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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2021 winter break

1/18(Mon.) – 1/22(Fri.) 14:00-17:40

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

Lecture 2

2021/1/19 updated

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 (items 1–2)

Day 4~5: Experiments (item 3)

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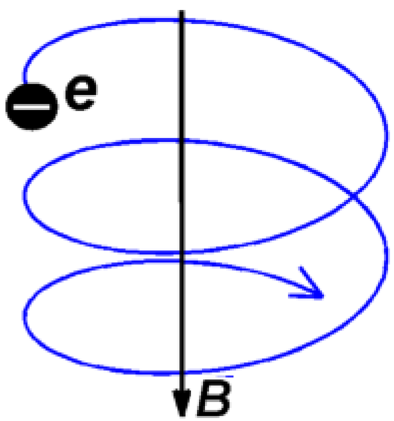
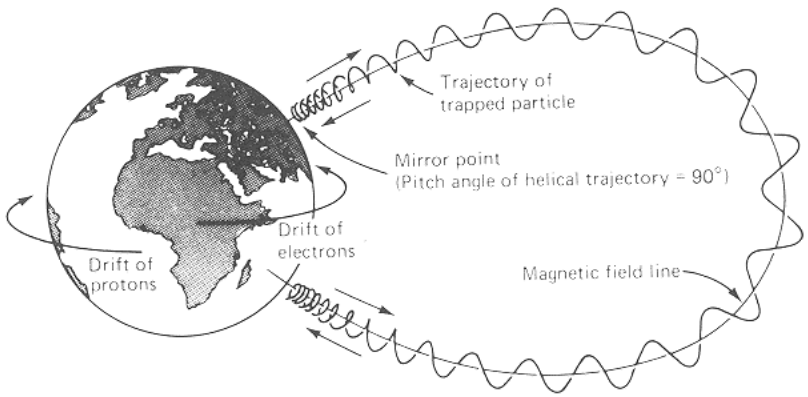
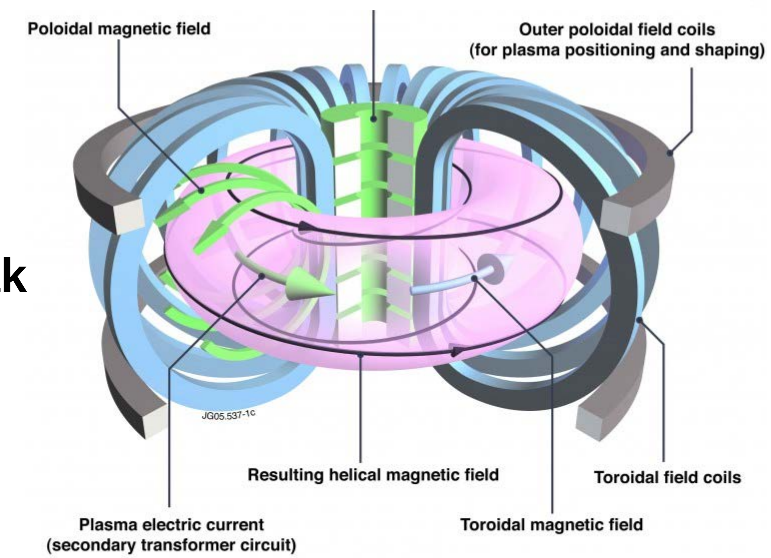
Charged particles gyro around magnetic field lines





Tokamak



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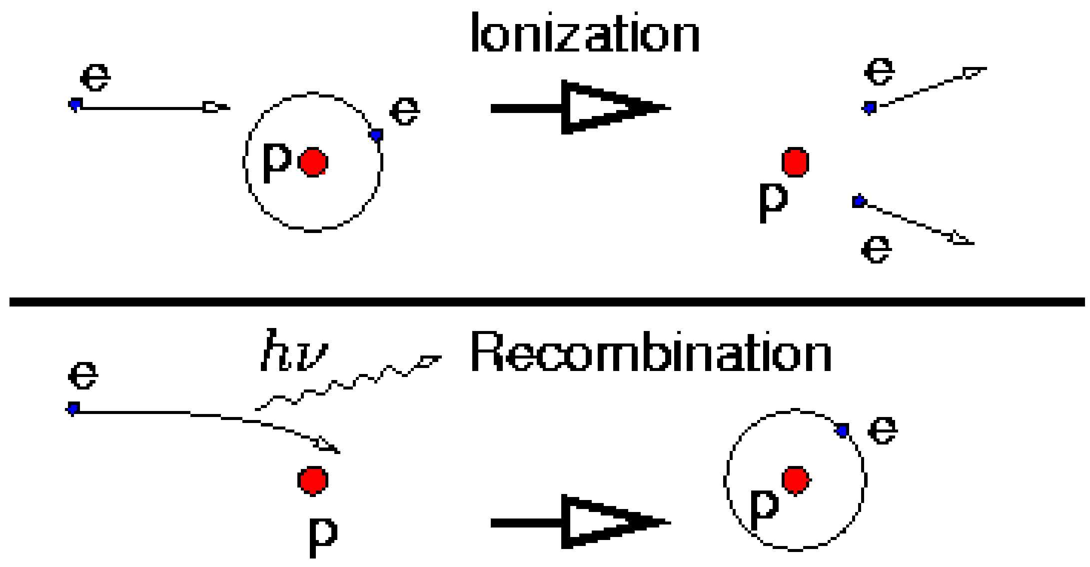
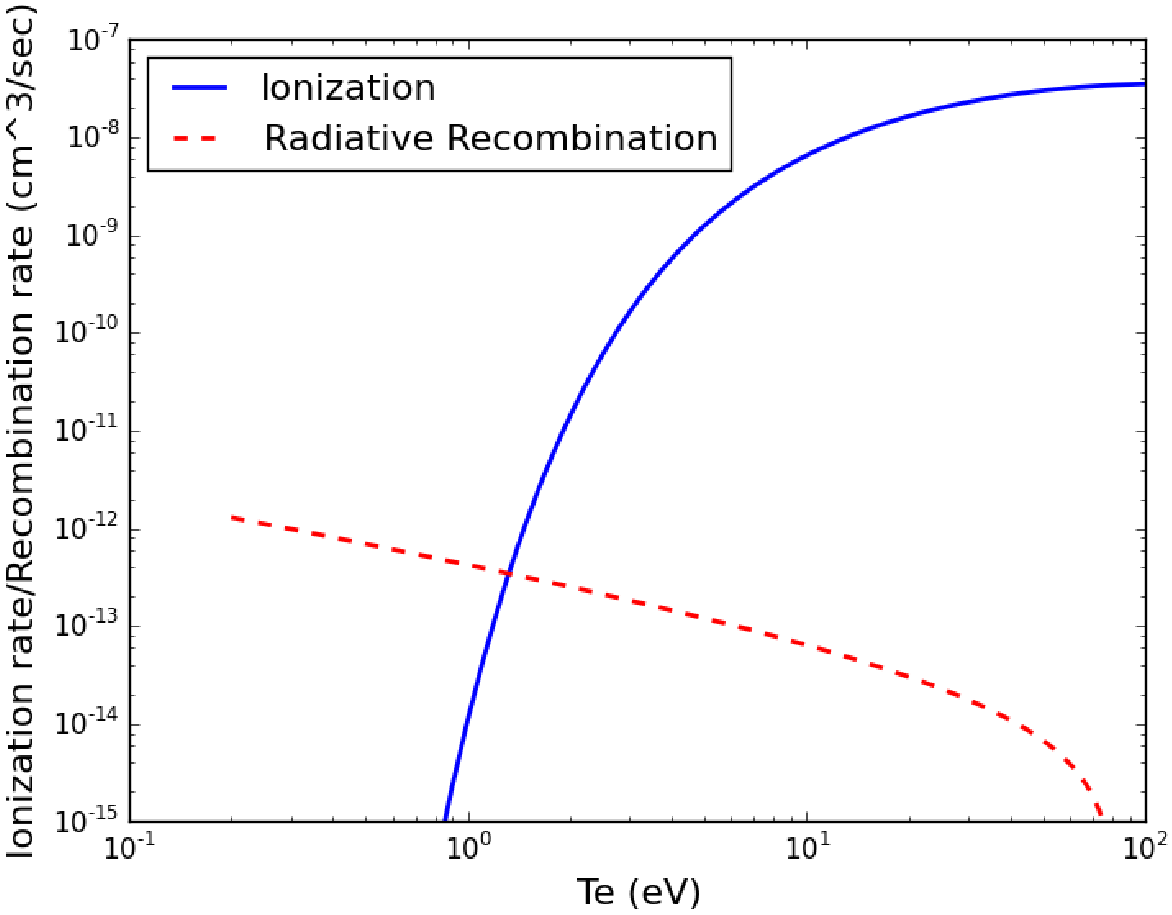
http://www.ipp.cas.cz/vedecka_struktura_ufp/tokamak/tokamak_compass/diagnostics/mikrovlnne-diagnostiky/ece-ebw-radiometr.html
http://www-ssg.sr.unh.edu/tof/Smart/Students/lees/periods.html
https://www.euro-fusion.org/2011/09/tokamak-principle-2/

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

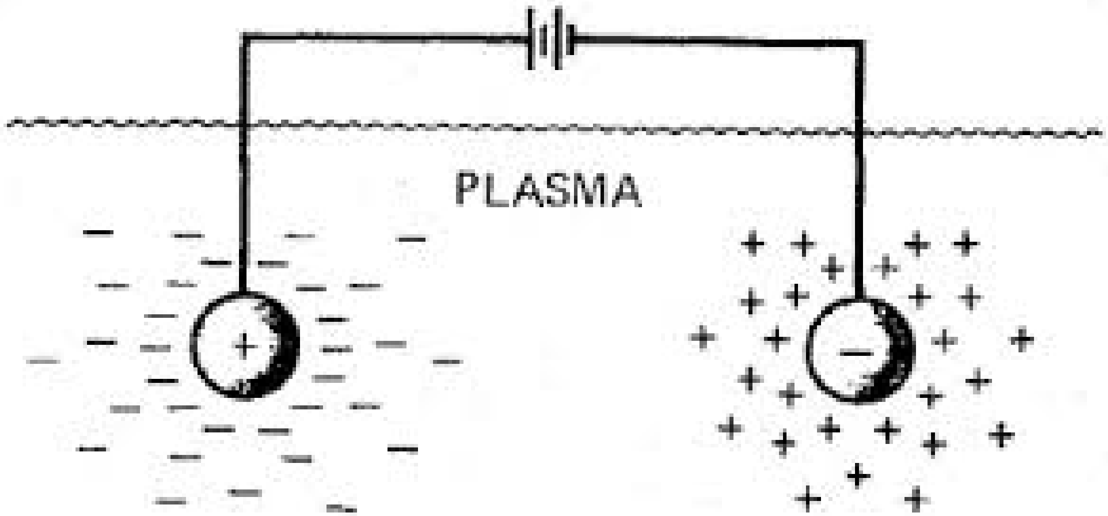


J. D. Huba \NRL Plasma Formulary", Naval Research Laboratory, 2013

There are several Important plasma parameters that need to be considered

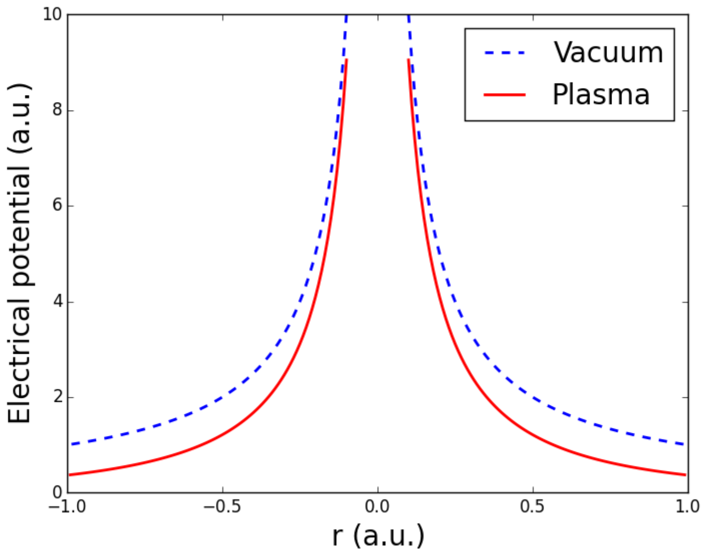
- **Debye length** $\lambda_D \equiv \left(\frac{KT_e}{4\pi n e^2}\right)^{1/2}$
- **Plasma parameter** $\Lambda \equiv n \frac{4\pi}{3} {\lambda_D}^3$
- **Plasma frequency** $\omega_{\mathrm{pe}} \equiv \left(\frac{4\pi n_e e^2}{m_e}\right)^{1/2}$
- **Collision time** $\tau_e \equiv \frac{3\sqrt{m_e}(KT_e)^{3/2}}{4\sqrt{2\pi} n \ln\Lambda}$
- **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



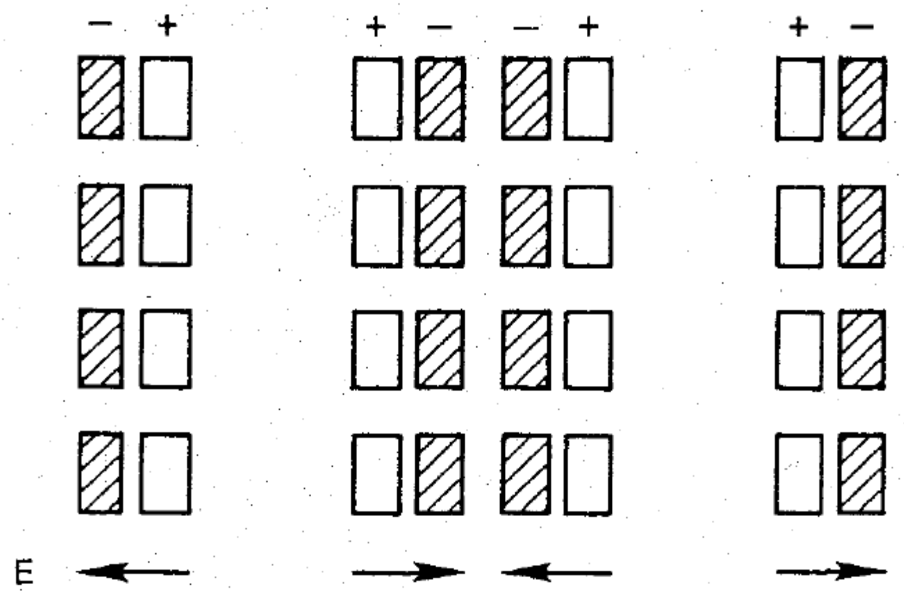
- **Vacuum potential:**

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

- **Potential in a plasma**

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

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



Mechanism of plasma oscillations.

