Theory and demonstration of plasma measurement using Langmuir probe
電漿量測之蘭摩爾探針原理與實作

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2020 winter break

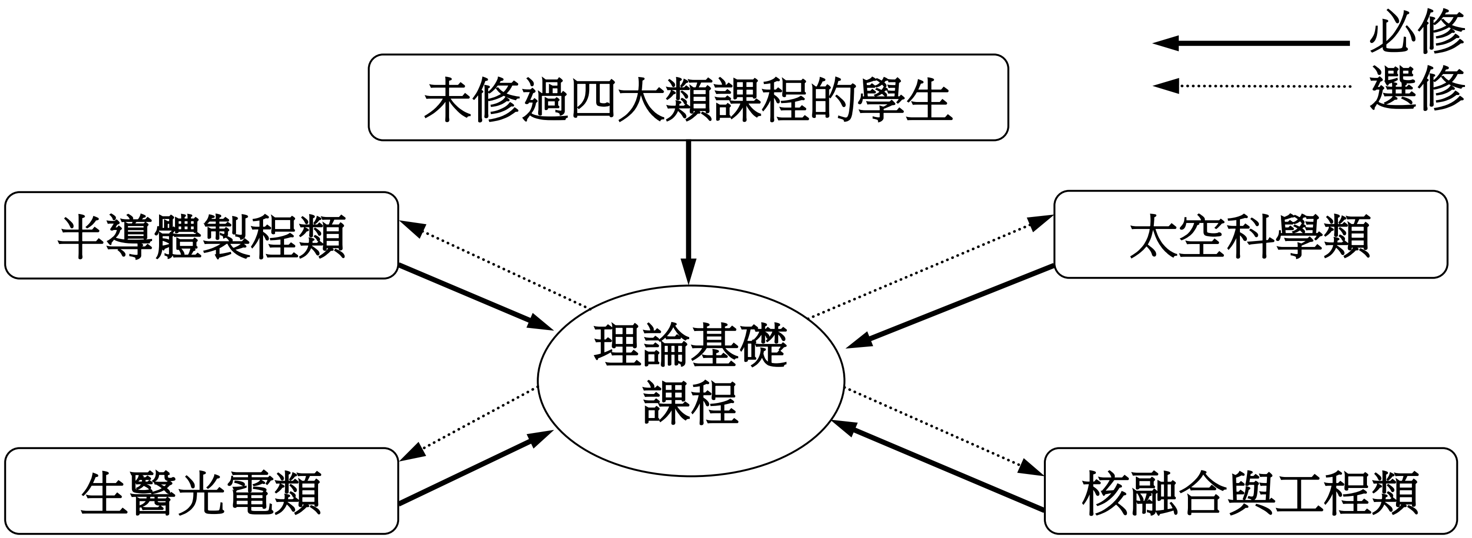
1/18(Mon.) – 1/22(Fri.) 14:00-17:40

http://capst.ncku.edu.tw/PGS/index.php/teaching/

Lecture 1

2021/1/19 updated

深入的電漿知識請選修 電漿學分學程



- 將培養具備電漿科技研究與產業應用等多元專業且更具競爭力之跨領域人才.

課程列表

- 先修課程

開課系所	課程名稱	說明
全校	工程數學	符合其中一門或相對應之數學課程
物理系	物理數學	
數學系	應用數學方法	
全校	電磁學	或相對應之課程

- 理論基礎課程

開課系所	課程名稱	說明
電漿所	電漿物理	必修
電漿所	電漿現象之應用	
電漿所	太空物理	(任選三學分)
電漿所	電動力學與電漿物理之數值模擬	
應數所	數值分析	
應數所	氣體動力學方程的數學理論	
物理所	電動力學	
化學系	電分析化學	
化學系	應用電化學	

課程列表(續)

- 太空科學類

開課系所	課程名稱
電漿所	高等太空物理
電漿所	閃電物理
電漿所	高等磁層物理(一)(二)
電漿所	電磁層磁層耦合與電離層物理
電漿所	太空物理專題
電漿所	數據處理與資料分析
地科所	太空物理
地科所	太空天氣
地科所	高層大氣與電離層特論
地科所	電離層模式數值模擬(一)(二)
地科所	全球導航衛星系統大氣遙測特論
測量系	空間資訊整合與應用

- 核融合與工程類

開課系所	課程名稱
電漿所	托克馬克物理
電漿所	核融合電漿科學
電漿所	高等電漿物理
電漿所	電漿波與加熱
電漿所	電漿量測
電漿所	脈衝功率系統
電機所	高電壓工程特論
電機所	電力測試與保護
電機所	能量轉換
微電所	高電壓工程特論

課程列表(續)

- 生醫光電類

開課系所	課程名稱
地科所	X光結晶學
化學所	蛋白質與蛋白質體學
化學所	核磁共振光譜學
光電所	奈米光學
光電所	電漿子光學原理與應用
光電所	生醫光譜學原理
光電所	生醫組織光學
光電所	光電數值模擬
光電系	生醫光電導論
口醫所	蛋白質結構與影像分析
醫工所	生物電化學

- 半導體製程類

開課系所	課程名稱
電漿所	半導體電漿製程原理
電機所	奈米世代半導體製程概論
機械系	半導體製程
微電所	半導體元件物理
微電所	半導體製程
工科所	半導體製程技術
工科所	奈米製程技術與實作
化工系	半導體材料與製程
材料系	微奈米元件製程與設計
材料系	奈米材料分析與實作

Course Outline

1. Introduction to plasma
   a. What is Plasma?
   b. How to generate plasma
   c. Applications of plasma
2. Theory of Langmuir probe
   a. Sheath
   b. Single Langmuir probe
   c. Double Langmuir probe
   d. Triple Langmuir probe
3. Demonstration of Langmuir probe
   a. Building vacuum systems
   b. Building Langmuir probes
   c. Measuring temperatures and densities of plasma

Day 1~3

Day 4~5: Experiments

Grading

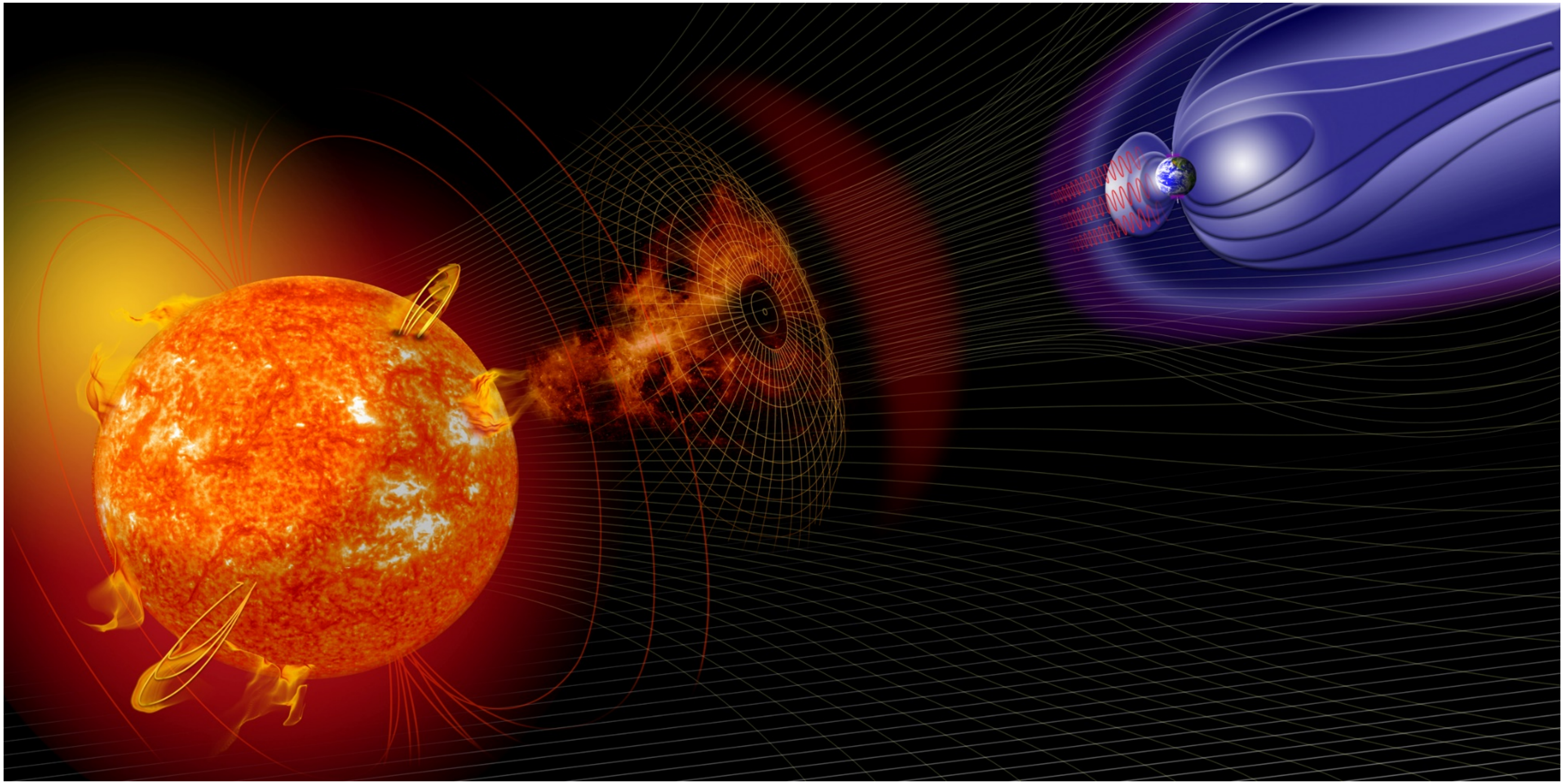
- Probe and vacuum system 25 %
  - Vacuum system (by group): 10 %
  - Probe (by group): 15 %
- Measurements (by group) 25 %
- Final report 50 %

References

- Plasma physics:
  - Principles of plasma physics for engineers and scientists,

    by Umran S. Inan and Marek Gołkowski
  - Introduction to plasma theory, by Dwight R. Nicholson
  - Introduction to plasma physics and controlled fusion, by Francis F. Chen
  - The physics of plasma, by T. J. M. Boyd and J. J. Sanderson
  - Principles of plasma physics, by Krall and Trivelpiece
  - NRL Plasma Formulary, Naval Research Laboratory, 2013 by J. D. Huba
- Langmuir probe:
  - Principles of plasma discharges and materials processing, by Michael A. Lieberman and Allan J. Lichtenberg
  - Plasma diagnostics by electrical probes - Practicum manual and documentation, by L. Sirghi, G. Popa, D. Alexandroaiei, C. Costin

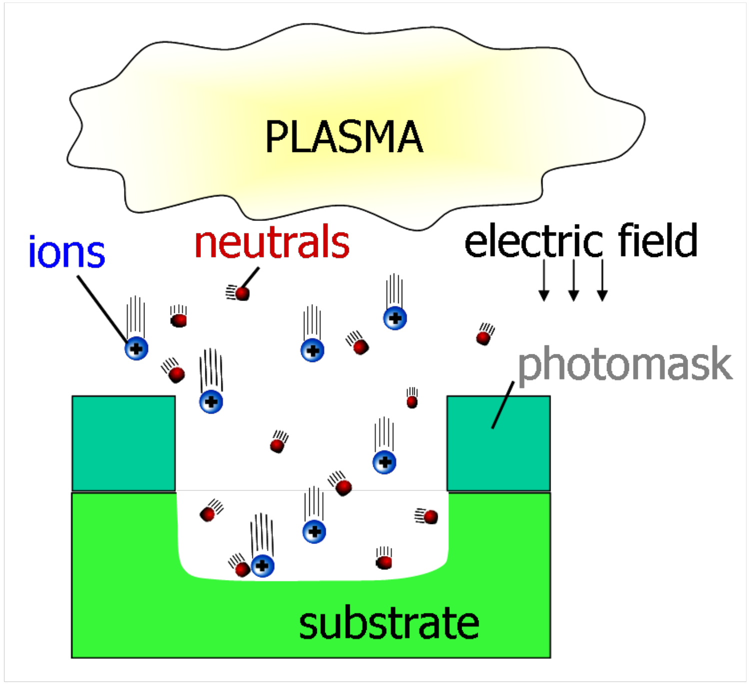
Most of the material in space is plasma



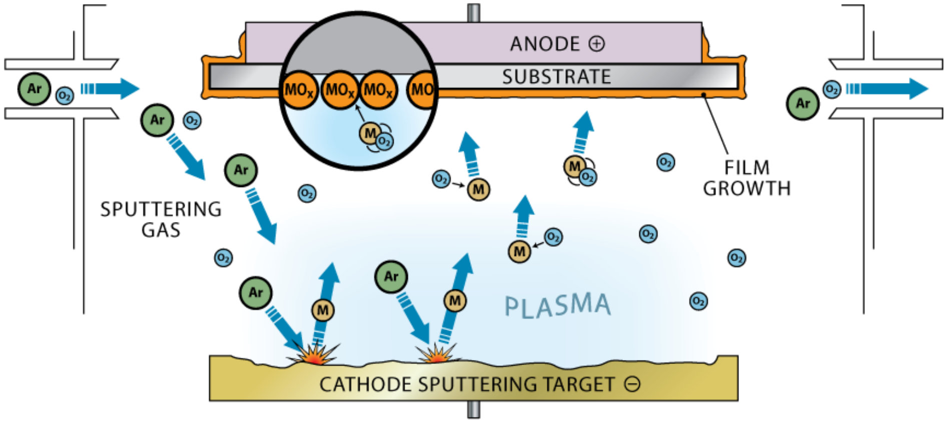
https://www.nasa.gov/mission_pages/sunearth/spaceweather/index.html

電漿被廣範的應用在半導體製程上

- 蝕刻

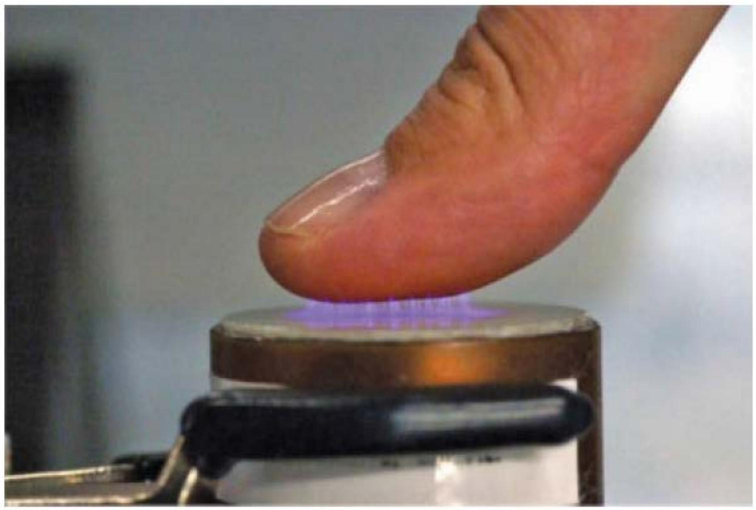


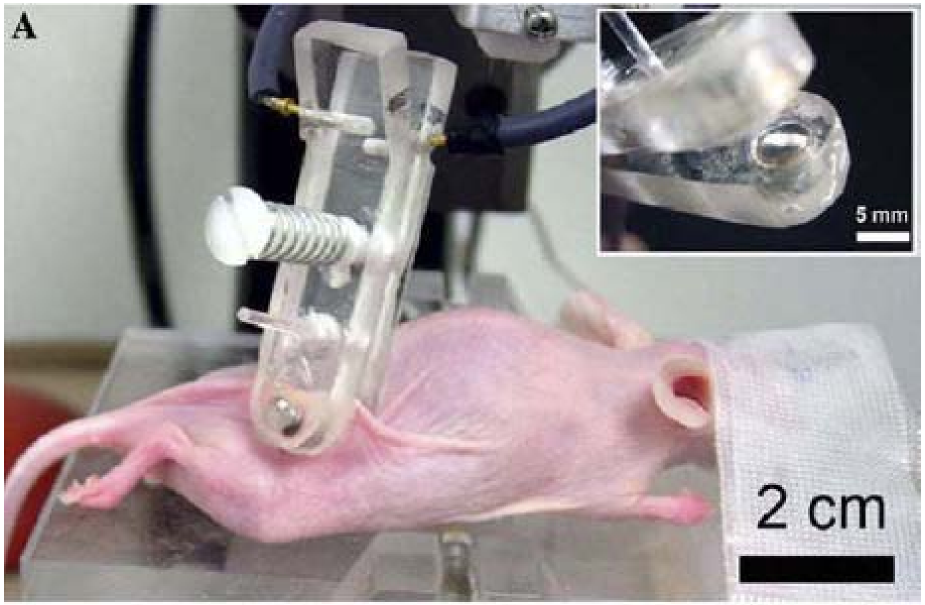
- 鍍膜



https://www.scorec.rpi.edu/research_plasmaetchmodeling.php
http://lnf-wiki.eecs.umich.edu/wiki/Sputter_deposition

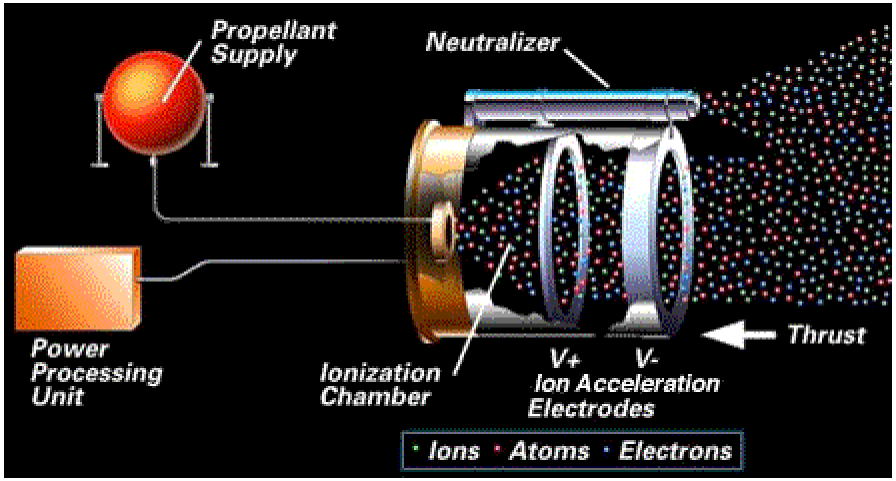
低溫電漿可應用在醫療保健上





Plasma medicine, by Alexander Fridman and Gary Friedman
Biochem Biophys Res Commun. 2006 May 5; 343(2): 351–360.

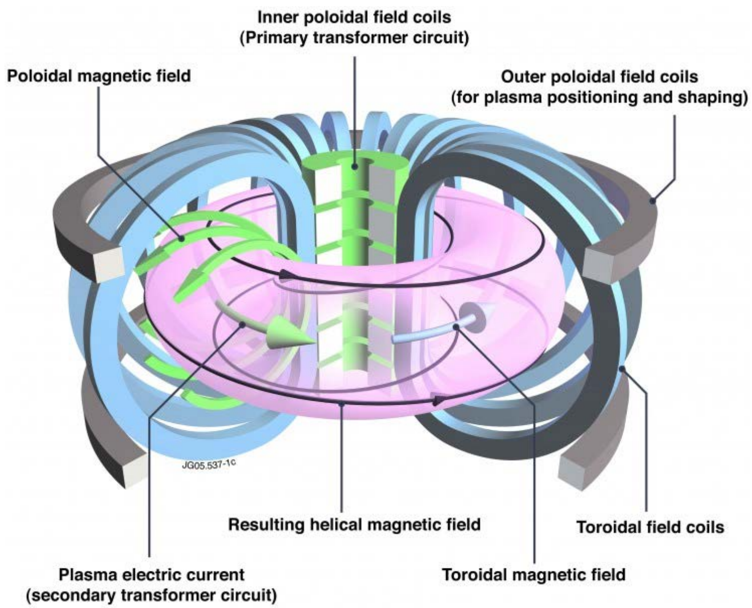
Plasma can be used as a propulsion



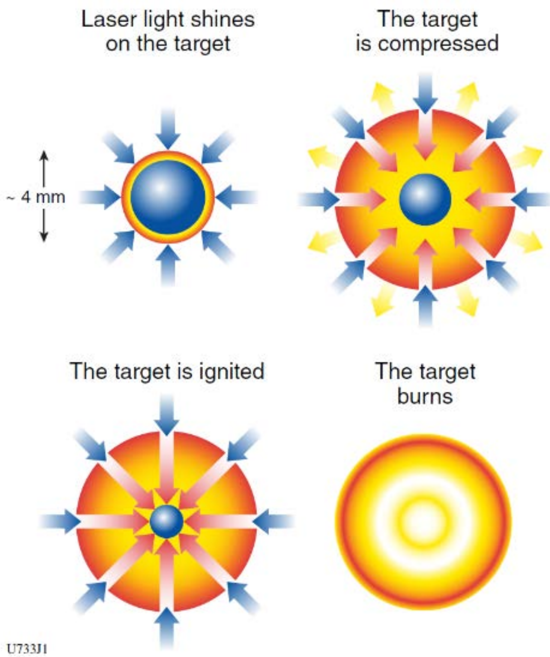
https://defence.pk/pdf/threads/isro-to-test-electric-propulsion-on-satellites.411176/

核融合發展所帶來的永續的能源正在逐步實現中

- 磁場控制核融合



- 慣性控制核融合



https://www.euro-fusion.org/2011/09/tokamak-principle-2/
Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester

Course Outline

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   a. **What is Plasma?**
   b. **How to generate plasma**
   c. **Applications of plasma**

Day 1

2. **Theory of Langmuir probe**
   a. **Sheath**
   b. **Single Langmuir probe**
   c. **Double Langmuir probe**
   d. **Triple Langmuir probe**

Day 2

3. **Demonstration of Langmuir probe**
   a. **Building vacuum systems**
   b. **Building Langmuir probes**
   c. **Measuring temperatures and densities of plasma**

Day 3~4: Experiments

Day 5: presentations

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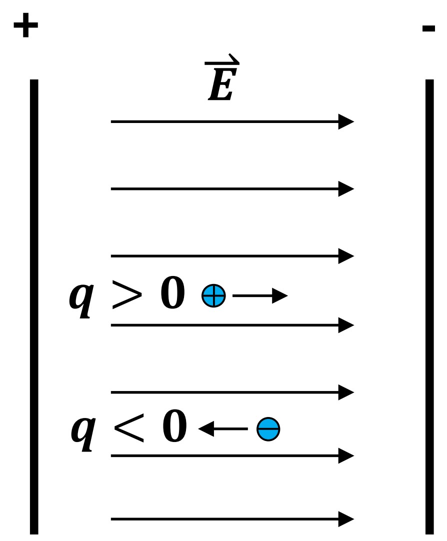
Day 1~3

Day 4~5: Experiments

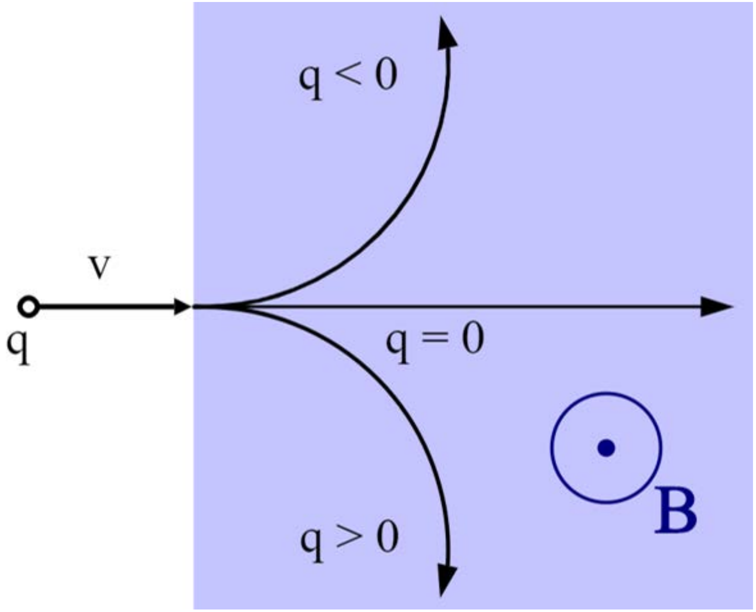
Charged particles are accelerated due to Lorentz force under electromagnetic fields

- **Lorentz force:** $\vec{F} = q\,\vec{E} + q\,\vec{v} \times \vec{B}$

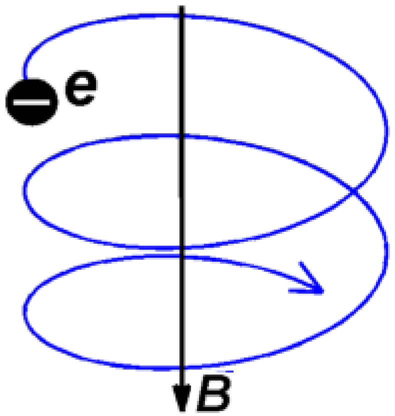
- **Force under electric fields**

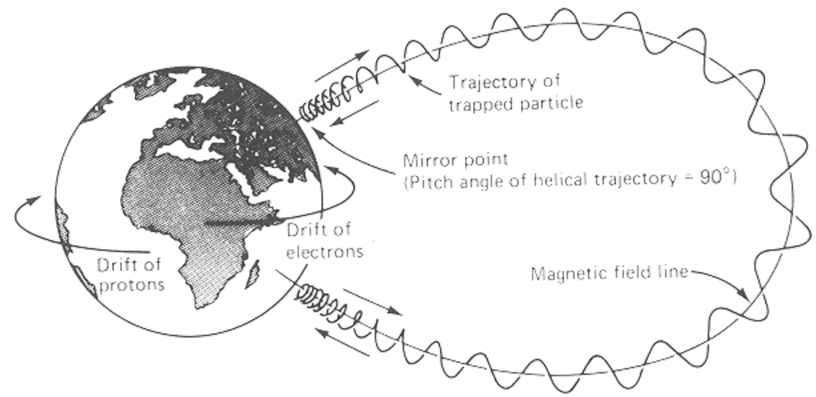


- **Force under magnetic fields**

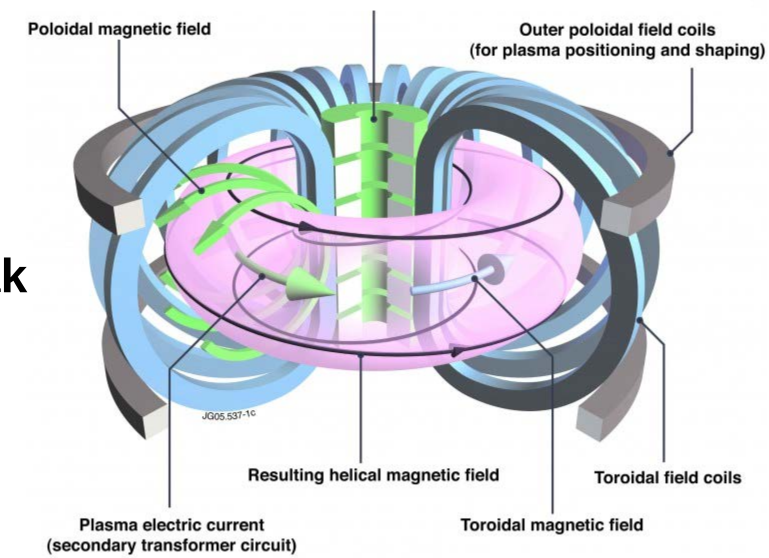


Charged particles gyro around magnetic field lines



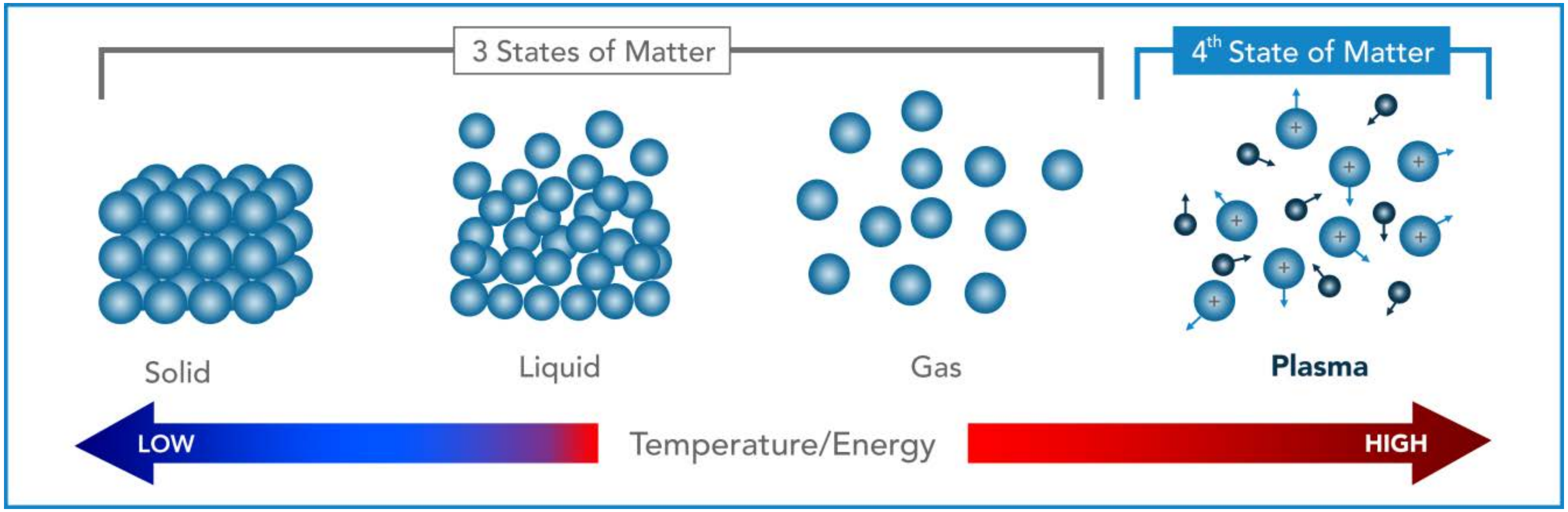


Tokamak



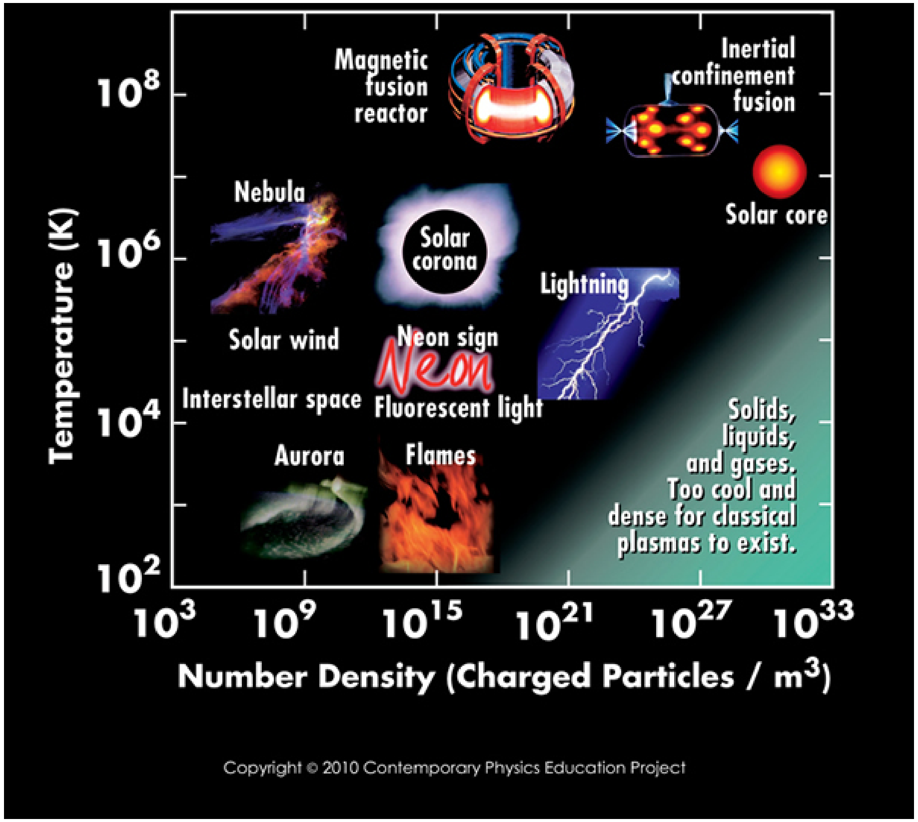
http://www.ipp.cas.cz/vedecka_struktura_ufp/tokamak/tokamak_compass/diagnostics/mikrovlnne-diagnostiky/ece-ebw-radiometr.html
http://www-ssg.sr.unh.edu/tof/Smart/Students/lees/periods.html
https://www.euro-fusion.org/2011/09/tokamak-principle-2/

