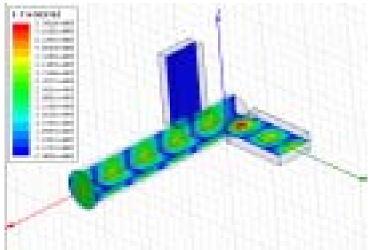
Bio-molecular and Bio-medical Imaging Core Facility

(Courtesy of 奈米中心 曾正中主任) 楊俊達、楊士禮、林凡異、江安世、高甫仁

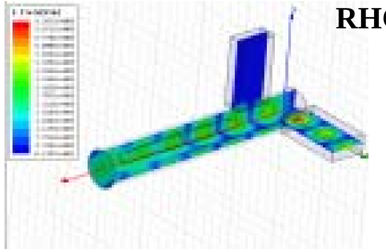
TE_{11} Mode Converter For Laser Cooling Experiment

HFSS simulation

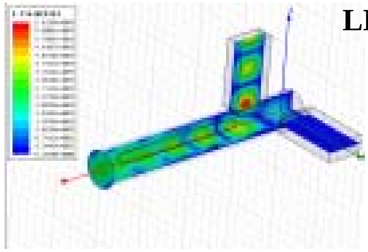
Linear



RHCP

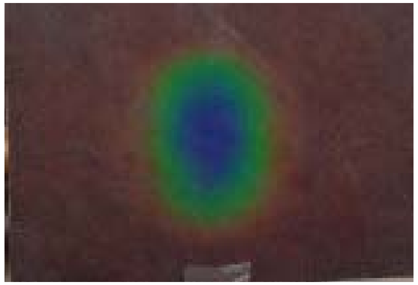


LHCP

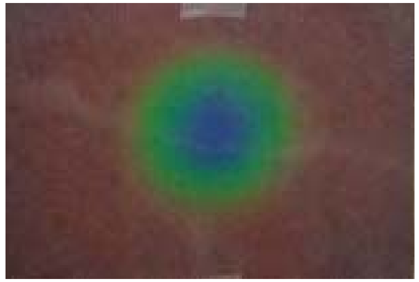


Linearly and Circularly Polarized rf Fields

Linear polarization

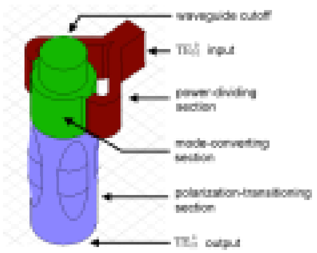


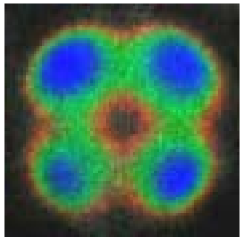
Circular polarization

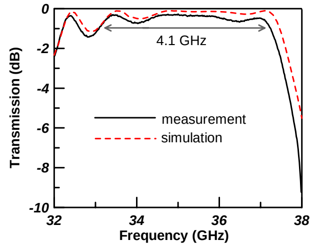


Field patterns directly visualize on thermal sensitive LCD film.

Terahertz Radiation and Device Physics

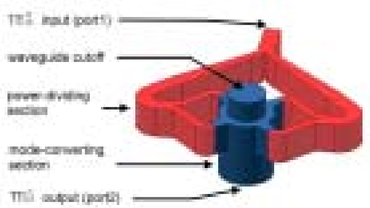


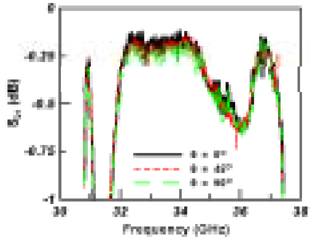


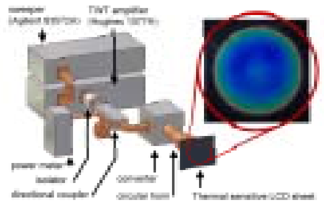


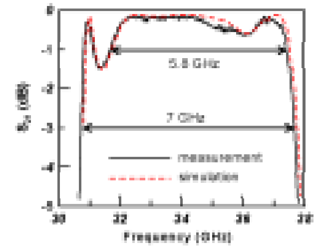
T. H. Chang, C. F. Yu, and C. T. Fan, "Novel polarization controllable TE21 mode converter", Rev. Sci. Instrum., **76**, 074703 (2005).

Terahertz Radiation and Device Physics









C. F. Yu and T. H. Chang, "High Performance Circular TE01 Mode Converter", IEEE Trans. Microwave Theory Tech. **53**, No.12, 3794 (2005).