- **Plasma frequency:**

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

- **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

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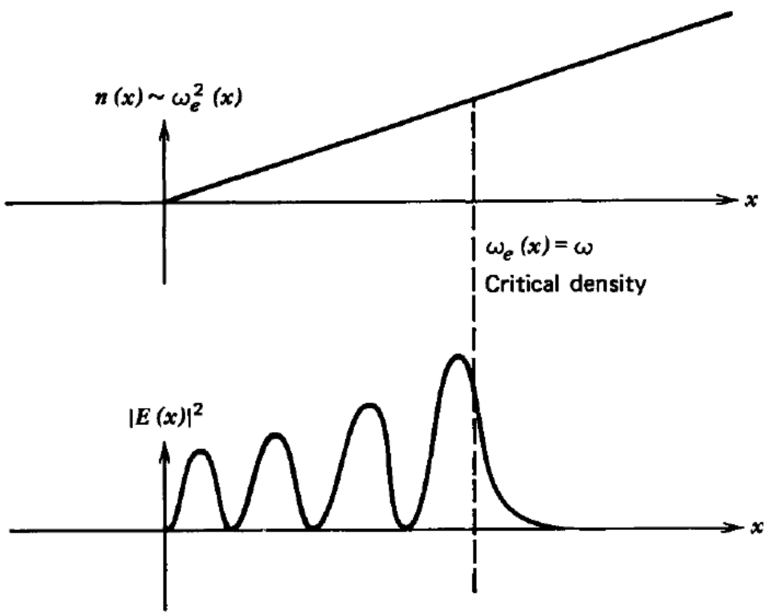

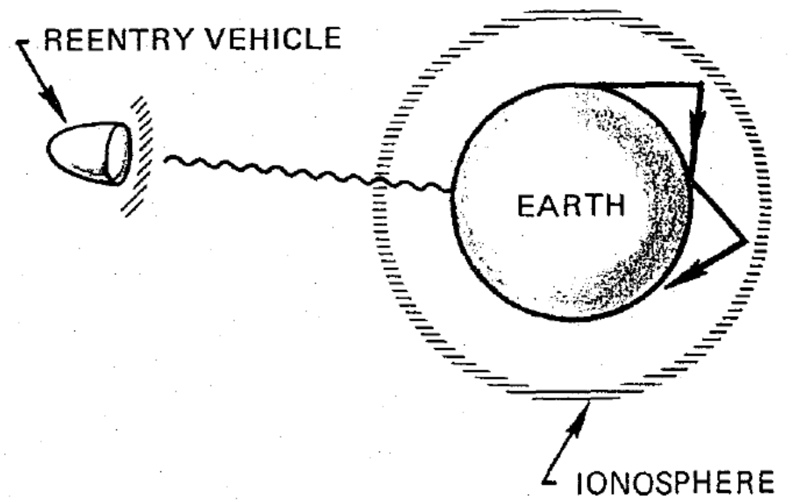

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Day 1~3

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**
  - **Pulsed-power generated plasma**

Methods of plasma production

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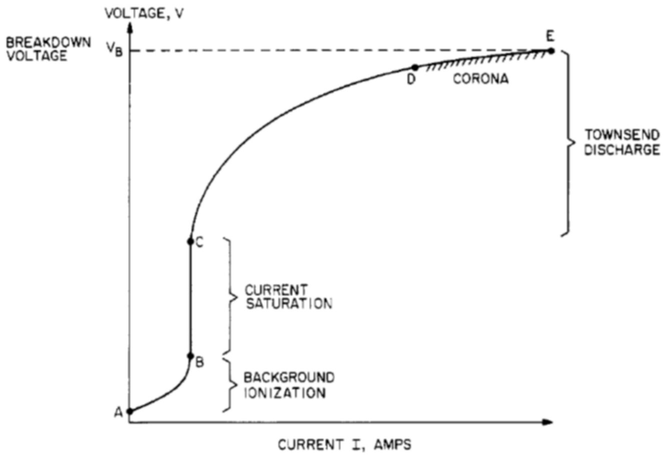
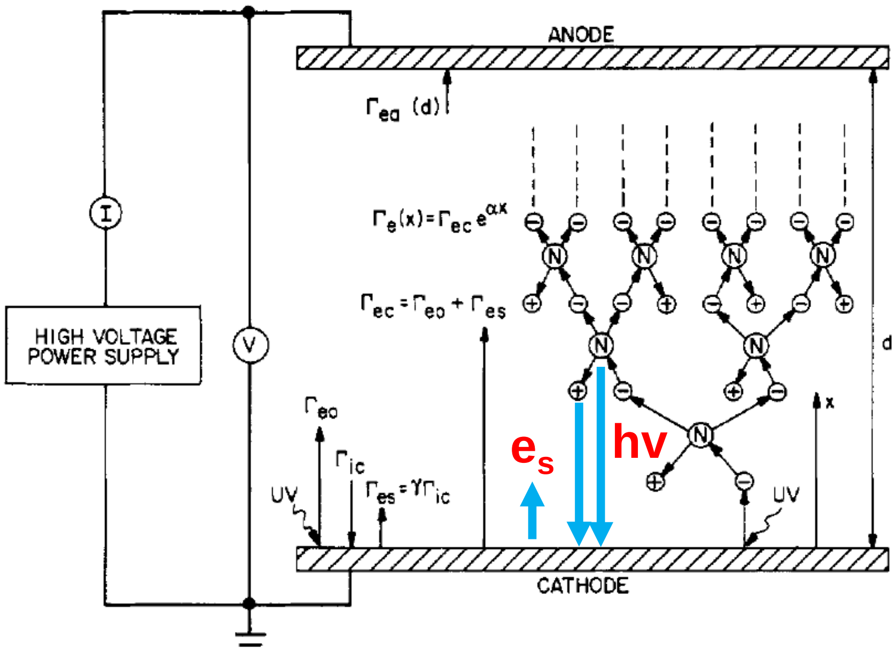
The region where the current exponentially increases is called the Townsend discharge



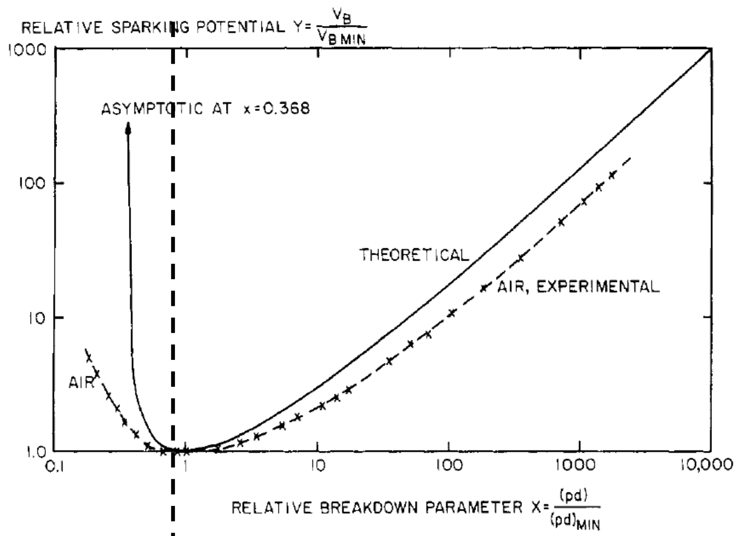


- **Primary electrons: electrons from the cathode due to photoemission, background radiation, static chages, or other processes.**
- **Secondary electrons: electrons emitted from the cathode per incident ion or photon created from ionization in gas.**

- **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

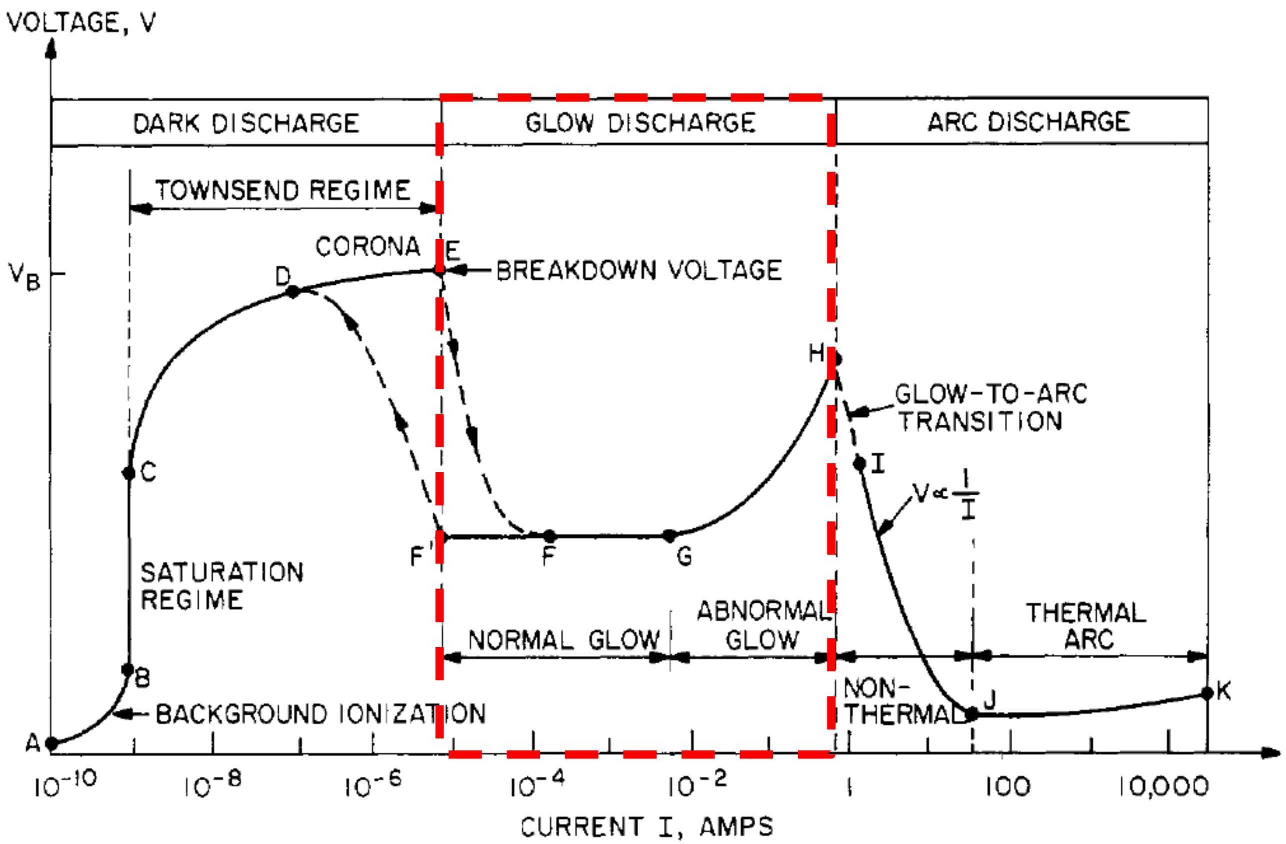


- **Collision is not frequent enough even the electrons gain large energy between each collision.**
- **Electrons do not gain enough energy between each collision even collisions happen frequently.**

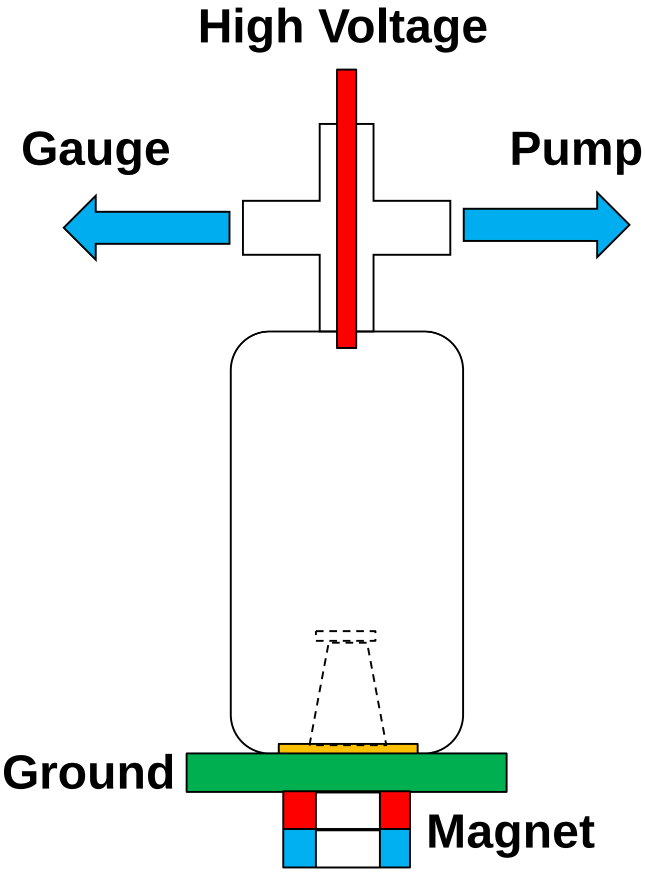
- **The minimum of the Paschen curve corresponds to the Stoletow point, the pressure at which the volumetric ionization rate is a maximum.**

DC electrical glow discharges in gases

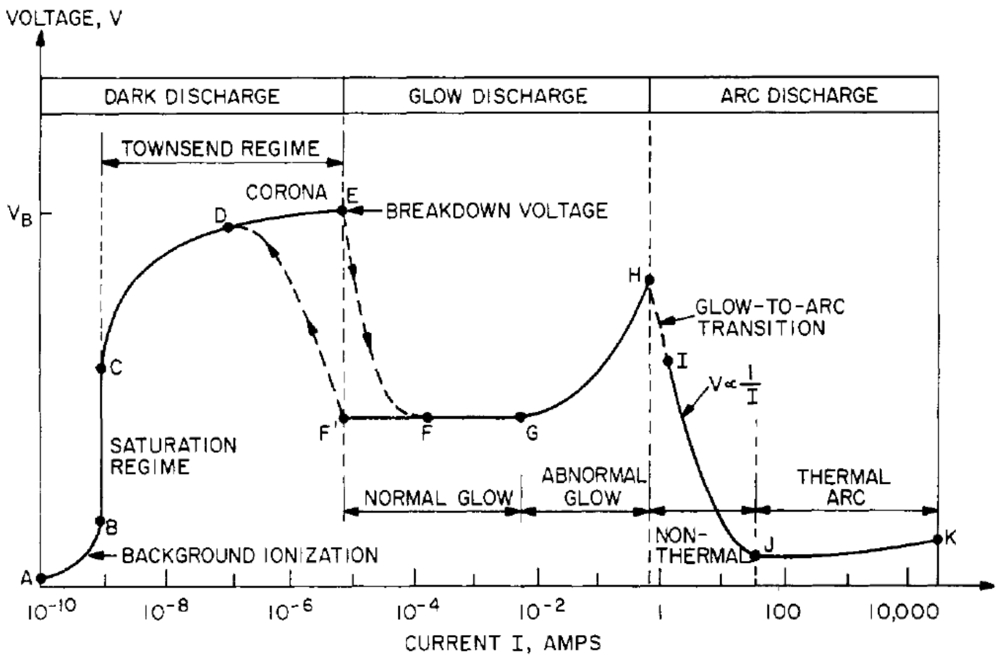
- The internal resistance of the power supply is relatively low, then the gas will break down at the voltage V_B, and the discharge tube will move from the dark discharge regime into the low pressure normal glow discharge regime.

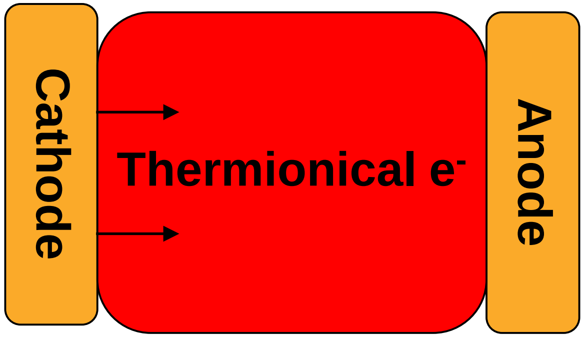


Glow discharge in a glass jar



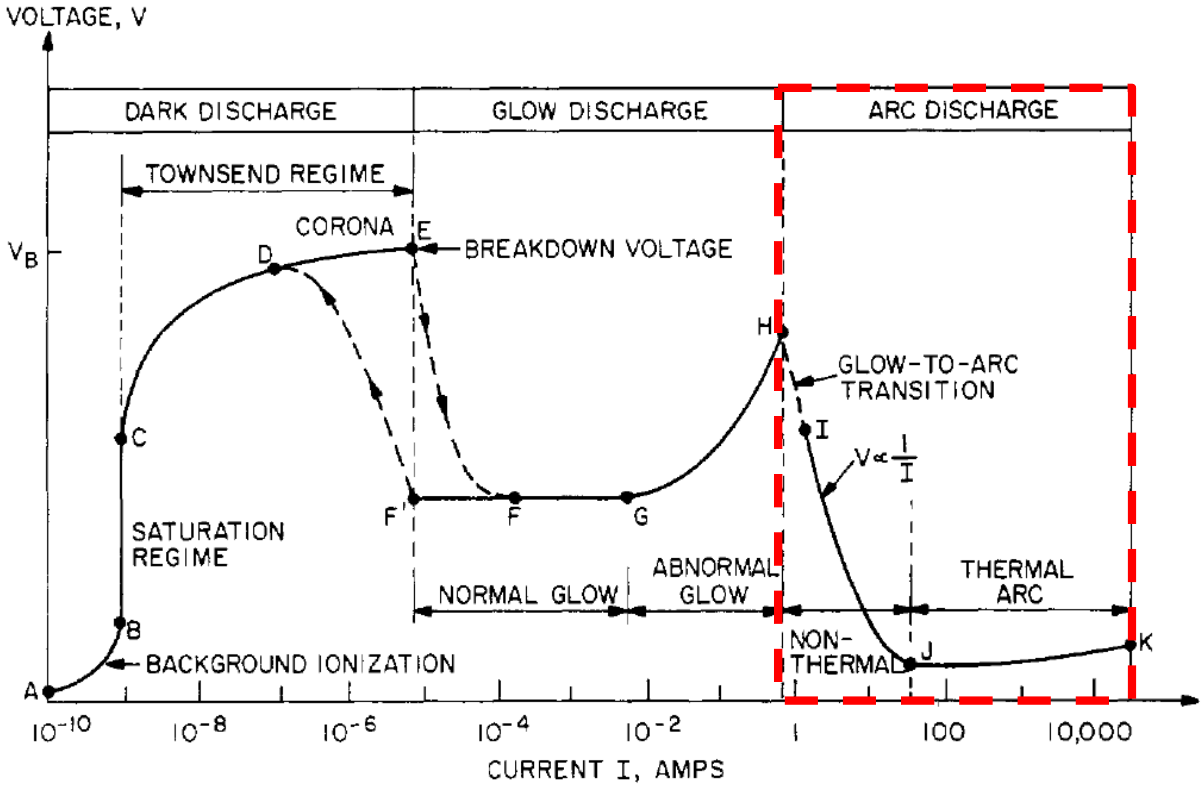
Discharge may enter glow-to-arc transition region if the cathode gets hot enough to emit electrons thermionically