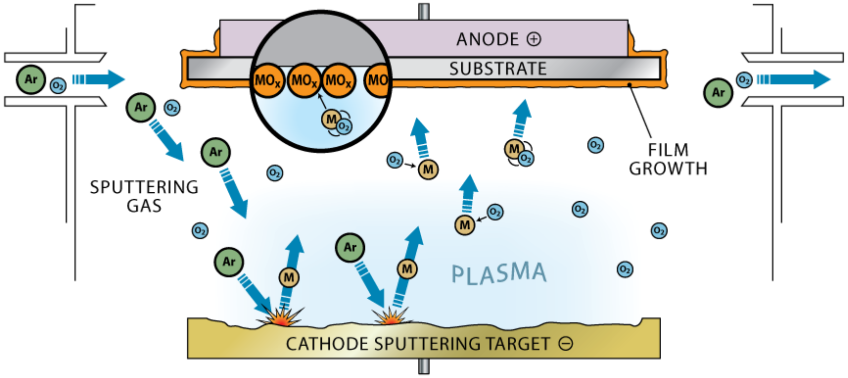
Plasma is the 4th state of matter



http://tetronics.com/our-technology/what-is-plasma/

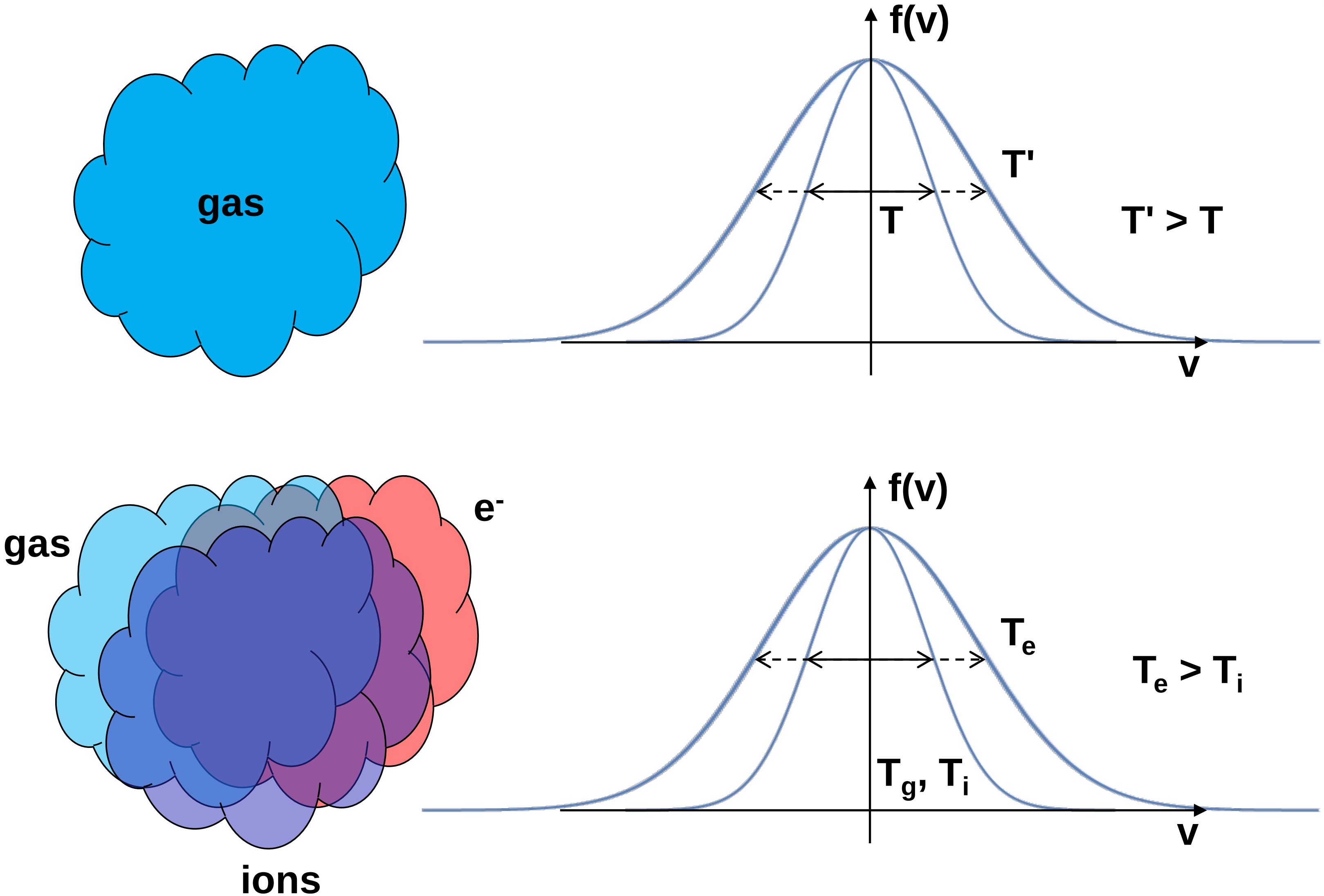
Plasma is everywhere



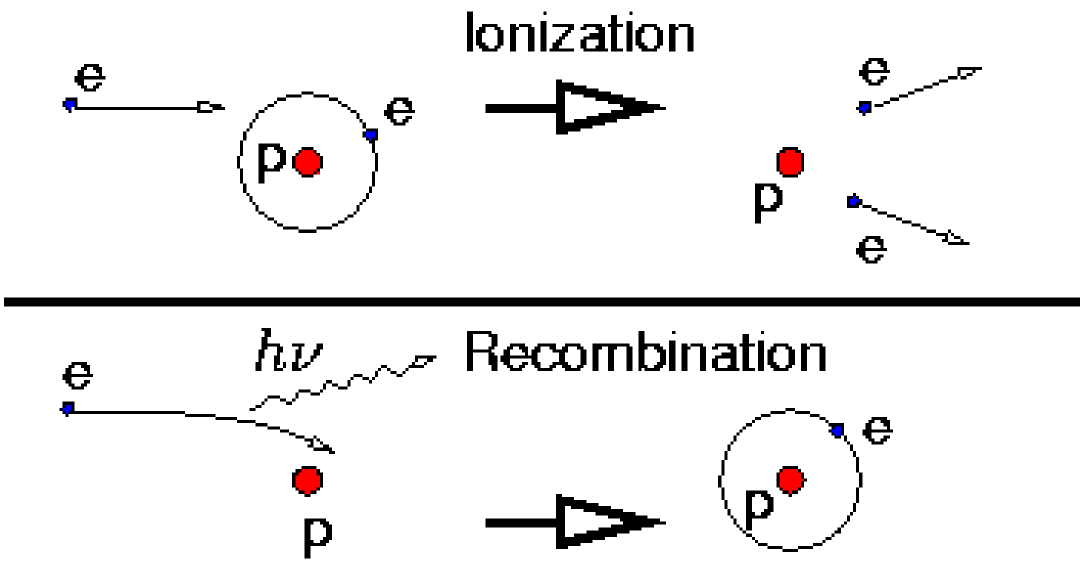


https://lasers.llnl.gov/science/understanding-the-universe/plasma-physics
http://lnf-wiki.eecs.umich.edu/wiki/Sputter_deposition
https://simple.wikipedia.org/wiki/Fluorescent_lamp

In plasma, there are ions, electrons, and neutral gas

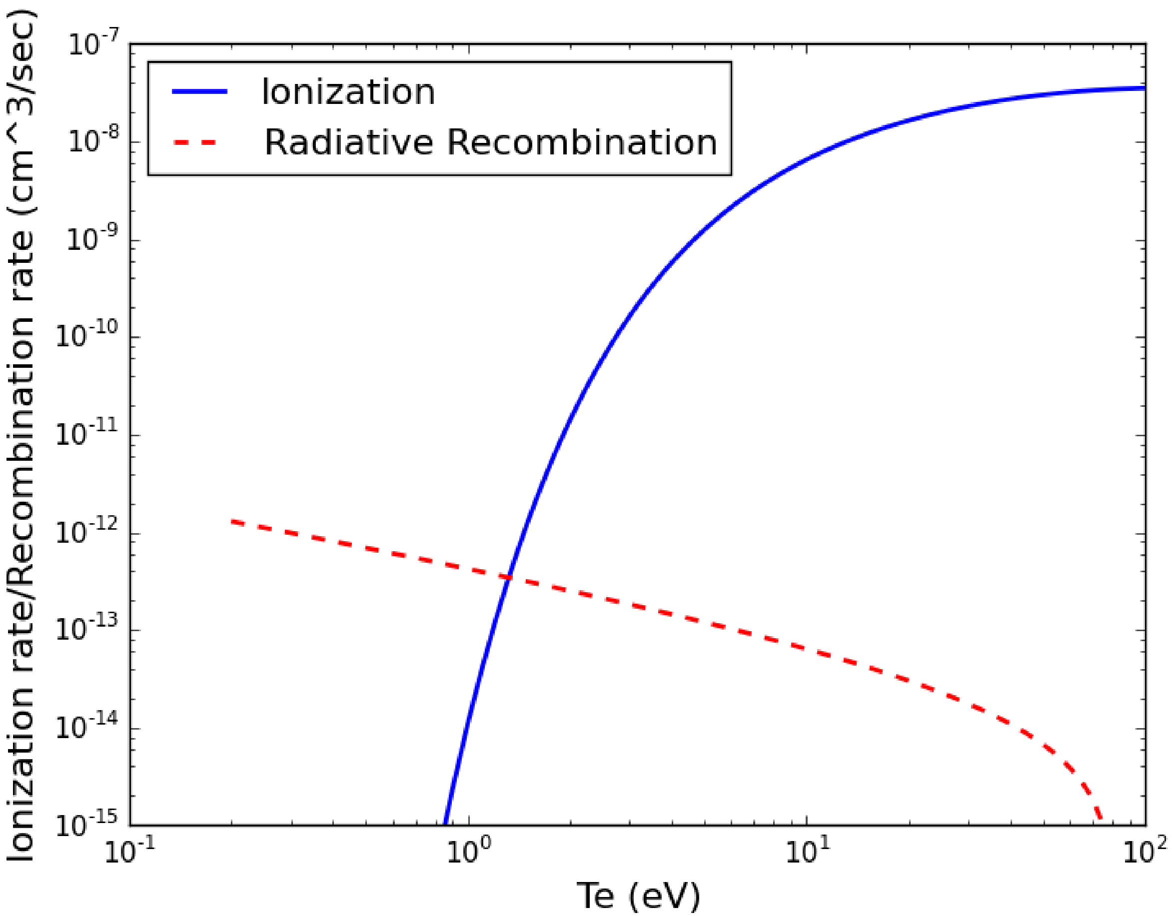


A plasma is a gas in which an important fraction of the atoms is ionized so that the electrons and ions are separated freely



http://ocw.mit.edu/courses/nuclear-engineering/22-611j-introduction-to-plasma-physics-i-fall-2003/lecture-notes/

A plasma can be created when the ionization rate is higher than the recombination rate

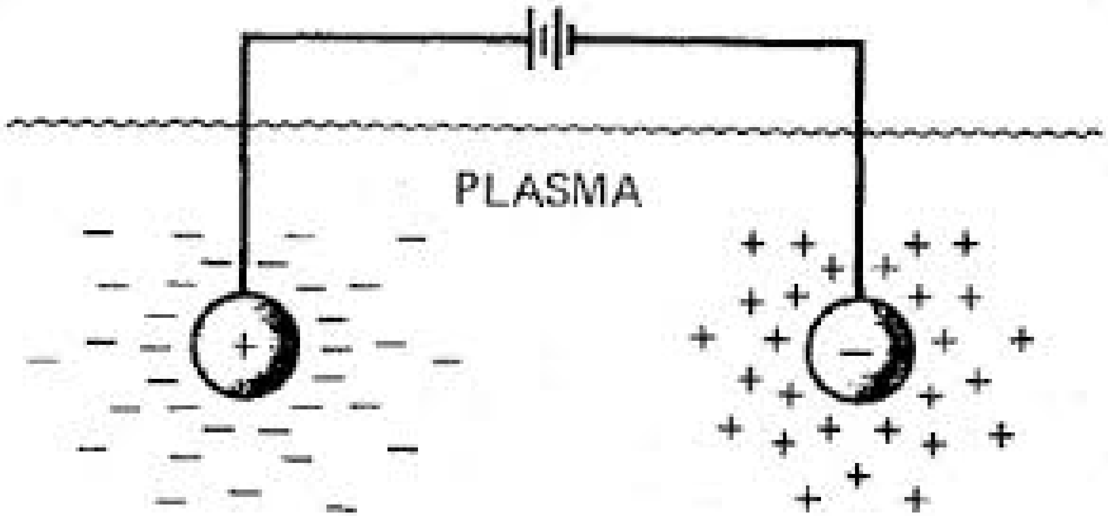


J. D. Huba \NRL Plasma Formulary", Naval Research Laboratory, 2013

There are several Important plasma parameters that need to be considered

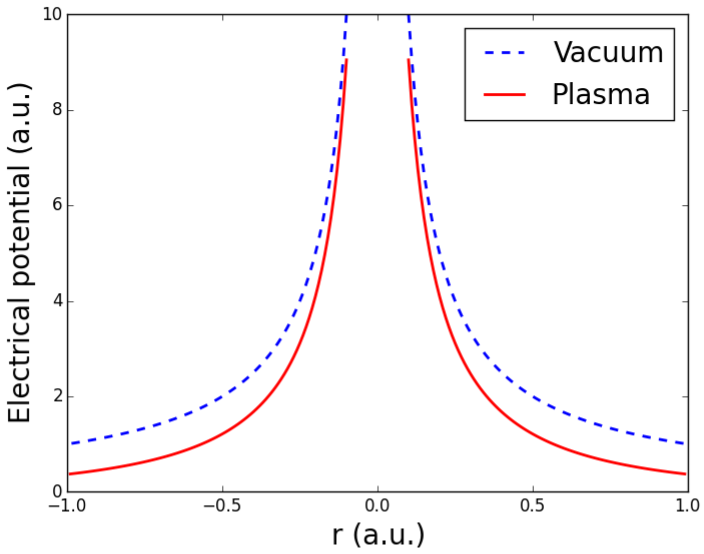
- **Debye length** $\lambda_D \equiv \left(\frac{KT_e}{4\pi n e^2}\right)^{1/2}$
- **Plasma parameter** $\Lambda \equiv n \frac{4\pi}{3} {\lambda_D}^3$
- **Plasma frequency** $\omega_{\mathrm{pe}} \equiv \left(\frac{4\pi n_e e^2}{m_e}\right)^{1/2}$
- **Collision time** $\tau_e \equiv \frac{3\sqrt{m_e}(KT_e)^{3/2}}{4\sqrt{2\pi} n \ln\Lambda}$
- **Hall parameter** $\chi \equiv \omega_{\mathrm{ce}}\tau_e$ **, where** $\omega_{\mathrm{ce}} \equiv \frac{eB}{m_e c}$ **is the electron gyrofrequency**
- **Plasma beta** $\beta \equiv \frac{P}{P_B}$ **, where** $P_B \equiv \frac{B^2}{8\pi}$ **is the magnetic pressure**

A test ion in the plasma gathers a shielding cloud that tends to cancel its own charge



Francis F. Chen, \Introduction to plasma physics and controlled fusion\"

Debye shielding is a phenomenon such that the potential due to a test charge in a plasma falls off much faster than in vacuum



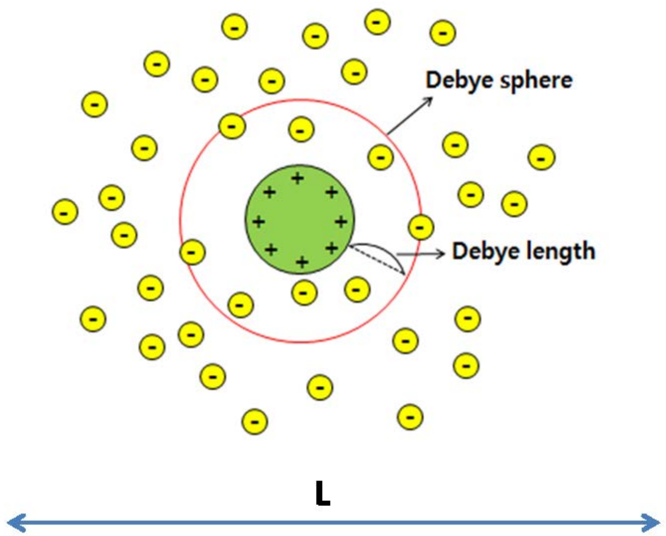
- **Vacuum potential:**

$$\phi = \frac{\phi_0}{r}$$

- **Potential in a plasma**

$$\phi = \frac{\phi_0}{r}\exp\left(-\frac{r}{\lambda_D}\right) \quad \lambda_D \approx \left(\frac{KT_e}{4\pi n e^2}\right)^{1/2}$$

Plasma parameter Λ is the number of particles in a sphere with radius of λ_D



- **Plasma parameter:**

$$\Lambda \equiv n\frac{4\pi}{3}{\lambda_D}^3$$

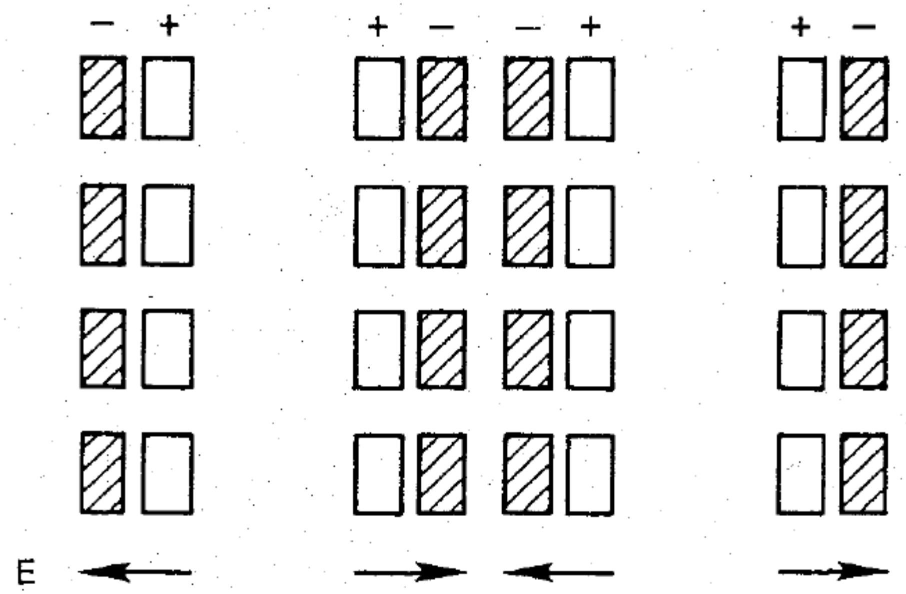
- **Criterion for an ionized gas to be plasma:**

$$\lambda_D \ll L$$

- **Requirement of "collective behavior":**

$$\Lambda \gg 1$$

Electron plasma frequency is the characteristic frequency such that electrons oscillate around their equilibrium positions



Mechanism of plasma oscillations.

- **Plasma frequency:**

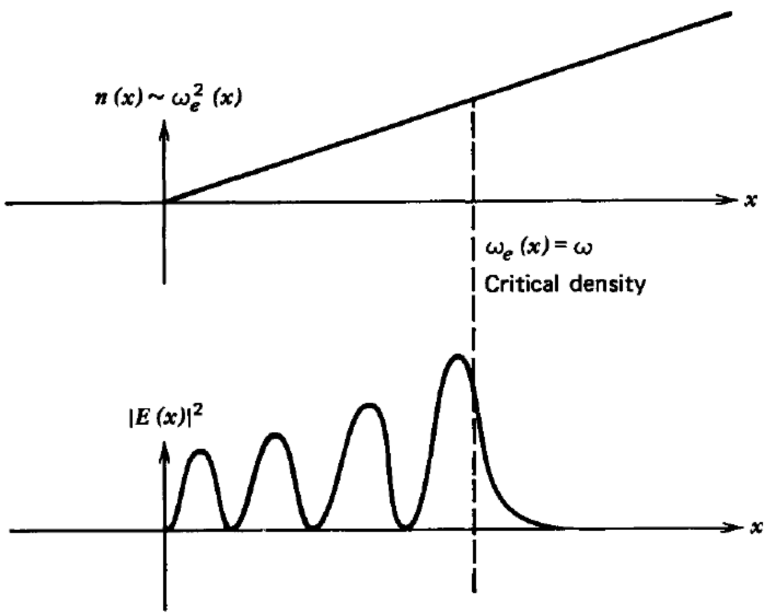
$$\omega_{\rm pe} \equiv \omega = \left(\frac{4\pi n_e e^2}{m_e}\right)^{1/2}$$

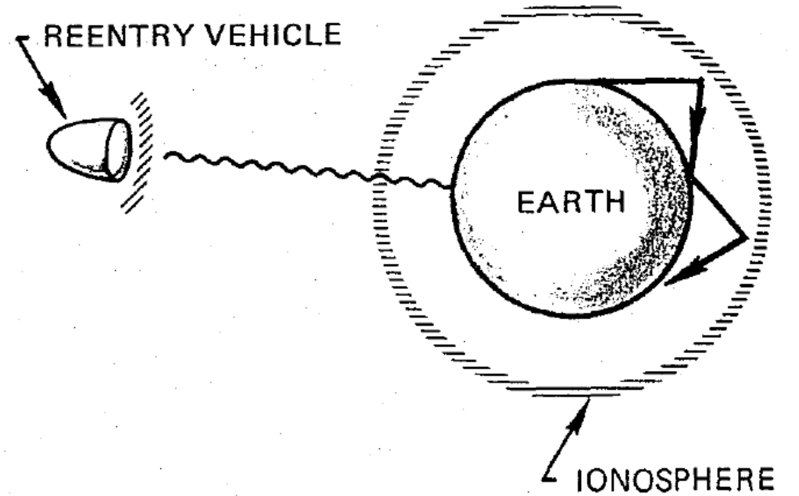
- **Wave number k becomes imaginary when** $\omega < \omega_e$.

$$E = E_0 e^{i(\mathrm{kx}-\omega \mathrm{t})} = E_0 e^{-k_I t} e^{i(k_R x-\omega \mathrm{t})}$$

The cutoff of the electromagnetic wave is important in laser fusion and in the interaction of radio waves with the ionosphere

$$\omega_{\mathrm{pe}} \equiv \omega = \left(\frac{4\pi n_e e^2}{m_e}\right)^{1/2}$$





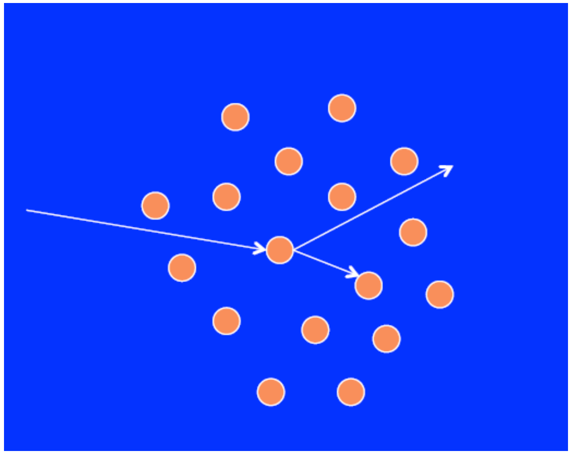
Comparison between the mean free path and the system size L determines the regime of the plasma

- **With more careful derivation, the collisional time is obtained:**

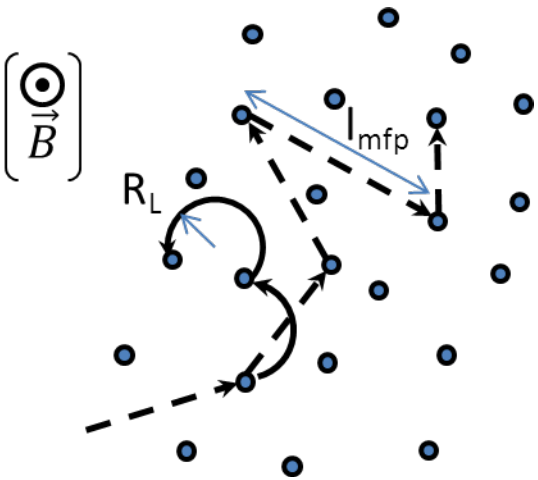
$$\boldsymbol{\tau_e = {\nu_c}^{-1} = \frac{4\sqrt{2\pi}n\ln\Lambda}{3\sqrt{m_e}(KT_e)^{3/2}}}$$

- **Mean free path:** $\boldsymbol{l_{\mathrm{mfp}} = v_e \tau_e}$

$$\begin{cases} l_{\mathrm{mfp}} < L & \textbf{Fluid Theory} \\ l_{\mathrm{mfp}} > L & \textbf{Kinetic Theory} \end{cases}$$



Thermal conduction perpendicular to the magnetic field can be suppressed when the plasma is magnetized



- **Plasma is magnetized when**

$$\frac{R_L}{l_{\mathrm{mfp}}} = \frac{v_e}{\omega_{\mathrm{ce}}}\frac{1}{v_e\tau_e} < 1$$

i.e., the hall parameter

$$\chi \equiv \omega_{\mathrm{ce}}\tau_e > 1$$

$$m_e\frac{d\vec{v}}{\mathrm{dt}} = -\frac{e}{c}\vec{v}\times\vec{B}$$

- **Assuming** $\vec{B} = B\hat{z}$ **and the electron oscillates in x-y plane**

$$m_e\dot{v}_x = -\frac{e}{c}Bv_y \qquad m_e\dot{v}_z = 0$$

$$m_e\dot{v}_y = \frac{e}{c}Bv_x$$

$$\ddot{v}_x = -\frac{eB}{m_e c}\dot{v}_y = -\left(\frac{eB}{m_e c}\right)^2 v_x$$

$$\ddot{v}_y = -\frac{eB}{m_e c}\dot{v}_x = -\left(\frac{eB}{m_e c}\right)^2 v_y$$

- **Therefore**

$$\omega_{\mathrm{ce}} = \frac{eB}{m_e c}$$

Plasma β is the ratio between hydro pressure and magnetic pressure

- **Momentum equation in Magnetohydrodynamics (MHD) approach:**

$$\rho \frac{d\vec{v}}{\mathrm{dt}} + \rho(\vec{v}\cdot\vec{\nabla})\vec{v} = -\vec{\nabla}p + \frac{1}{c}\vec{j}\times\vec{B}$$

$$\vec{\nabla}\times\vec{B} = \frac{4\pi}{c}\vec{j}$$

$$\vec{j}\times\vec{B} = \frac{c}{4\pi}(\vec{\nabla}\times\vec{B})\times\vec{B} = \frac{c}{4\pi}\left[(\vec{B}\cdot\vec{\nabla})\times\vec{B} - \frac{1}{2}\vec{\nabla}B^2\right]$$

$$\rho \frac{d\vec{v}}{\mathrm{dt}} + \rho(\vec{v}\cdot\vec{\nabla})\vec{v} = -\vec{\nabla}\left(p + \frac{B^2}{8\pi}\right) + \frac{1}{4\pi}(\vec{B}\cdot\vec{\nabla})\times\vec{B}$$

- **Magnetic pressure:** $\frac{B^2}{8\pi}$

$$\beta \equiv \frac{p}{B^2/8\pi}$$

- **Magnetic tension:** $\frac{1}{4\pi}(\vec{B}\cdot\vec{\nabla})\times\vec{B}$

- **Pressure can be treated as energy density, i.e., energy per volume.**

There are several Important plasma parameters that need to be considered

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Day 1~3

Day 4~5: Experiments

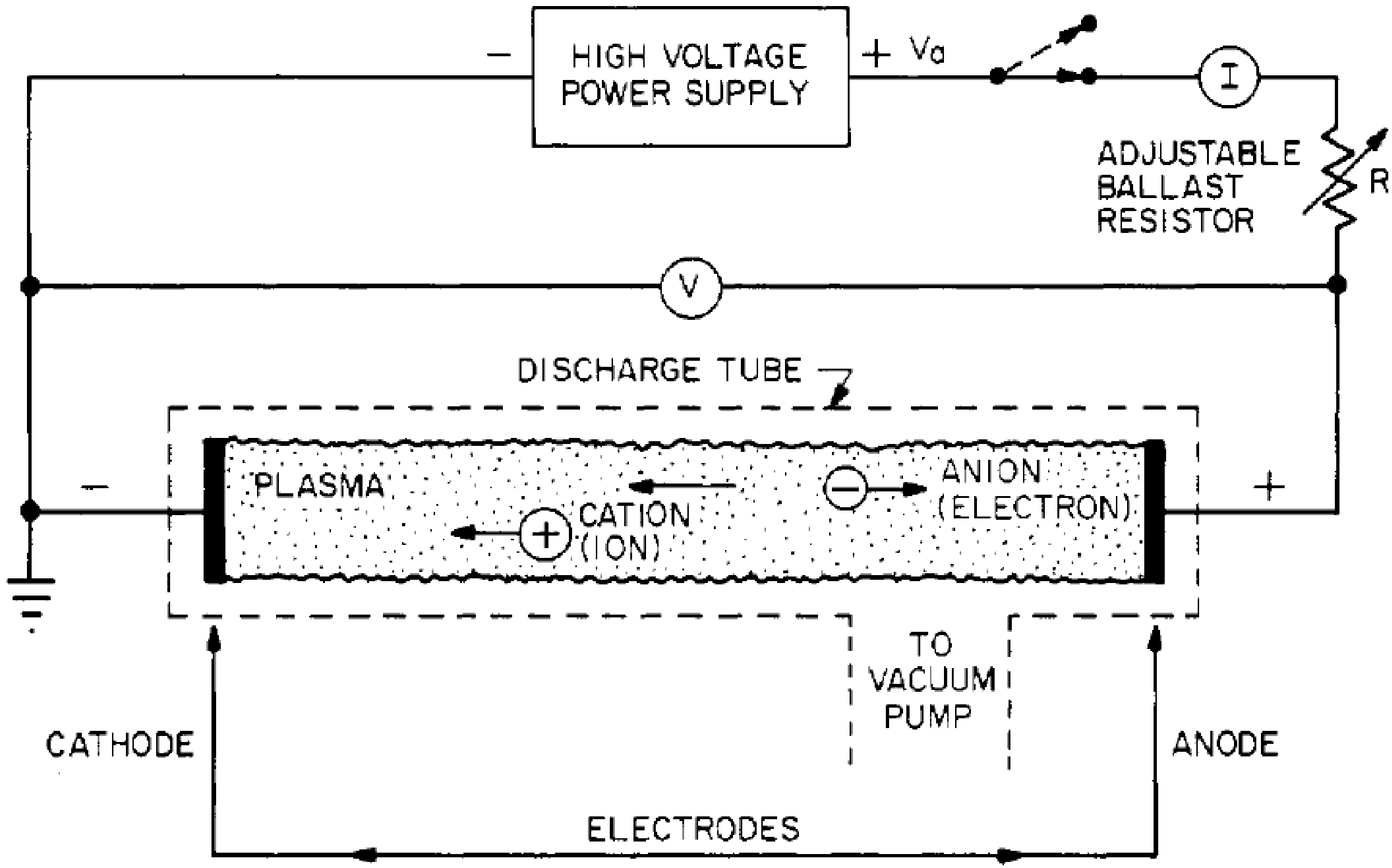
Methods of plasma production

- DC electrical discharges
  - Dark electrical discharges in gases
  - DC electrical glow discharges in gases
  - DC electrical arc discharges in gases
- AC electrical discharges
  - RF electrical discharges in gases
  - Microwave electrical discharges in gases
  - Dielectric-barrier discharges (DBDs)
- Other mechanism
  - Laser produced plasma

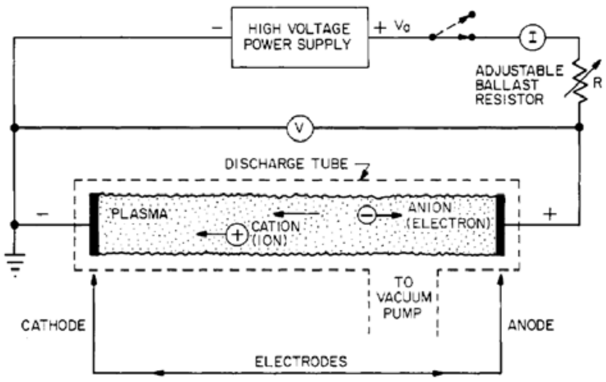
Methods of plasma production

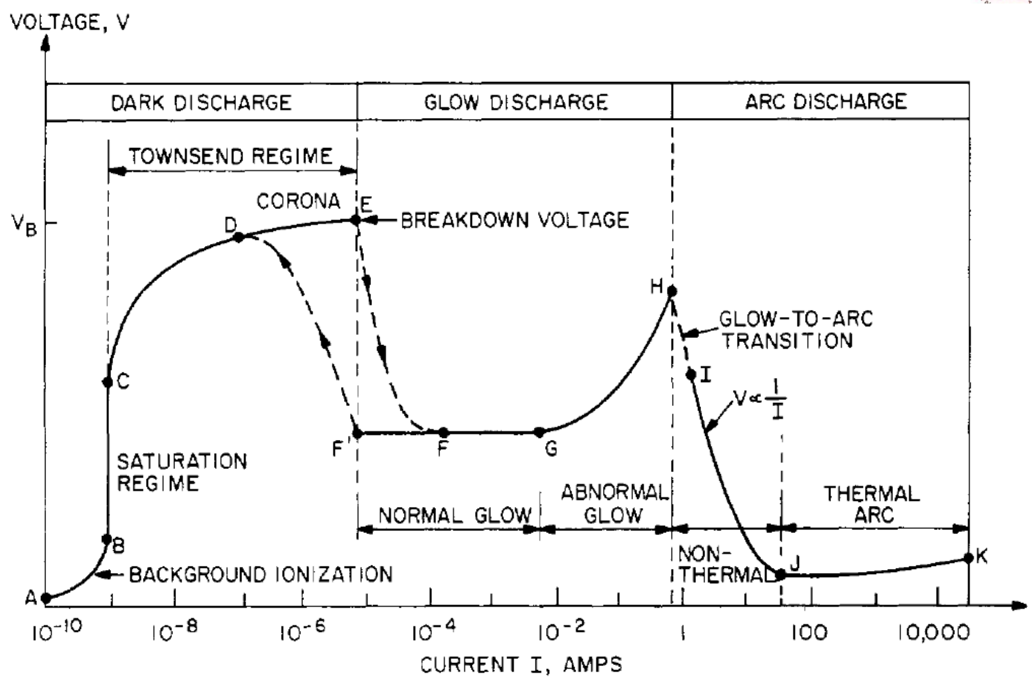
- DC electrical discharges
  - Dark electrical discharges in gases
  - DC electrical glow discharges in gases
  - DC electrical arc discharges in gases
- AC electrical discharges
  - RF electrical discharges in gases
  - Microwave electrical discharges in gases
  - Dielectric-barrier discharges (DBDs)
- Other mechanism
  - Laser produced plasma

Electrical discharge physics was studied using the classical low pressure electrical discharge tube



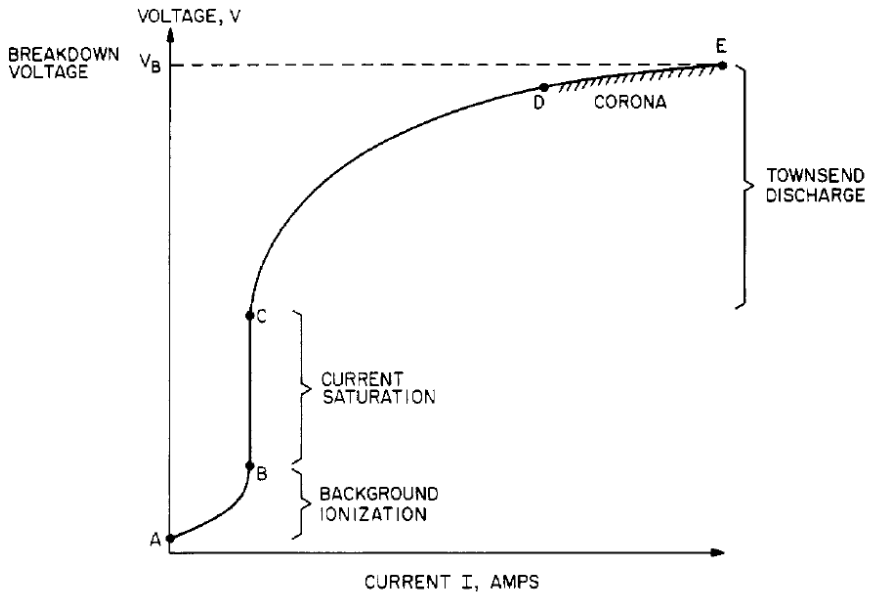
The V-I curve is nonlinear in a DC electrical discharge tube

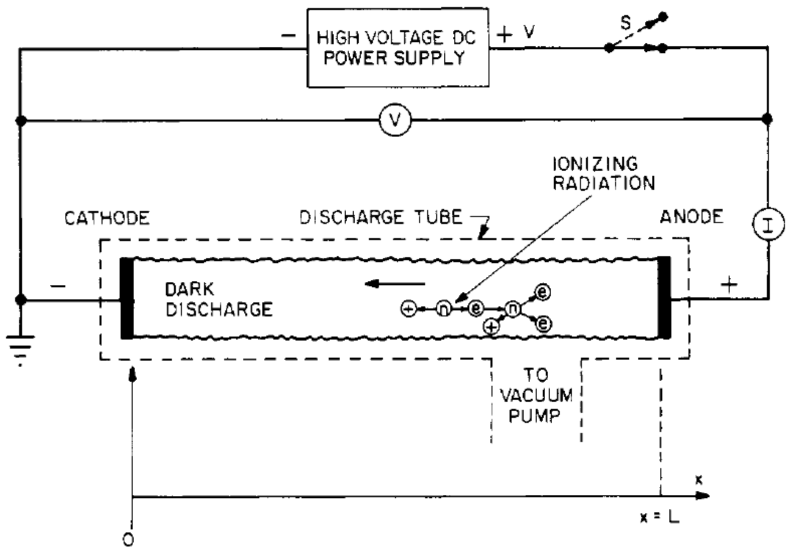




- **Depends on the voltage, the adjustable ballast resistor, the voltage-current characteristic behaves differently in different regime.**
  - **Dark discharge**
  - **Glow discharge**
  - **Arc discharge**