International Cooperation on THz


200 W, 300 GHz @ Far Infrared Region Research Center, Fukui Univ., Japan.

High Frequency Electrodynamics Lab

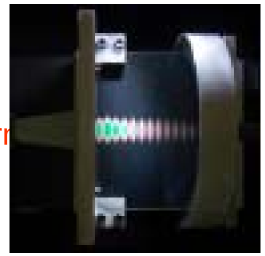
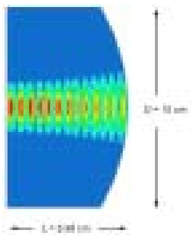
(iii) Application of Micro/mm-Wave Technology on Material Science

Quasi-optical applicator: Major challenges

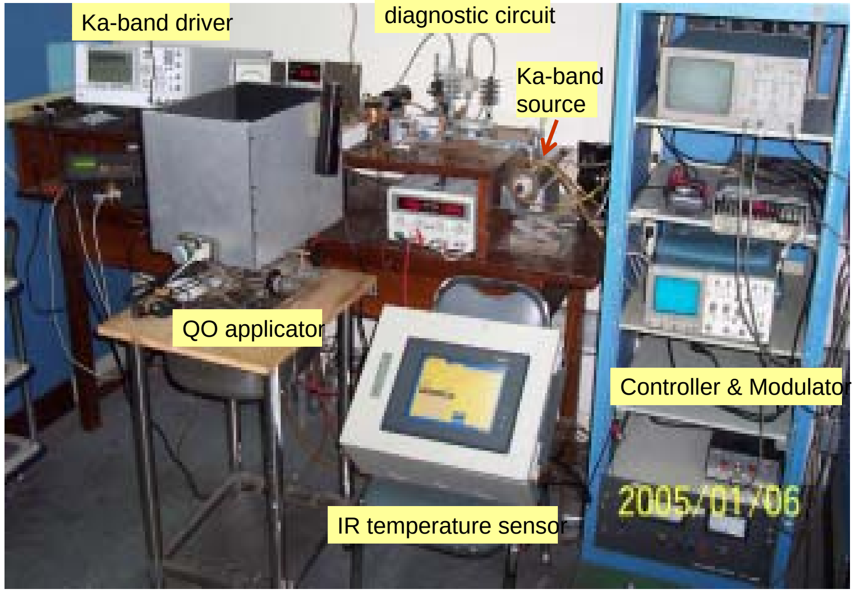
Critical coupling

Resonant detecting

Field pattern

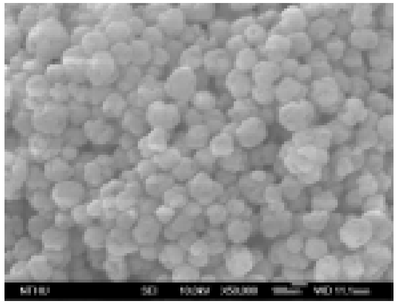
Experimental setup for quasi-optical applicator



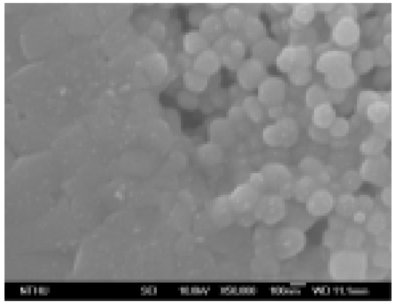
Quasi-optical cavity: $BaTiO_3$ SEM results

Source: EIA, Frequency~ 35 GHz (operating at $TEM_{0,0,12}$ mode)
Quasi-optical Cavity: L~146-9 mm, R=140 mm, d=200 mm Q~11000

before



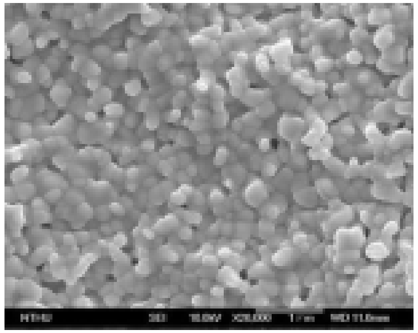
after

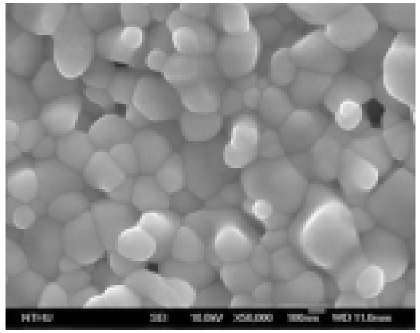


Quasi-optical cavity: PZT SEM results

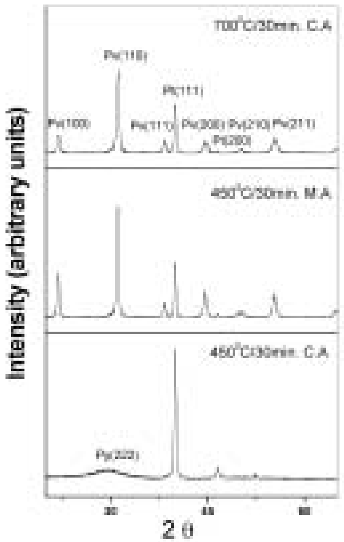
Source: EIA, Frequency~ 35 GHz (operating at $TEM_{0,0,12}$ mode)
Quasi-optical Cavity: L~146-9 mm, R=140 mm, d=200 mm Q~11000

Necking effect observed on the surface

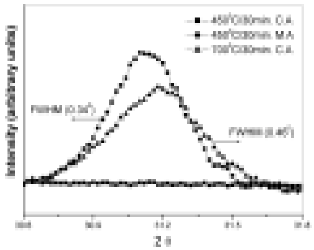




Low-temperature processing of PZT thin films using 2.45 GHz microwave annealing



XRD results



High Performance Ferroelectric Material

The microwave annealing of PZT thin film
- dielectric constant: 560
- dissipation factor: 0.025% of dielectric constant.

The conventional annealing of PZT thin film
- dielectric constant : 345
- dissipation factor : 0.03% of dielectric constant.