- **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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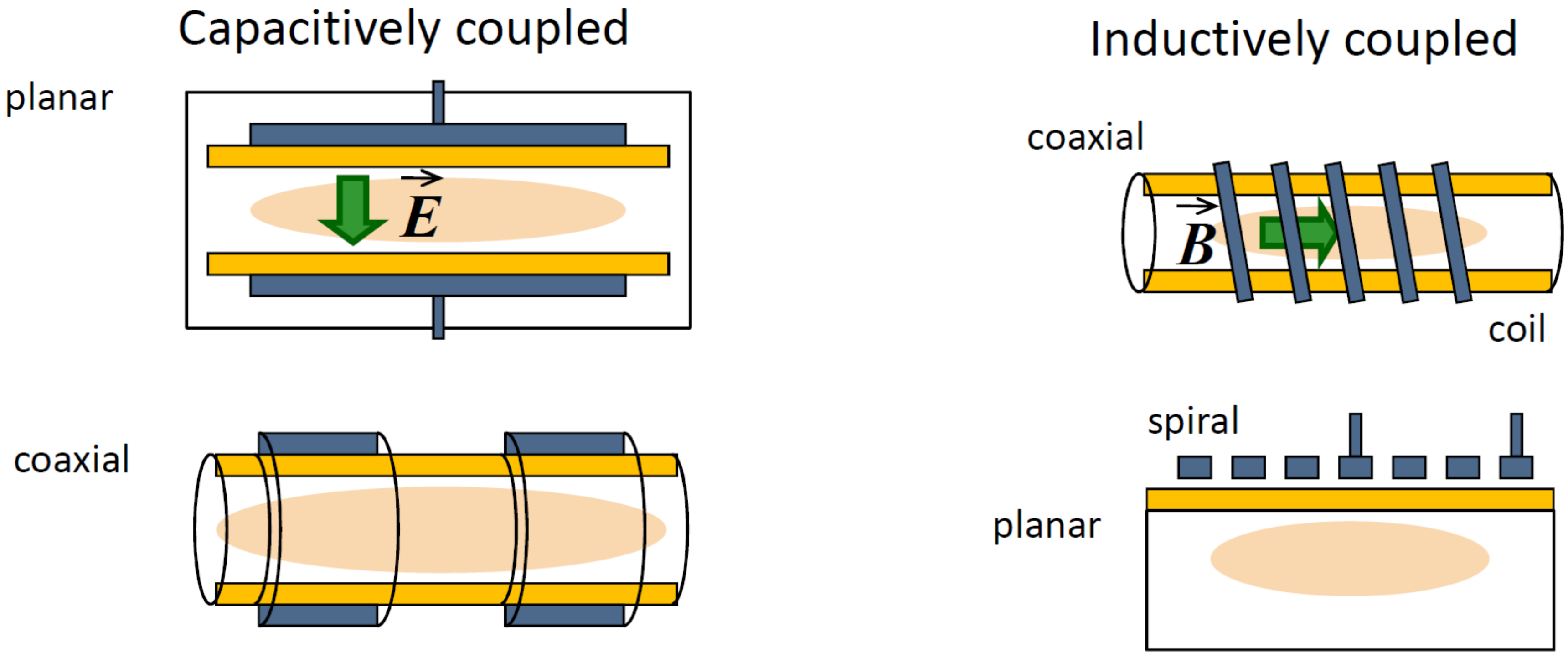
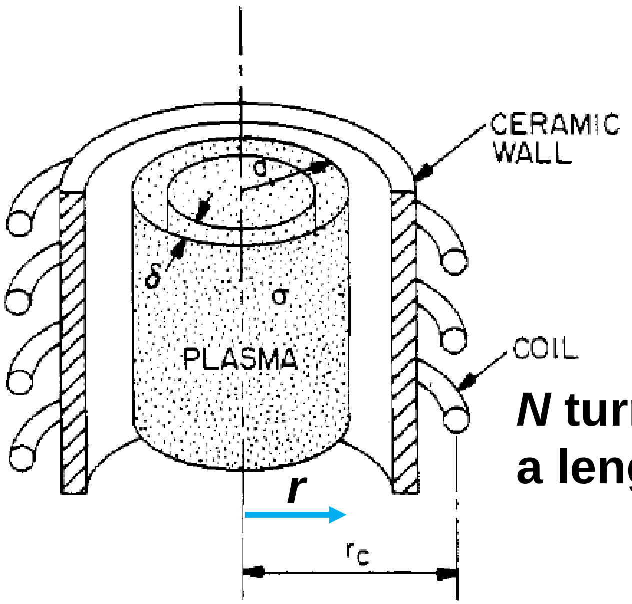
- **Optical (laser) produced plasma**

RF can interact with plasma inductively or capacitively



The plasma is generated by the induced electric field from the oscillating magnetic field



N **turn within a length of *l***

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\int (\nabla \times \vec{E})\, d\vec{A} = \int \left(-\frac{\partial \vec{B}}{\partial t}\right) d\vec{A}$$

$$2\pi r E = -\pi r^2 \frac{\partial B}{\partial t}$$

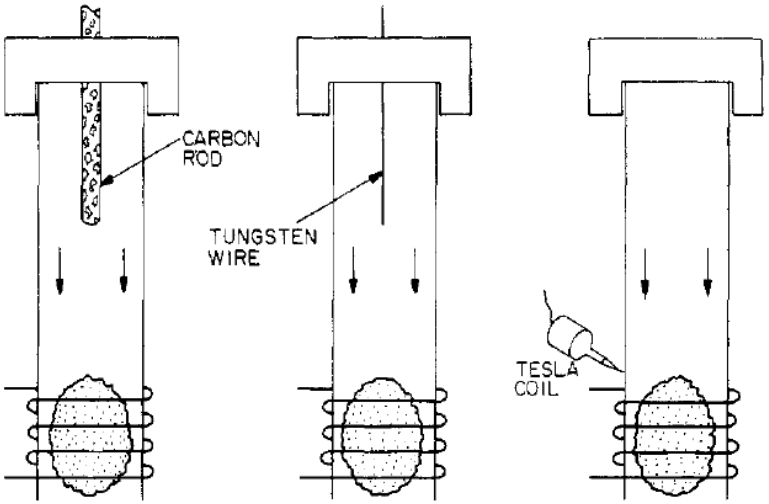
$$E = -\frac{r}{2}\frac{\partial B}{\partial t}$$

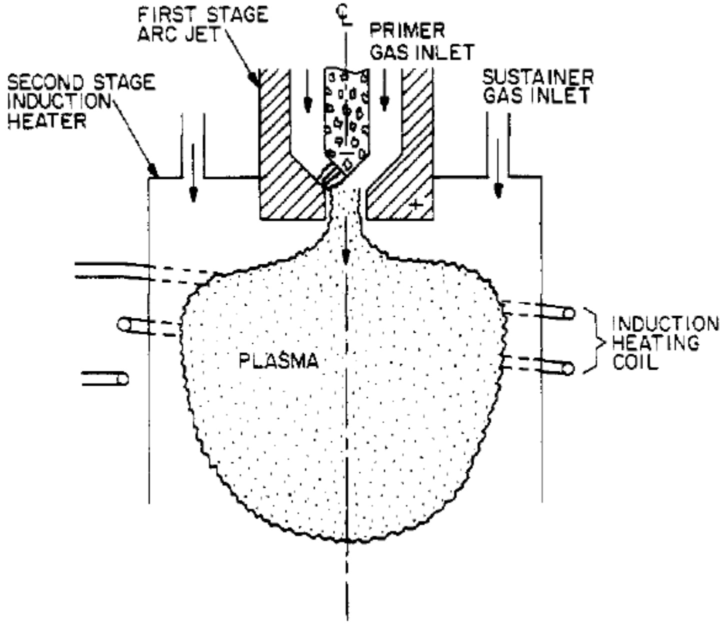
$$B \times l = \mu_o N I$$

$$E = -\frac{r}{2}\mu_o \frac{N}{l}\frac{\partial I}{\partial t}$$

$$|E| = \frac{r}{2}\mu_o \frac{N}{l}\omega I$$

High voltage initiation is usually required for inductive RF plasma torches





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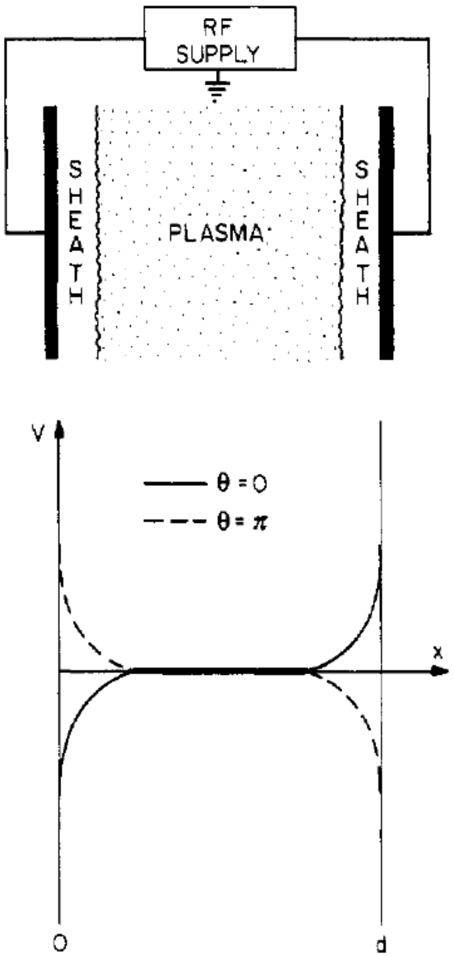
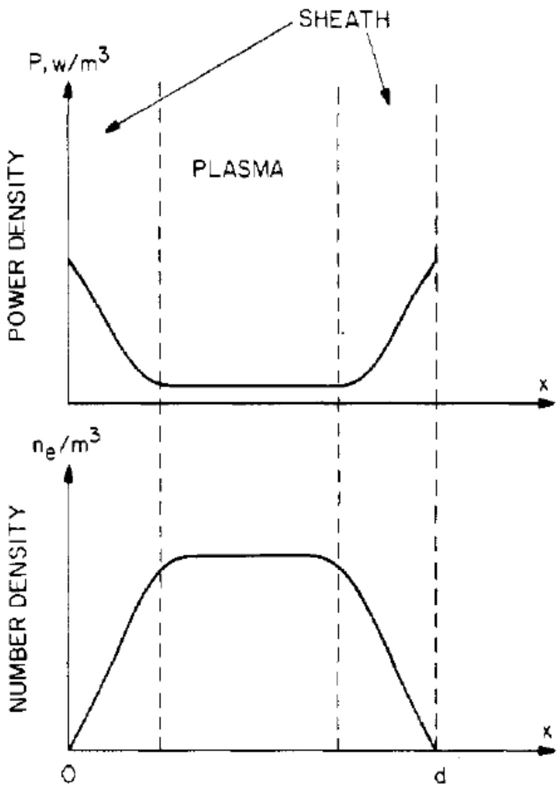
Symmetrical capacitive RF discharge model





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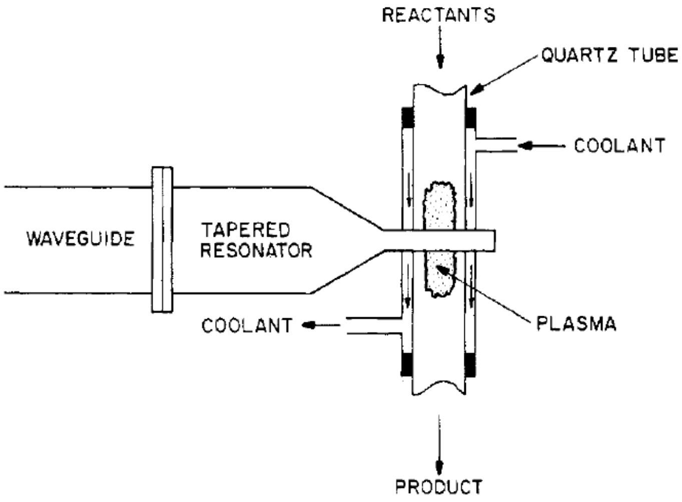
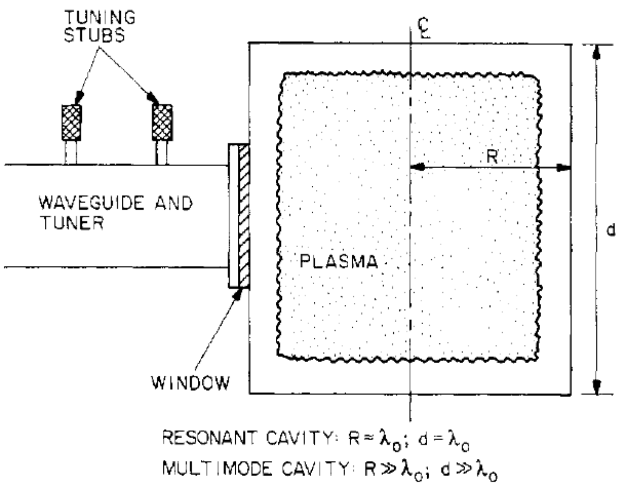
Microwave plasma reactor configurations

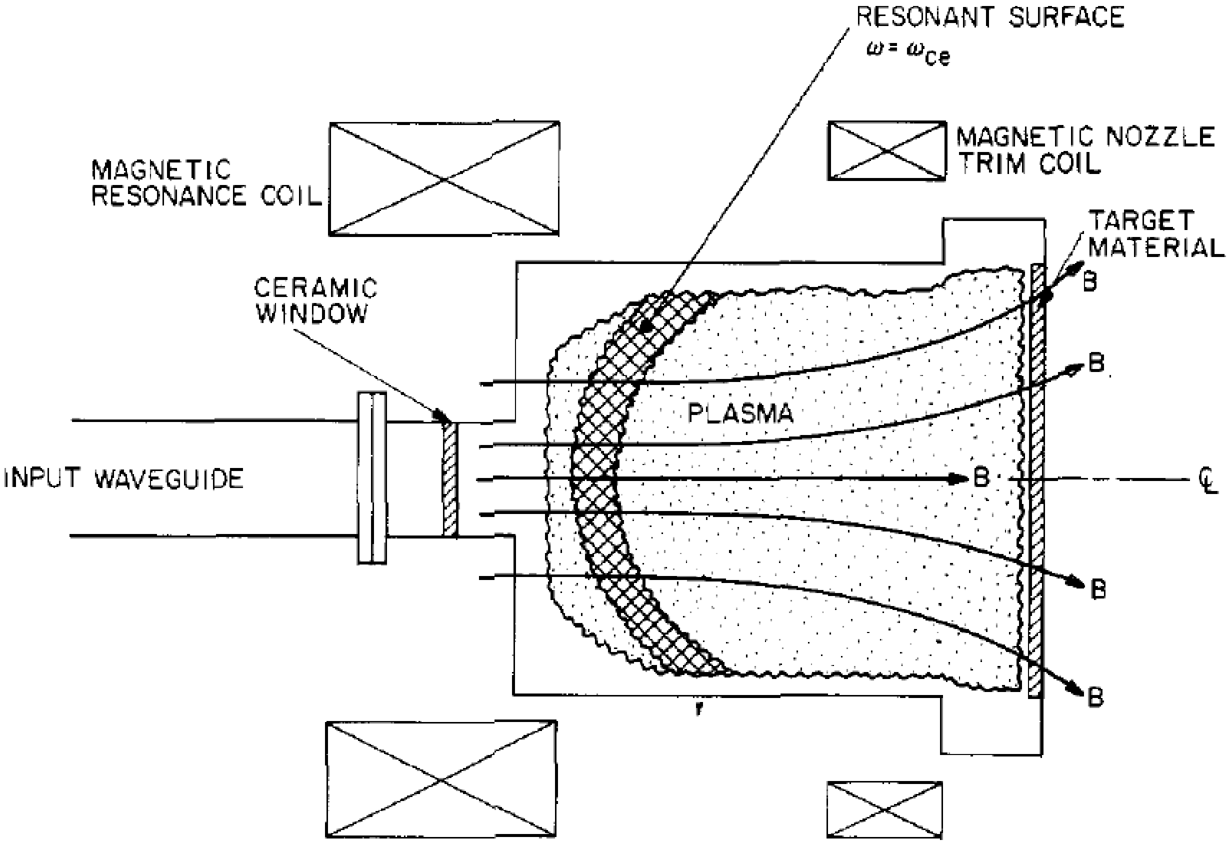
- **Waveguide coupled reactor**
- **Resonant or multimode cavity – if the impedance matching is good, more energy can be fed into the cavity.**