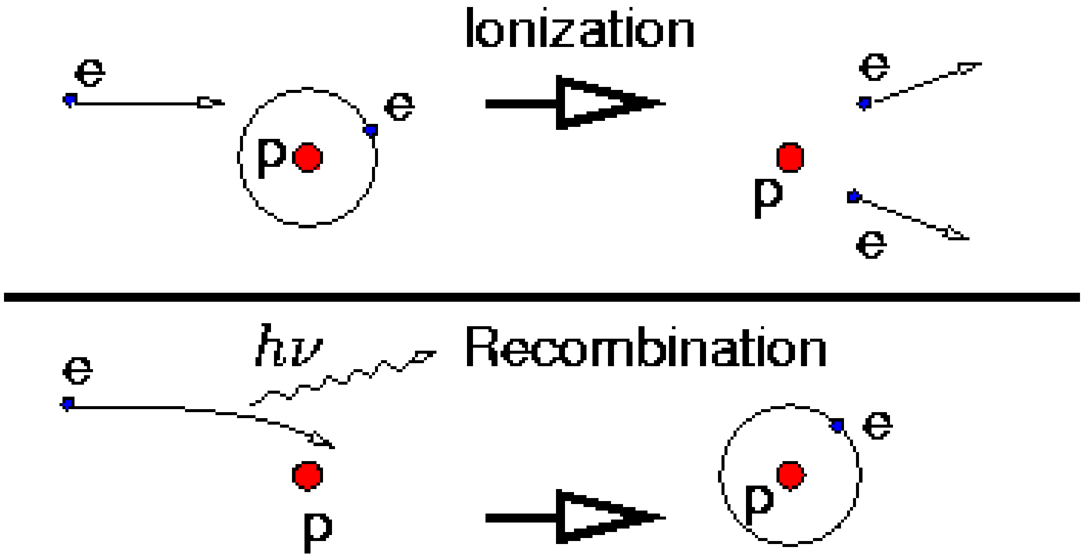
In background ionization, ions and electrons are created by ionization from background radiation





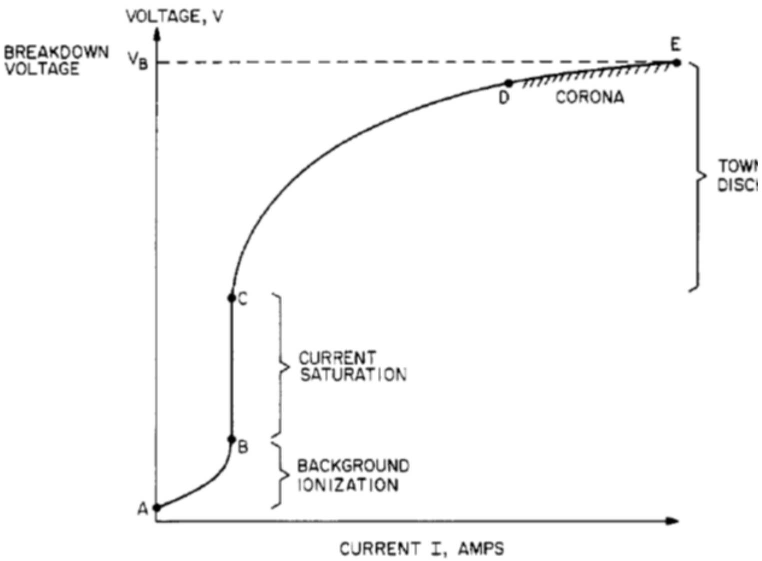
- **Sources of background radiation:**
  - **Cosmic rays**
  - **Radioactive minerals in the surroundings**
  - **Static charges**
  - **Other sources**
- **In a dark discharge, the excitation light is so little and is not visible**

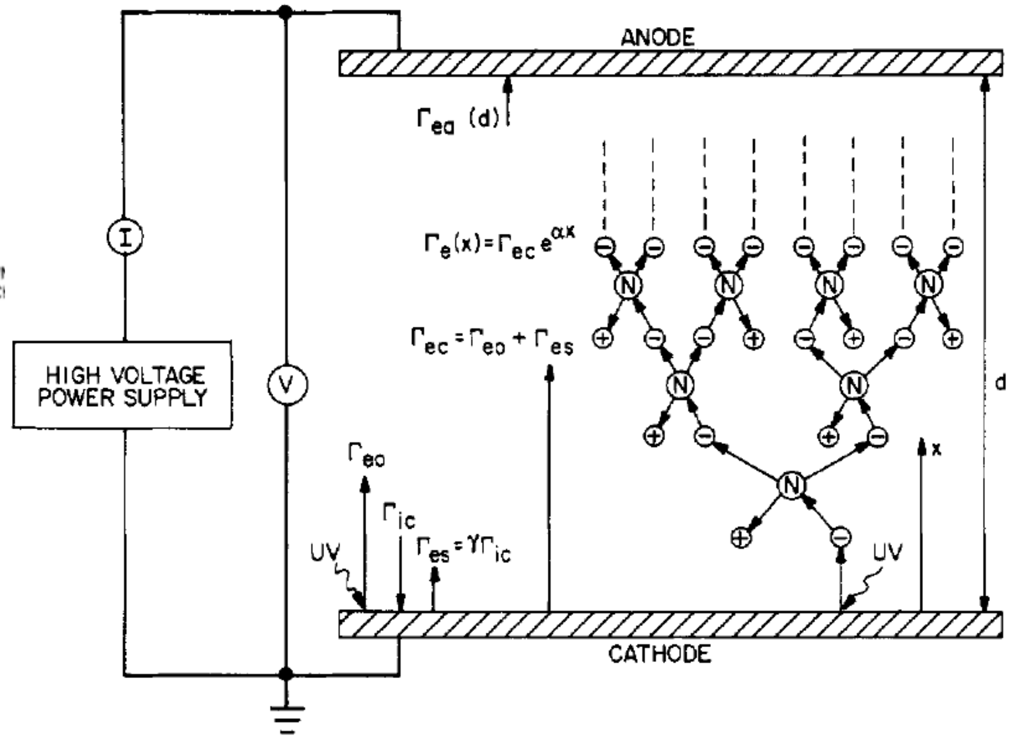
A plasma is a gas in which an important fraction of the atoms is ionized so that the electrons and ions are separated freely



http://ocw.mit.edu/courses/nuclear-engineering/22-611j-introduction-to-plasma-physics-i-fall-2003/lecture-notes/

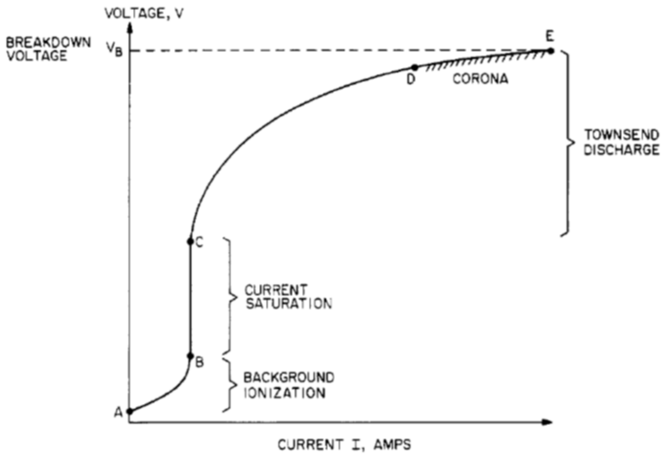
The region where the current exponentially increases is called the Townsend discharge

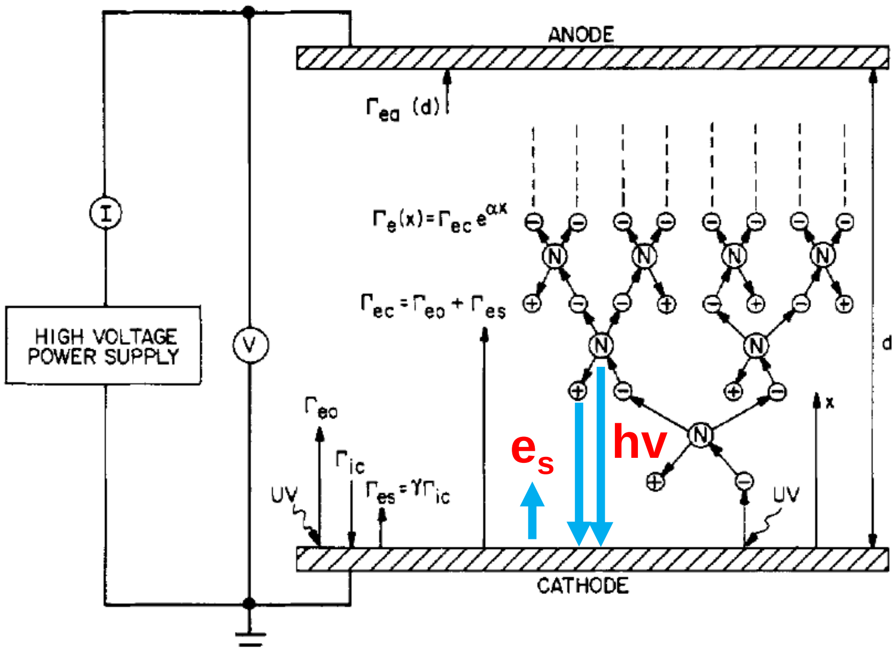




- **The phenomenon of the number of electrons increase exponentially is called the avalanche breakdown.**

The region where the current exponentially increases is called the Townsend discharge



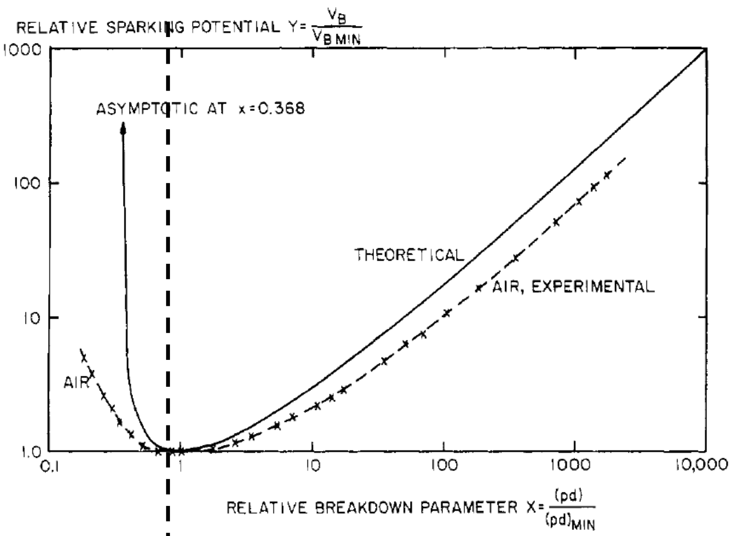


- **Primary electrons: electrons from the cathode due to photoemission, background radiation, static chages, or other processes.**
- **Secondary electrons: electrons emitted from the cathode per incident ion or photon created from ionization in gas.**

- **Electrical breakdown occurs when applied voltage is greater than the breakdown voltage**

Collision frequency and electron energy gained from electric field are both important to electrical breakdown

Paschen curve

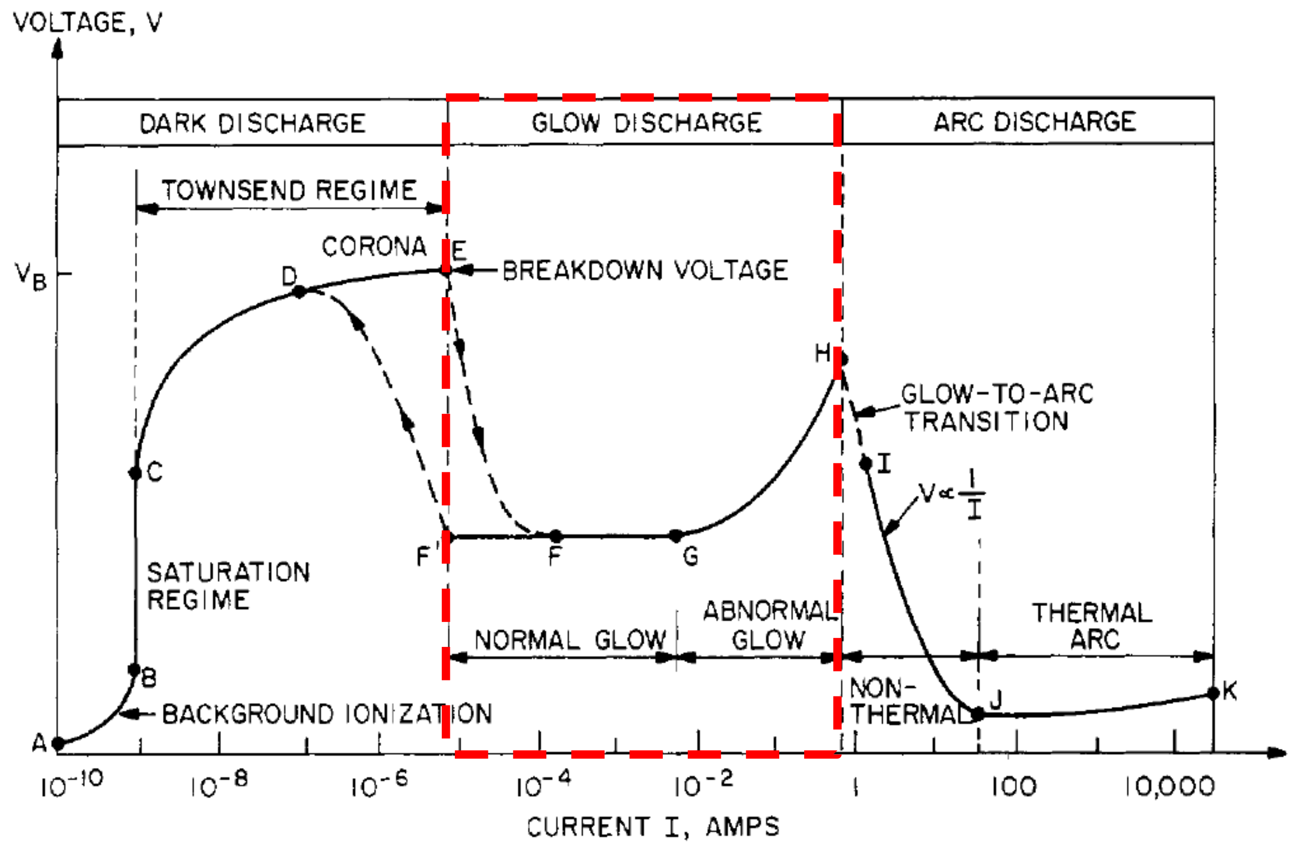


- **Collision is not frequent enough even the electrons gain large energy between each collision.**
- **Electrons do not gain enough energy between each collision even collisions happen frequently.**

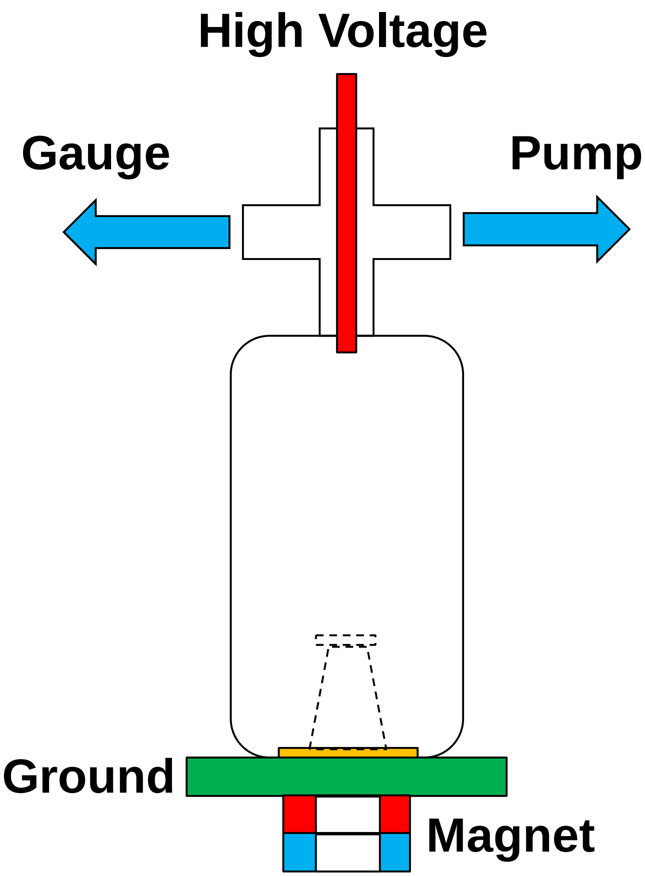
- **The minimum of the Paschen curve corresponds to the Stoletow point, the pressure at which the volumetric ionization rate is a maximum.**

DC electrical glow discharges in gases

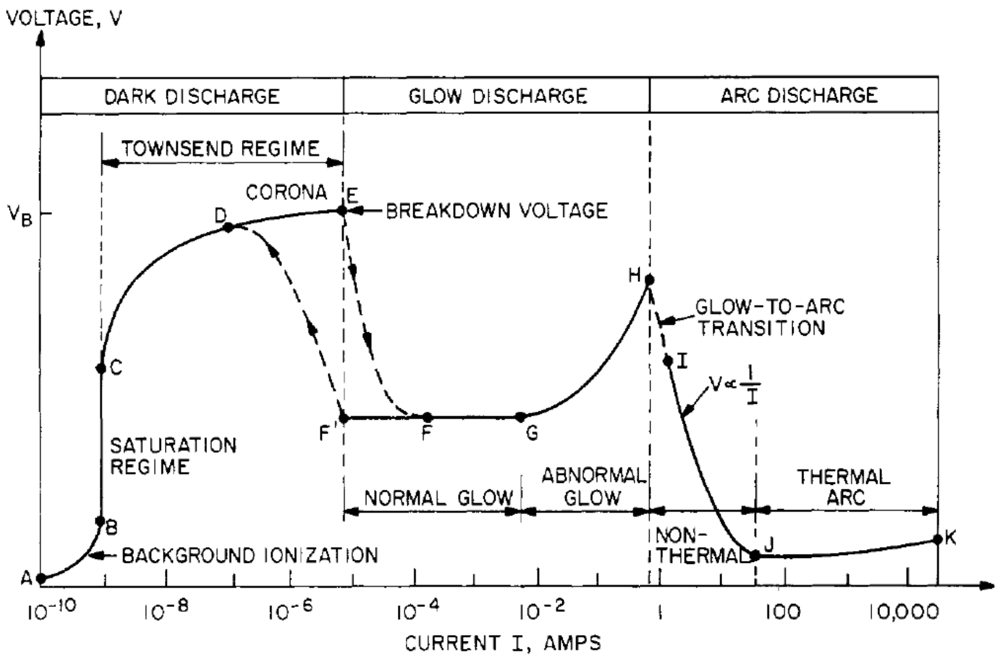
- The internal resistance of the power supply is relatively low, then the gas will break down at the voltage V_B, and the discharge tube will move from the dark discharge regime into the low pressure normal glow discharge regime.

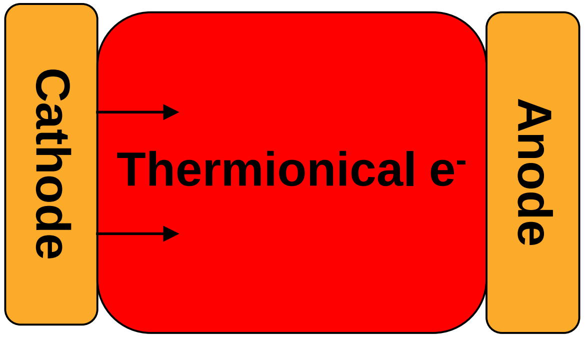


Glow discharge in a glass jar



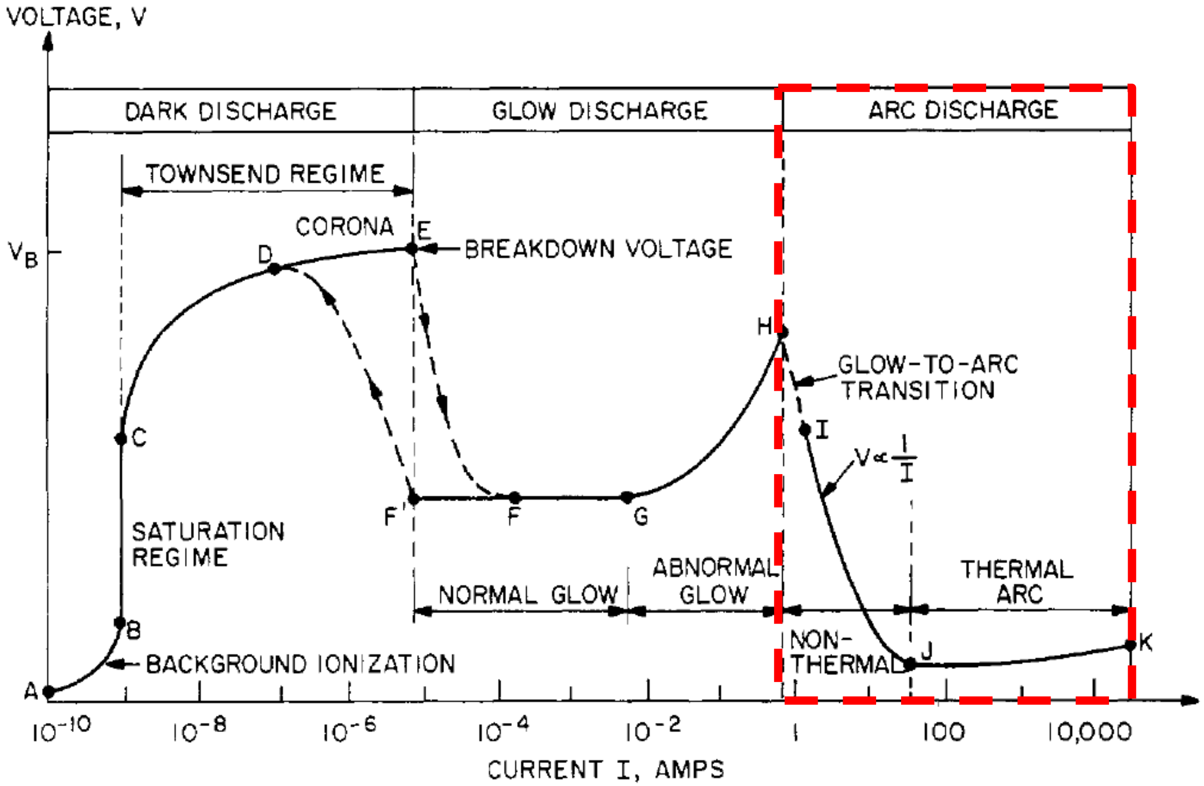
Discharge may enter glow-to-arc transition region if the cathode gets hot enough to emit electrons thermionically





- If the cathode gets hot enough to emit electrons thermionically and the internal impedance of the power supply is sufficiently low, the discharge will make a transition into the arc regime.

DC electrical arc discharges in gases



- An arc is highly luminous and is characterized by high currents (> 1 A) and current densities (A=cm² ≳ kA/cm²).
- Cathode voltage fall is small (≤10 V) in the region of high spatial gradients within a few mm of the cathode.

AC electrical discharges deliver energy to the plasma without contact between electrodes and the plasma

- **DC electrical discharge – a true current in the form of a flow of ions or electrons to the electrodes.**
- **AC electrical discharge – the power supply interacts with the plasma by displacement current.**
  - **Inductive radio frequency (RF) electrical discharges**
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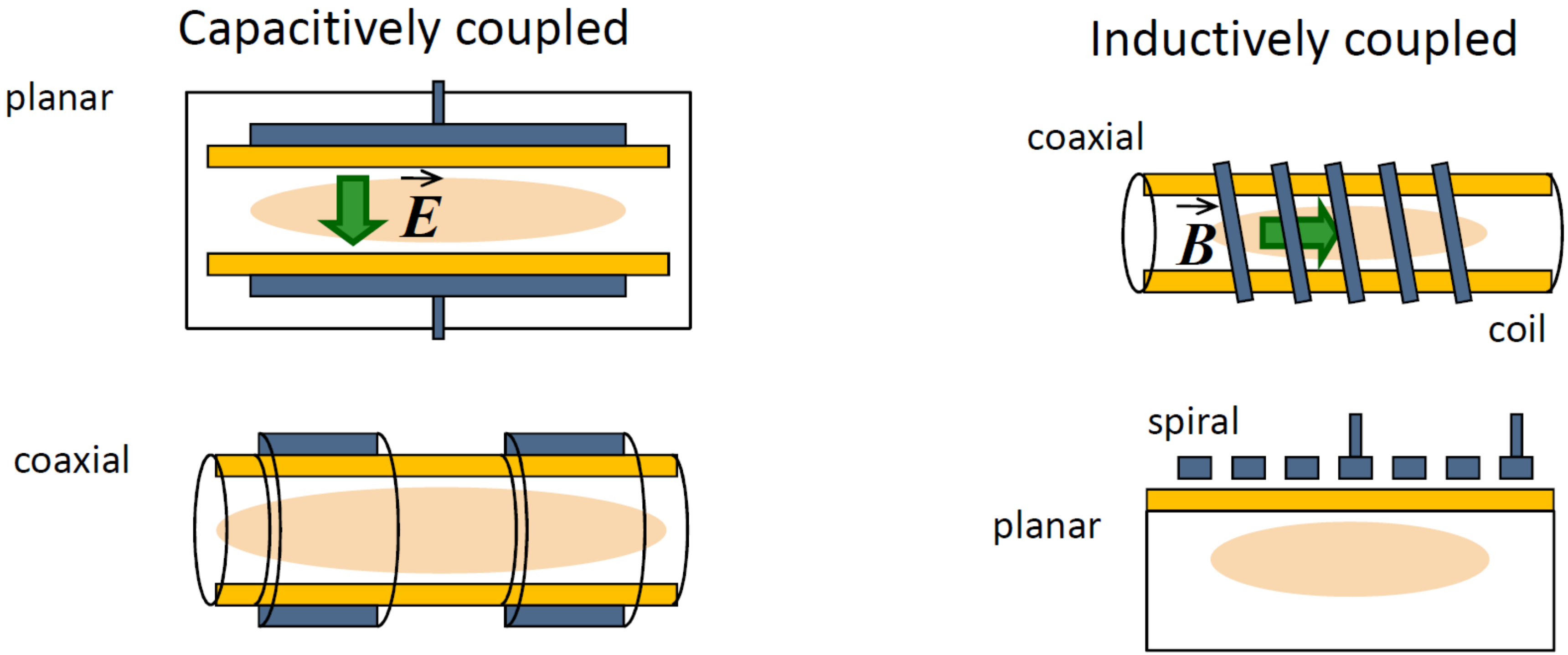
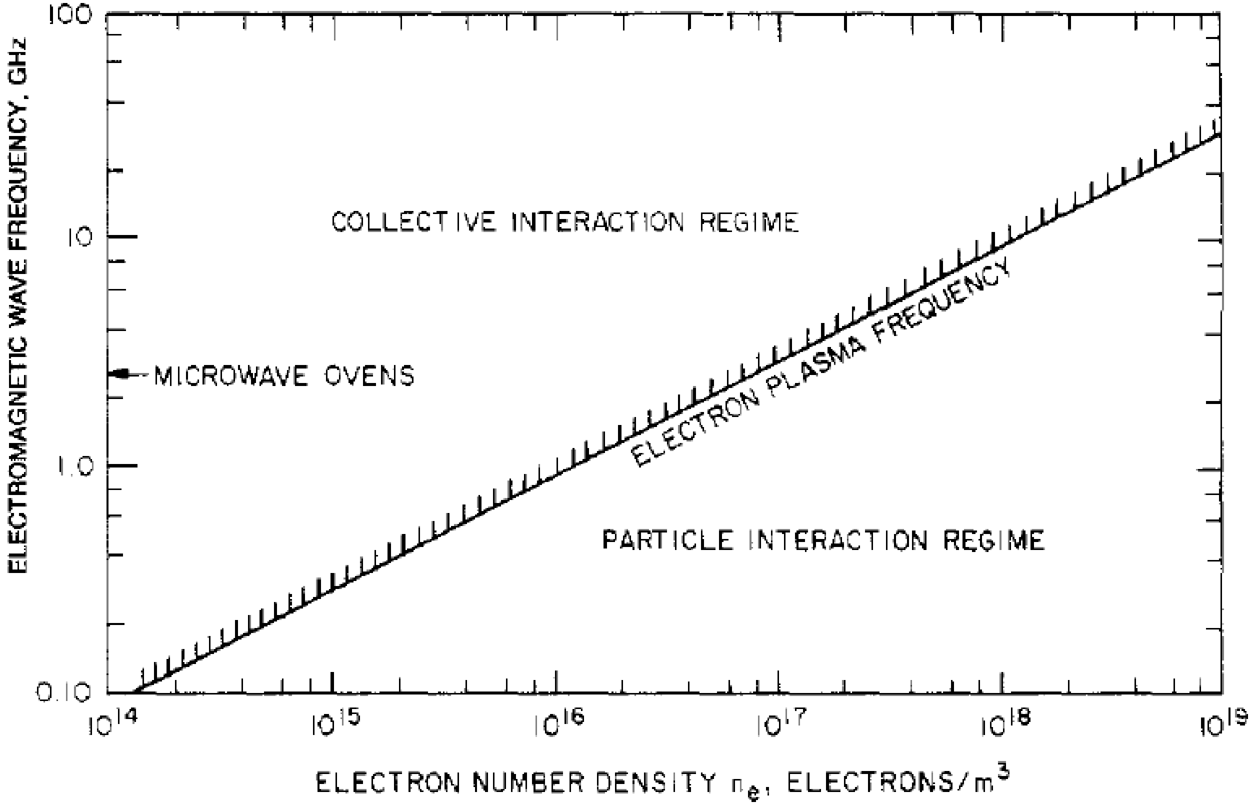
  - **Microwave electrical discharges**
  - **Dielectric-barrier discharges (DBDs)**
- **Optical (laser) produced plasma**

RF can interact with plasma inductively or capacitively

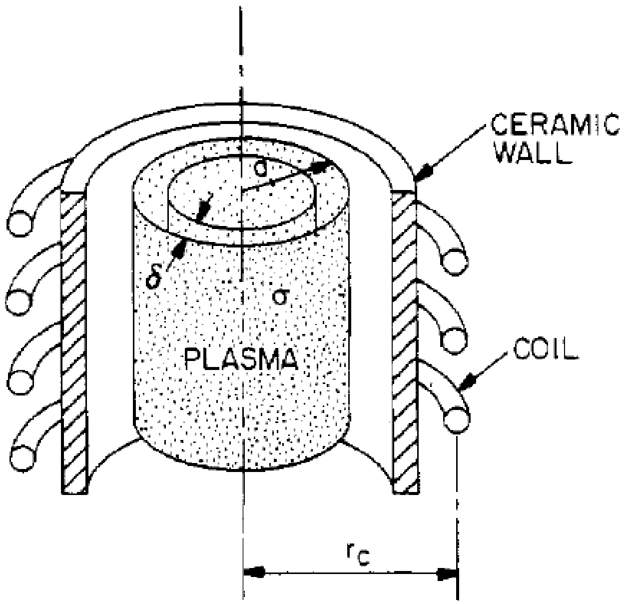


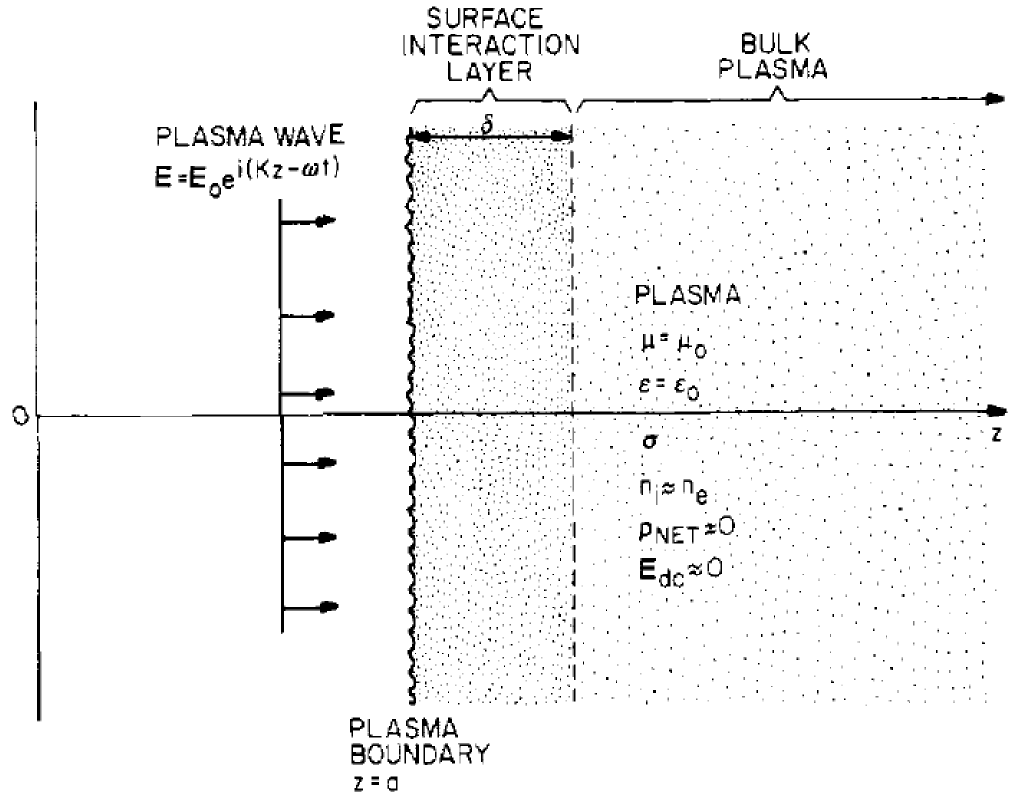
How an electromagnetic wave interacts with a plasma depends on its frequency



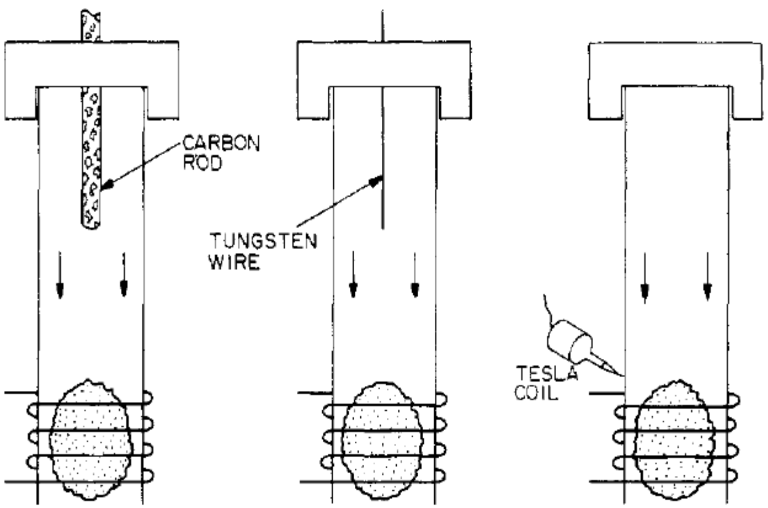
$$\omega_{pe} = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}} (\mathrm{rad}/s) \qquad n_{cri} = \frac{\epsilon_0 m_e}{e^2} \omega_{pe}{}^2 (m^{-3})$$

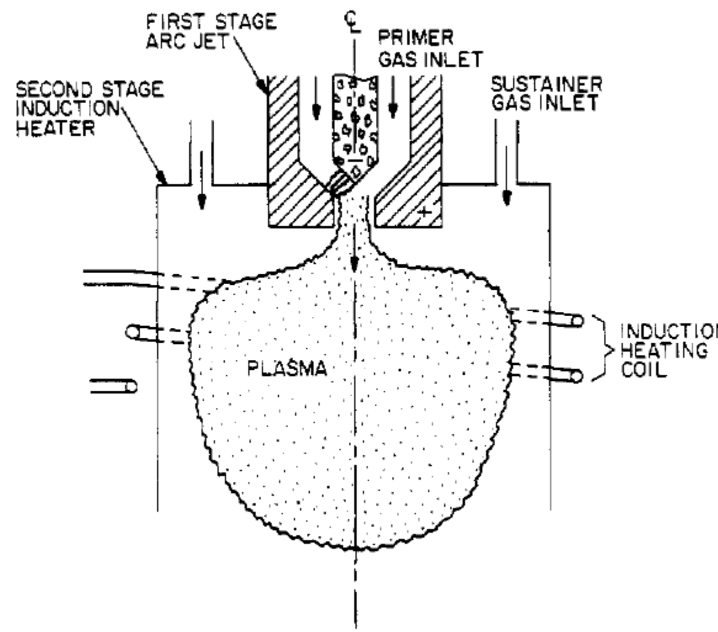
RF energy is strongly absorbed within the skin depth if the frequency is below the electron plasma frequency