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

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

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

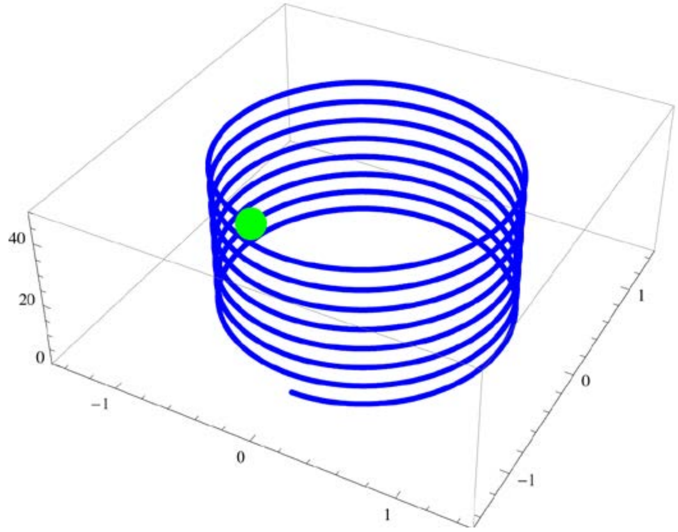
$$m_e \dot{v}_z = 0$$

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

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

- Therefore

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



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

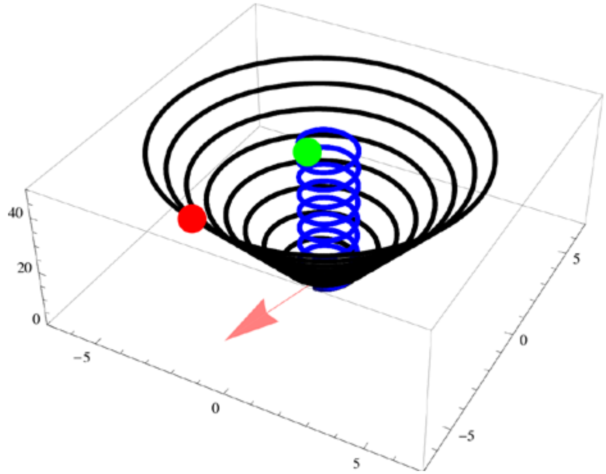
$$m_e \frac{d\vec{v}}{\mathrm{dt}} = -\frac{e}{c}\vec{v}\times\vec{B} - e\vec{E} \qquad \vec{B} = B_0\hat{z} \qquad \vec{E} = E_0[\hat{x}\cos(\omega t) + \hat{y}\sin(\omega t)]$$

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

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

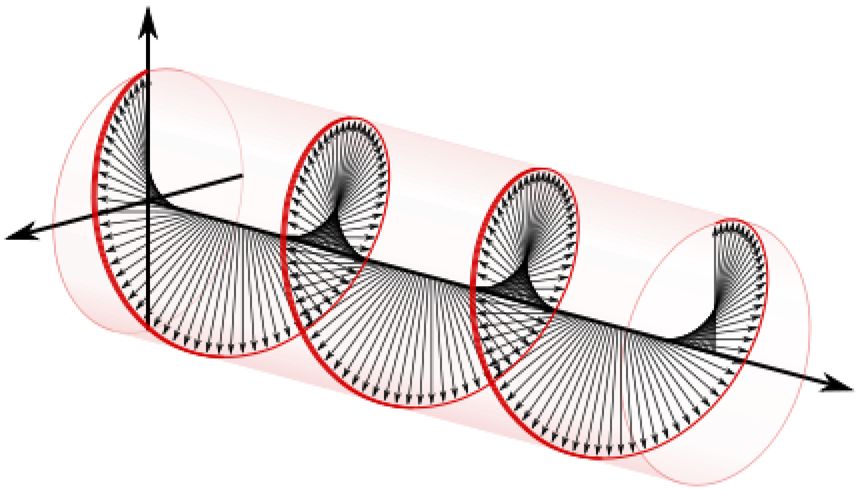
$$\ddot{v}_y = -\frac{eB}{m_e c}\dot{v}_x + \frac{E_0}{m_e}\omega\sin(\omega t) = -\omega_{\mathrm{ce}}{}^2 v_y + \frac{E_0}{m_e}(\omega_{\mathrm{ce}} + \omega)\sin(\omega t)$$

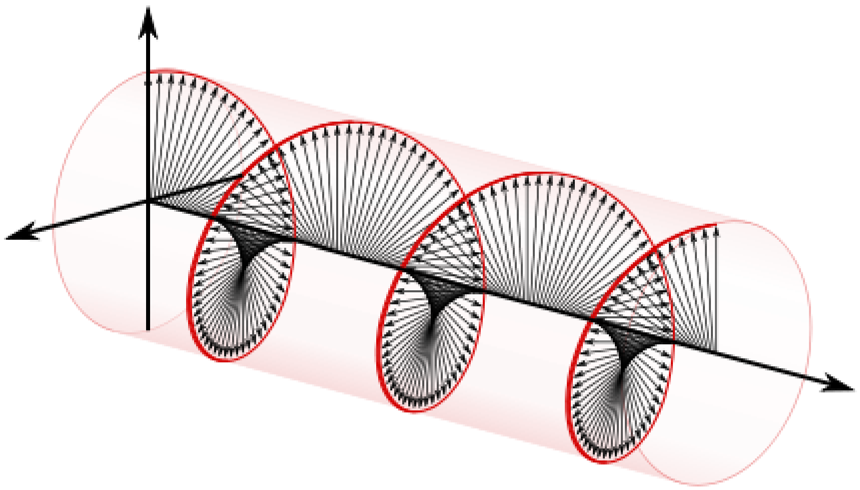
$$\omega_{\mathrm{ce}} = \frac{eB}{m_e c}$$



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

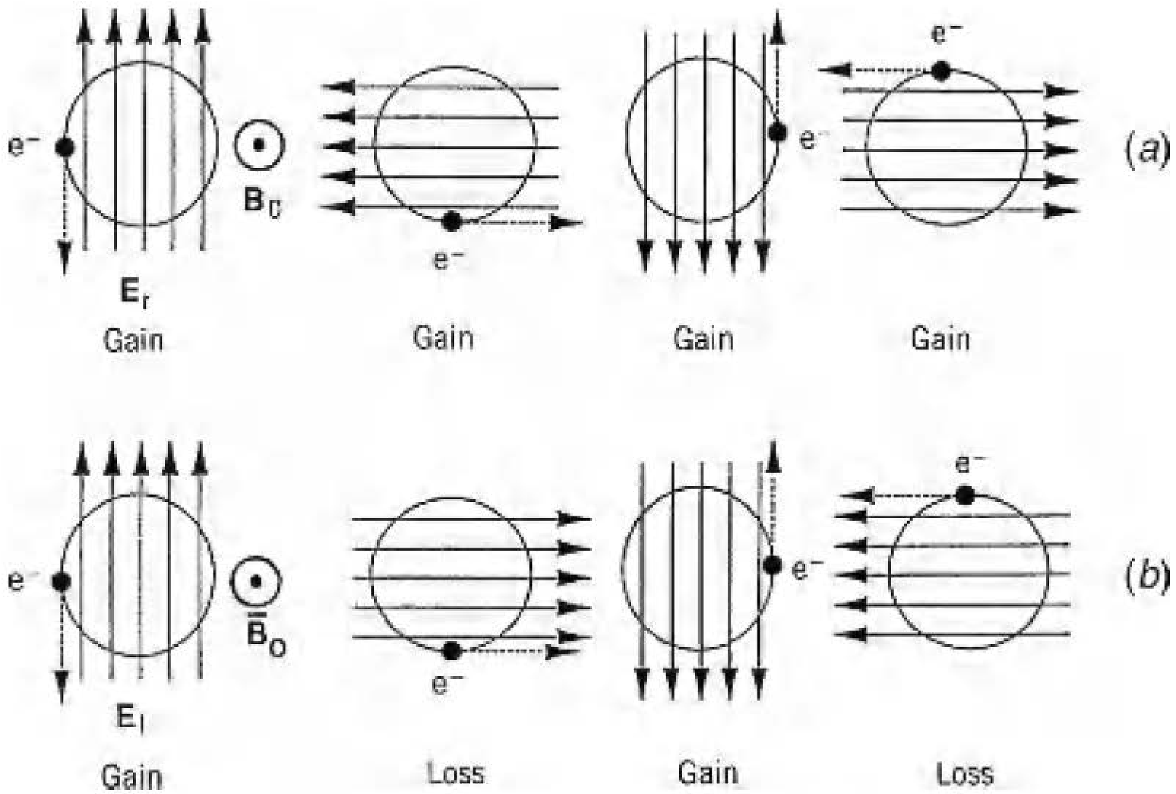
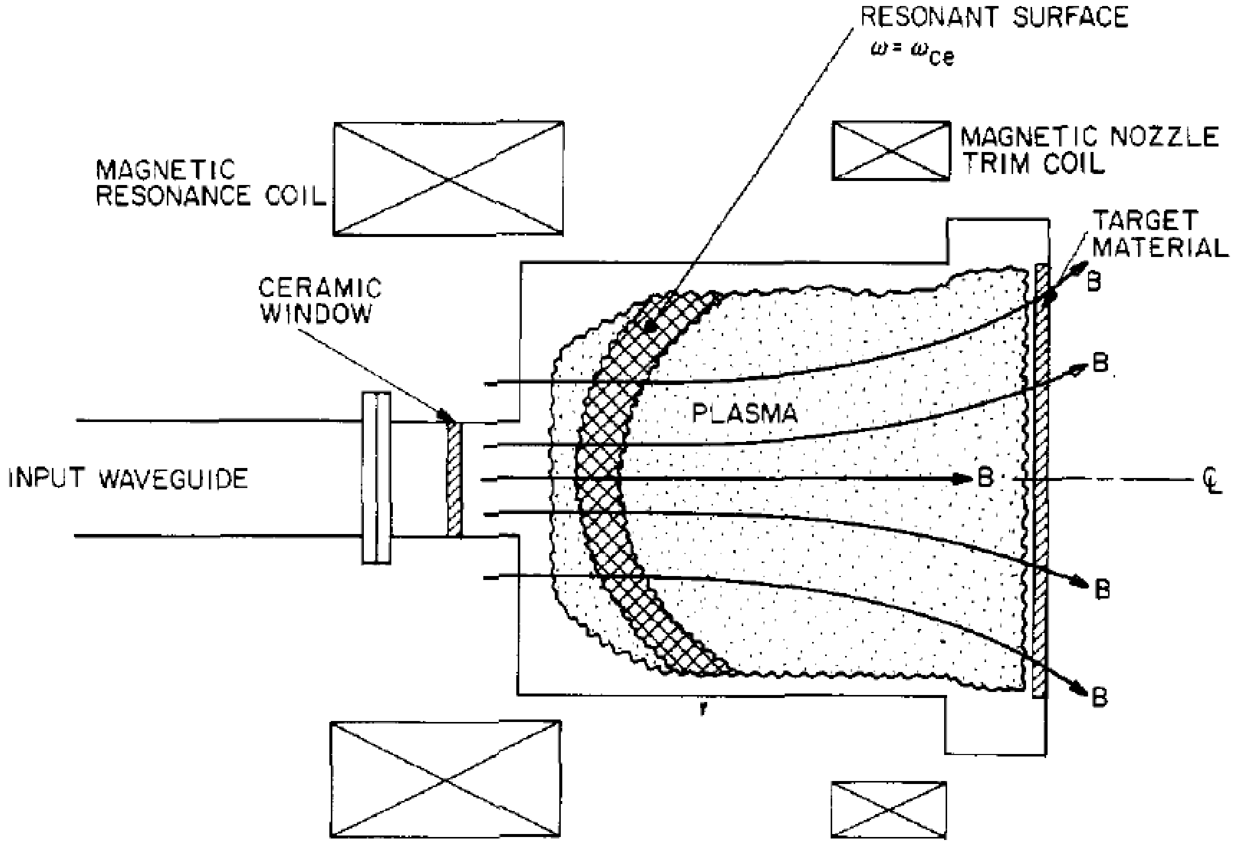


FIGURE 13.5. Basic principle of ECR heating: (*a*) continuous energy gain for right-hand polarization; (*b*) oscillating energy for left-hand polarization (after Lieberman and Gottscho, 1994).

Strong absorption occurs when the frequency matches the electron cyclotron frequency

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



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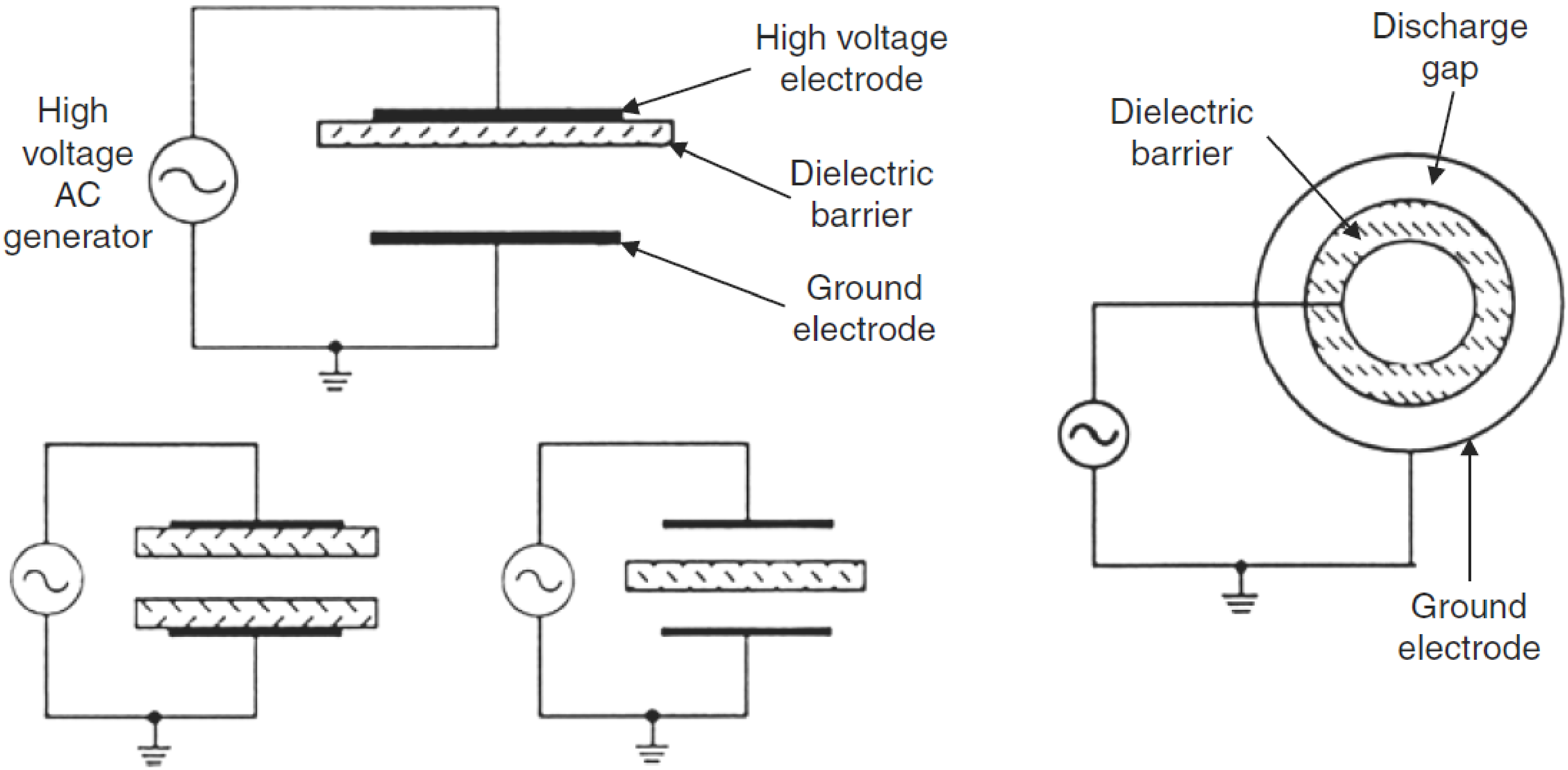
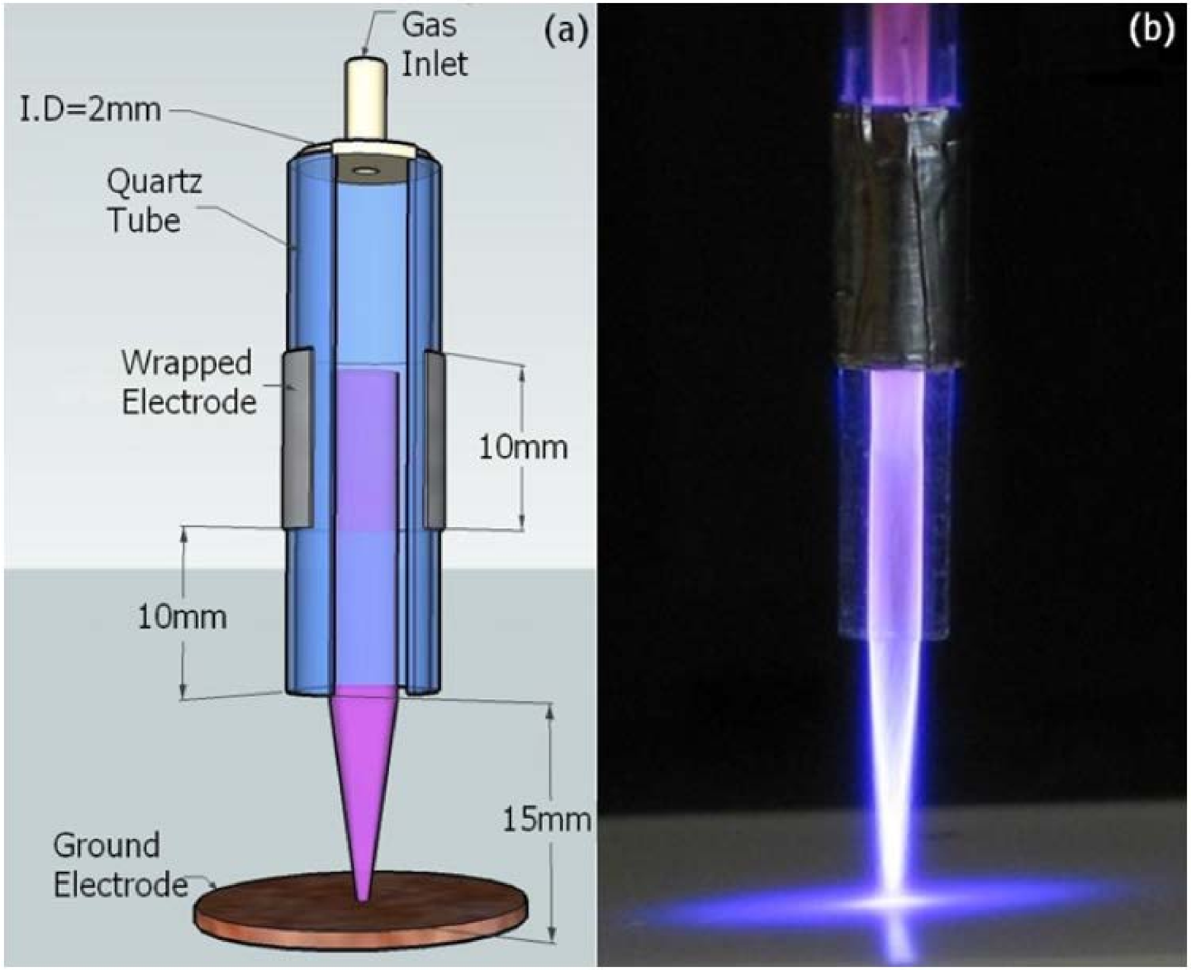
Dielectric-barrier discharges (DBDs)

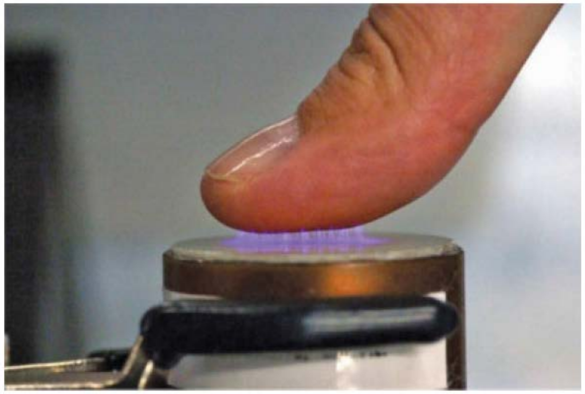


Atmospheric-pressure cold helium microplasma jets



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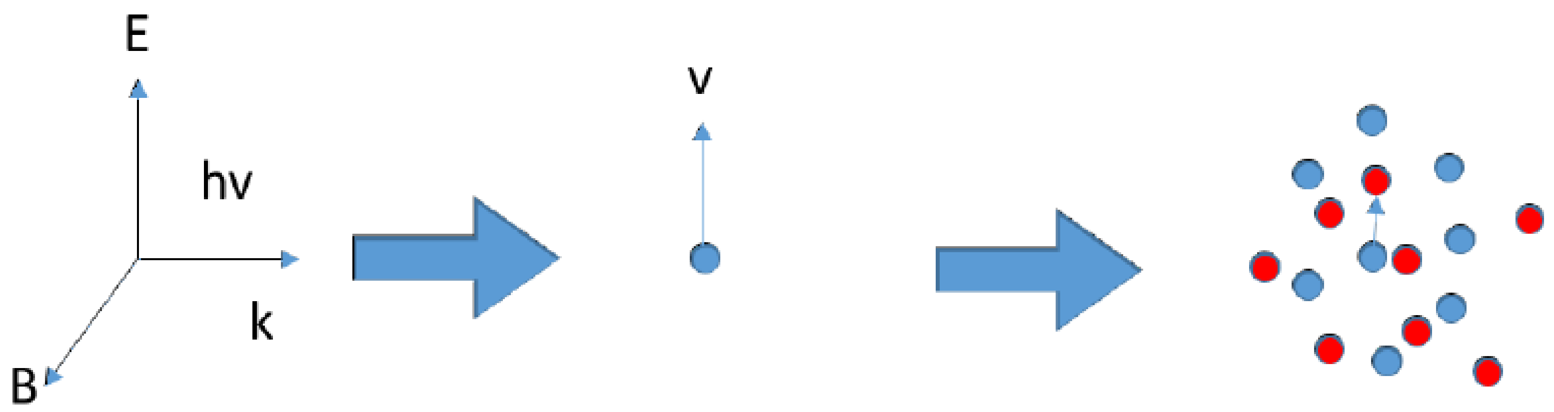
Laser is absorbed in underdense plasma through collisional process called inverse bremsstrahlung



Electrons accelerated by electric fields

Electrons collide with other electrons / ions

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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

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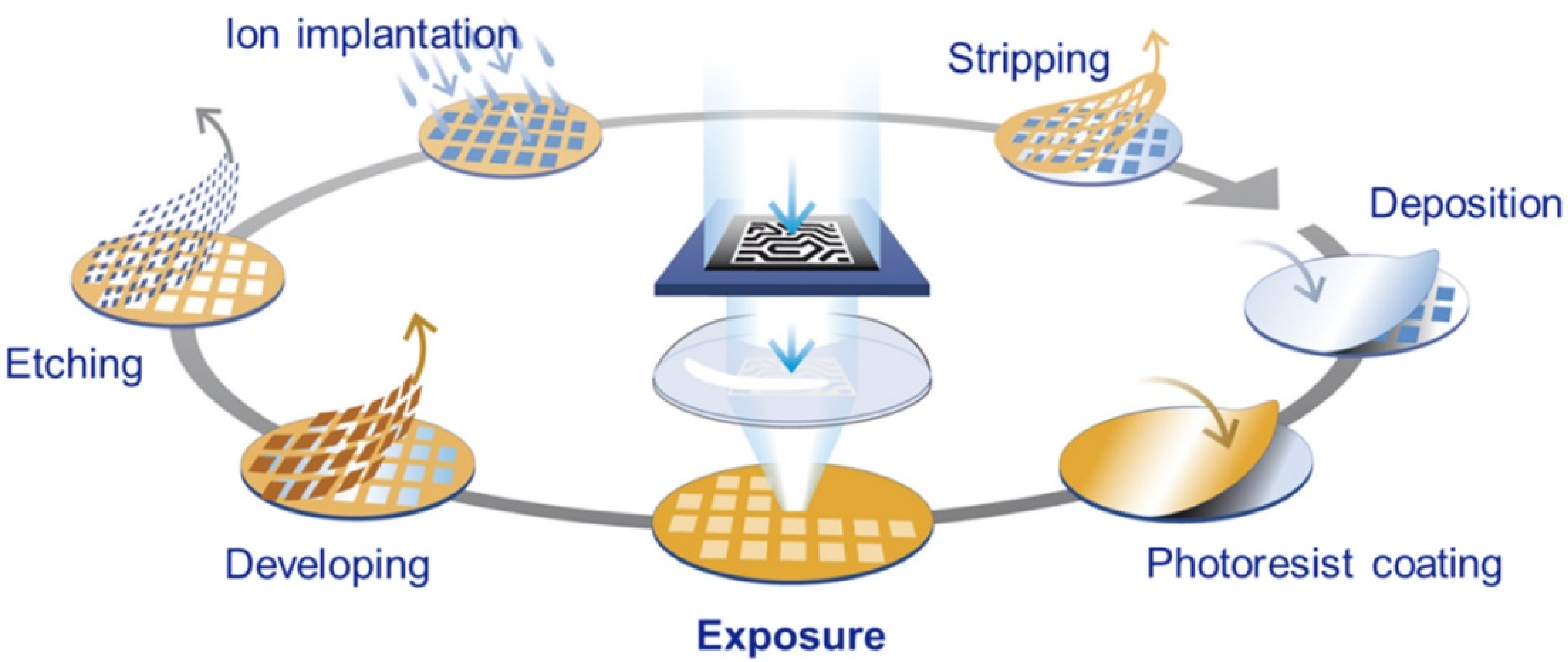
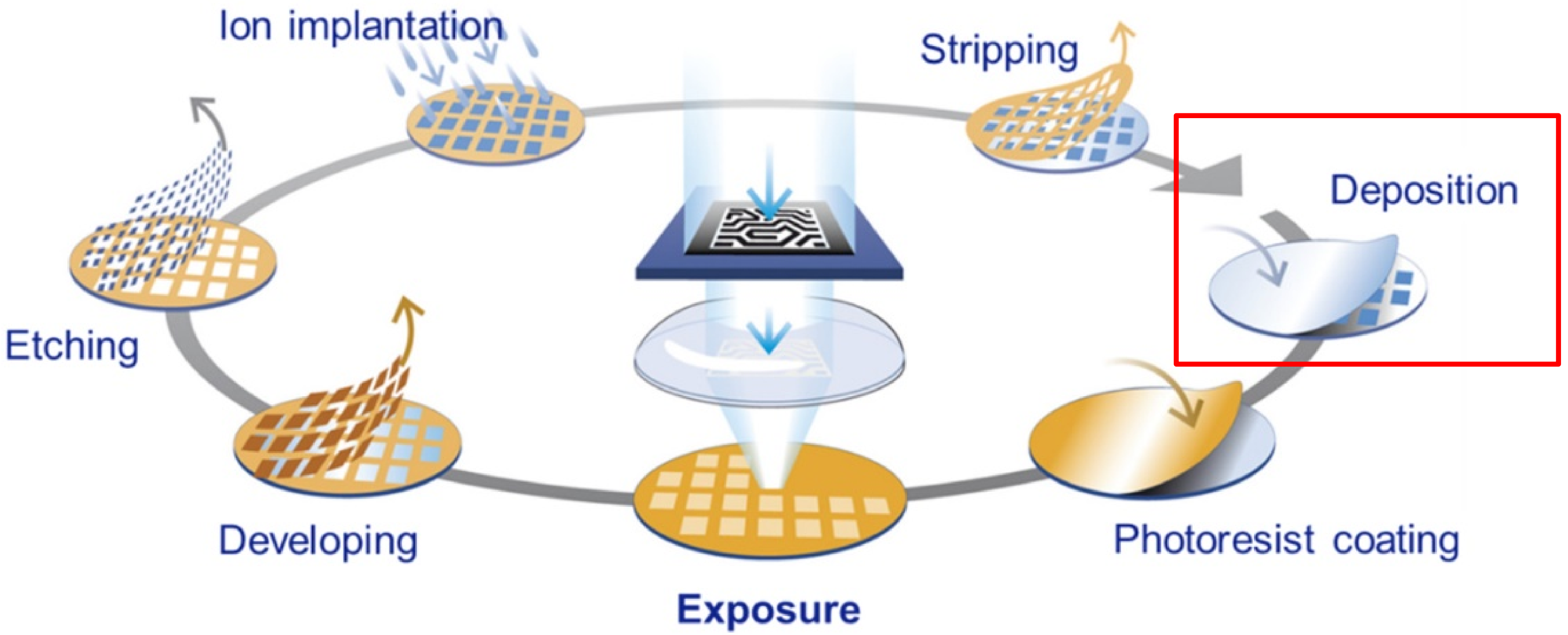
6. Controlled thermonuclear fusion