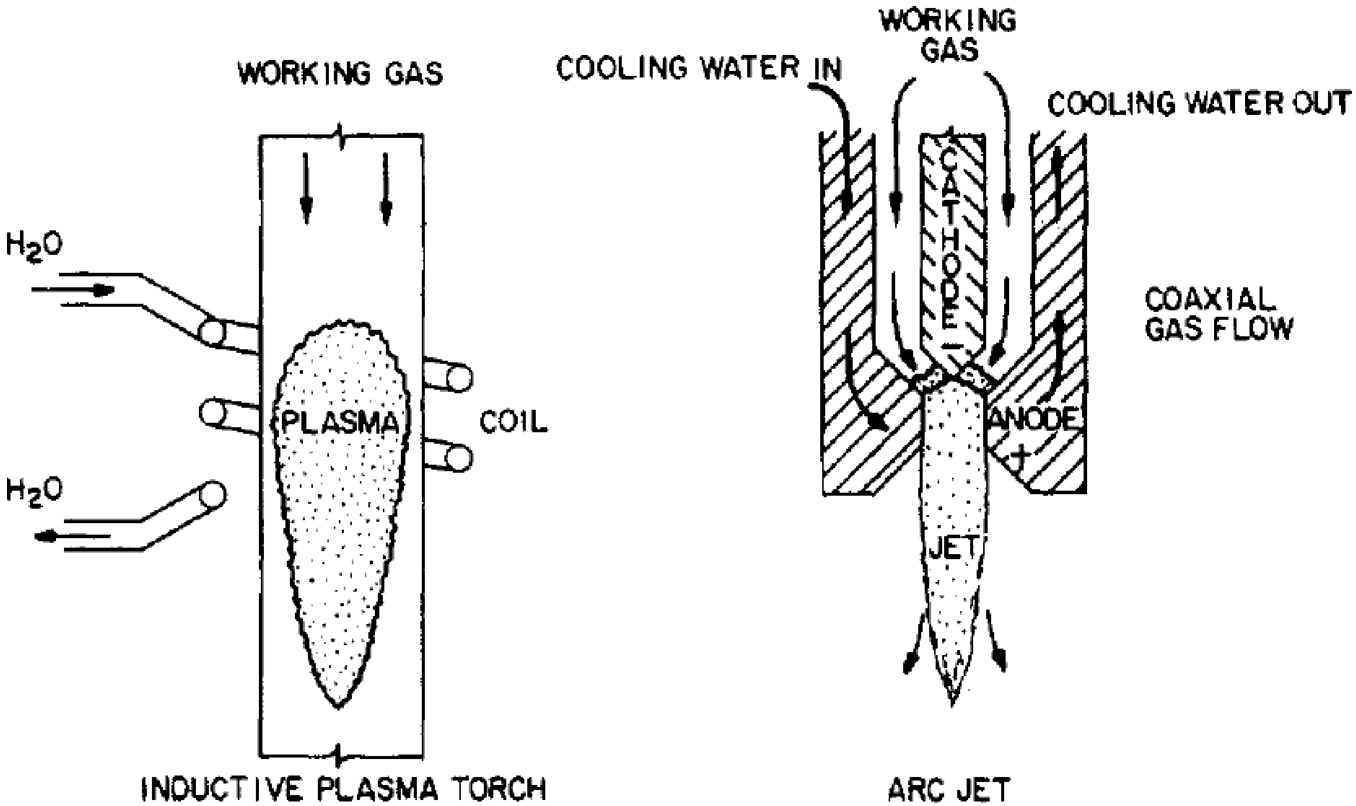


High voltage initiation is usually required for inductive RF plasma torches



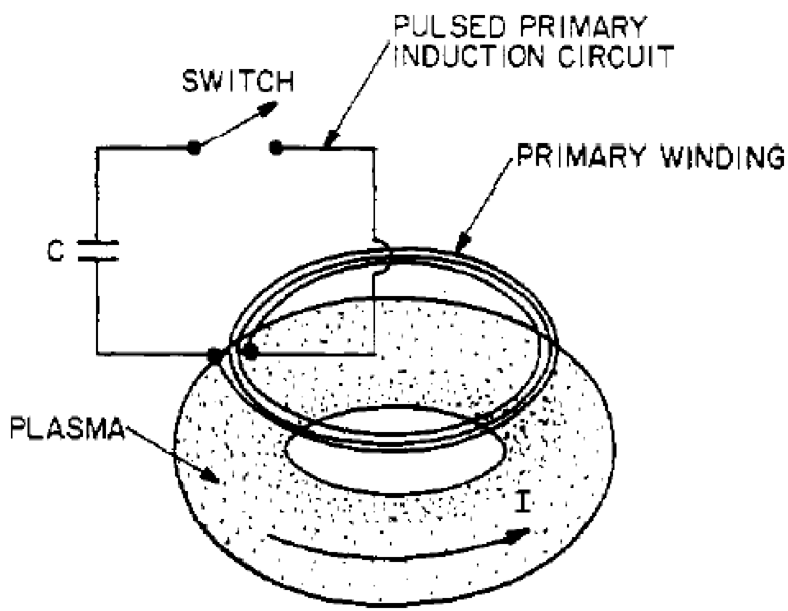


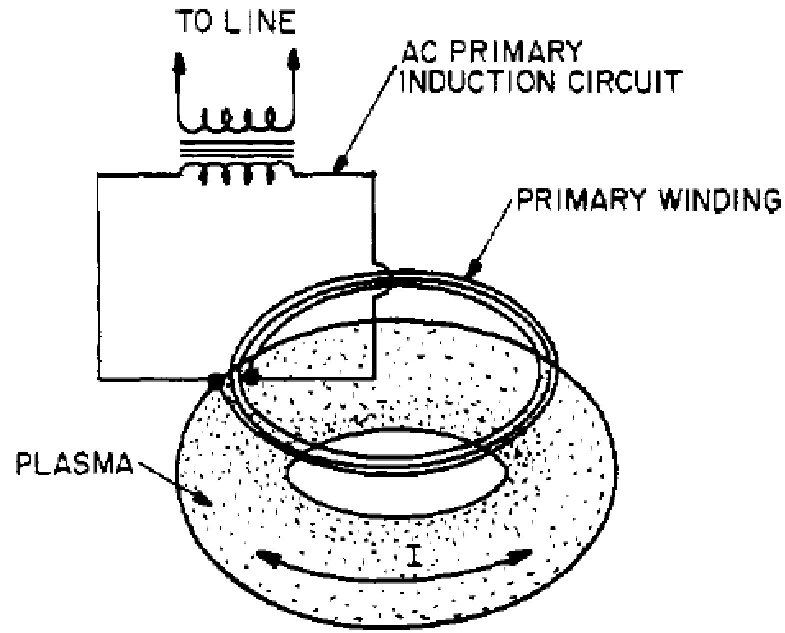
Inductive RF coupling provides a plasma with less contamination from the electrode



10 - 200 m/sec	JET VELOCITY	500-150 m/sec
4-40 mm	JET DIAMETER	6-10 mm
VARIABLE	JET SHAPE	CYLINDRICAL

Inductively heated toroidal plasmas





- **Large currents are induced in the plasma by transformer action from a ramped current in a pulsed primary induction circuit.**

AC electrical discharges deliver energy to the plasma without contact between electrodes and the plasma

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- **AC electrical discharge – the power supply interacts with the plasma by displacement current.**
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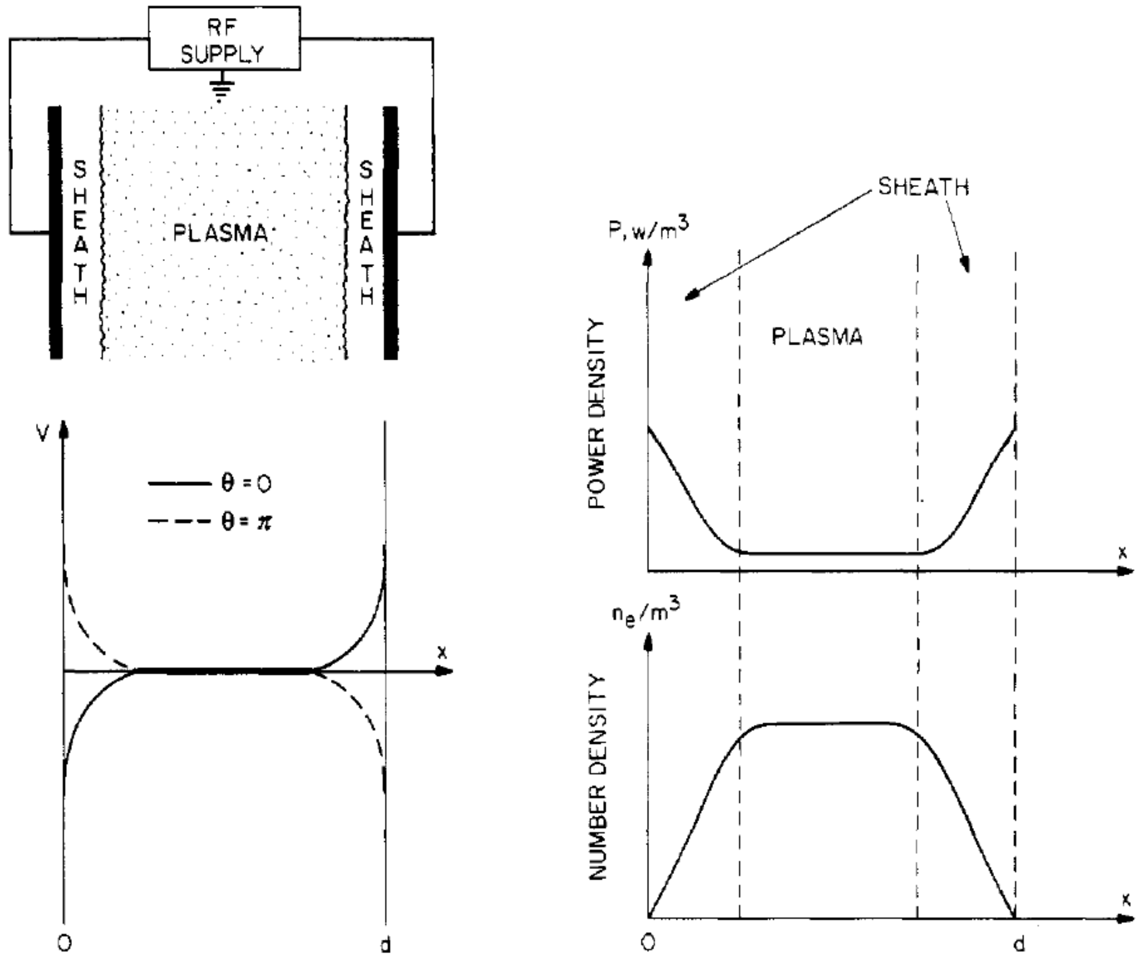
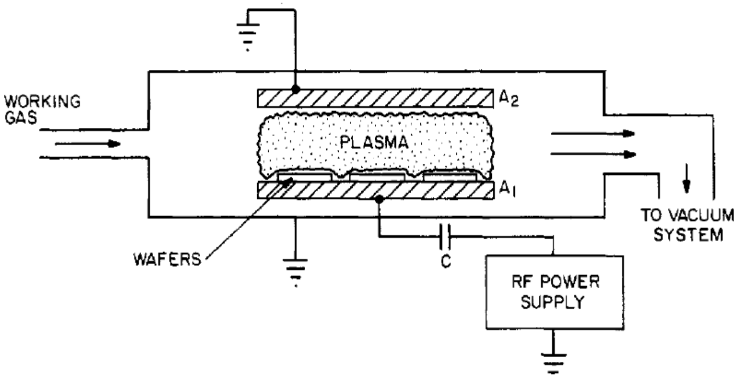
  - **Microwave electrical discharges**
  - **Dielectric-barrier discharges (DBDs)**
- **Optical (laser) produced plasma**

Symmetrical capacitive RF discharge model

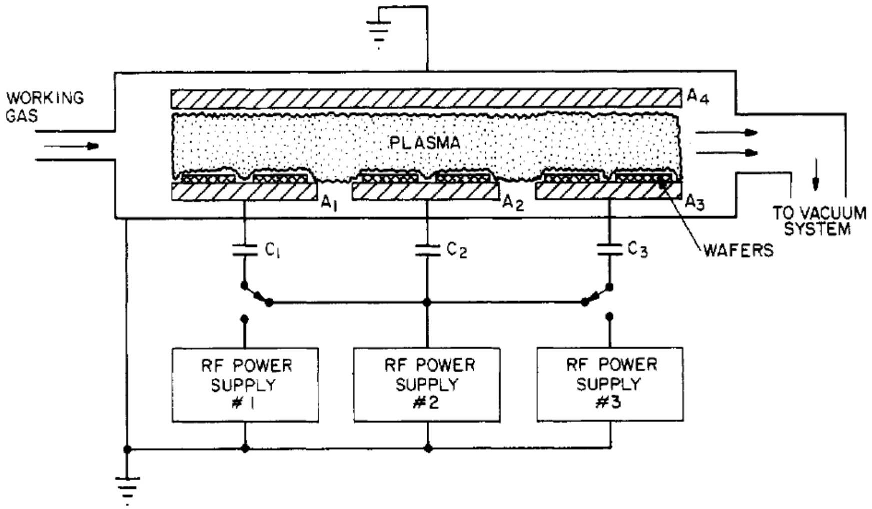


Example of capacitively coupled RF plasma source 2

- **Plane parallel reactor**



- **Multiple electrode system**



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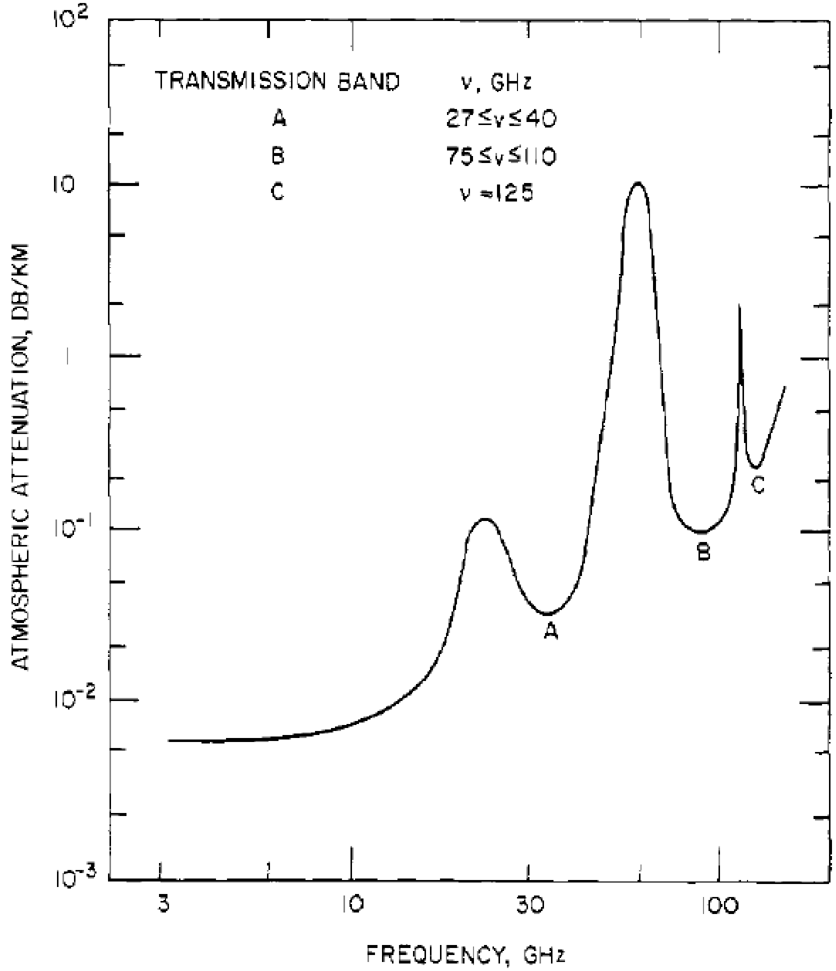
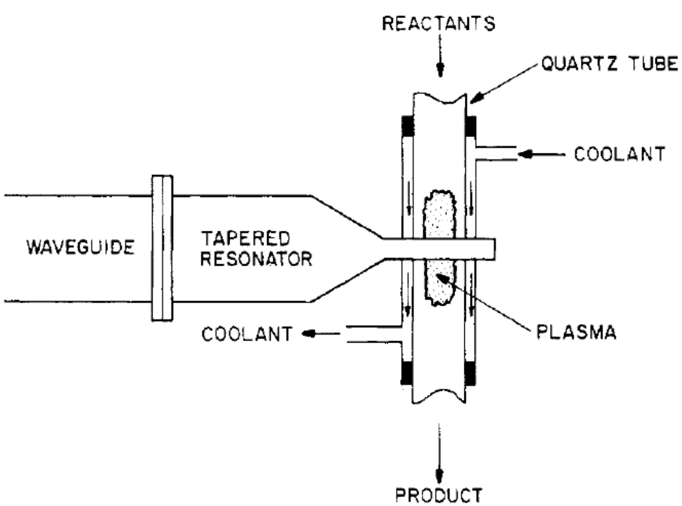
- **Optical (laser) produced plasma**

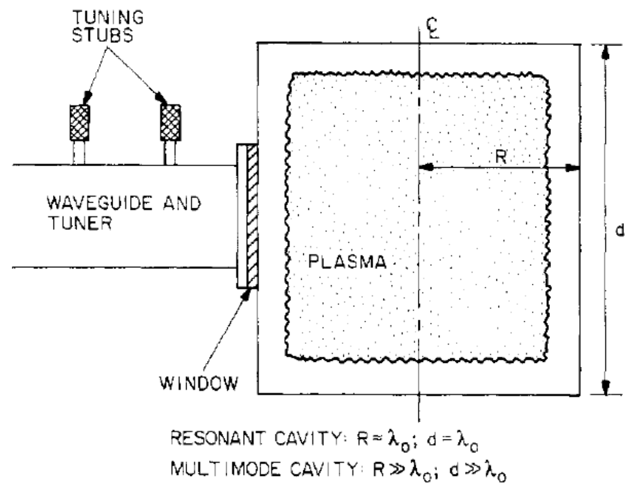
Microwave frequency is determined for those used in communications and radar purposes



Microwave plasma reactor configurations

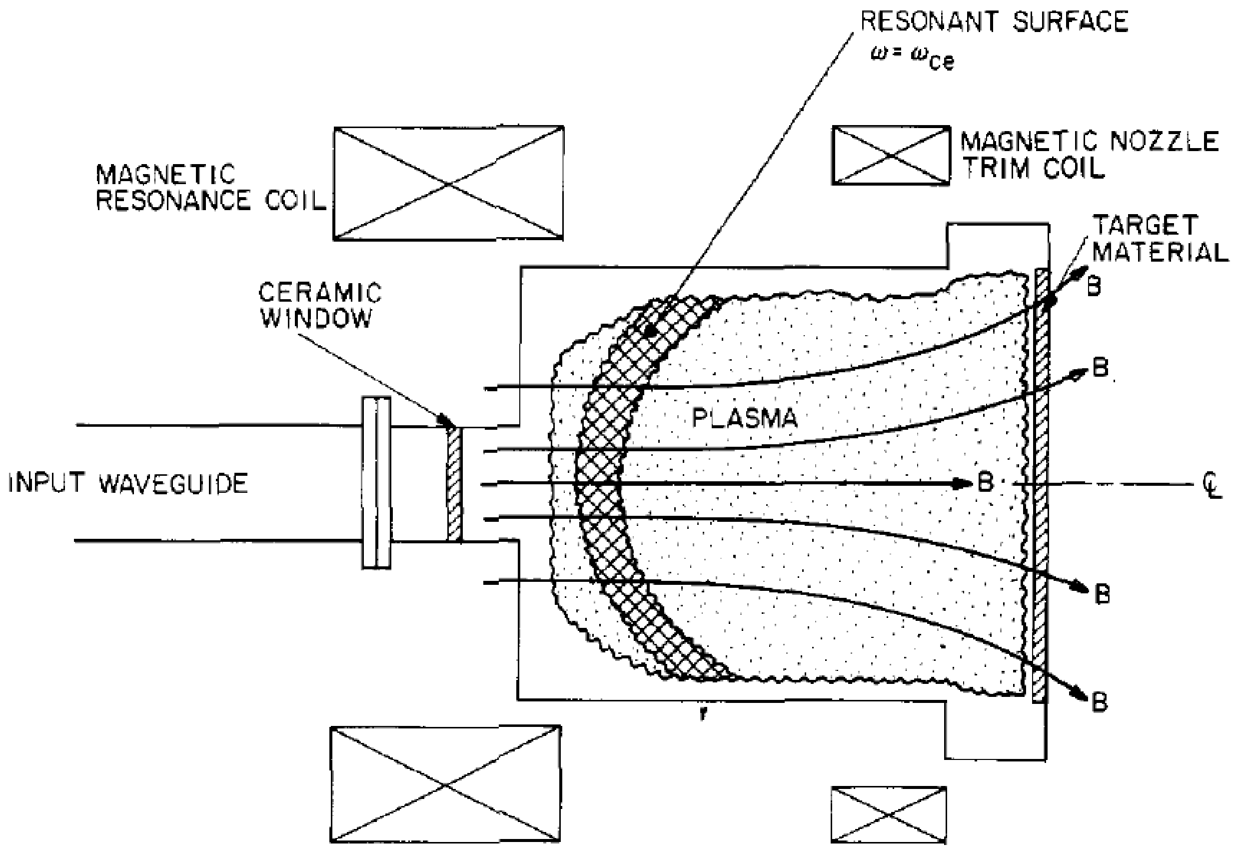
- **Waveguide coupled reactor**
- **Resonant or multimode cavity – if the impedance matching is good, more energy can be fed into the cavity.**





Strong absorption occurs when the frequency matches the electron cyclotron frequency

- **Electron cyclotron resonance (ECR) plasma reactor**



Electron cyclotron frequency depends on magnetic field only

$$m_e \frac{d\vec{v}}{\mathrm{dt}} = -\frac{e}{c}\,\vec{v} \times \vec{B}$$

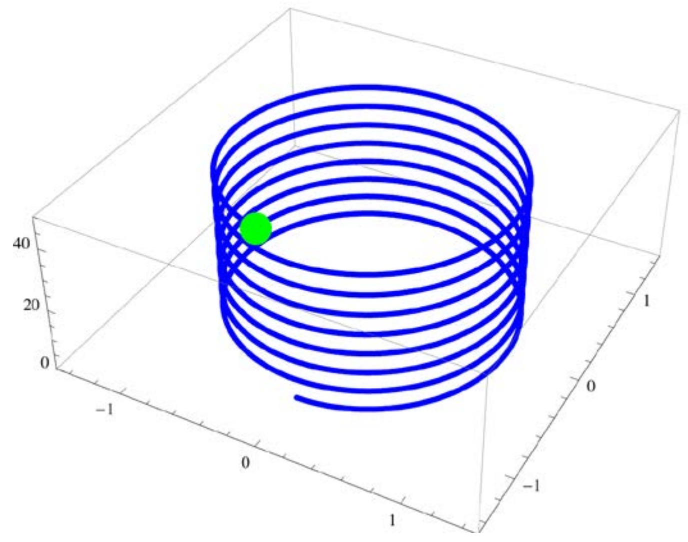
- Assuming $\vec{B} = B\hat{z}$ and the electron oscillates in x-y plane

$$m_e \dot{v}_x = -\frac{e}{c} B v_y \qquad m_e \dot{v}_z = 0$$

$$m_e \dot{v}_y = \frac{e}{c} B v_x$$

$$\ddot{v}_x = -\frac{eB}{m_e c}\dot{v}_y = -\left(\frac{eB}{m_e c}\right)^2 v_x$$

$$\ddot{v}_y = -\frac{eB}{m_e c}\dot{v}_x = -\left(\frac{eB}{m_e c}\right)^2 v_y$$



- Therefore

$$\omega_{\mathrm{ce}} = \frac{eB}{m_e c}$$

Electrons keep getting accelerated when a electric field rotates in electron's gyrofrequency

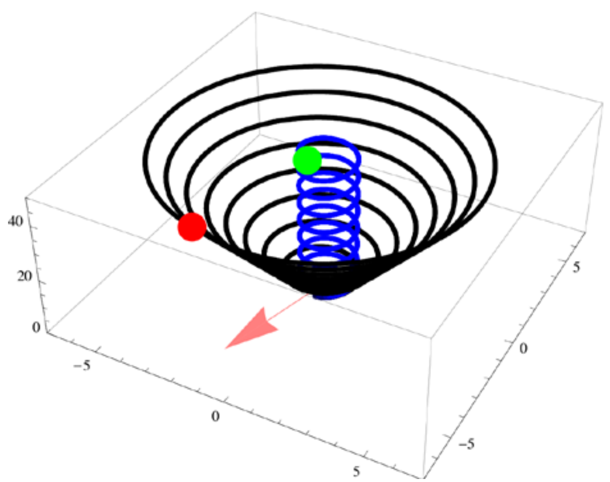
$$m_e \frac{d\vec{v}}{\mathrm{dt}} = -\frac{e}{c}\,\vec{v} \times \vec{B} - e\,\vec{E} \qquad \vec{B} = B_0\hat{z} \qquad \vec{E} = E_0[\hat{x}\cos(\omega t) + \hat{y}\sin(\omega t)]$$

$$m_e\dot{v}_x = -\frac{e}{c}Bv_y + E_0\cos(\omega t) \qquad m_e\dot{v}_y = \frac{e}{c}Bv_x + E_0\cos(\omega t) \qquad m_e\dot{v}_z = 0$$

$$\ddot{v}_x = -\frac{eB}{m_e c}\dot{v}_y - \frac{E_0}{m_e}\omega\cos(\omega t) = -\omega_{ce}{}^2 v_x - \frac{E_0}{m_e}(\omega_{ce} + \omega)\cos(\omega t)$$

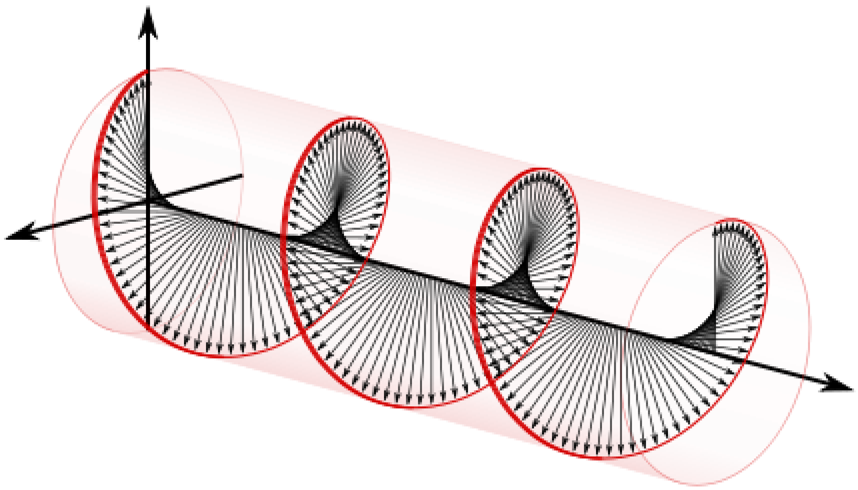
$$\ddot{v}_y = -\frac{eB}{m_e c}\dot{v}_x + \frac{E_0}{m_e}\omega\sin(\omega t) = -\omega_{ce}{}^2 v_y + \frac{E_0}{m_e}(\omega_{ce} + \omega)\sin(\omega t)$$

$$\omega_{ce} = \frac{eB}{m_e c}$$

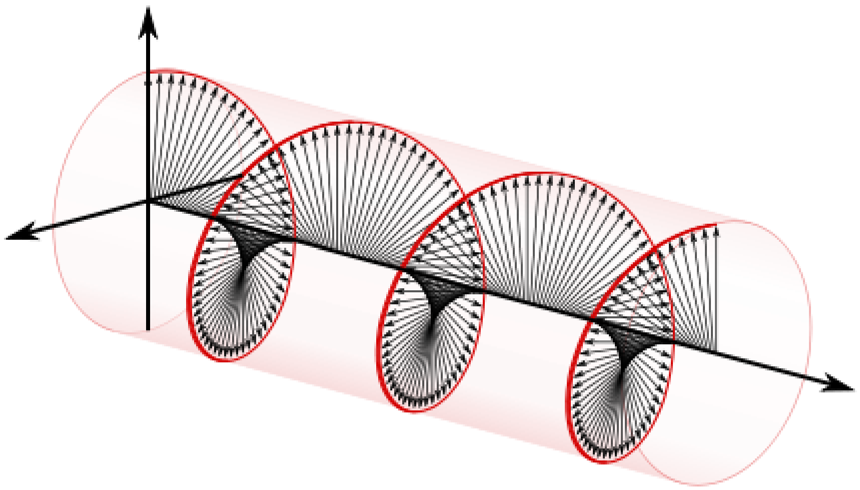


Electric field in a circular polarized electromagnetic wave keeps rotating as the wave propagates

- **Right-handed polarization**



- **Left-handed polarization**



https://en.wikipedia.org/wiki/Circular_polarization

Only right-handed polarization can resonance with electron's gyromotion

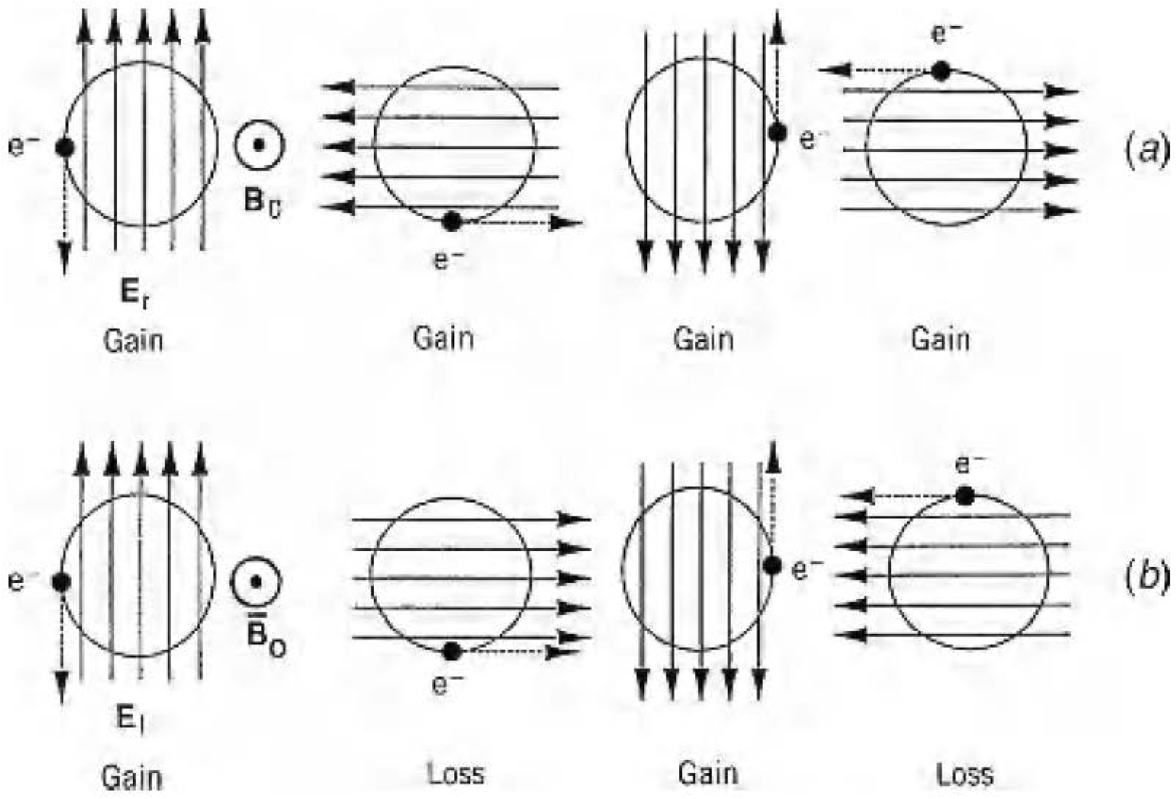
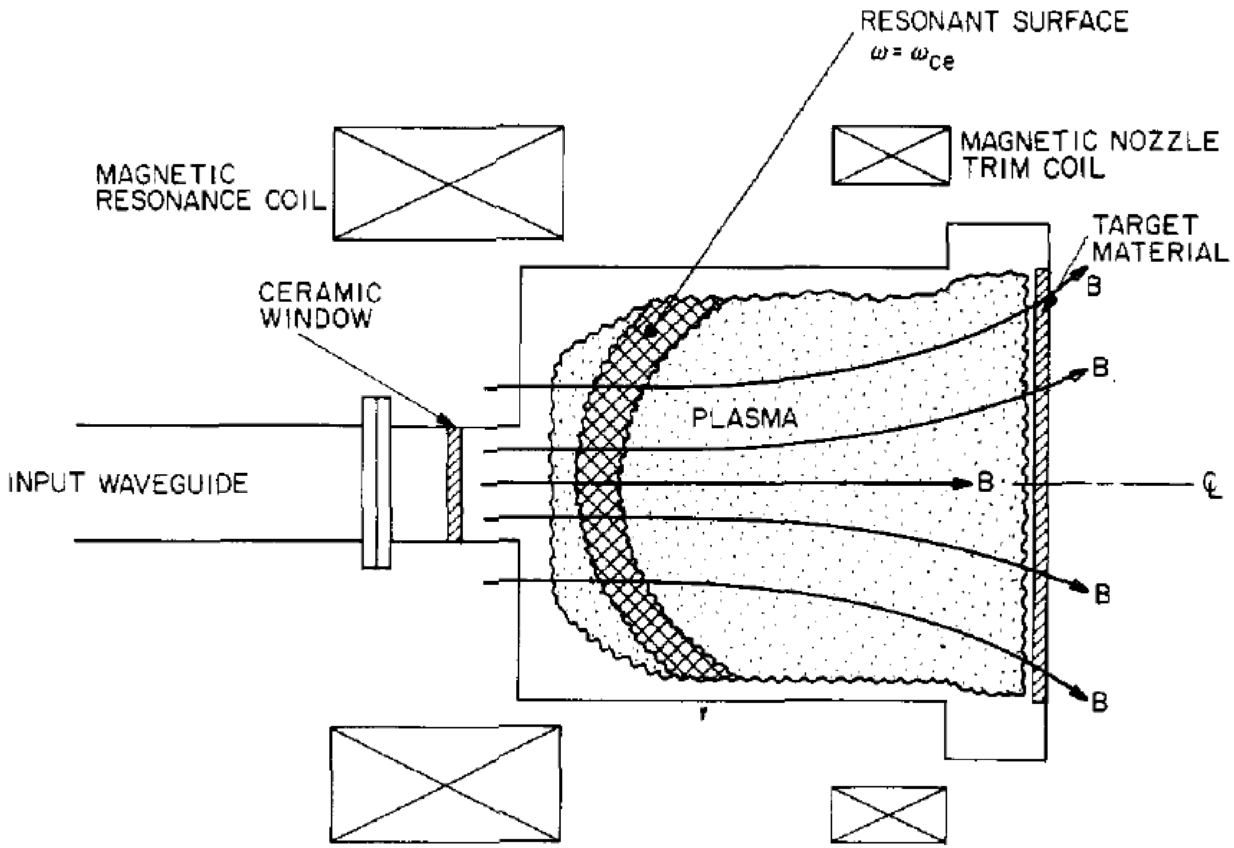


FIGURE 13.5. Basic principle of ECR heating: (*a*) continuous energy gain for right-hand polarization; (*b*) oscillating energy for left-hand polarization (after Lieberman and Gottscho, 1994).