A semiconductor device is fabricated by many repetitive production process



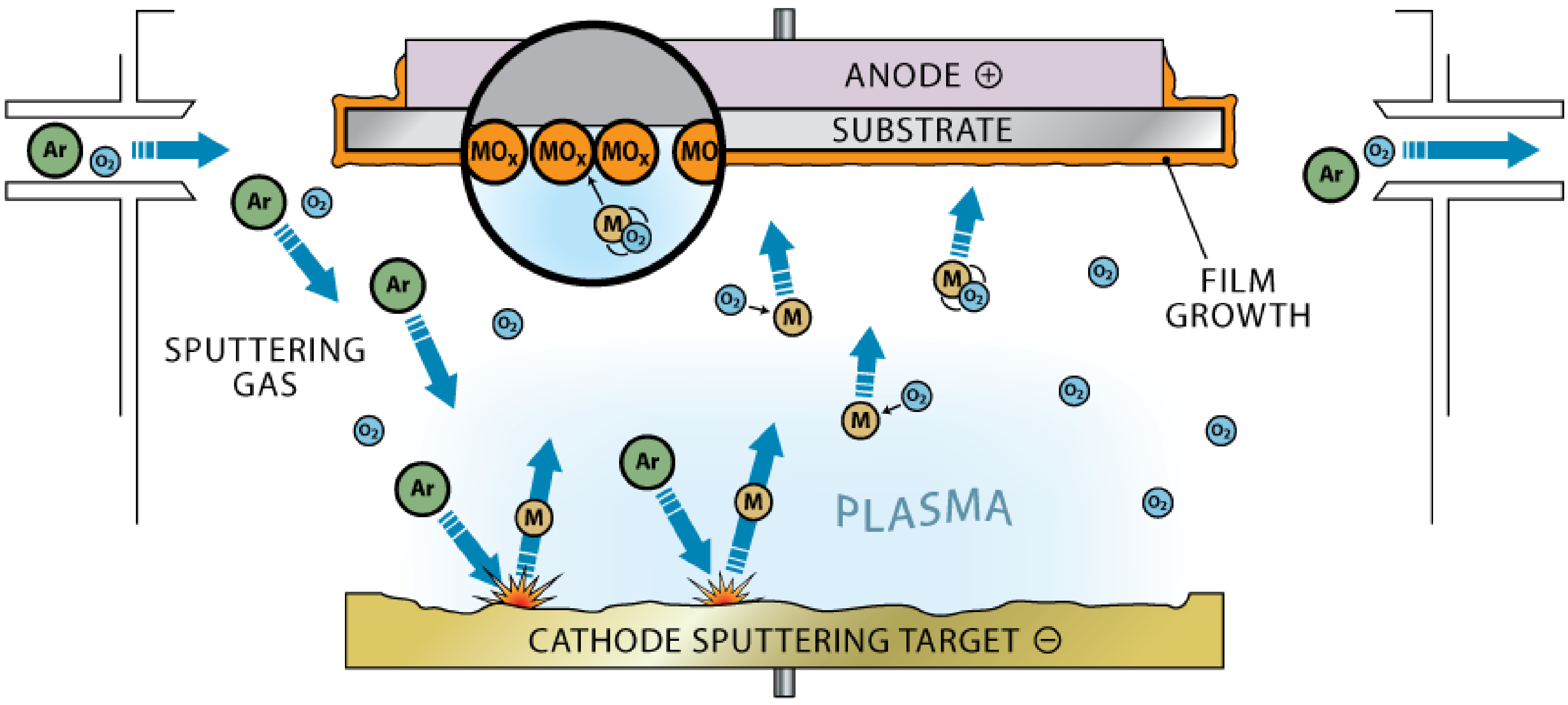
Surf. Topogr.: Metrol. Prop. **4** (2016) 023001

A semiconductor device is fabricated by many repetitive production process



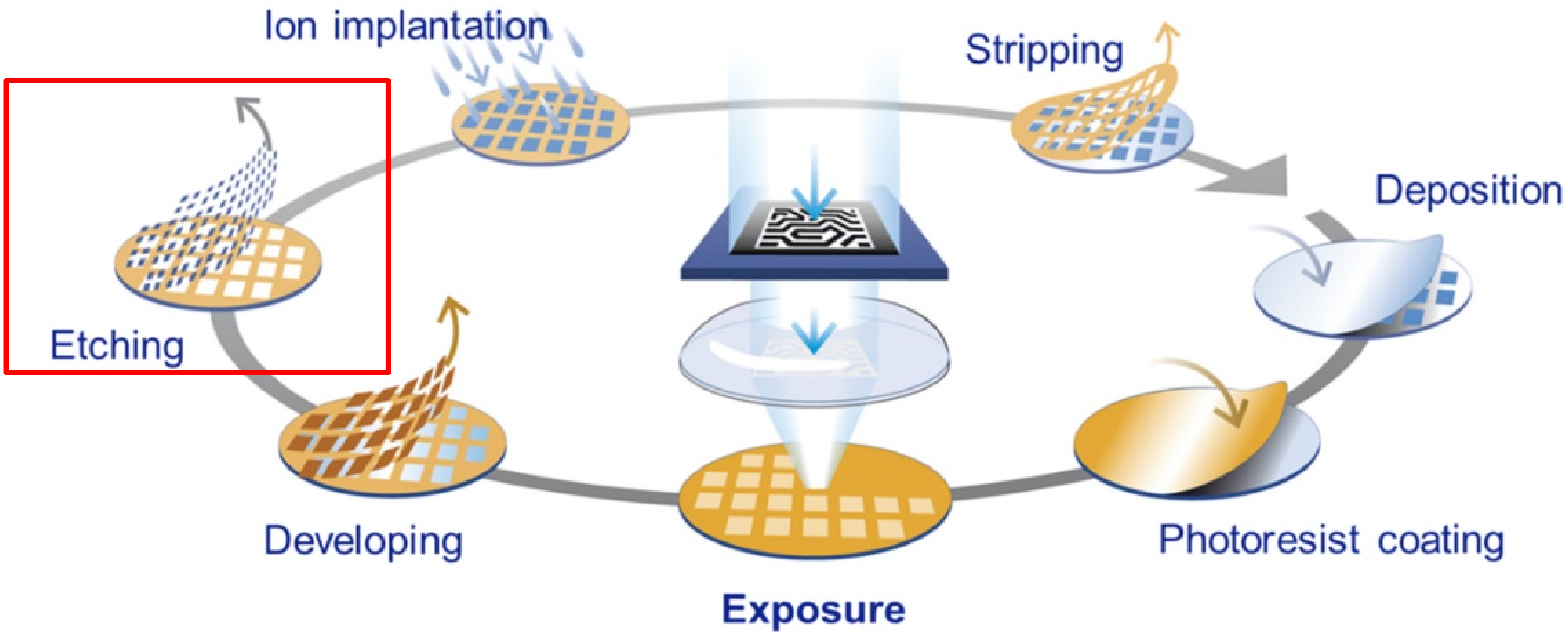
Surf. Topogr.: Metrol. Prop. **4** (2016) 023001

Sputtering deposition



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

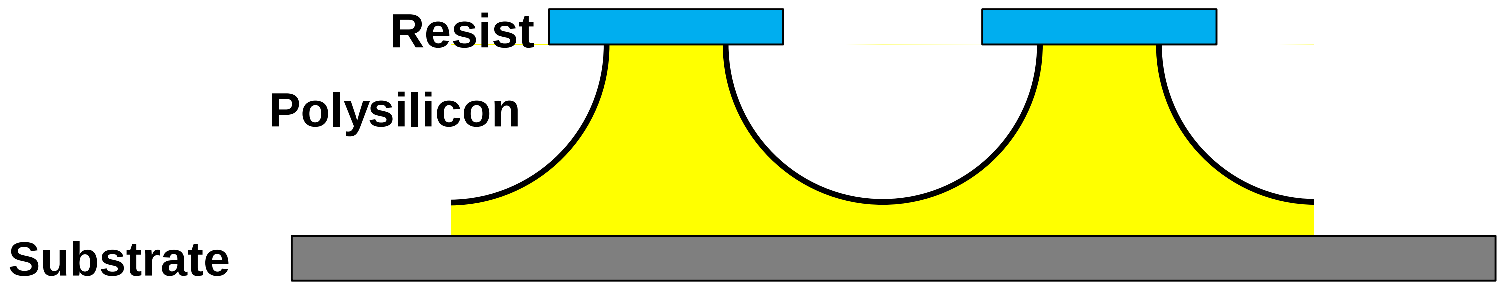
A semiconductor device is fabricated by many repetitive production process



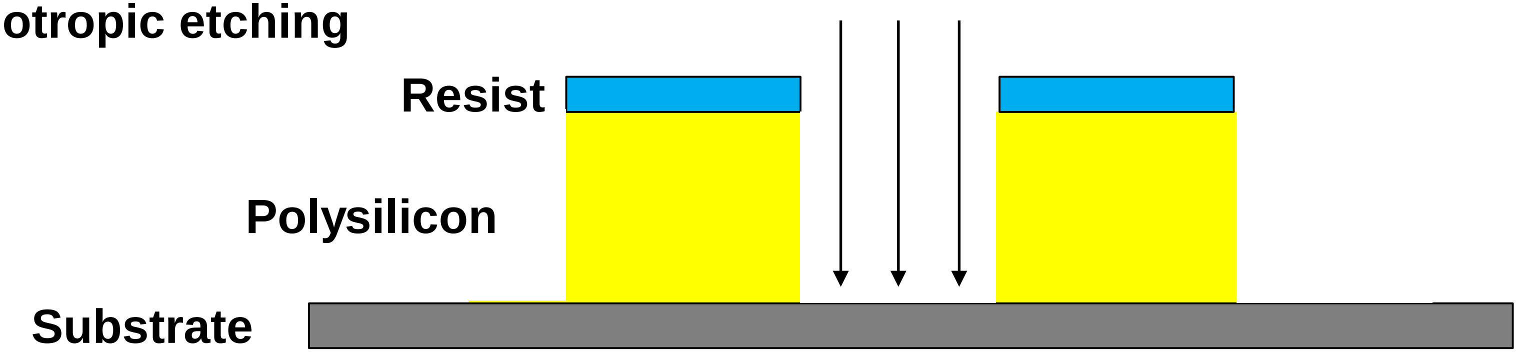
Surf. Topogr.: Metrol. Prop. **4** (2016) 023001

There are two types of etching: isotropic vs anistropic

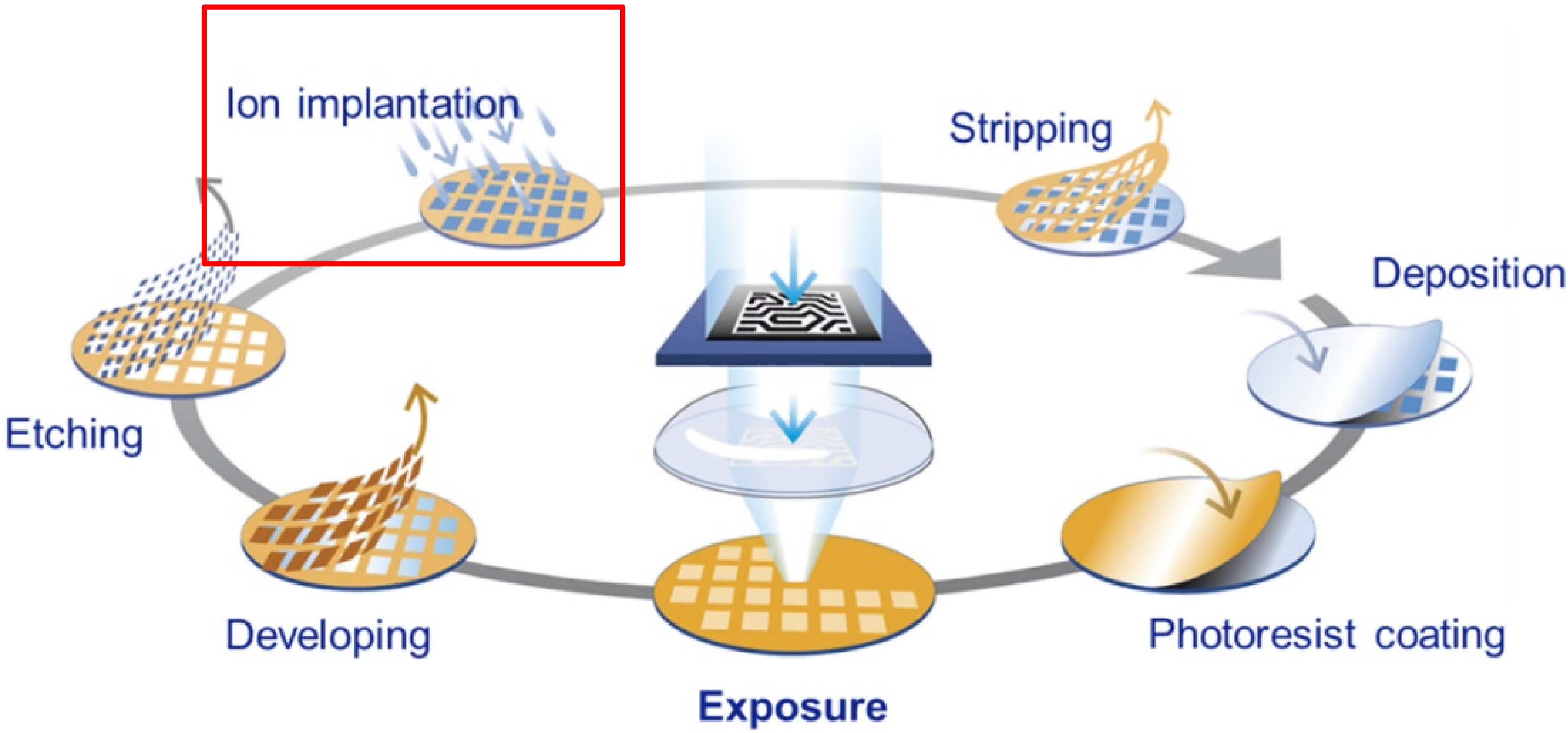
- Isotropic etching



- Anisotropic etching

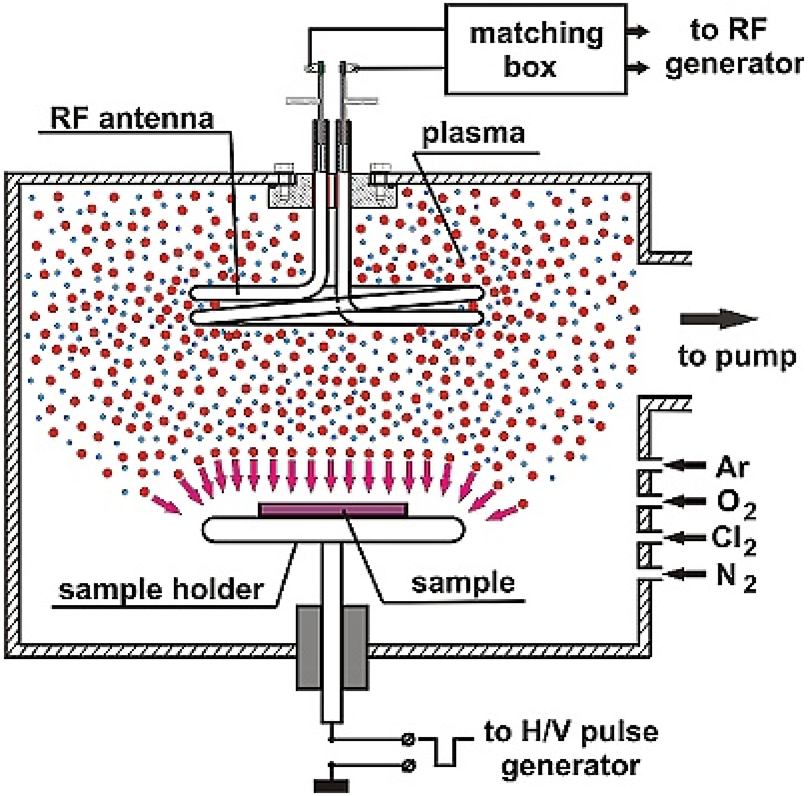


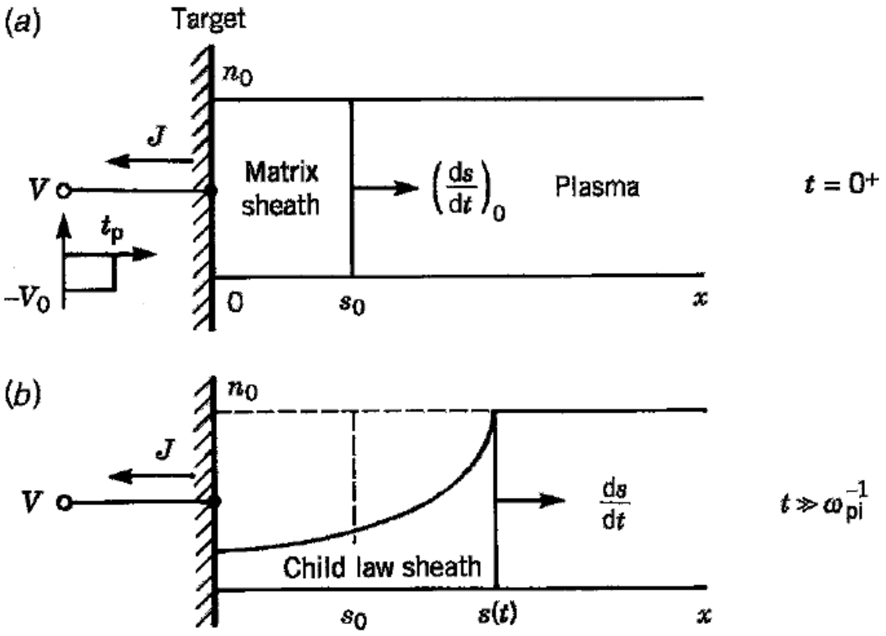
A semiconductor device is fabricated by many repetitive production process