Strong absorption occurs when the frequency matches the electron cyclotron frequency

- **Electron cyclotron resonance (ECR) plasma reactor**



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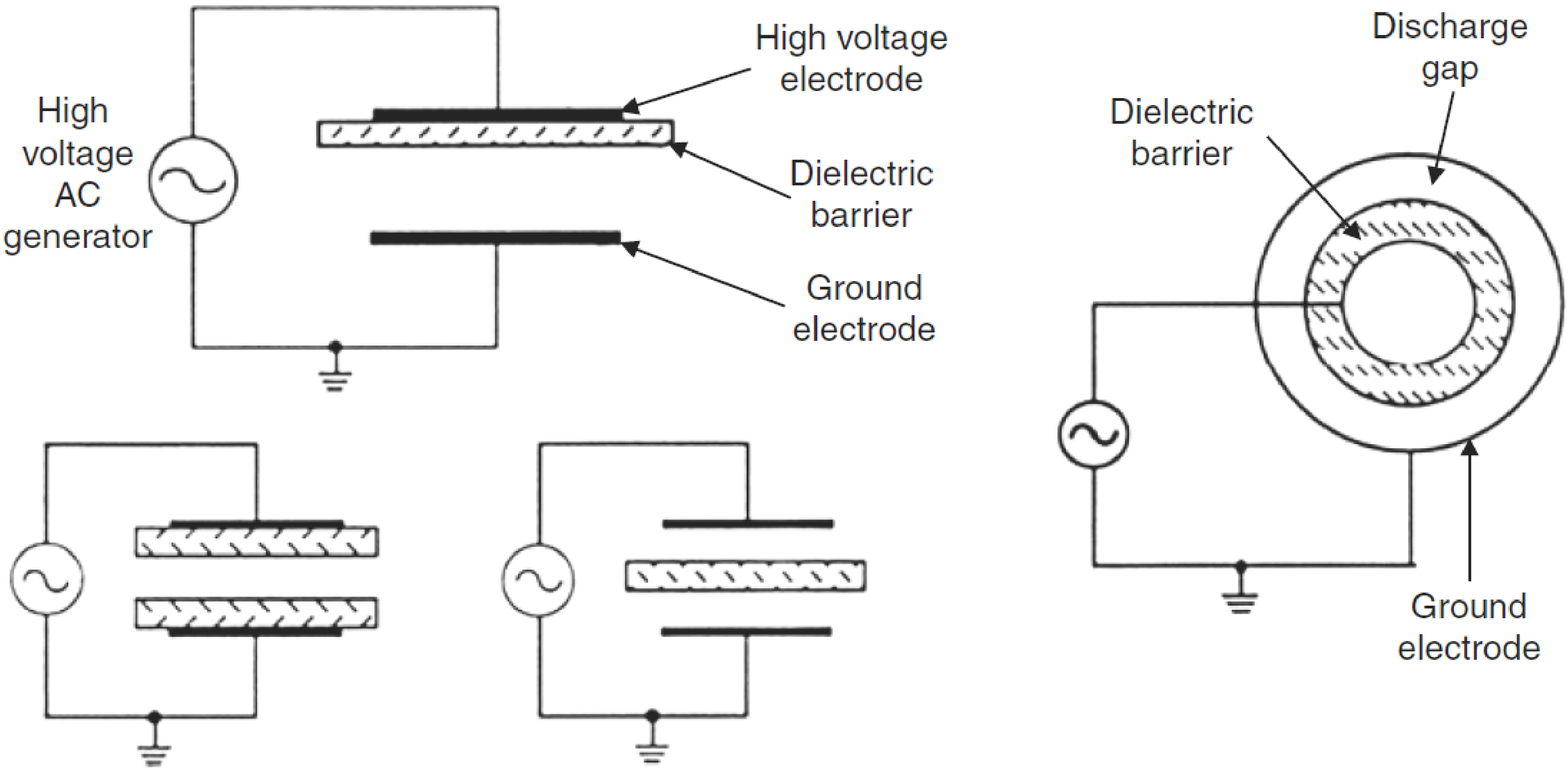
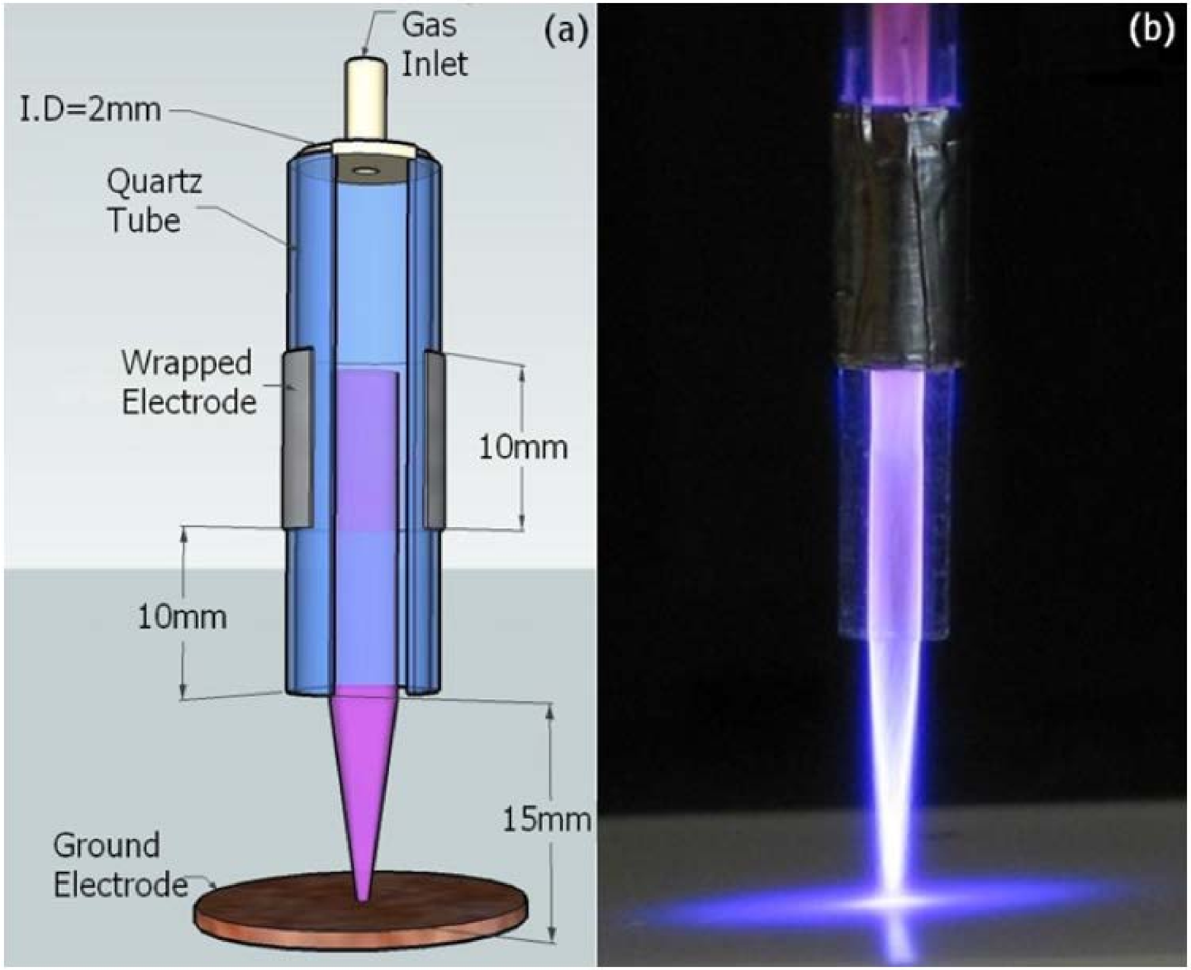
Dielectric-barrier discharges (DBDs)

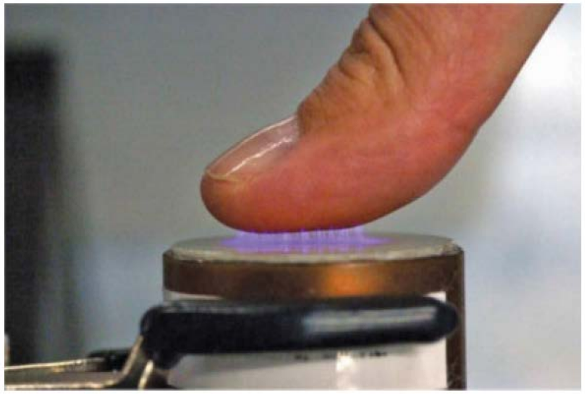


Atmospheric-pressure cold helium microplasma jets



J. L. Walsh, *et al.*, J. Phys. D: Appl. Phys., **43**, 075201 (2010)

Atmospheric-Pressure Plasma



https://www.itri.org.tw/chi/Content/Publications/contents.aspx?SiteID=1&MmmID=2000&MSid=745416417706673311
Plasma medicine, by Alexander Fridman and Gary Friedman

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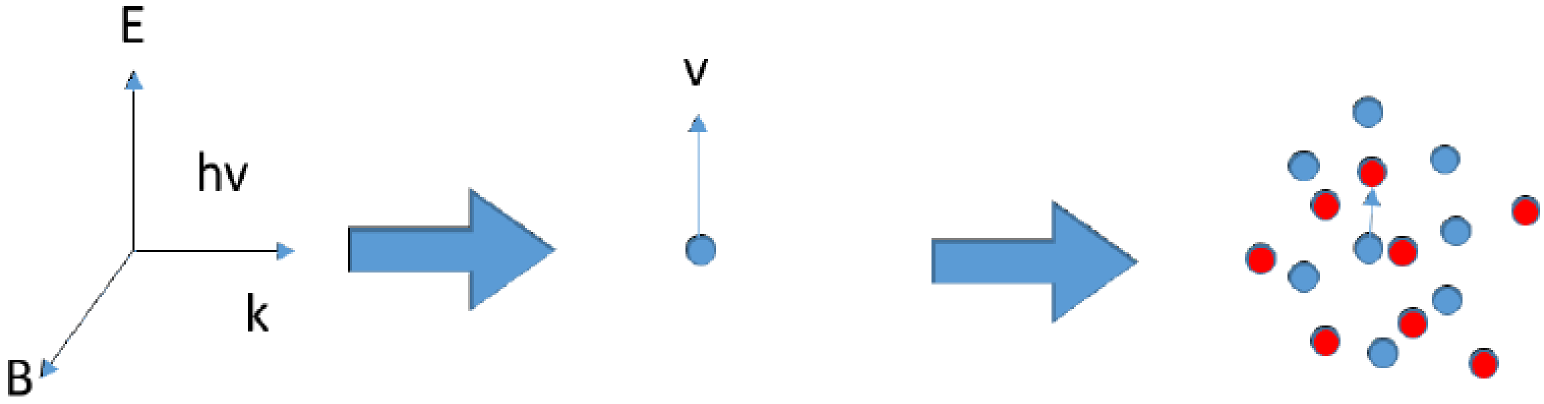
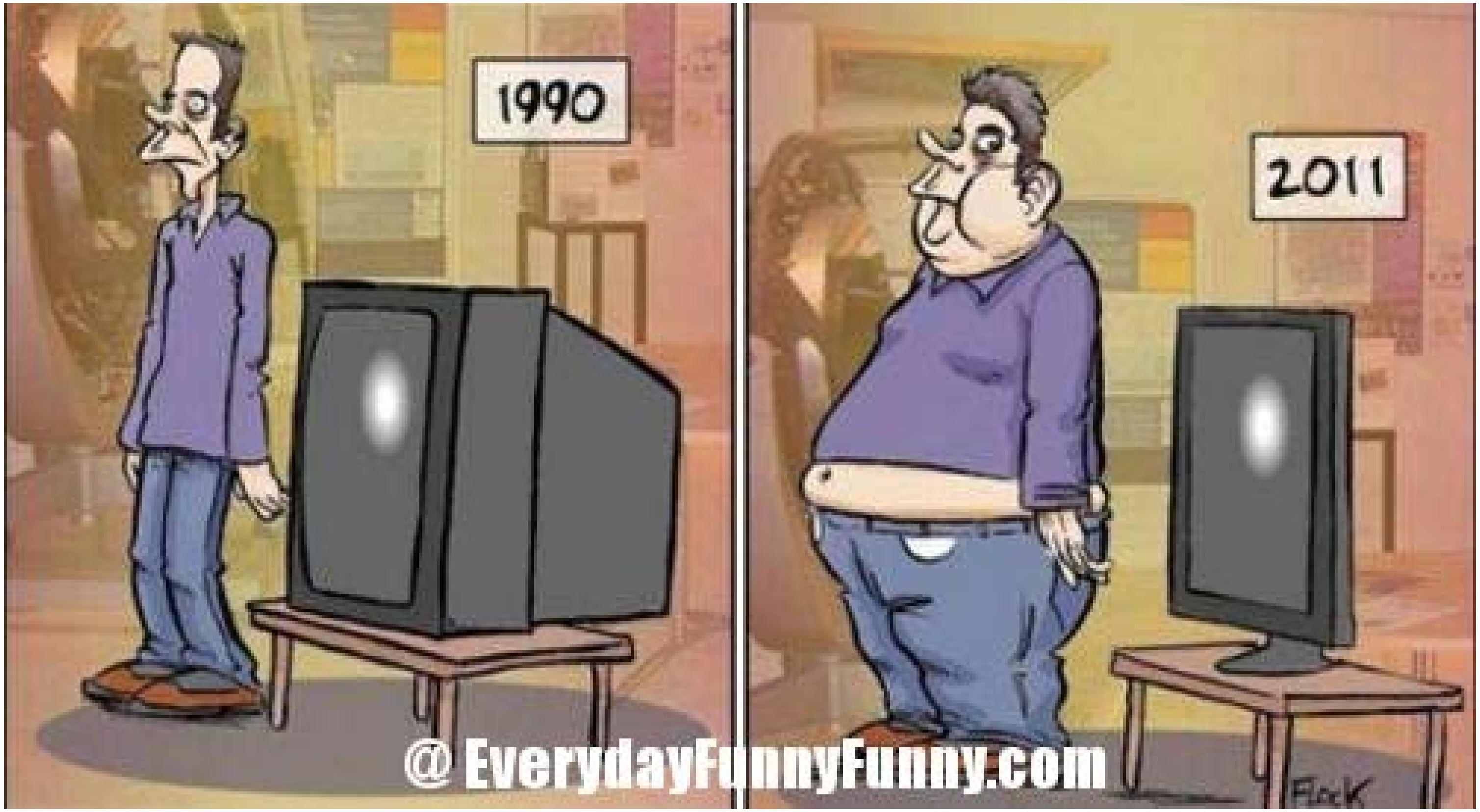
Laser is absorbed in underdense plasma through collisional process called inverse bremsstrahlung



Electrons accelerated by electric fields

Electrons collide with other electrons / ions

Let’s stand up and do exercise!!



Course Outline

1. **Introduction to plasma**
    a. What is Plasma?
    b. How to generate plasma
    c. **Applications of plasma**
2. Theory of Langmuir probe
    a. Sheath
    b. Single Langmuir probe
    c. Double Langmuir probe
    d. Triple Langmuir probe
3. Demonstration of Langmuir probe
    a. Building vacuum systems
    b. Building Langmuir probes
    c. Measuring temperatures and densities of plasma

Day 1~3

Day 4~5: Experiments

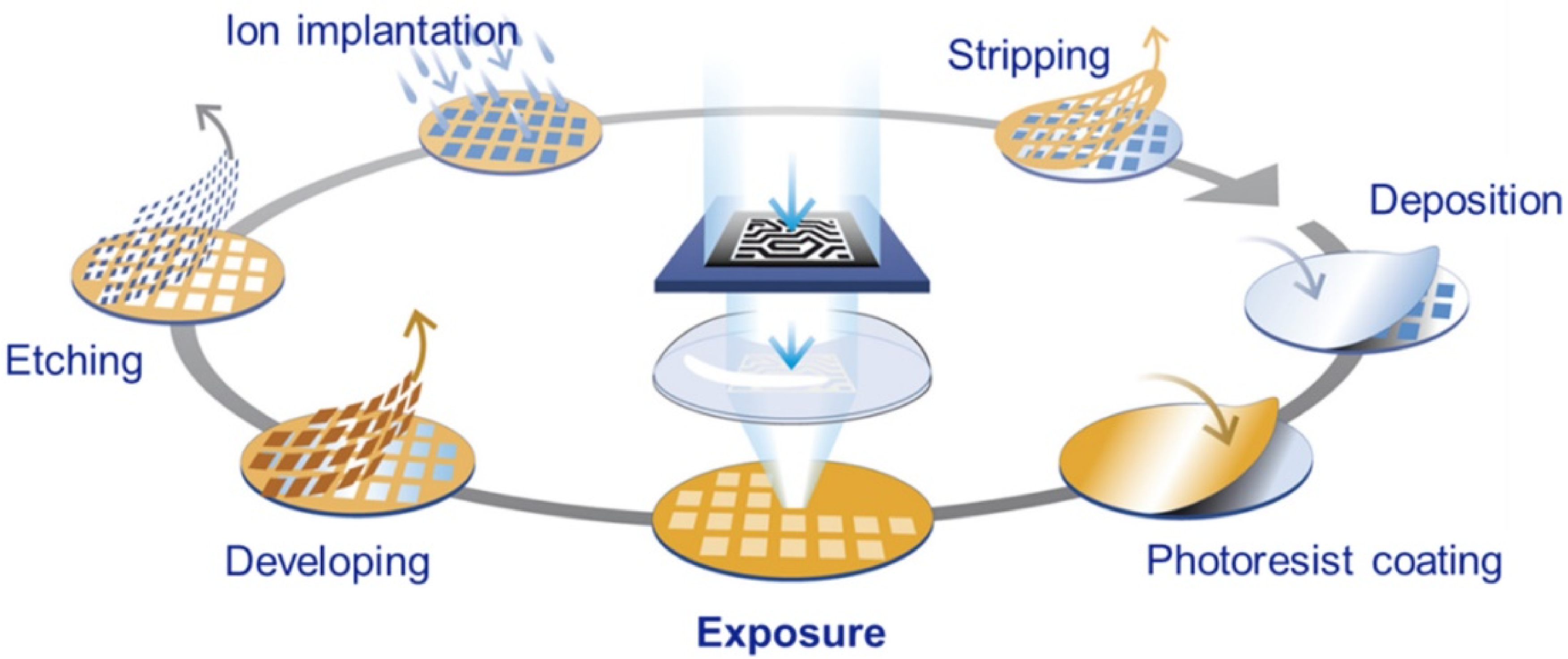
Applications of plasma

1. Material Processing
2. Plasma in space
3. Biomedical application
4. High energy particle accelerator
5. Electric propulsion
6. Controlled thermonuclear fusion

Applications of plasma

1. **Material Processing**
2. **Plasma in space**
3. **Biomedical application**
4. **High energy particle accelerator**
5. **Electric propulsion**
6. **Controlled thermonuclear fusion**

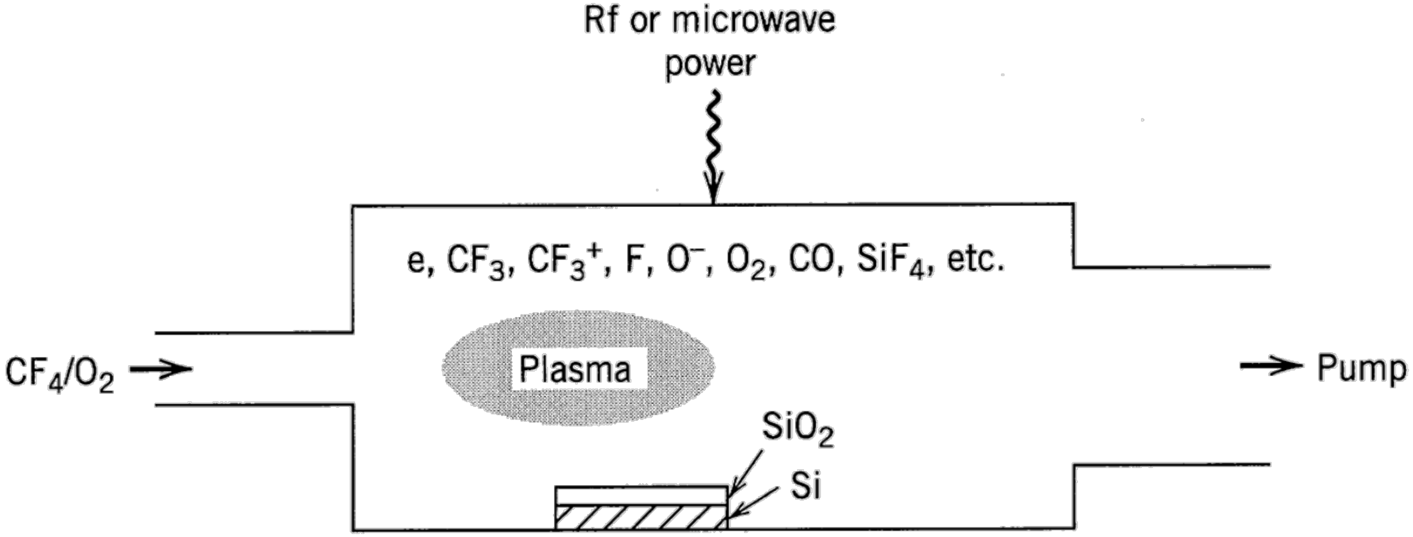
A semiconductor device is fabricated by many repetitive production process



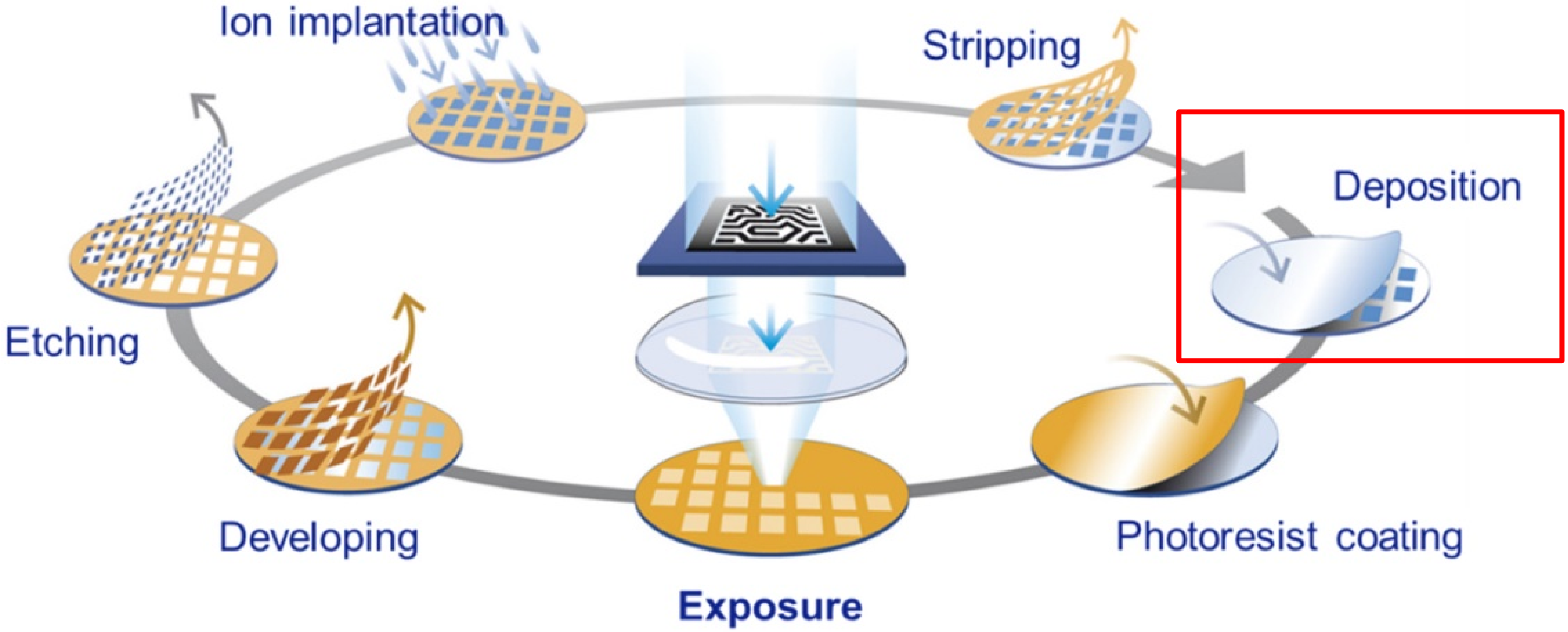
Surf. Topogr.: Metrol. Prop. **4** (2016) 023001

Reference for material processing

- Principles of plasma discharges and materials processing, 2nd edition, by Michael A. Lieberman and Allan J. Lichtenberg
- http://www.eecs.berkeley.edu/~lieber/
- Materials science of thin films, 2nd edition, by Milton Ohring
- Plasma etching, by Dennis M. Manos and Daniel L. Flamm
- Industrial plasma engineering, volume 1, by J. Reece Roth



A semiconductor device is fabricated by many repetitive production process



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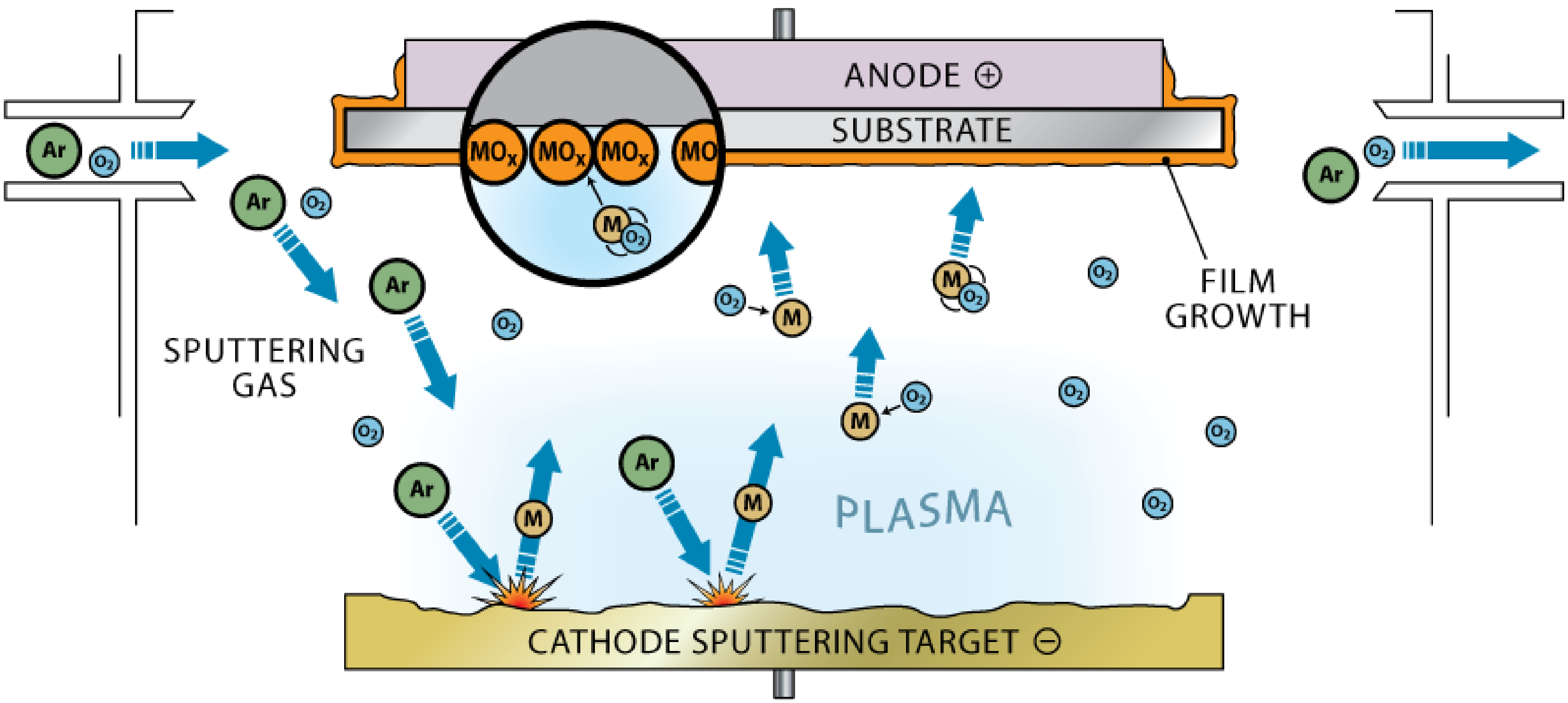
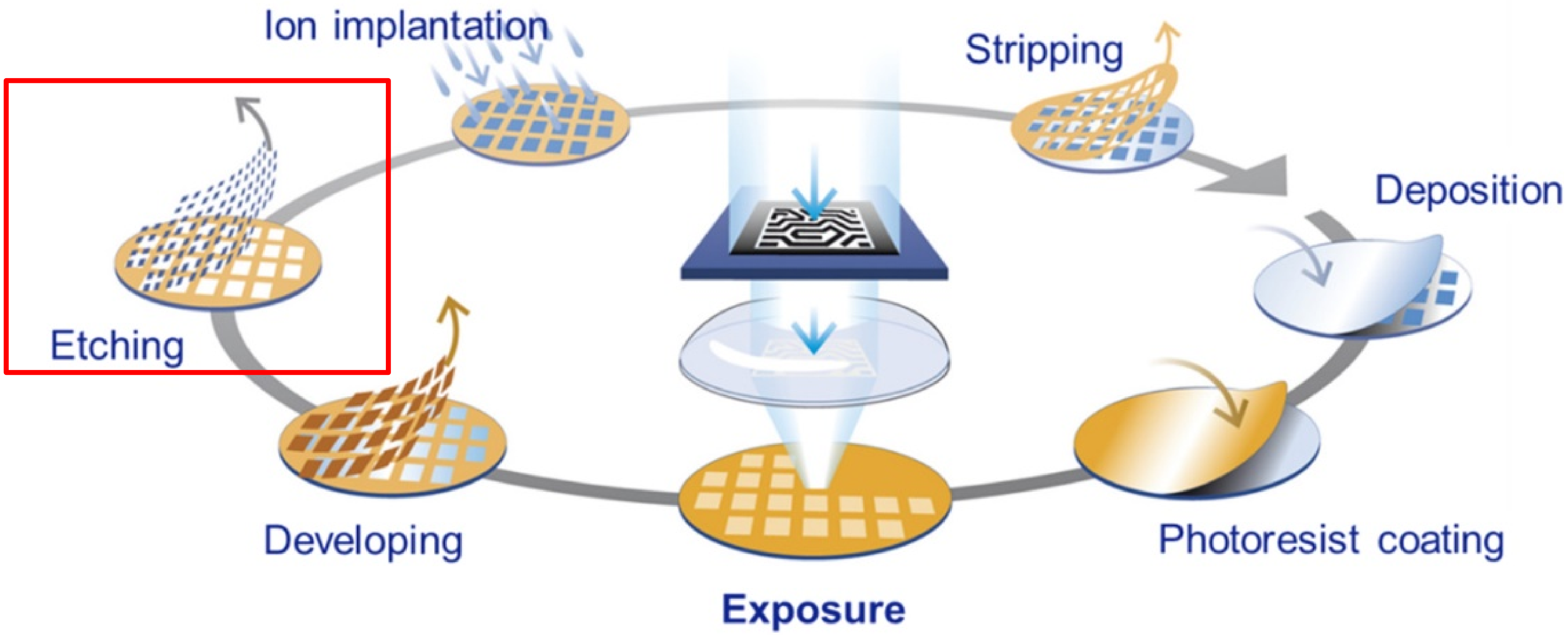
Sputtering deposition



http://lnf-wiki.eecs.umich.edu/wiki/Sputter_deposition

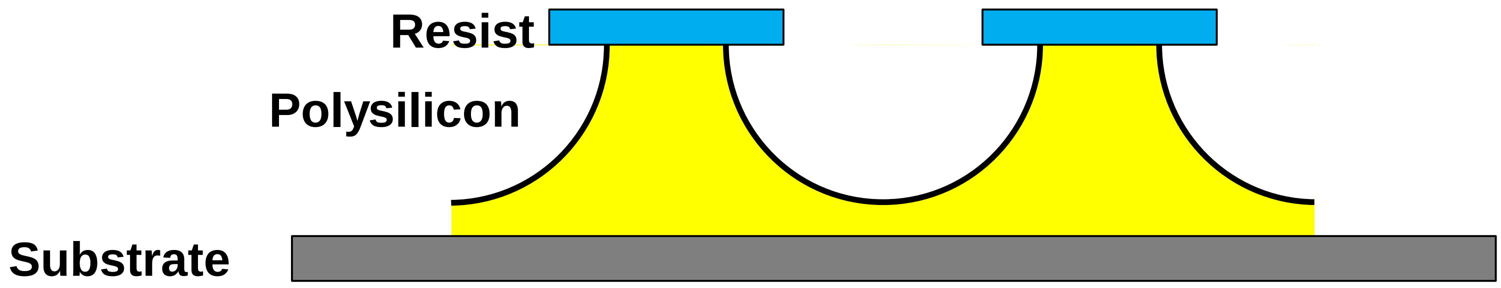
A semiconductor device is fabricated by many repetitive production process



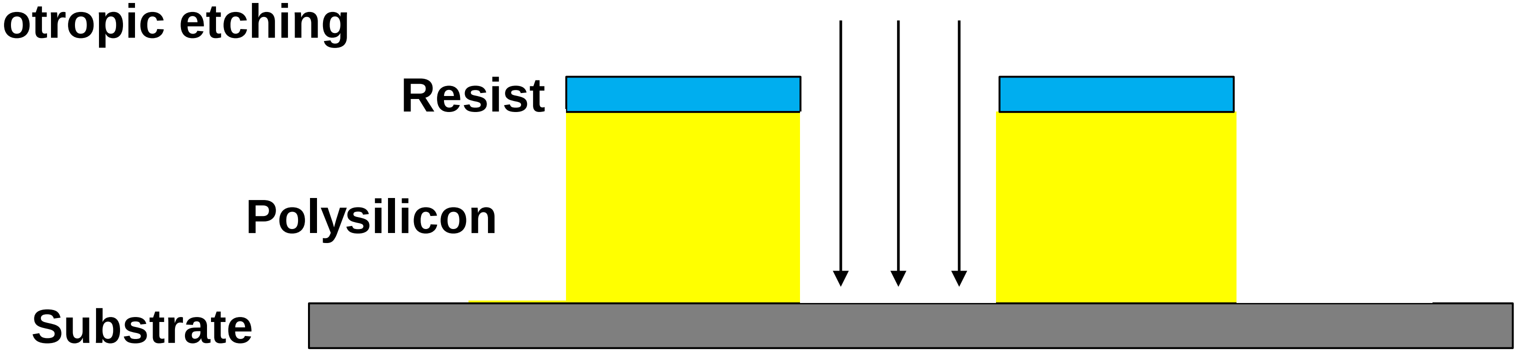
Surf. Topogr.: Metrol. Prop. **4** (2016) 023001

There are two types of etching: isotropic vs anistropic

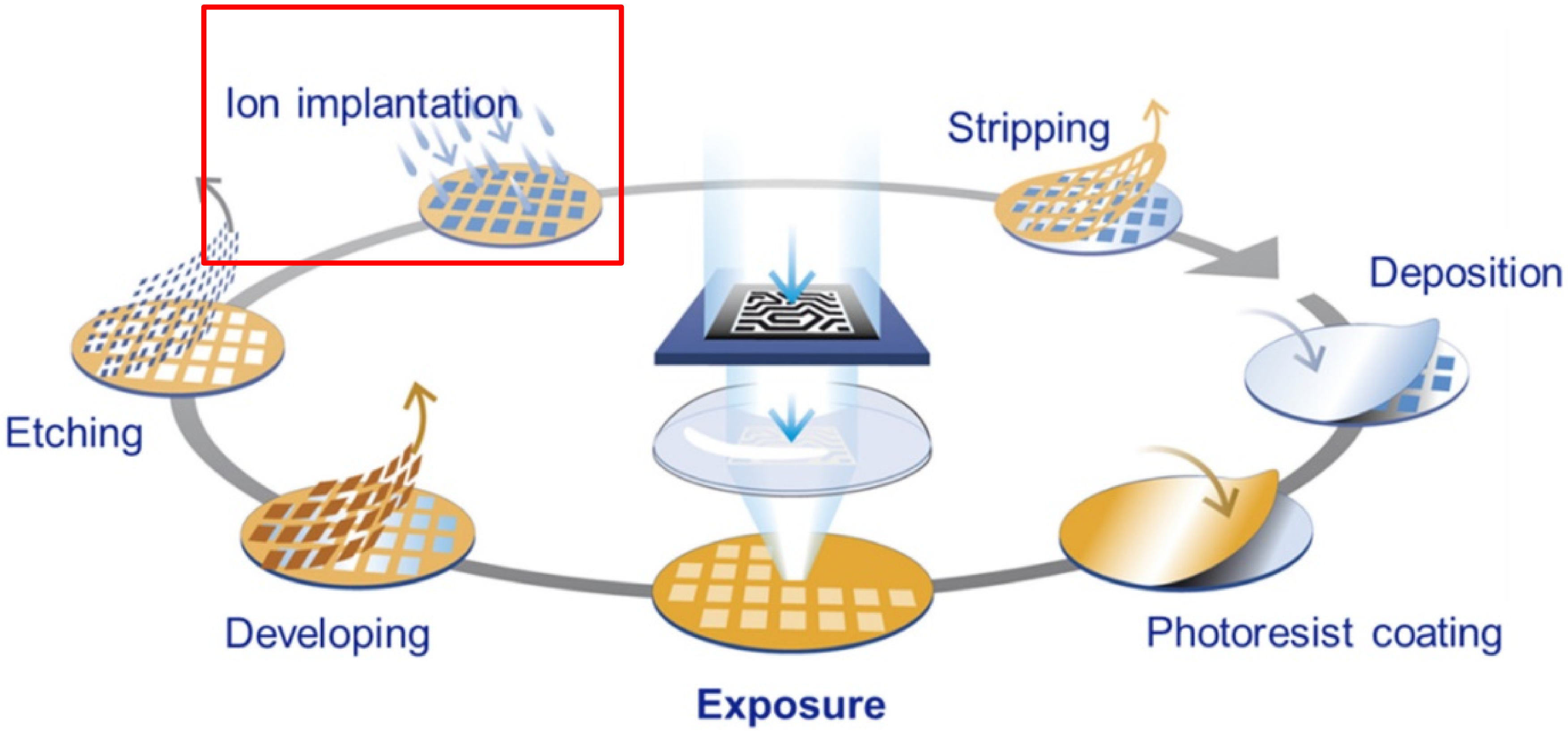
- **Isotropic etching**



- **Anisotropic etching**

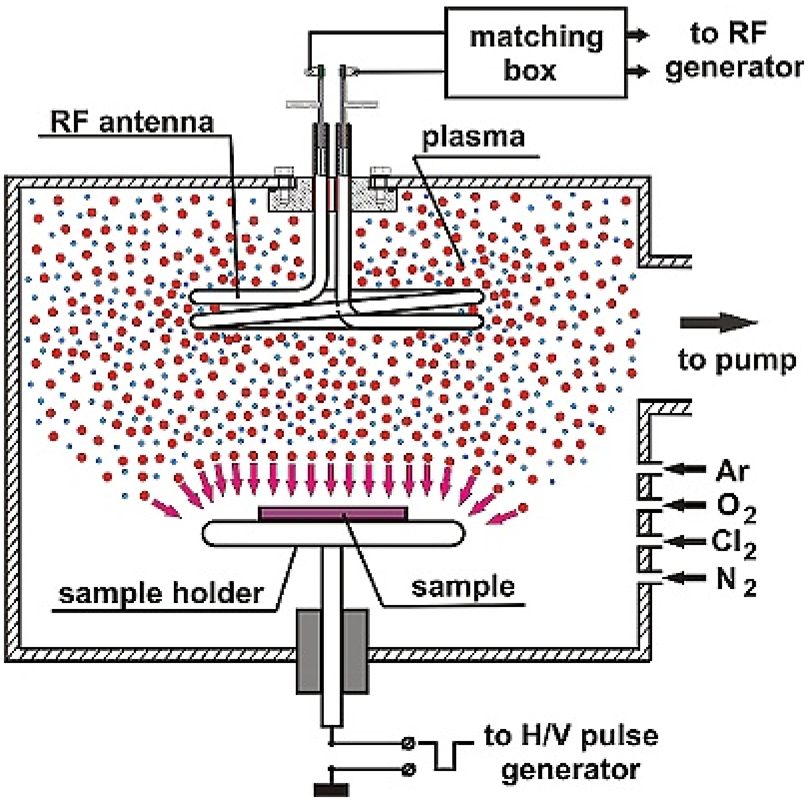


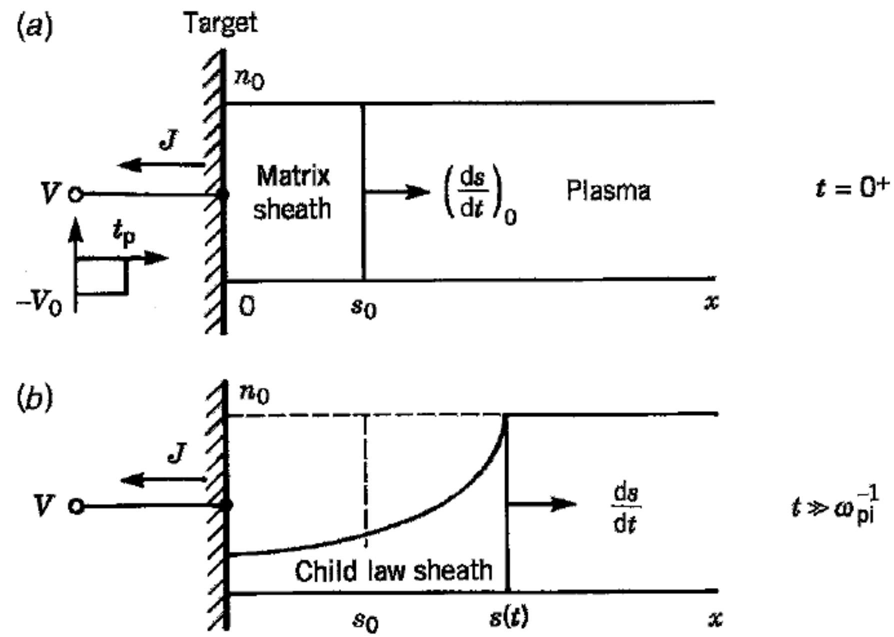
A semiconductor device is fabricated by many repetitive production process



Surf. Topogr.: Metrol. Prop. **4** (2016) 023001

Plasma-immersion ion implantation (PIII)

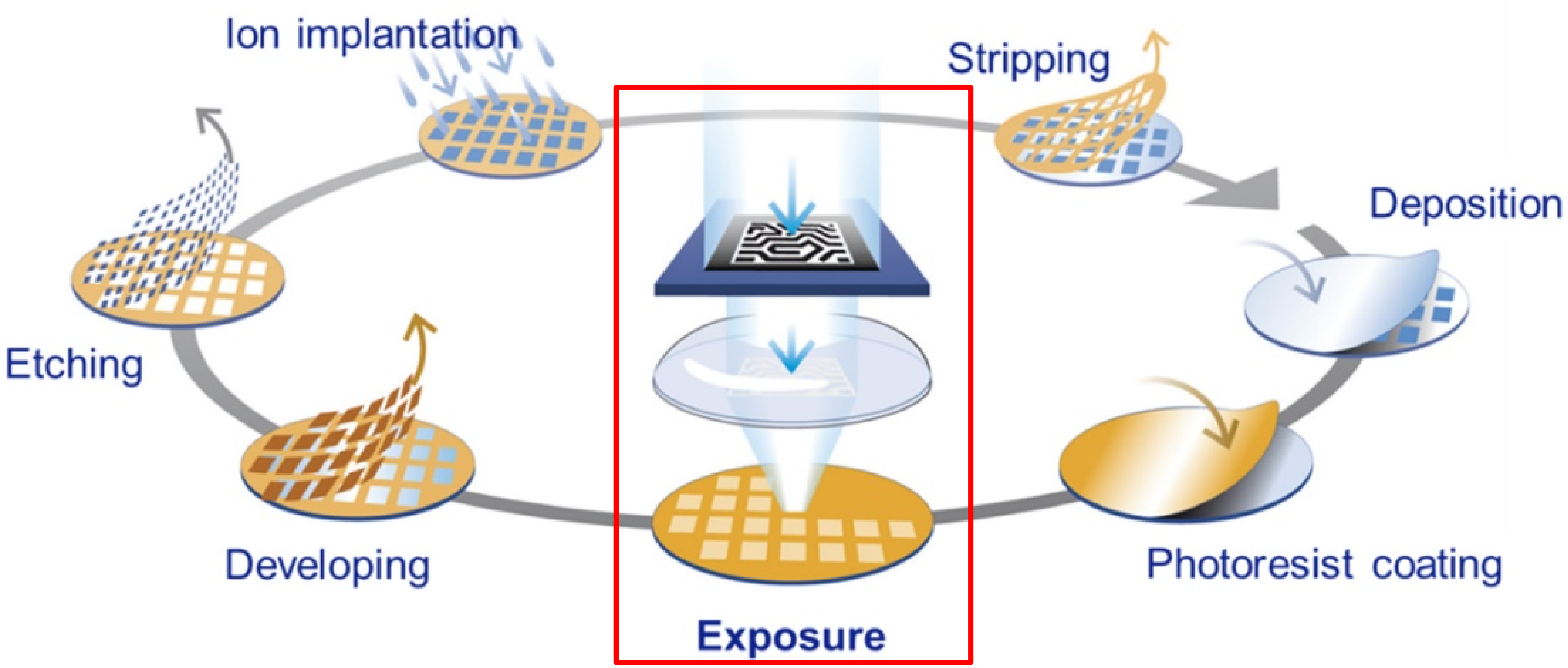




- **Silicon doping – ions such as B, P, As are implanted**
- **Surface hardening of metals – N, C are implanted**

https://www.hzdr.de/db/Cms?pOid=10890&pNid=306

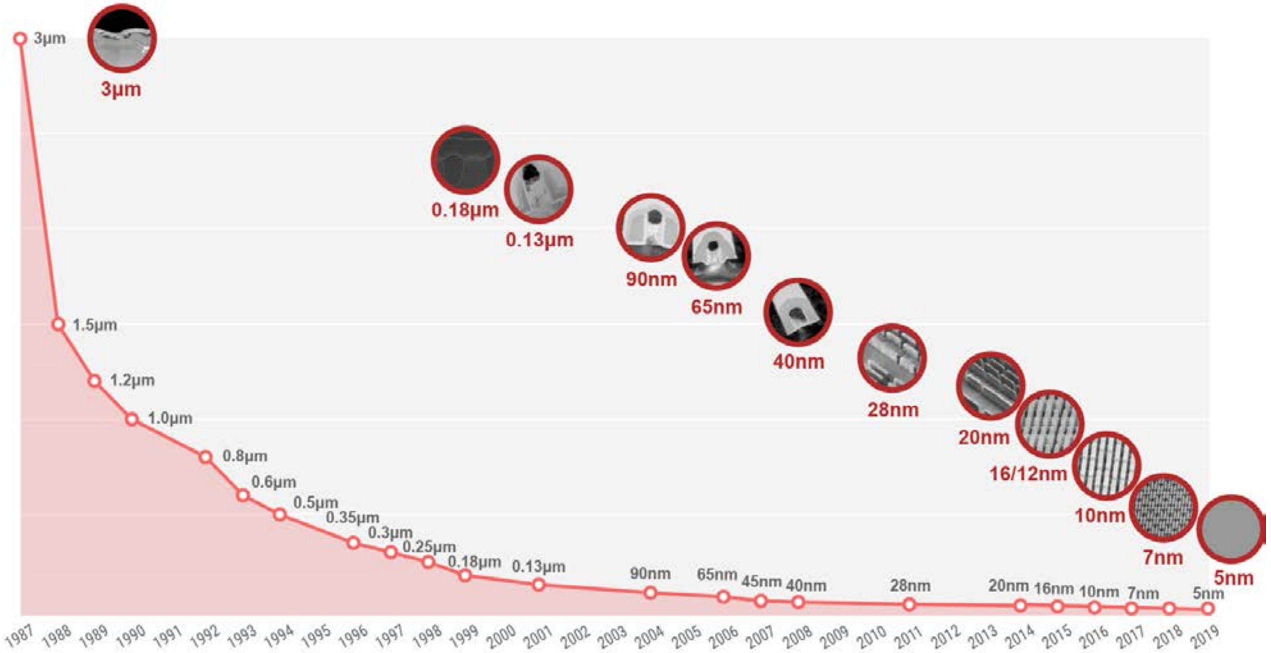
A semiconductor device is fabricated by many repetitive production process



Surf. Topogr.: Metrol. Prop. **4** (2016) 023001

Ultraviolet lithography (EUVL) is one of the key technologies in semiconductor manufacturing nowadays

- **The process technology of Taiwan Semiconductor Manufacturing Company Limited (TSMC):**



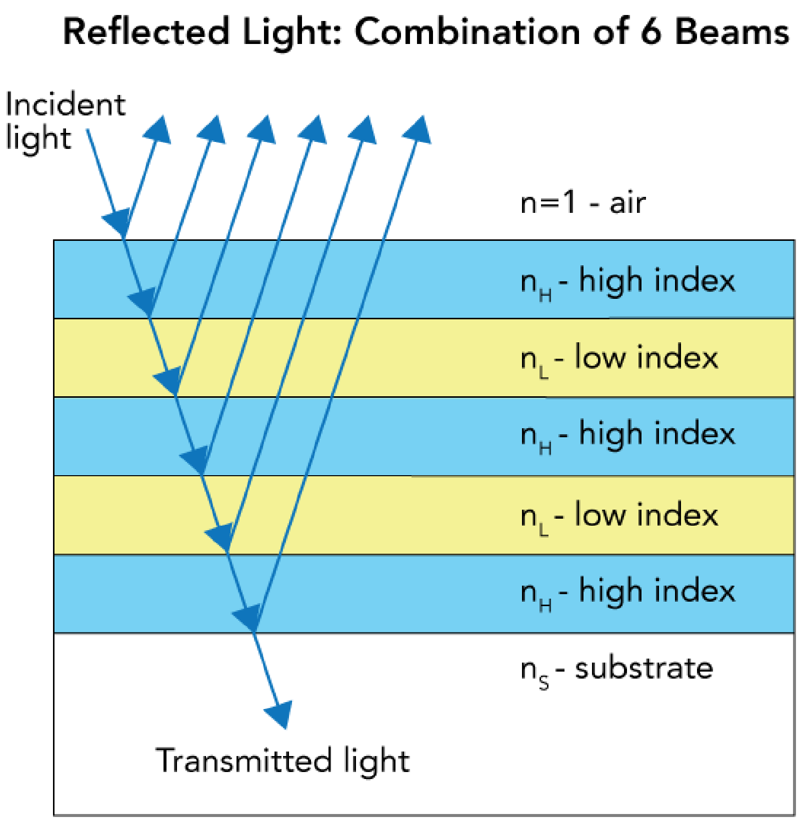
- **Optical diffraction needs to be taken into account.**
- **Shorter wavelength is preferred.**

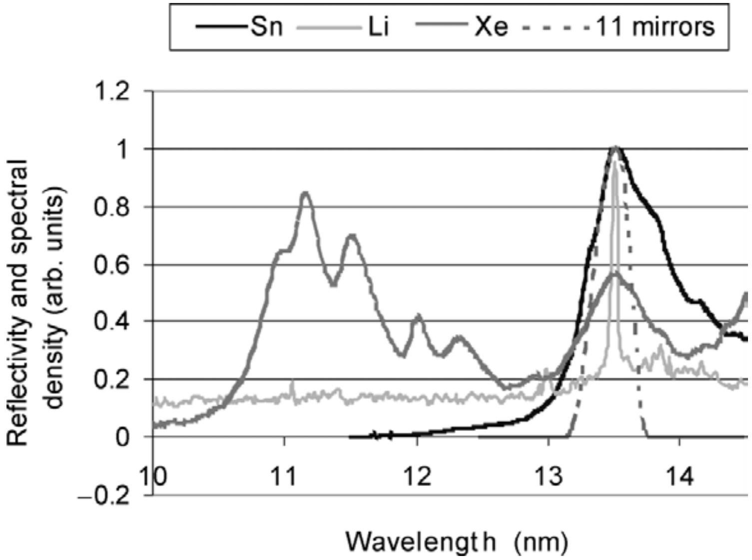
- **Light source with a center wavelength of 13.5 nm is used.**

https://www.tsmc.com/chinese/dedicatedFoundry/technology/logic.htm

EUV light with λ=13.5 nm is used

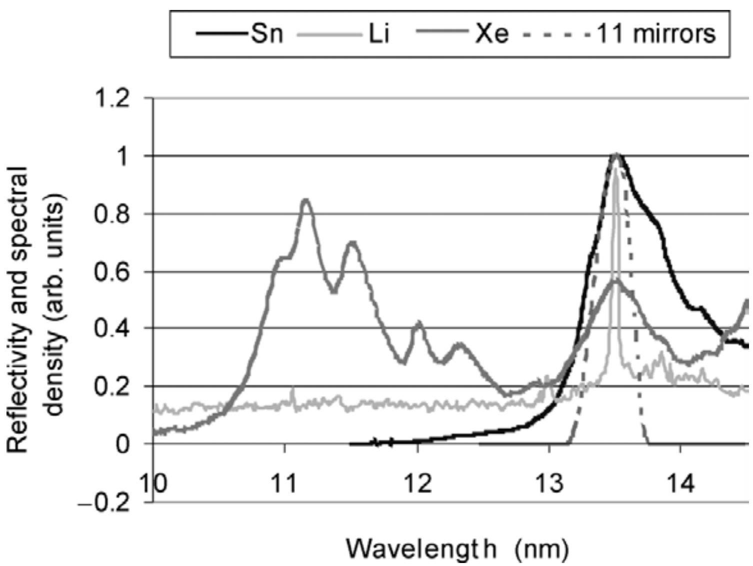
- **Multilayer mirrors is needed for reflecting EUV light.**





https://www.edmundoptics.com/knowledge-center/trending-in-optics/extreme-ultraviolet-optics/
V. Bakshi, EUV sources for lithography

EUV light is generated when material is heated to 35~40 eV (~450,000 K)

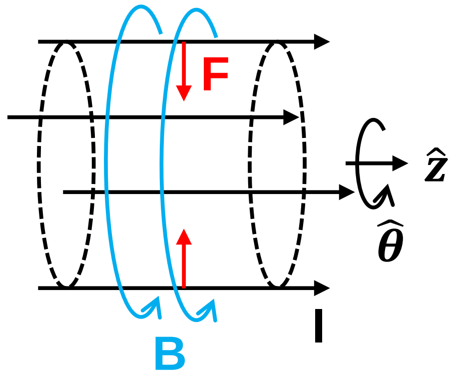


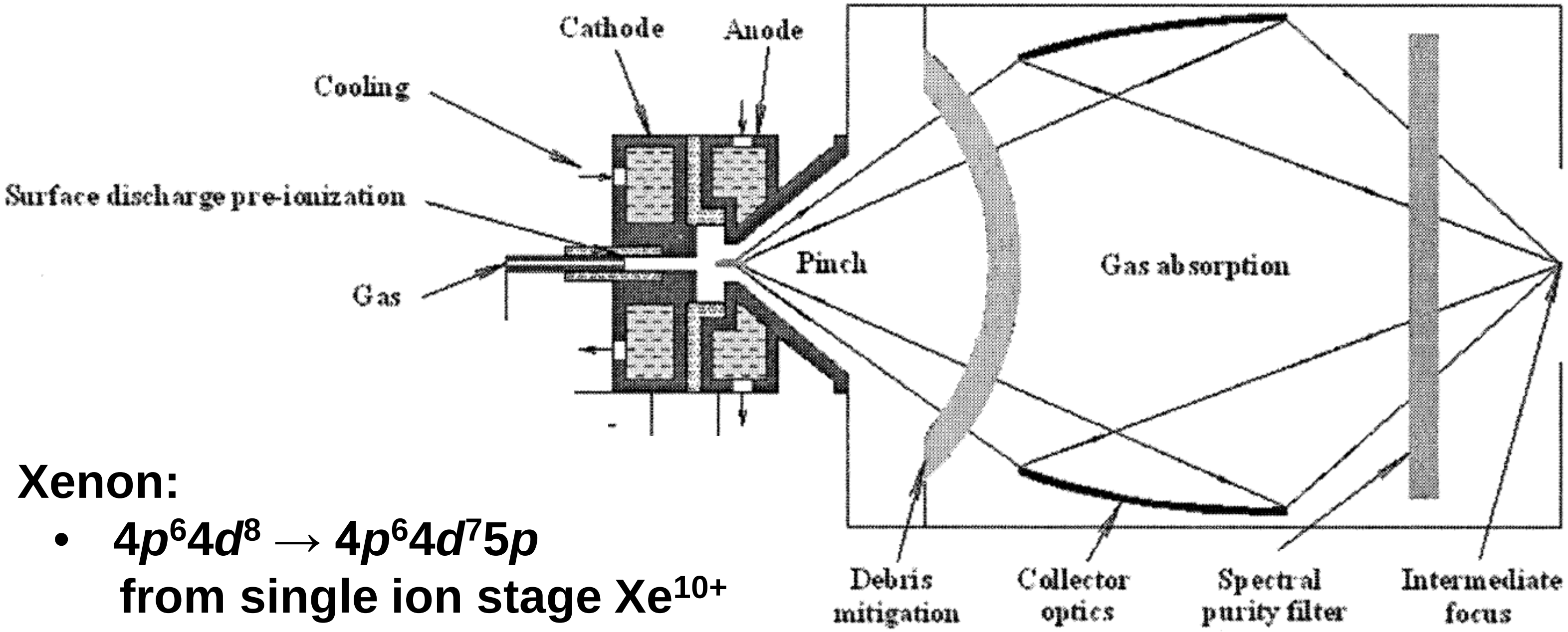
- **At T=35-40 eV (~450,000 K), in-band emission occurs.**
- **Xenon:**
  - **$4p^6 4d^8 \rightarrow 4p^6 4d^7 5p$ from single ion stage Xe^{10+}**
  - **UTA @ 11 nm**
- **Tin:**
  - **$4p^6 4d^N \rightarrow 4p^5 4d^{N+1} + 4p^6 4d^{N-1} 4f$ ($1 \leq N \leq 6$) in ions ranging from Sn^{8+} to Sn^{12+}**
  - **UTA @ 13.5 nm**

- UTA: unresolved transition array

V. Bakshi, EUV sources for lithography

Material can be heated via z pinches

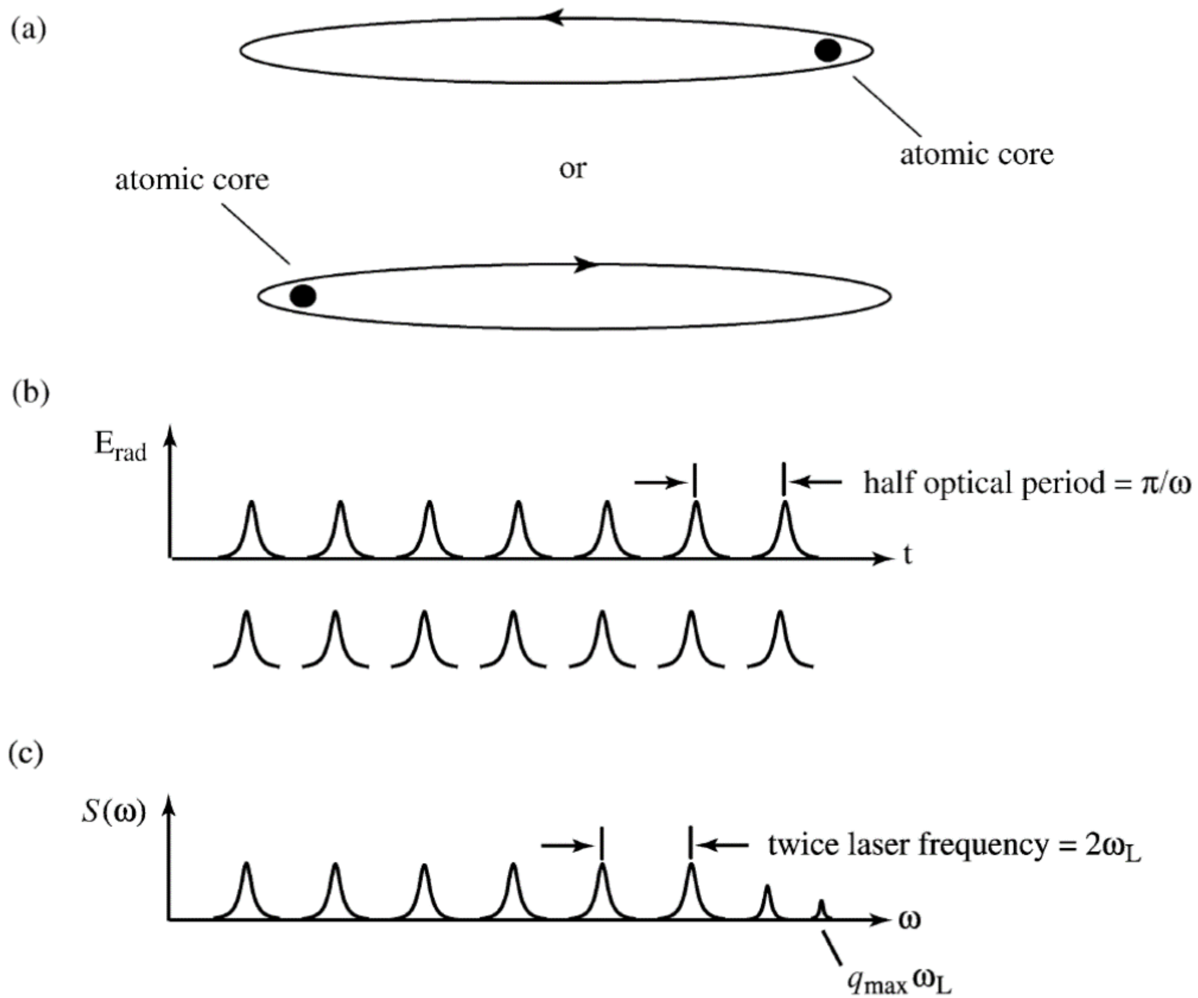




- **Xenon:**
  - ***$4p^64d^8 \rightarrow 4p^64d^75p$***
    from single ion stage Xe^{10+}
  - **UTA @ 11 nm**

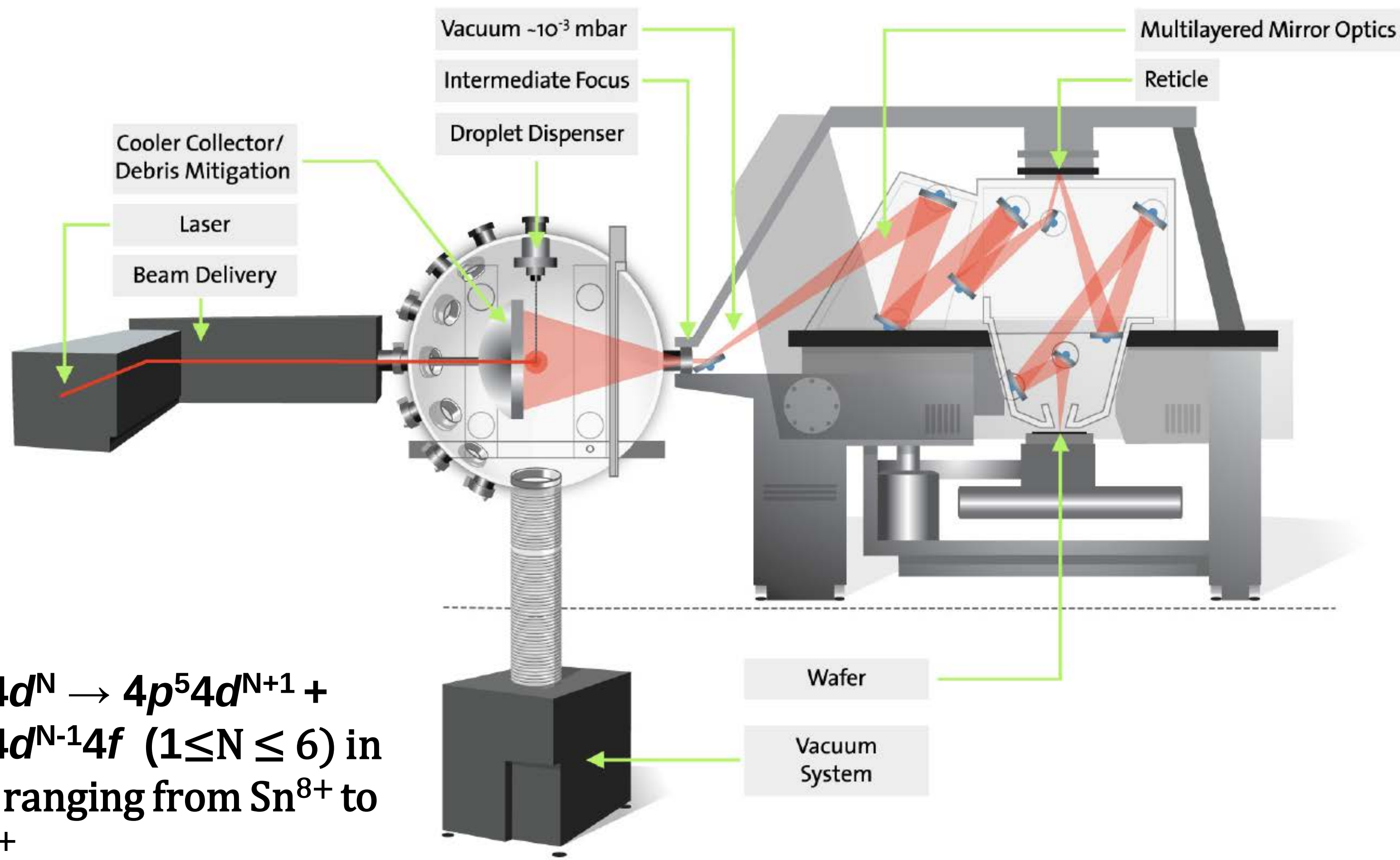
V. M. Borisov, etc., J. Phys. D: Appl. Phys., **37**, 3254 (2004)

EUV light can be generated via high-harmonic generations



Robert Boyd. Nonlinear optics. Academic Press, Amsterdam Boston, 2008

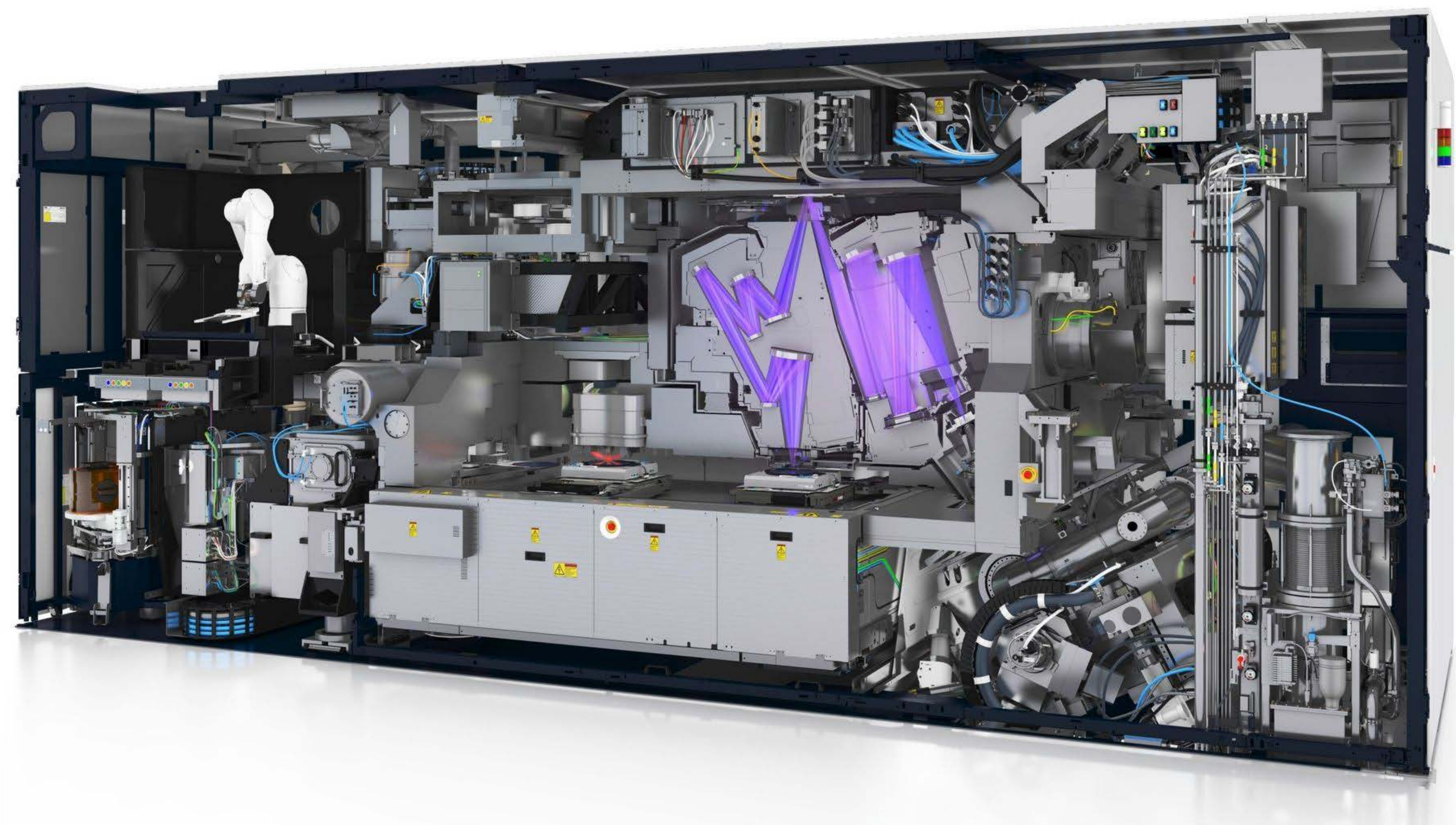
EUV light sources from laser-produced plasma (LPP)



- **Tin:**
  - $4p^6 4d^N \rightarrow 4p^5 4d^{N+1} + 4p^6 4d^{N-1} 4f$ $(1 \leq N \leq 6)$ in ions ranging from Sn^{8+} to Sn^{12+}
  - **UTA @ 13.5 nm**

R. S. Abhari, etc., J. Micro/Nanolithography, MEMS, and MOEMS, 11, 021114 (2012)

EUV lithography by ASML



https://www.asml.com/news/stories/2020/asml-wins-semi-americas-award-for-euv

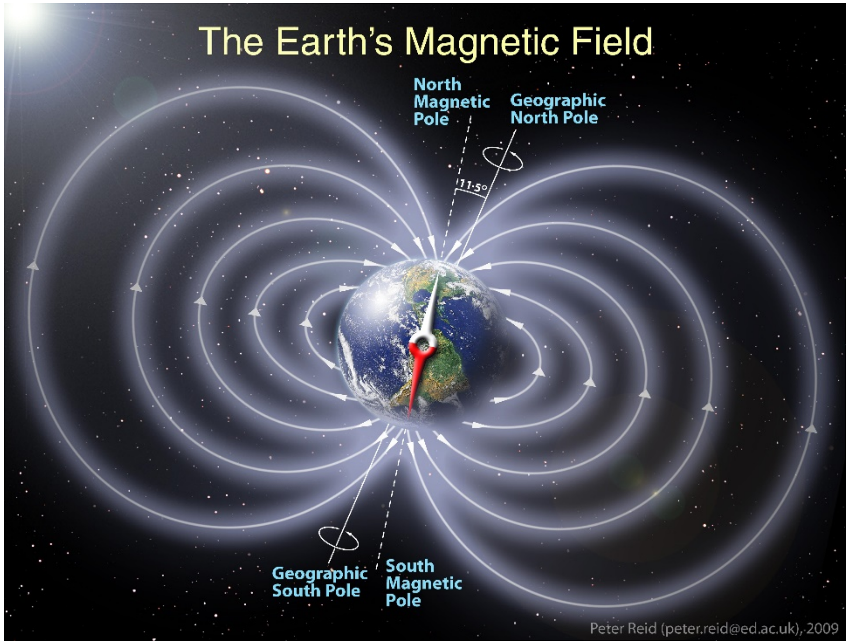
The price of each EUV lithography system is more than 4,000,000,000 NTD !