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

Plasma-immersion ion implantation (PIII)

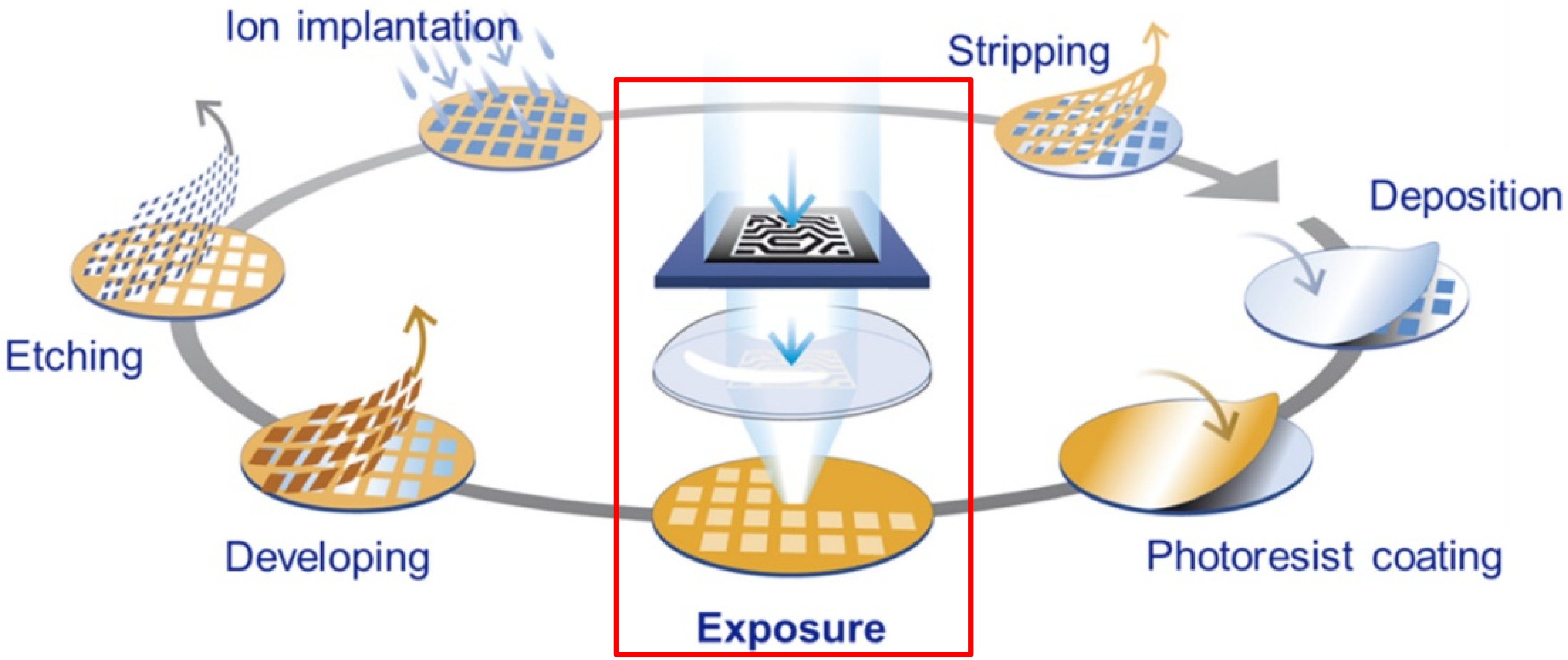




- **Silicon doping – ions such as B, P, As are implanted**
- **Surface hardening of metals – N, C are implanted**

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

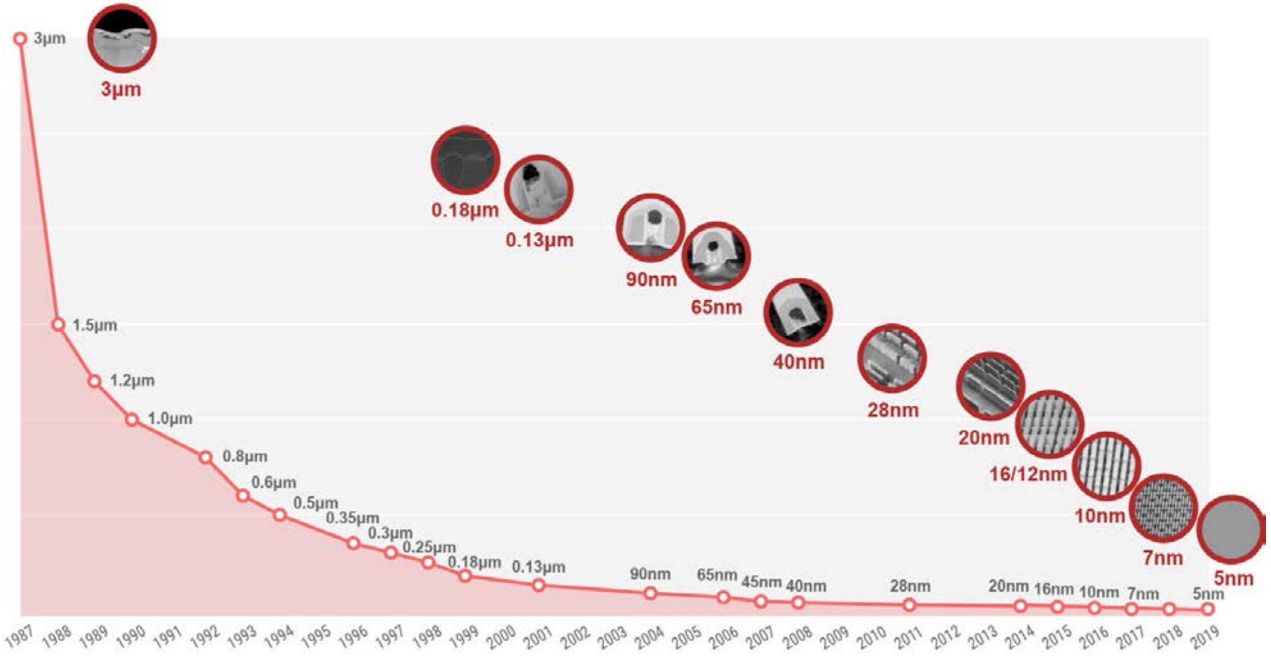
A semiconductor device is fabricated by many repetitive production process



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):**



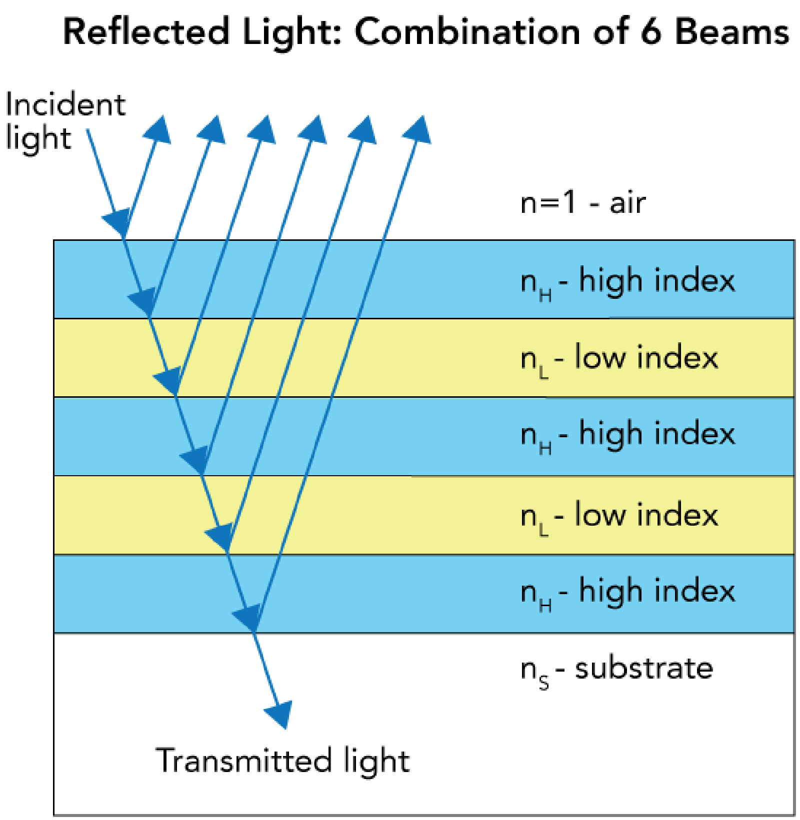
- **Optical diffraction needs to be taken into account.**
- **Shorter wavelength is preferred.**

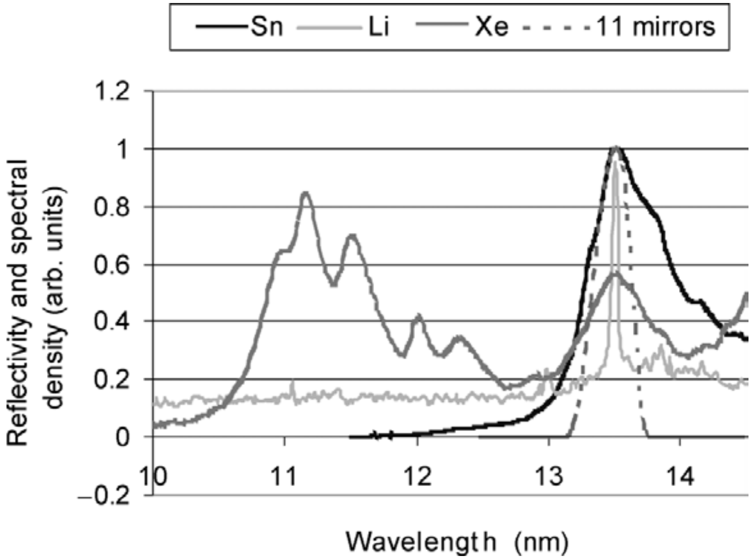
- **Light source with a center wavelength of 13.5 nm is used.**

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

EUV light with λ=13.5 nm is used

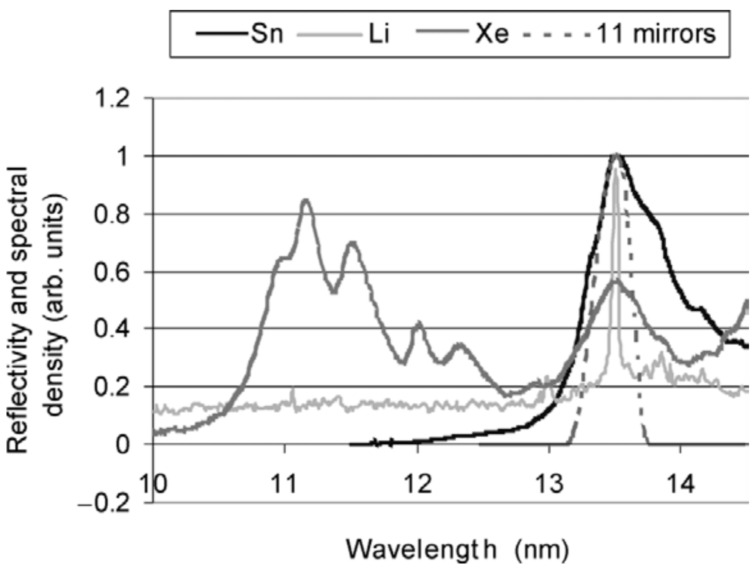
- **Multilayer mirrors is needed for reflecting EUV light.**





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)

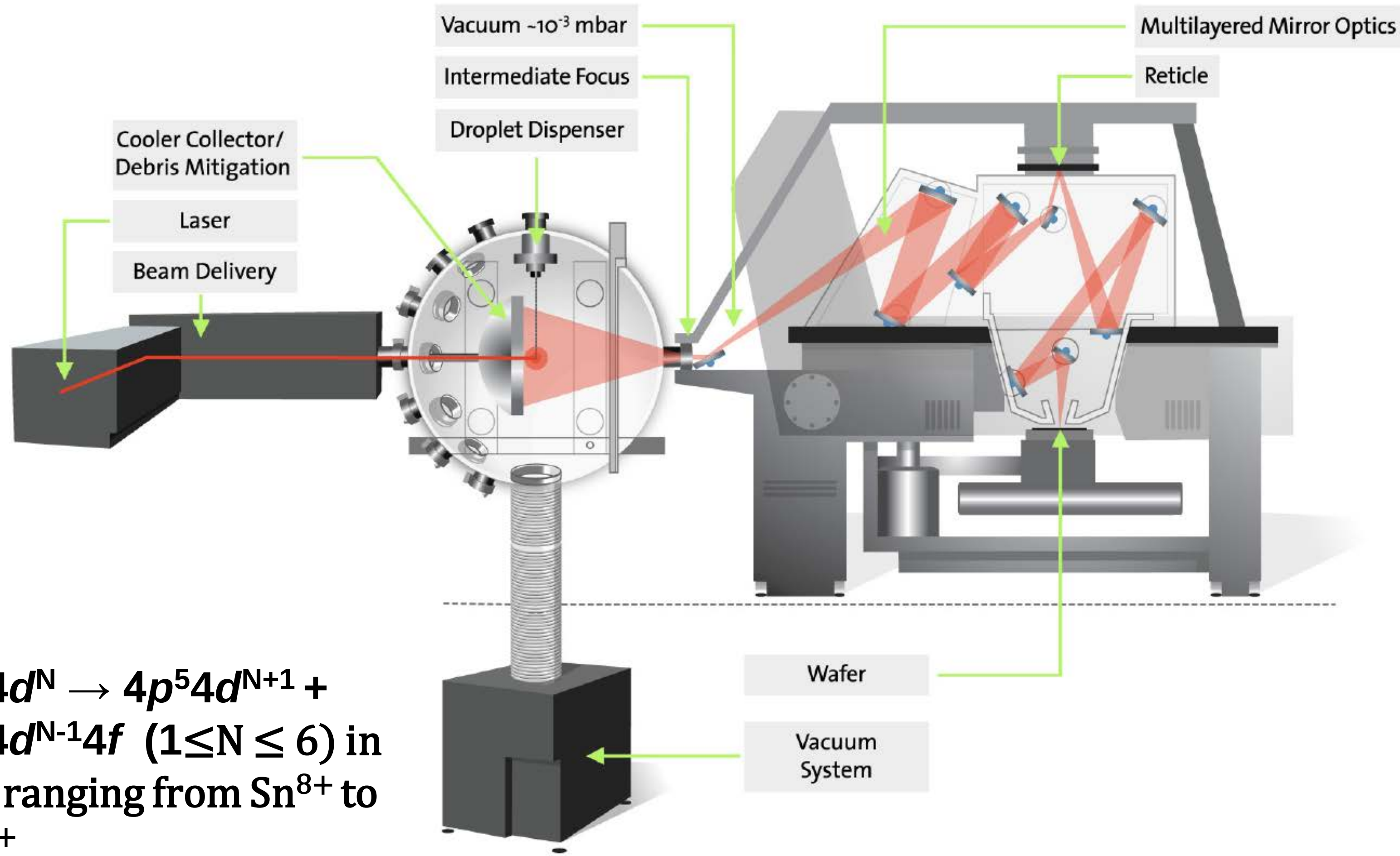


- **At T=35-40 eV (~450,000 K), in-band emission occurs.**
- **Xenon:**
  - **$4p^6 4d^8 \rightarrow 4p^6 4d^7 5p$ from single ion stage Xe^{10+}**
  - **UTA @ 11 nm**
- **Tin:**
  - **$4p^6 4d^N \rightarrow 4p^5 4d^{N+1} + 4p^6 4d^{N-1} 4f$ $(1 \leq N \leq 6)$ in ions ranging from Sn^{8+} to Sn^{12+}**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

- UTA: unresolved transition array

V. Bakshi, EUV sources for lithography

EUV light sources from laser-produced plasma (LPP)