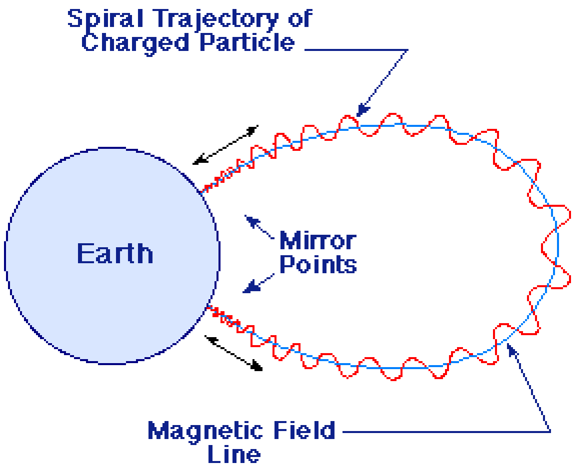
https://fnc.ebc.net.tw/fncnews/life/123737

Applications of plasma

1. Material Processing
2. **Plasma in space**
3. Biomedical application
4. High energy particle accelerator
5. Electric propulsion
6. Controlled thermonuclear fusion

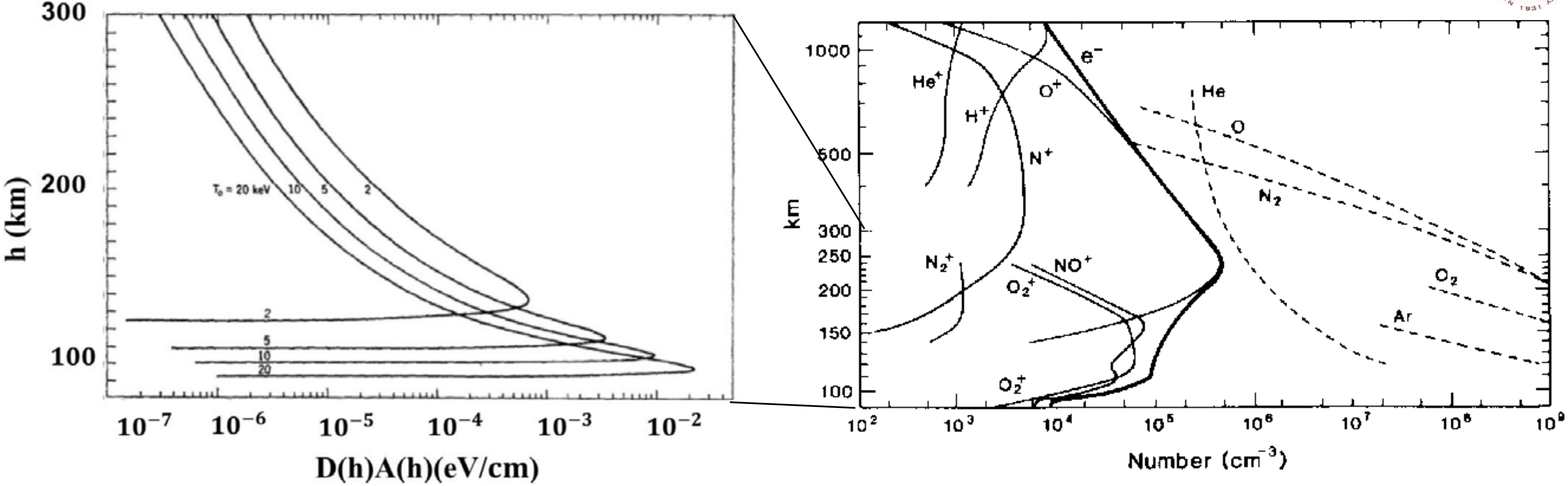
Earth’s magnetic field



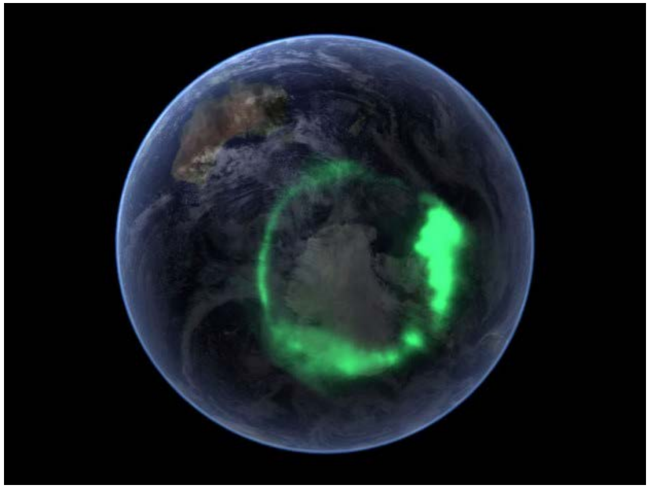


https://www.nasa.gov/mission_pages/sunearth/news/gallery/Earths-magneticfieldlines-dipole.html
http://www.pas.rochester.edu/~blackman/ast104/emagnetic.html

Aurora occurs when energetic electrons penetrating into atmosphere in the pole regions



- O_2: green or dark red
- N_2: blue or purple



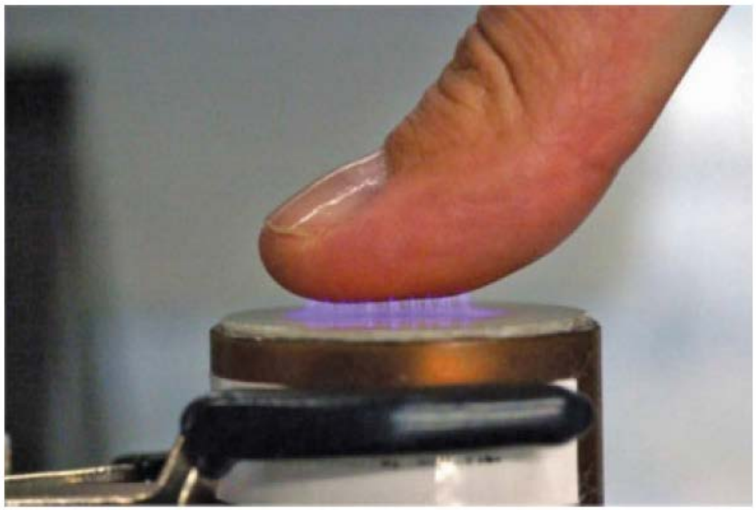
J. Atoms Terr. Phys., **32** (1970) 1015-1045
Johnson, 1969; Luhmann, 1995

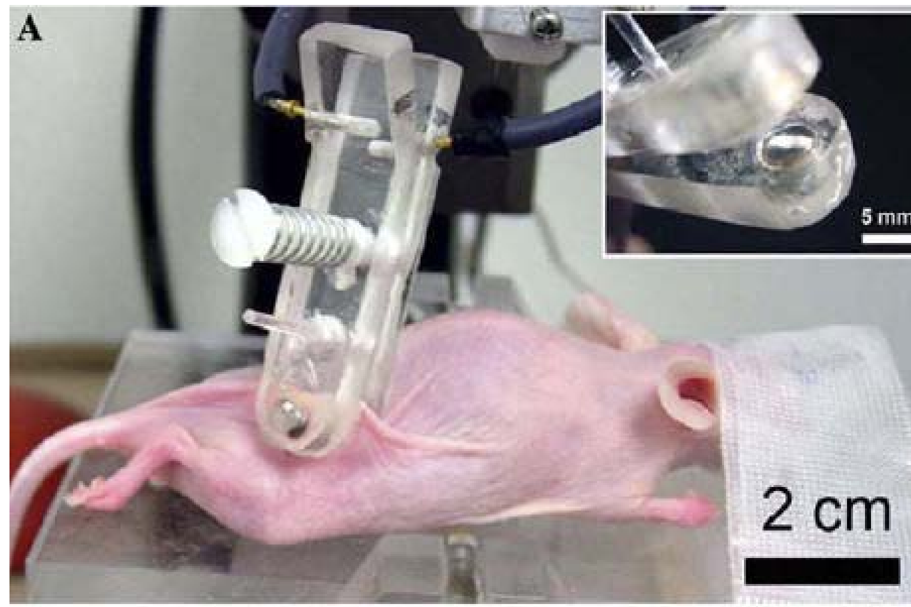
https://flashpack.com/insights/2014/11/20/aurora-australis-forget-the-northern-lights-have-you-heard-about-the-southern-lights/

Applications of plasma

1. Material Processing
2. Plasma in space
3. **Biomedical application**
4. High energy particle accelerator
5. Electric propulsion
6. Controlled thermonuclear fusion

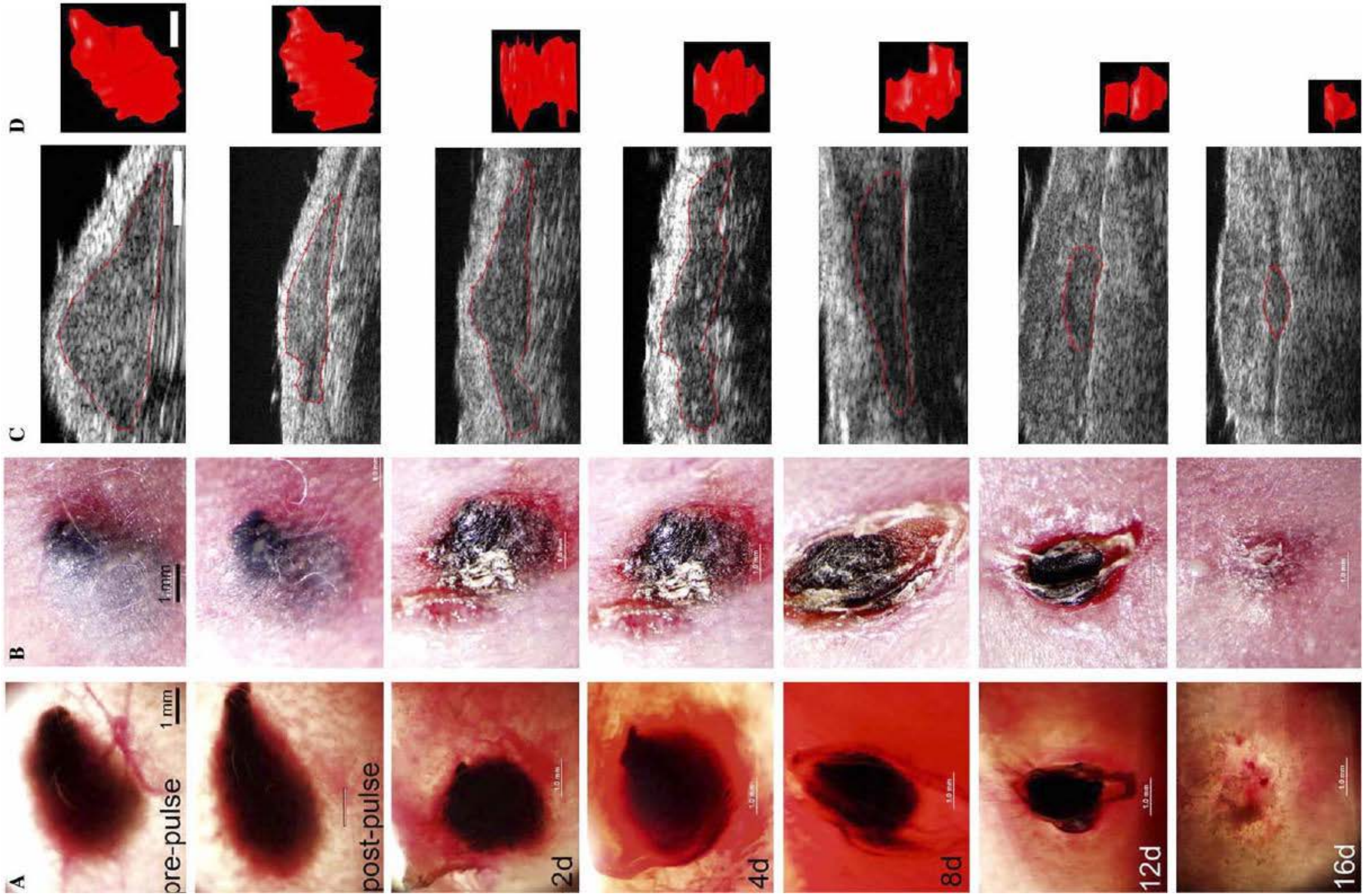
低溫電漿可應用在醫療保健上





Plasma medicine, by Alexander Fridman and Gary Friedman
Biochem Biophys Res Commun. 2006 May 5; 343(2): 351–360.

Melanoma shrinks after the treatment



- **Day 0-3: 3 applications of 100 pulses (300 ns, 40 kv/cm, 0.5 Hz), 30 min apart**
- **Day 4: single application using 5 mm diameter parallel plate electrode**

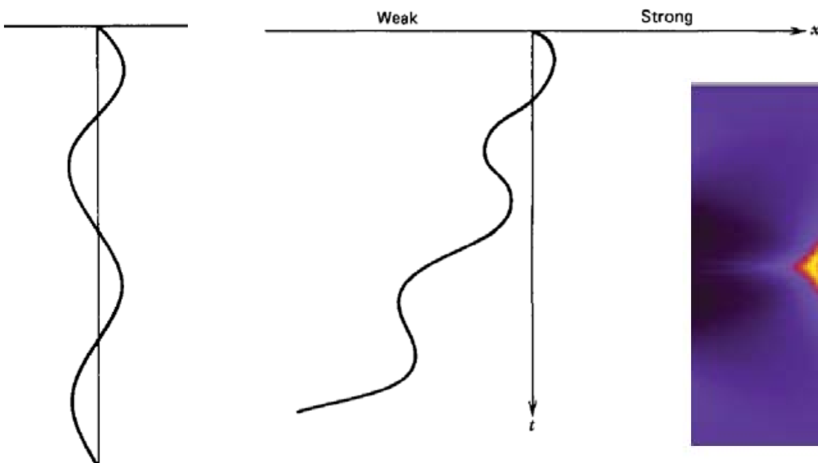
Biochem Biophys Res Commun. 2006 May 5; 343(2): 351–360.

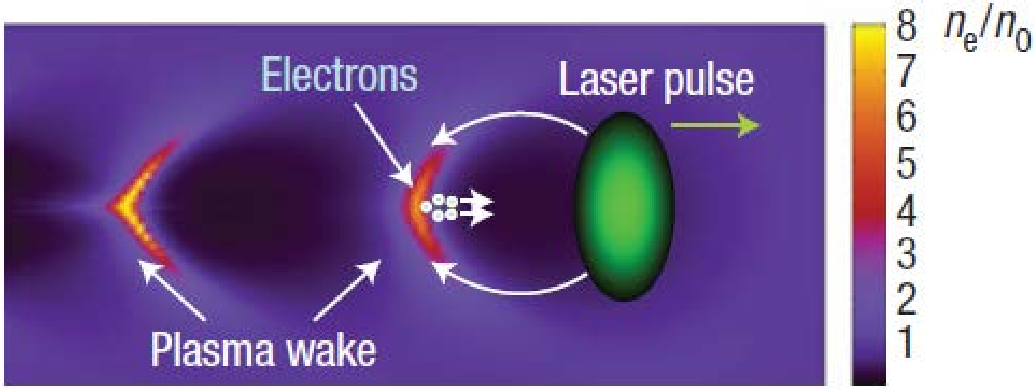
Applications of plasma

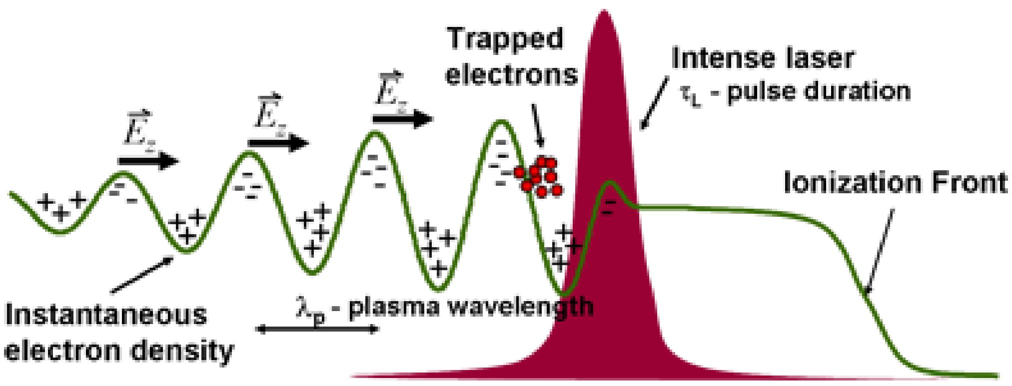
1. Material Processing
2. Plasma in space
3. Biomedical application
4. **High energy particle accelerator**
5. Electric propulsion
6. Controlled thermonuclear fusion

Electrons can be accelerated by a plasma wake generated by a short pulse laser

$$\frac{\mathbf{dE_0}}{\mathbf{dx}} = \mathbf{0} \qquad \frac{\mathbf{dE_0}}{\mathbf{dx}} > \mathbf{0}$$

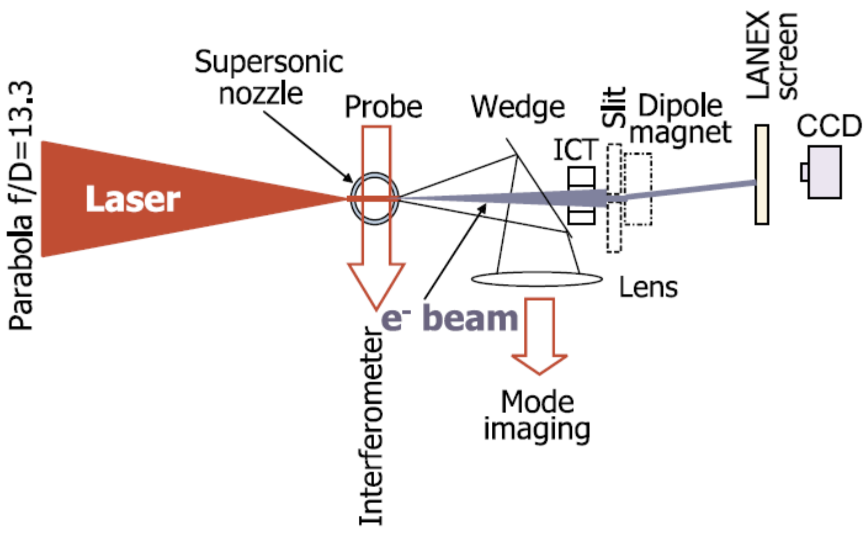


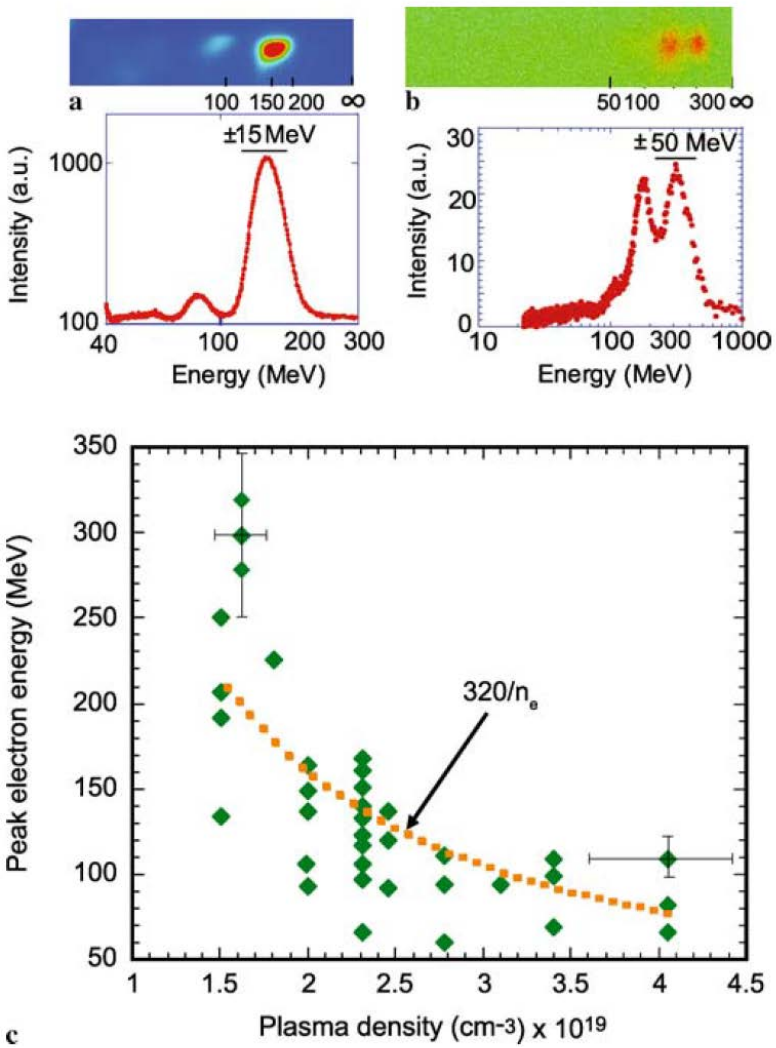




V. Malka, *et al.*, Nature Physics **4**, 447 (2008)
http://cuos.engin.umich.edu/researchgroups/hfs/research/laser-wakefield-acceleration/
https://i.ytimg.com/vi/CA-SDf1wvTQ/maxresdefault.jpg

Electrons with a maximum energy of 320 MeV are generated





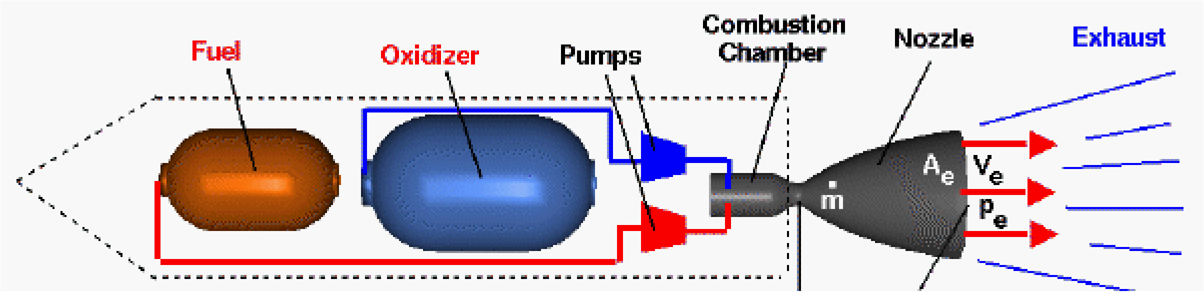
A. Maksimchuk, *et al.*, Appl. Phys. B **89**, 201 (2007)

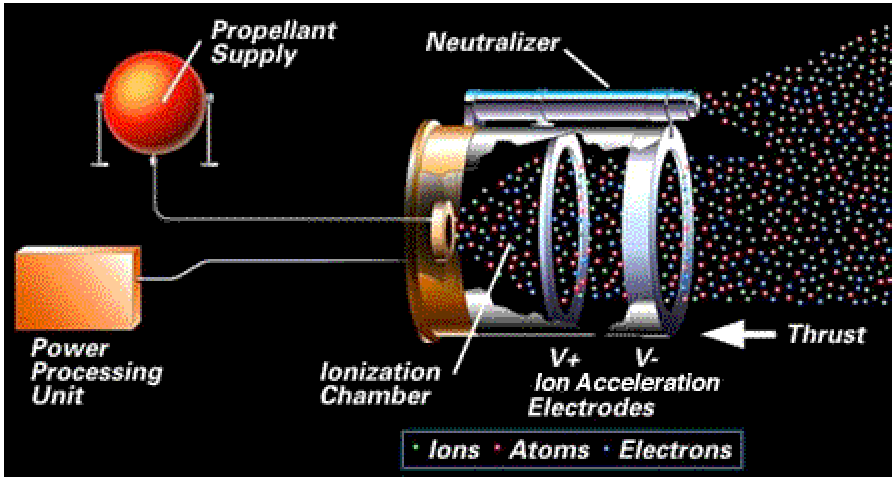
Applications of plasma

1. Material Processing
2. Plasma in space
3. Biomedical application
4. High energy particle accelerator
5. **Electric propulsion**
6. Controlled thermonuclear fusion

Comparison between liquid rockets and ion thrusters

- **Liquid rockets**
  - **u~4500 m/s**
  - **Isp~450 s**
  - **Energy ~ 100GJ**
  - **Power ~ 300MW**
  - **Thrust ~ 2x10^6 N**
- **Ion thrusters**
  - **u~30000 m/s**
  - **Isp~3000 s**
  - **Energy ~ 1000GJ**
  - **Power ~ 1kW**
  - **Thrust ~ 0.1 N**



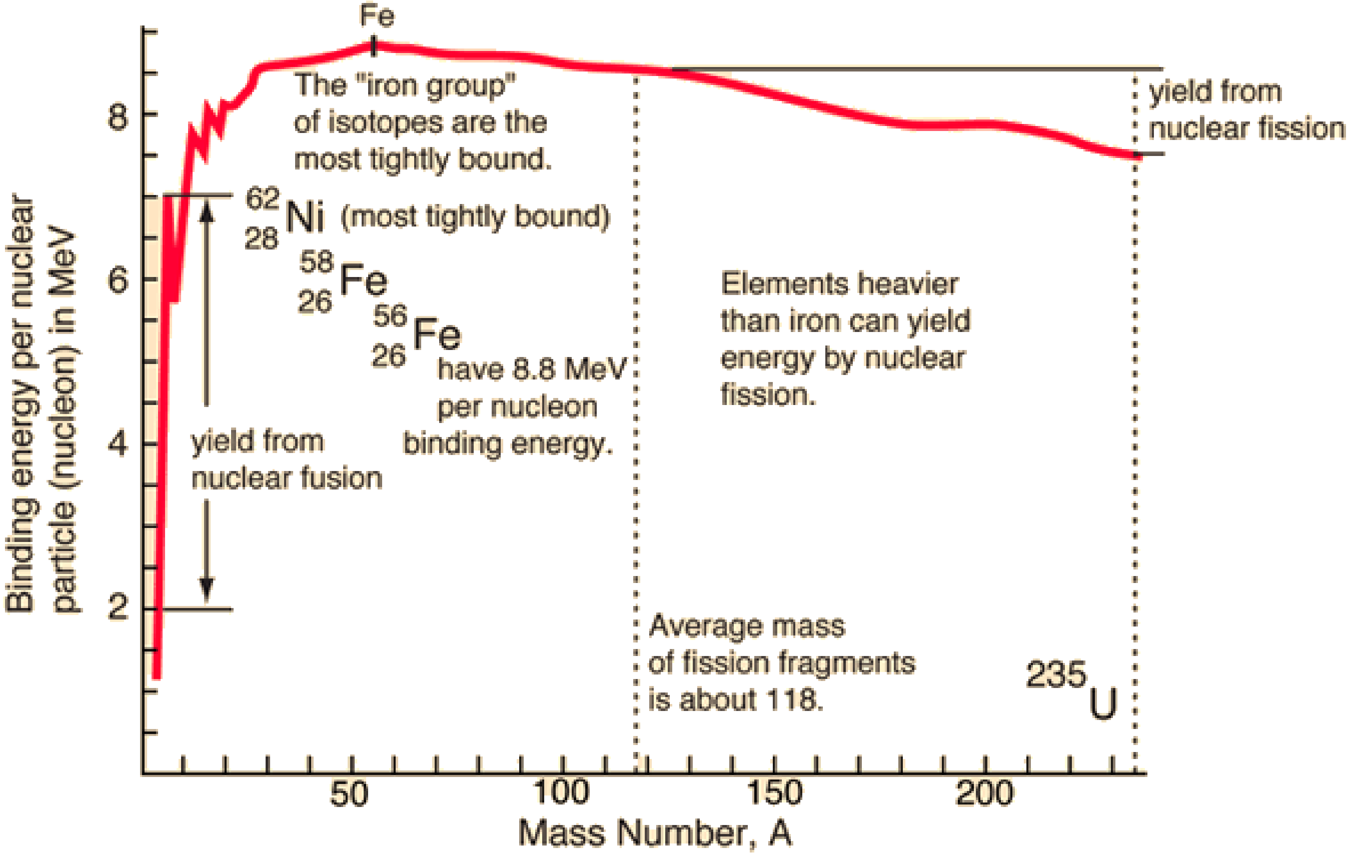


https://www.grc.nasa.gov/WWW/K-12/airplane/lrockth.html
https://defence.pk/pdf/threads/isro-to-test-electric-propulsion-on-satellites.411176/

Applications of plasma

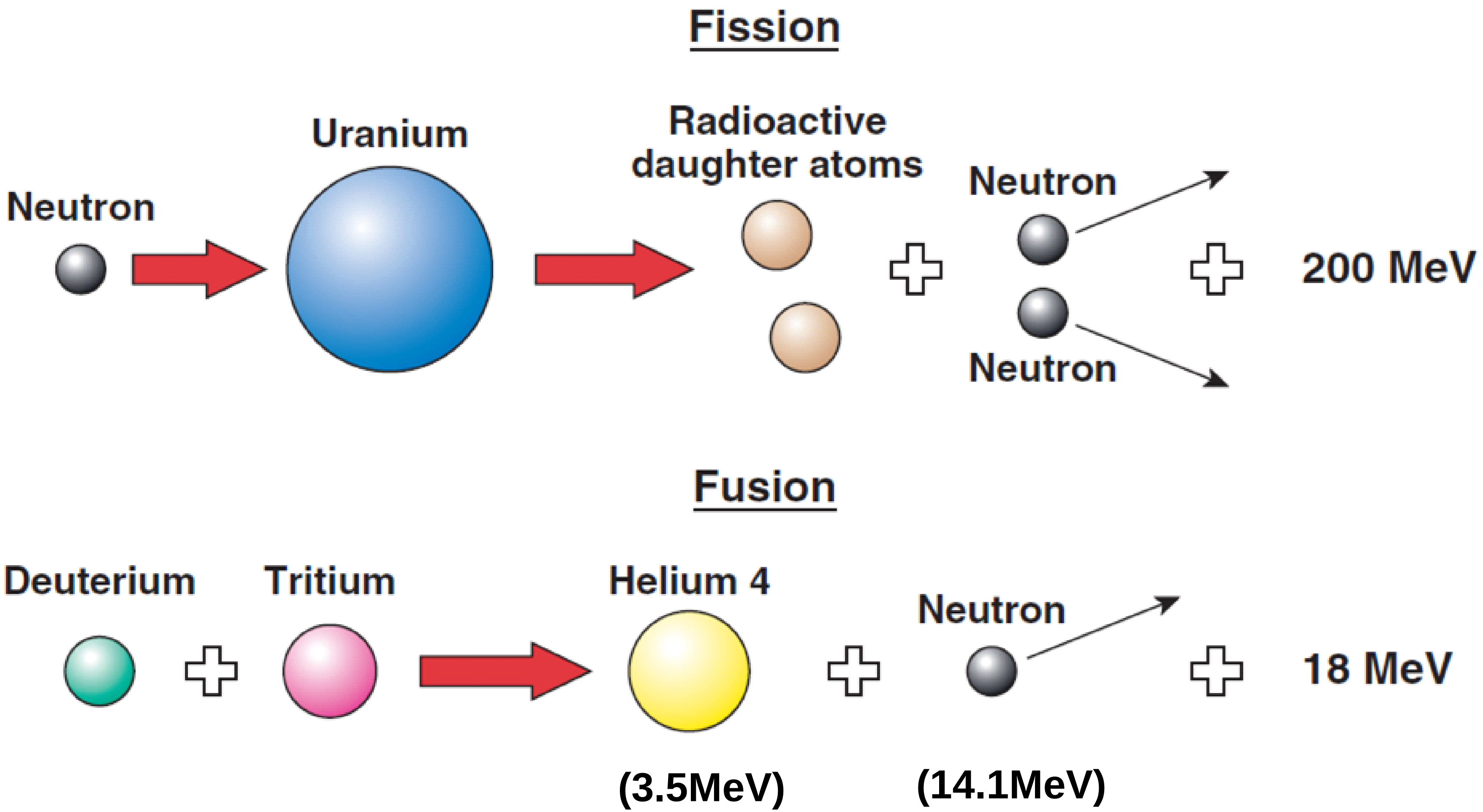
1. Material Processing
2. Plasma in space
3. biomedical application
4. high energy particle accelerator
5. Electric propulsion
6. **Controlled thermonuclear fusion**

The “iron group” of isotopes are the most tightly bound



http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html

Nuclear fusion and fission release energy through energetic neutrons



Nuclear fusion provides more energy per atomic mass unit (amu) than nuclear fission

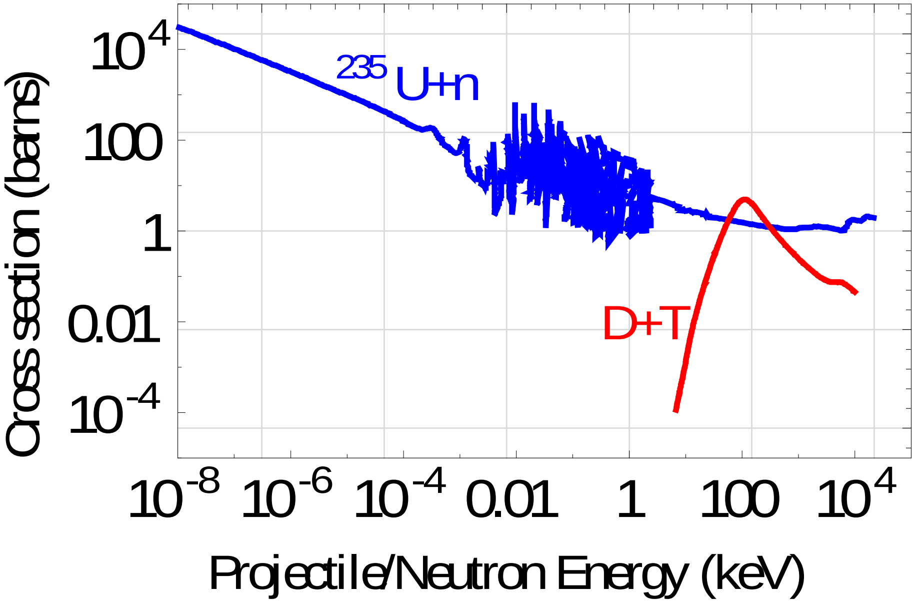
Fusion of $^{2}H+^{3}H$: $$\frac{Q}{A}=\frac{17.6\ MeV}{(3+2)\ amu}=3.5\ \frac{MeV}{amu}$$

Fission of ^{235}U: $$\frac{Q}{A}=\frac{200\ MeV}{236\ amu}=0.85\ \frac{MeV}{amu}$$

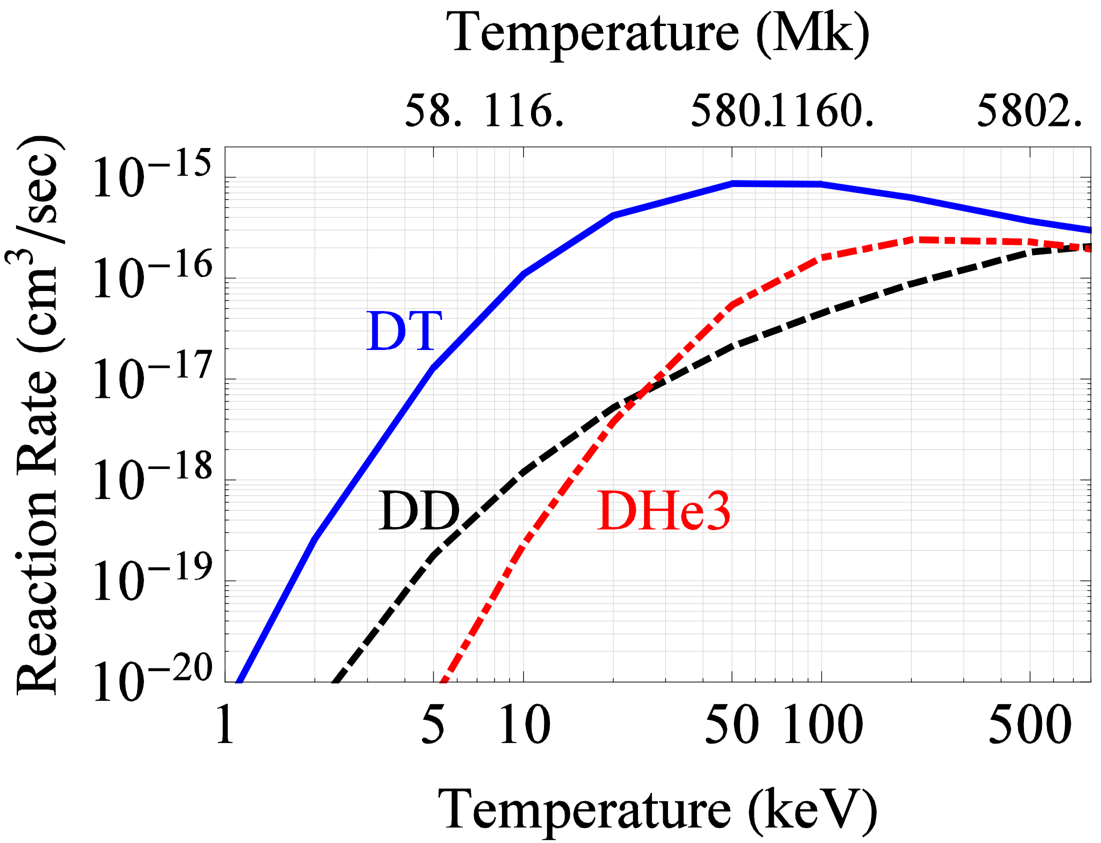
	Half-life (years)
U235	7.04×10^{8}
U238	4.47×10^{9}
…	
Tritium	12.3

Fusion is much harder than fission

- **Fission:** $n +_{92}^{235} U \rightarrow_{92}^{236} U \rightarrow_{56}^{144} Ba +_{36}^{89} Kr + 3n + 177 \text{ MeV}$
- **Fusion:** $D + T \rightarrow He^4\,(3.5 \text{ MeV}) + n\,(14.1 \text{ MeV})$



Fusion doesn't come easy

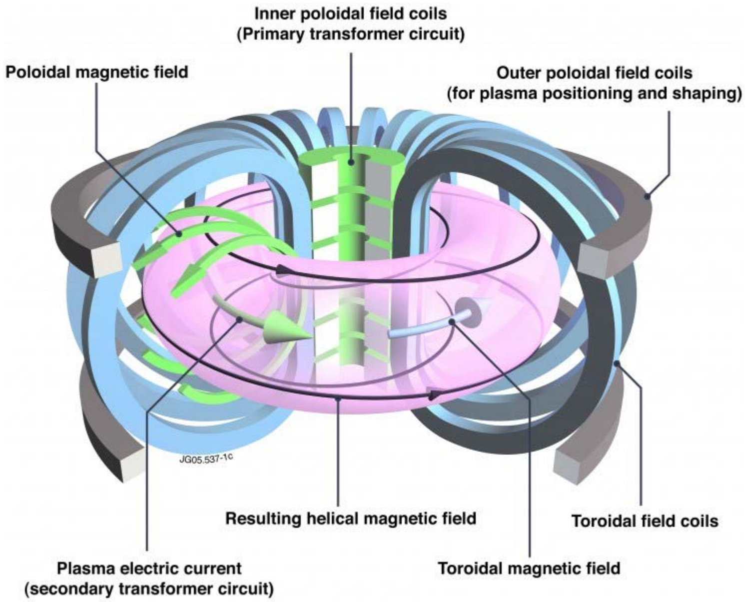


*NRL Plasma Formulary, Naval Research Laboratory, Washington, DC 203785-5320

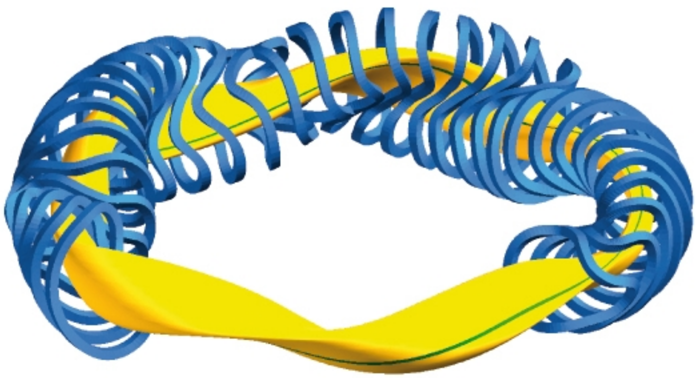
The plasma is too hot to be contained

- **Solution 1: Magnetic confinement fusion (MCF), use a magnetic field to contain it. P~atm, τ~sec, T~10 keV (10^8 ºC)**

Tokamak



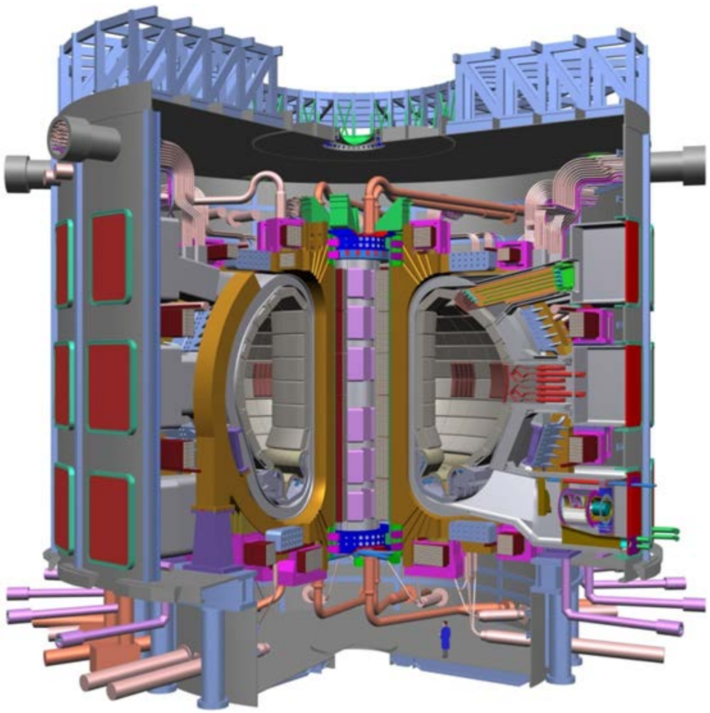
Stellarator



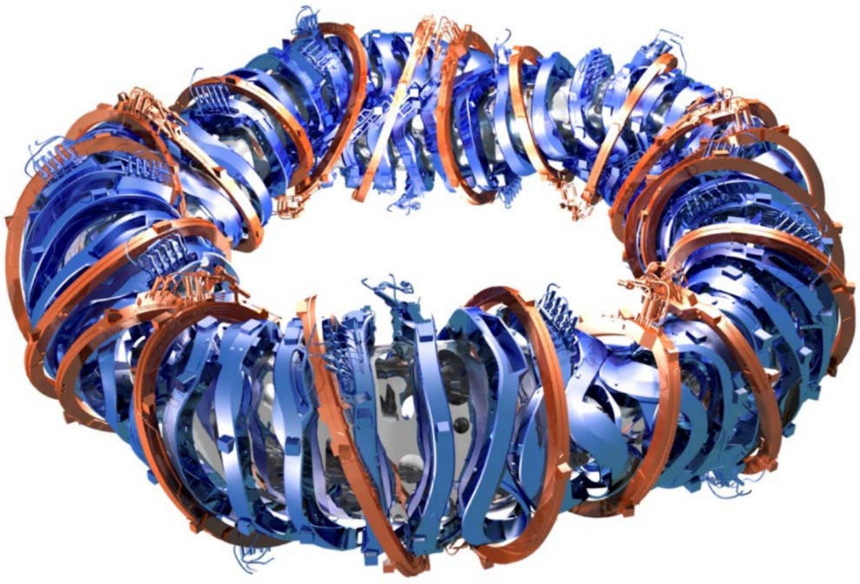
https://www.euro-fusion.org/2011/09/tokamak-principle-2/
https://en.wikipedia.org/wiki/Stellarator

There is a long way to go, but we are on the right path…

- **ITER**

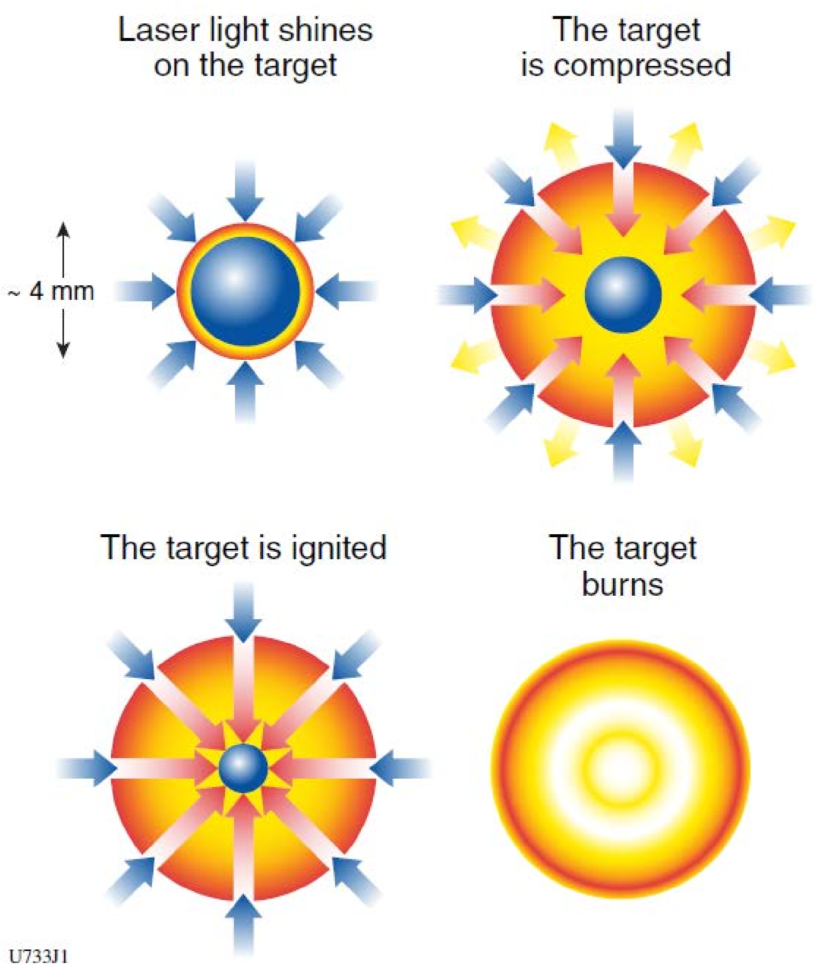


- **Wendelstein 7-X**

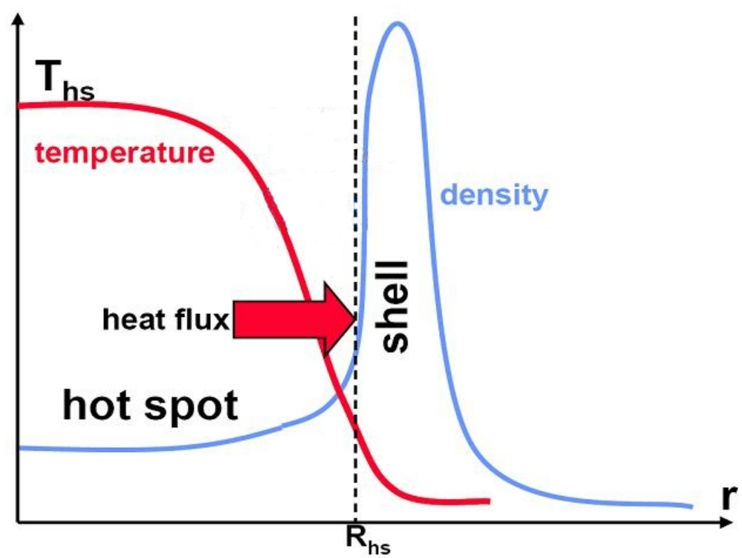


- **Schedule of ITER:**
  - **Dec 2025** **First Plasma**
  - **2035** **Deuterium-Tritium Operation begins**

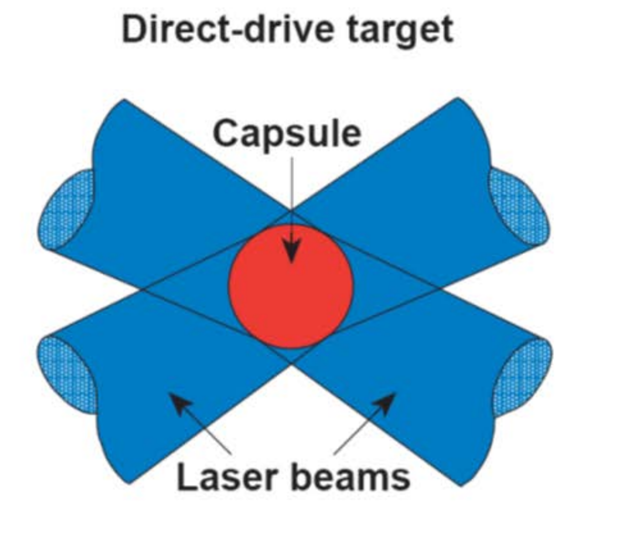
Plasma is confined by its own inertia in inertial confinement fusion (ICF)

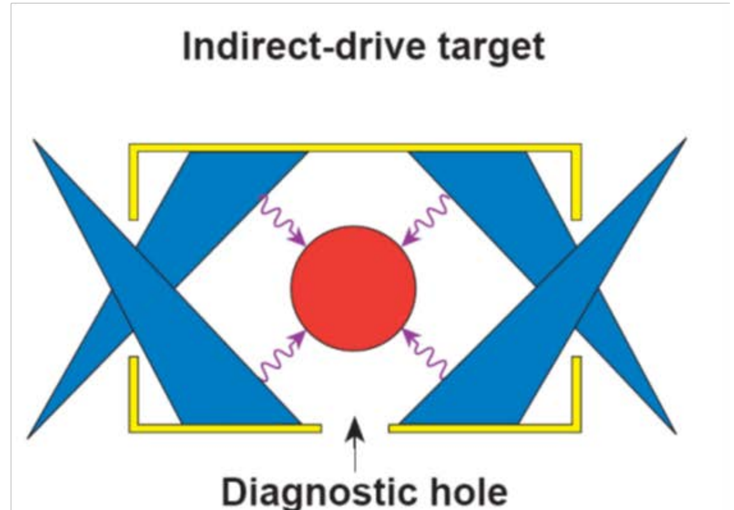


Spatial profile at stagnation



A spherical capsule can be imploded through directly or indirectly laser illumination



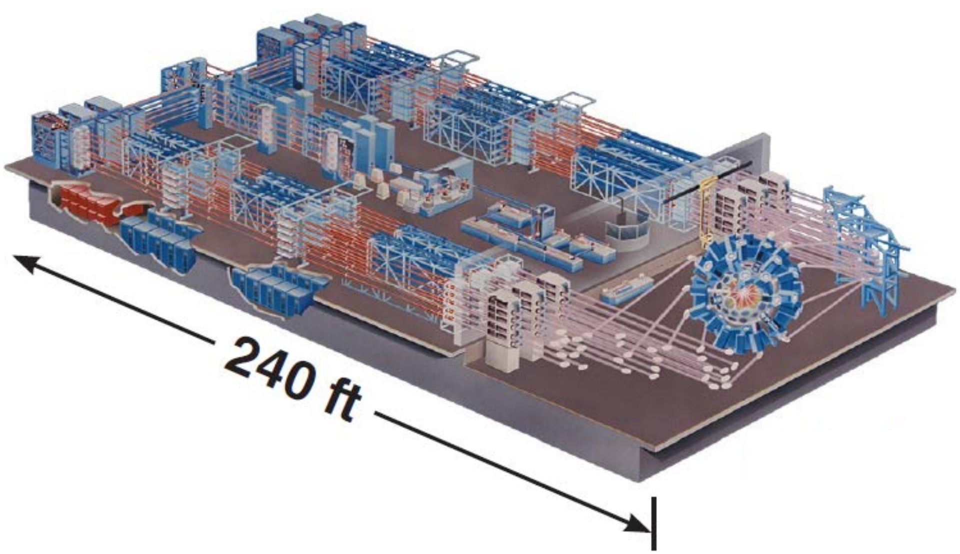


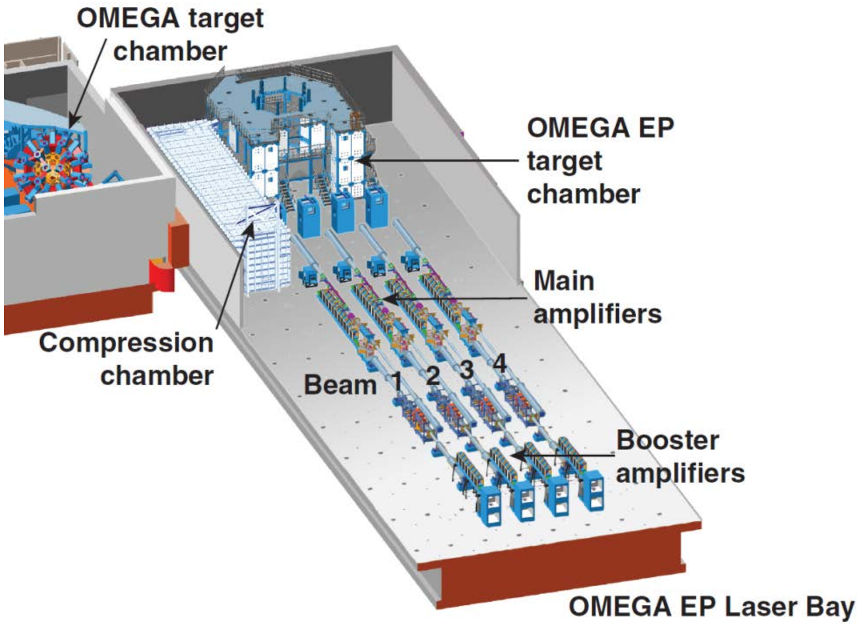
Hohlraum using
a cylindrical high-Z case

*R. Betti, HEDSA HEDP Summer School, 2015

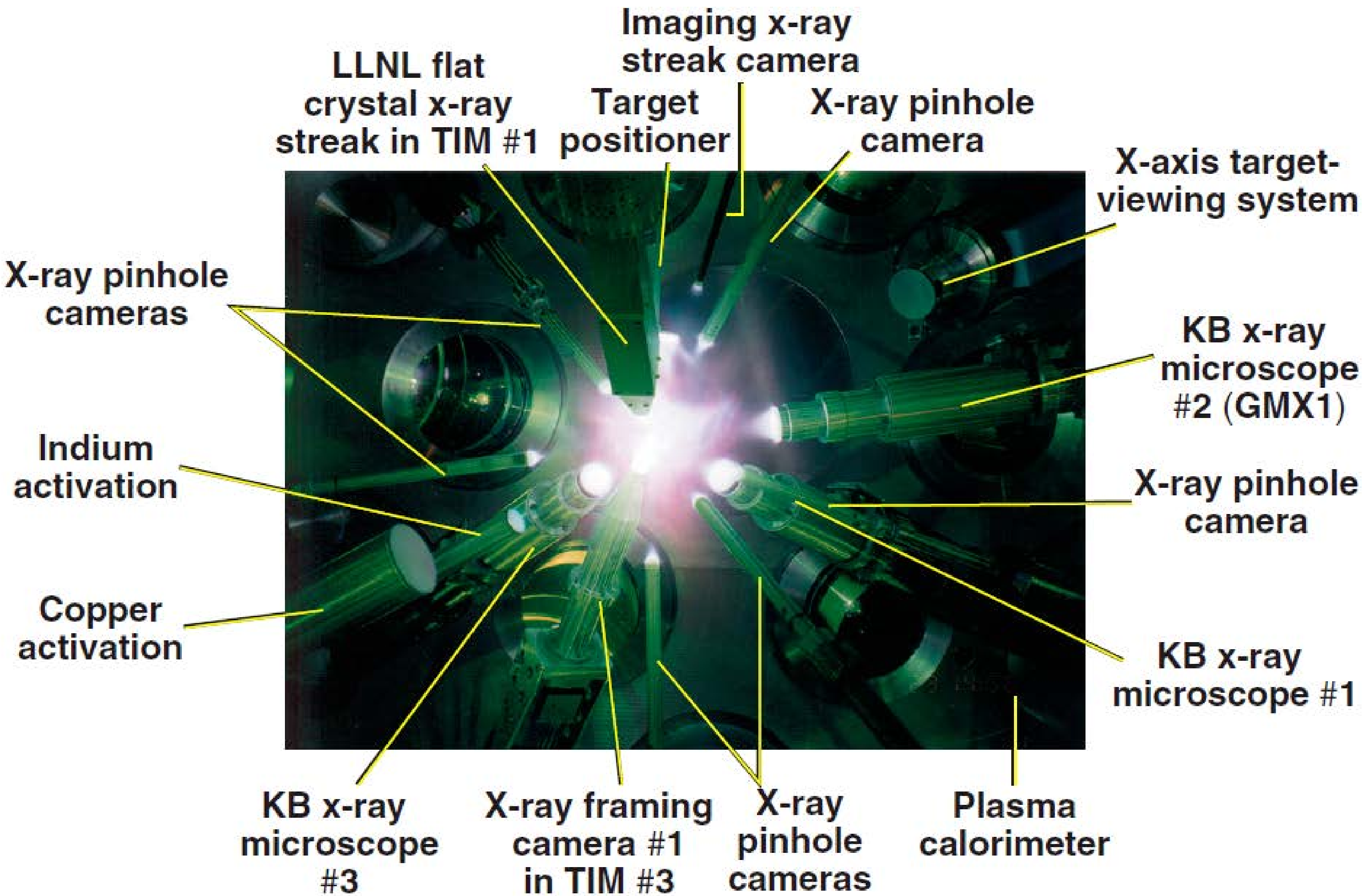
Laboratory for Laser Energetics, University of Rochester is a pioneer in laser fusion

- OMEGA Laser System
  - 60 beams
  - >30 kJ UV on target
  - 1%~2% irradiation nonuniformity
  - Flexible pulse shaping
- OMEGA EP Laser System
  - 4 beams; 6.5 kJ UV (10ns)
  - Two beams can be high-energy petawatt
    - 2.6 kJ IR in 10 ps
    - Can propagate to the OMEGA or OMEGA EP target chamber





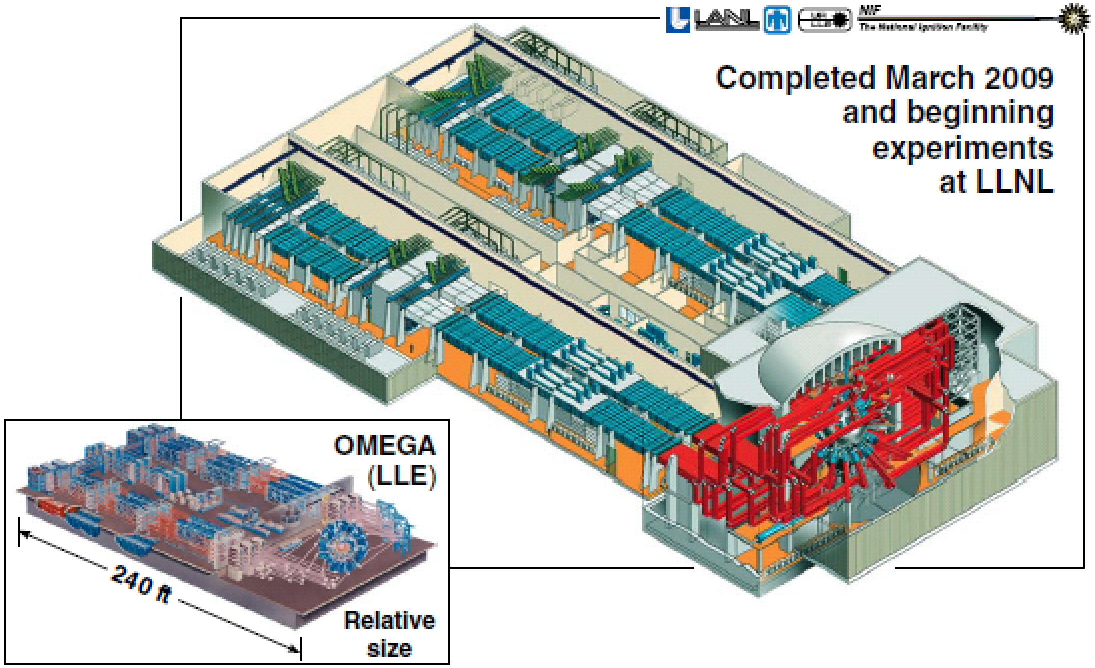
The OMEGA Facility is carrying out ICF experiments using a full suite of target diagnostics



E8012b

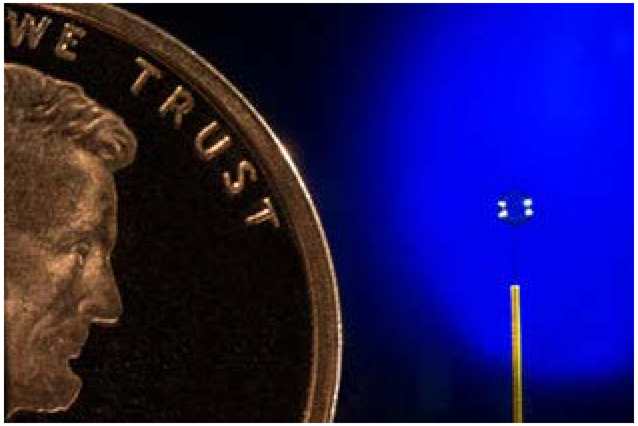
Photo taken from port H11B

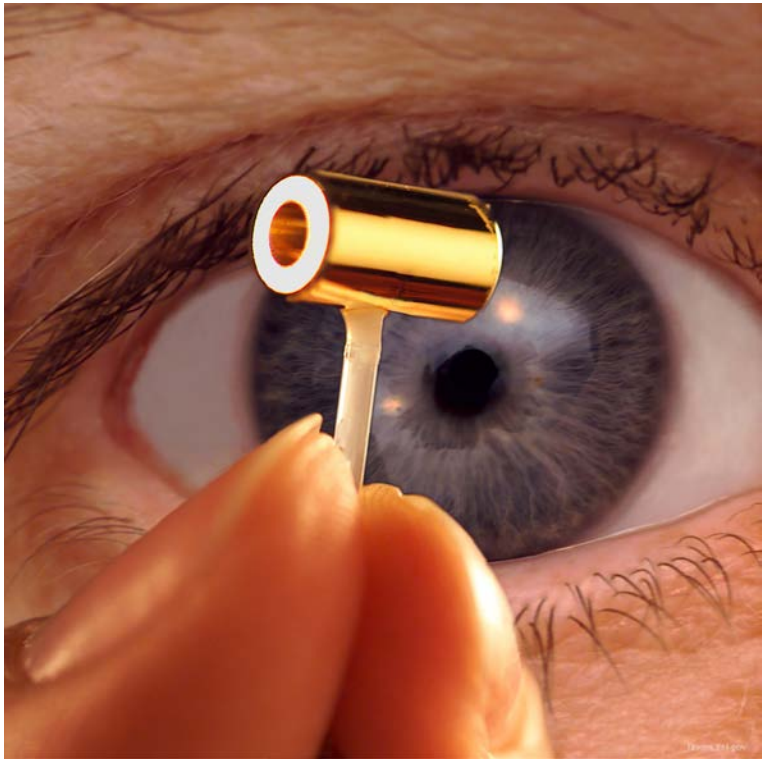
The 1.8-MJ National Ignition Facility (NIF) will demonstrate ICF ignition and modest energy gain



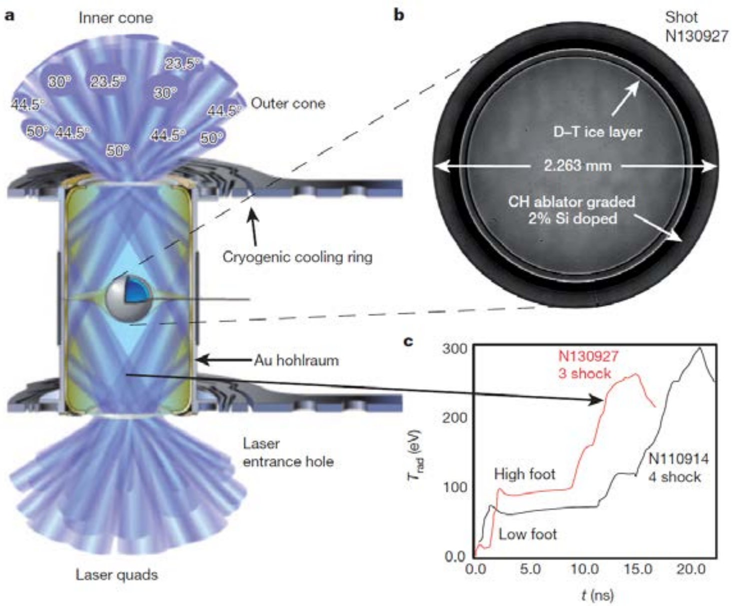
OMEGA experiments are integral to an ignition demonstration on the NIF.

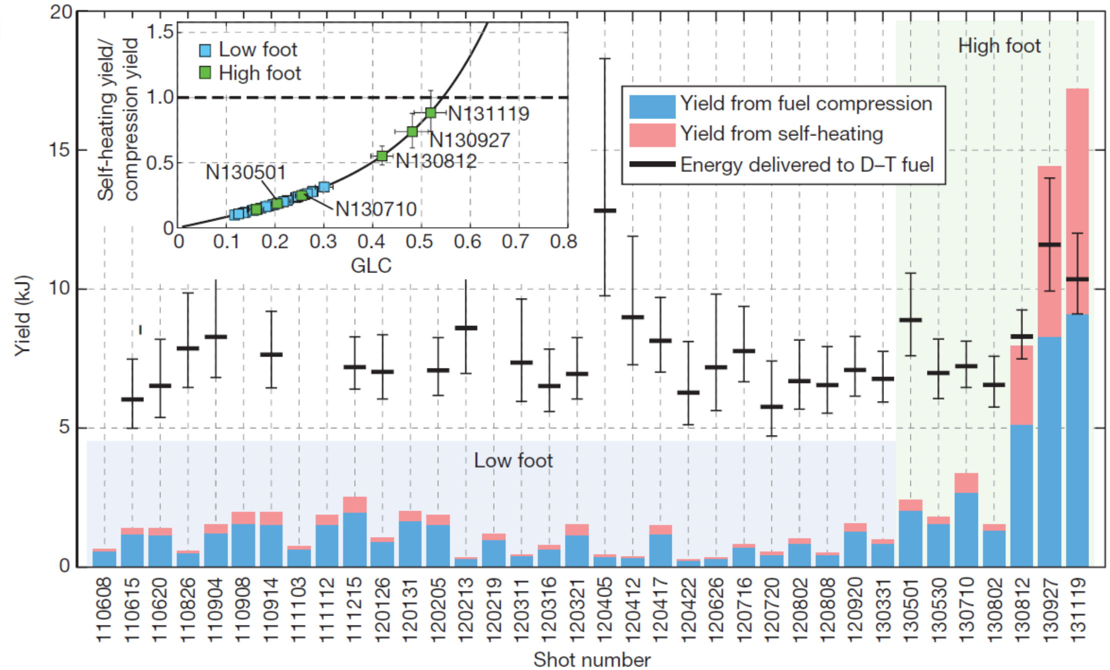
Targets used in ICF





Nature letter “Fuel gain exceeding unity in an inertially confined fusion implosion”

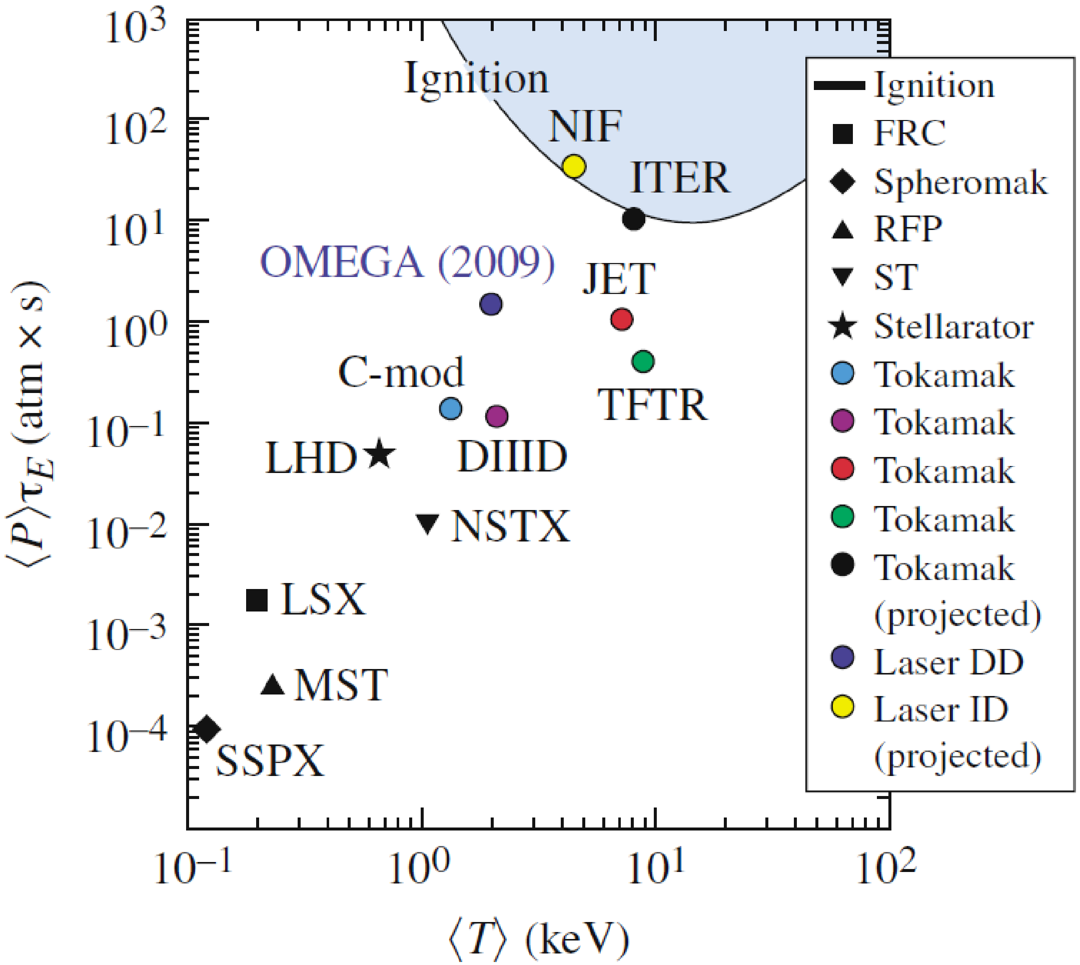




- **Fuel gain exceeding unity was demonstrated for the first time.**

Nature 506, p343, 2014

We are really closed!



Phys. Plasma 17, 058102 (2010)

Course Outline

1. Introduction to plasma
   a. What is Plasma?
   b. How to generate plasma
   c. Applications of plasma
2. Theory of Langmuir probe
   a. Sheath
   b. Single Langmuir probe
   c. Double Langmuir probe
   d. Triple Langmuir probe
3. Demonstration of Langmuir probe
   a. Building vacuum systems
   b. Building Langmuir probes
   c. Measuring temperatures and densities of plasma

Day 1~3

Day 4~5:
Experiments