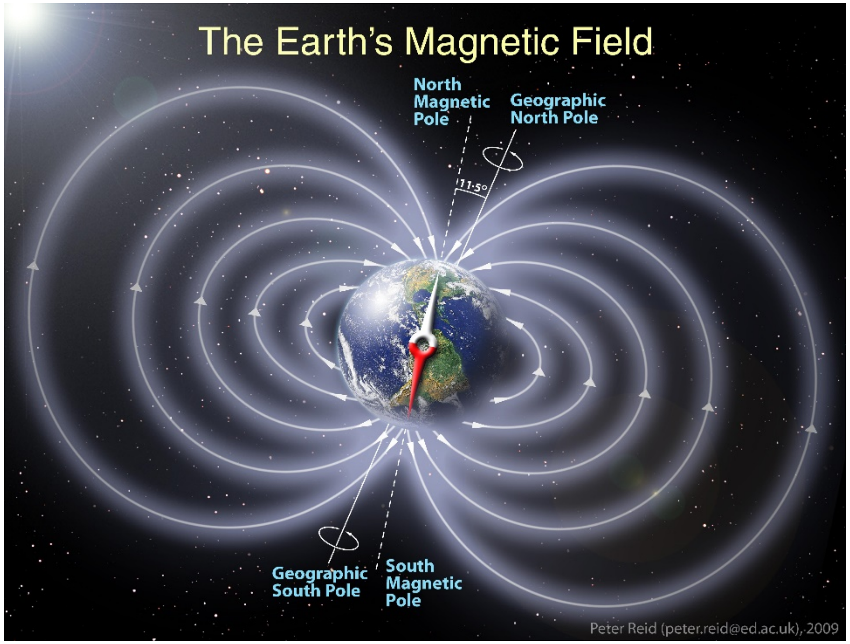
- **Tin:**
  - ***4p*^{6}*4d*^{N} → *4p*^{5}*4d*$^{N+1}$ + *4p*^{6}*4d*$^{N-1}$*4f*** (1≤N ≤ 6) in ions ranging from Sn^{8+} to Sn^{12+}
  - **UTA @ 13.5 nm**

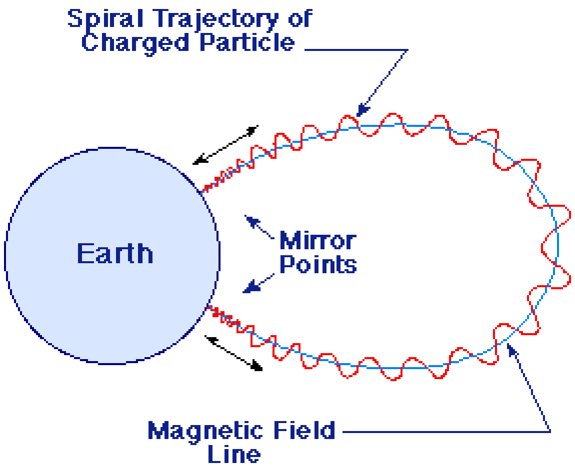
R. S. Abhari, etc., J. Micro/Nanolithography, MEMS, and MOEMS, 11, 021114 (2012)

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

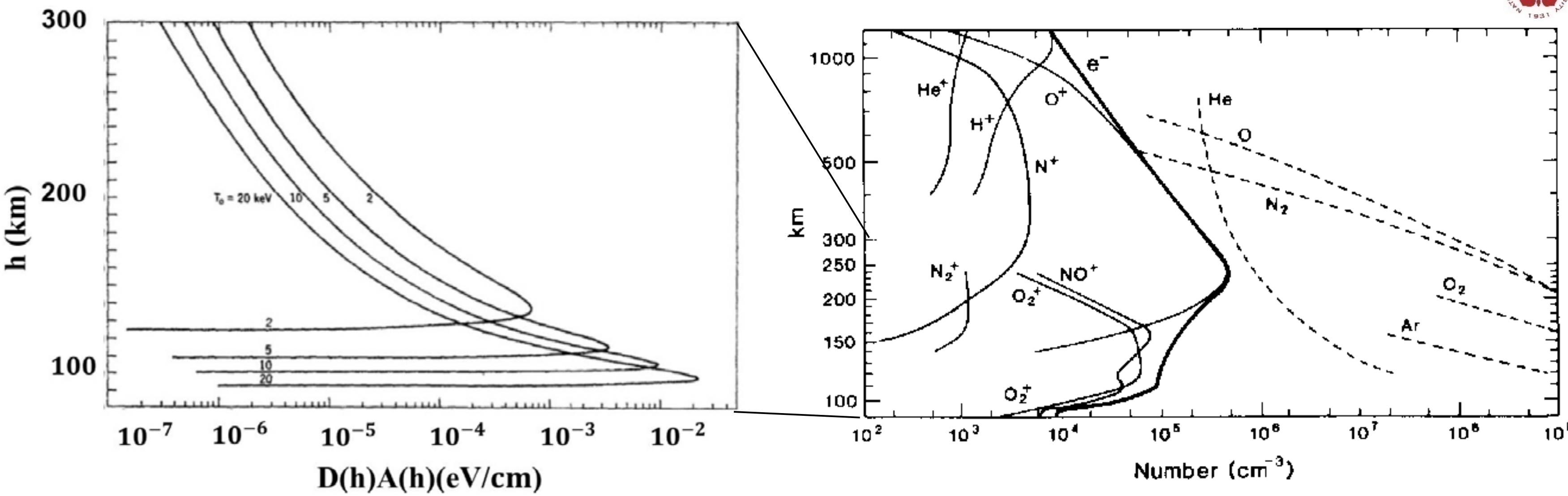
Earth's magnetic field



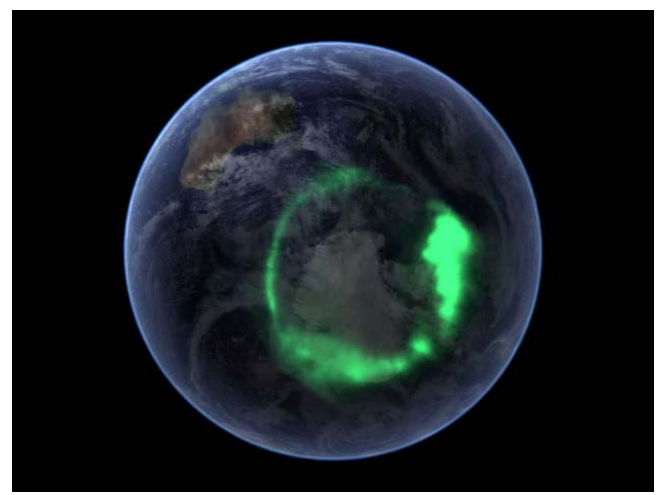


https://www.nasa.gov/mission_pages/sunearth/news/gallery/Earths-magneticfieldlines-dipole.html
http://www.pas.rochester.edu/~blackman/ast104/emagnetic.html

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



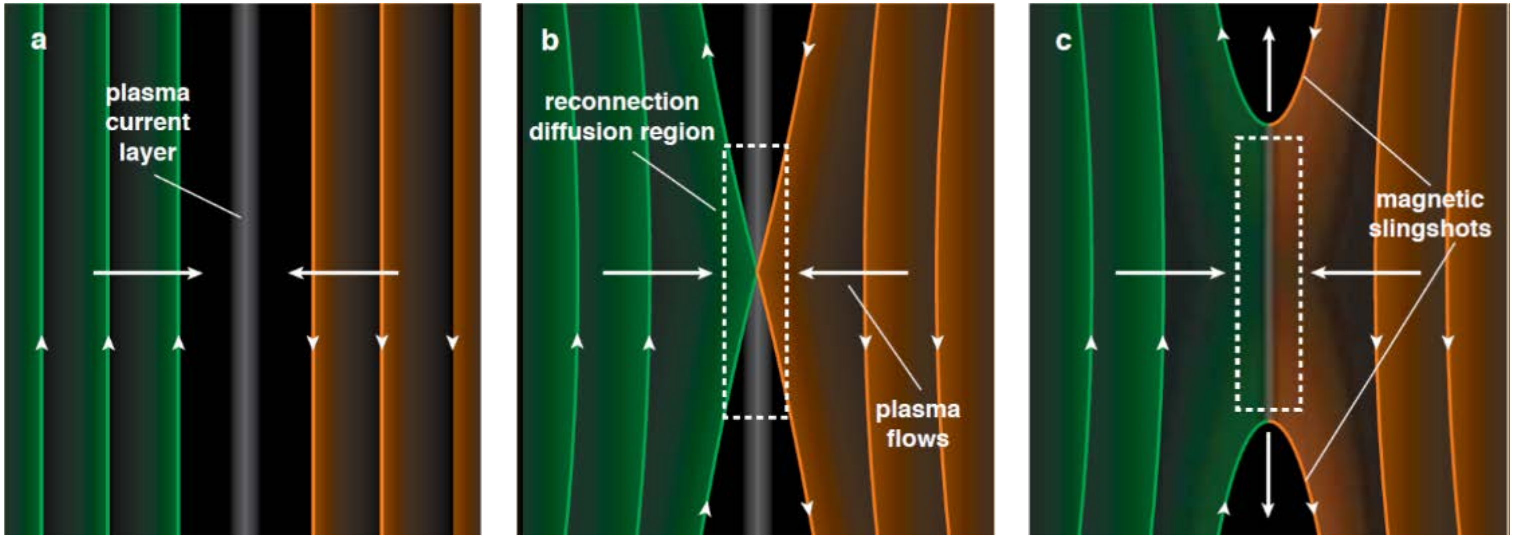
- O_2: green or dark red
- N_2: blue or purple



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

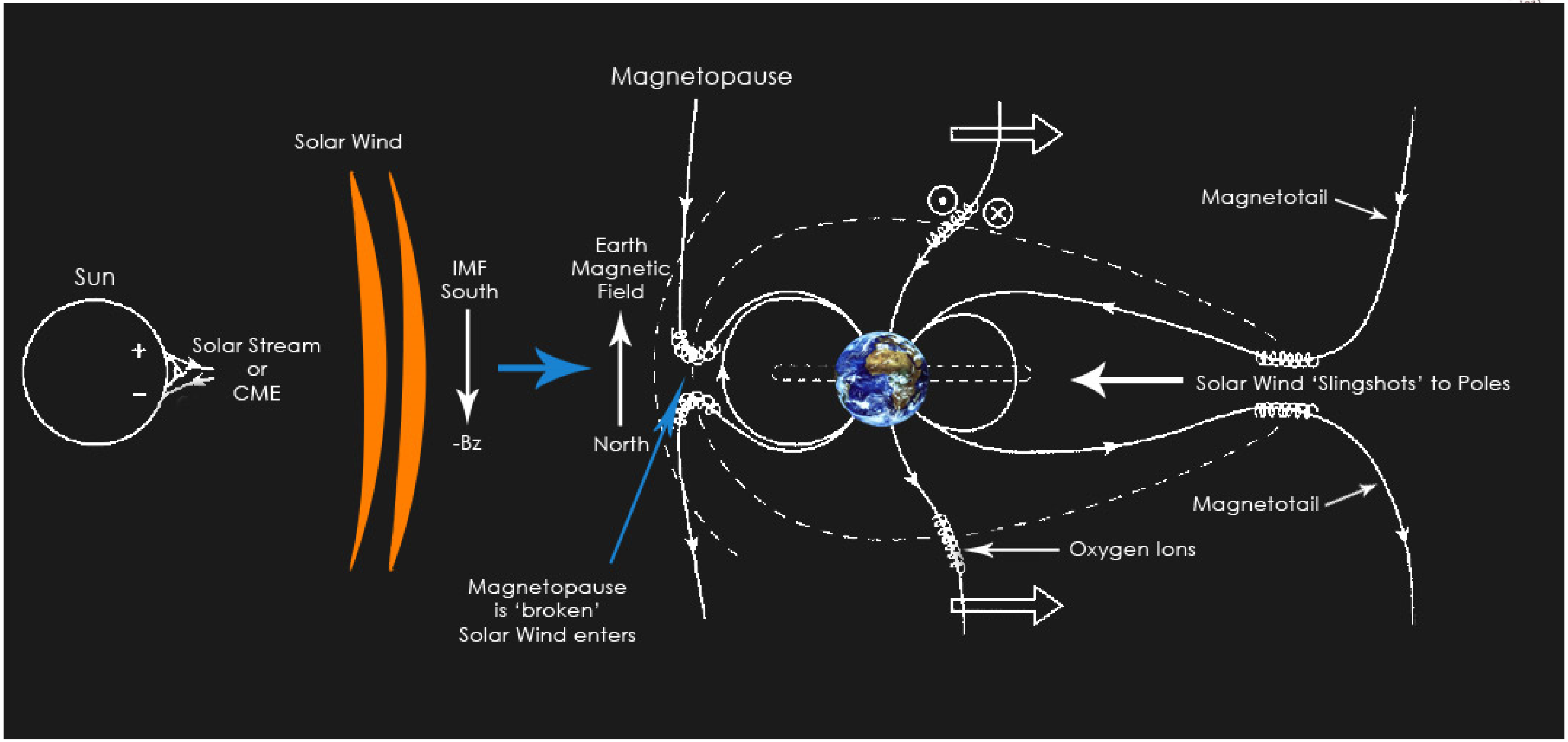
https://flashpack.com/insights/2014/11/20/aurora-australis-forget-the-northern-lights-have-you-heard-about-the-southern-lights/

Reconnection



https://www.youtube.com/watch?v=7sS3Lpzh0Zw

Reconnections occur in many locations



- **The Aurora Borealis:**

  https://www.youtube.com/watch?v=lT3J6a9p_o8

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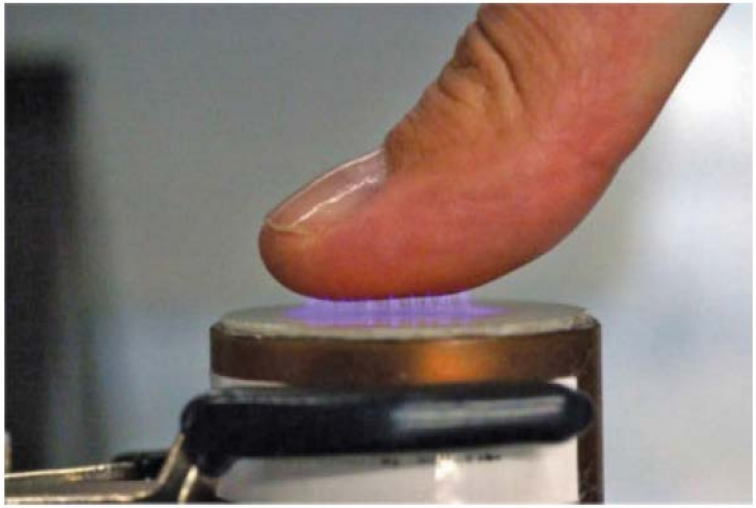
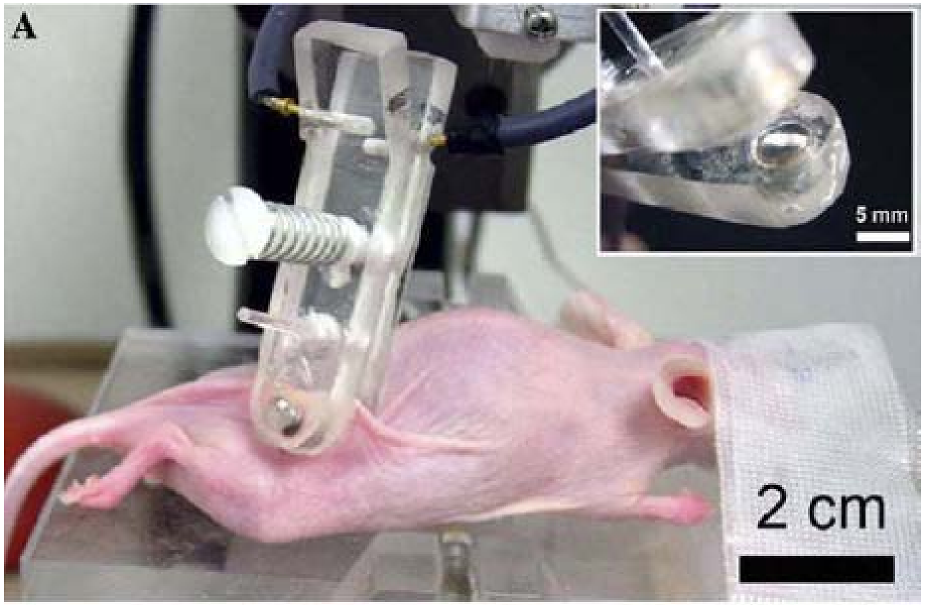
http://www.natalia-robba.com/myblog/travel/the-aurora-borealis-the-northern-lights-everything-you-need-to-know/

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

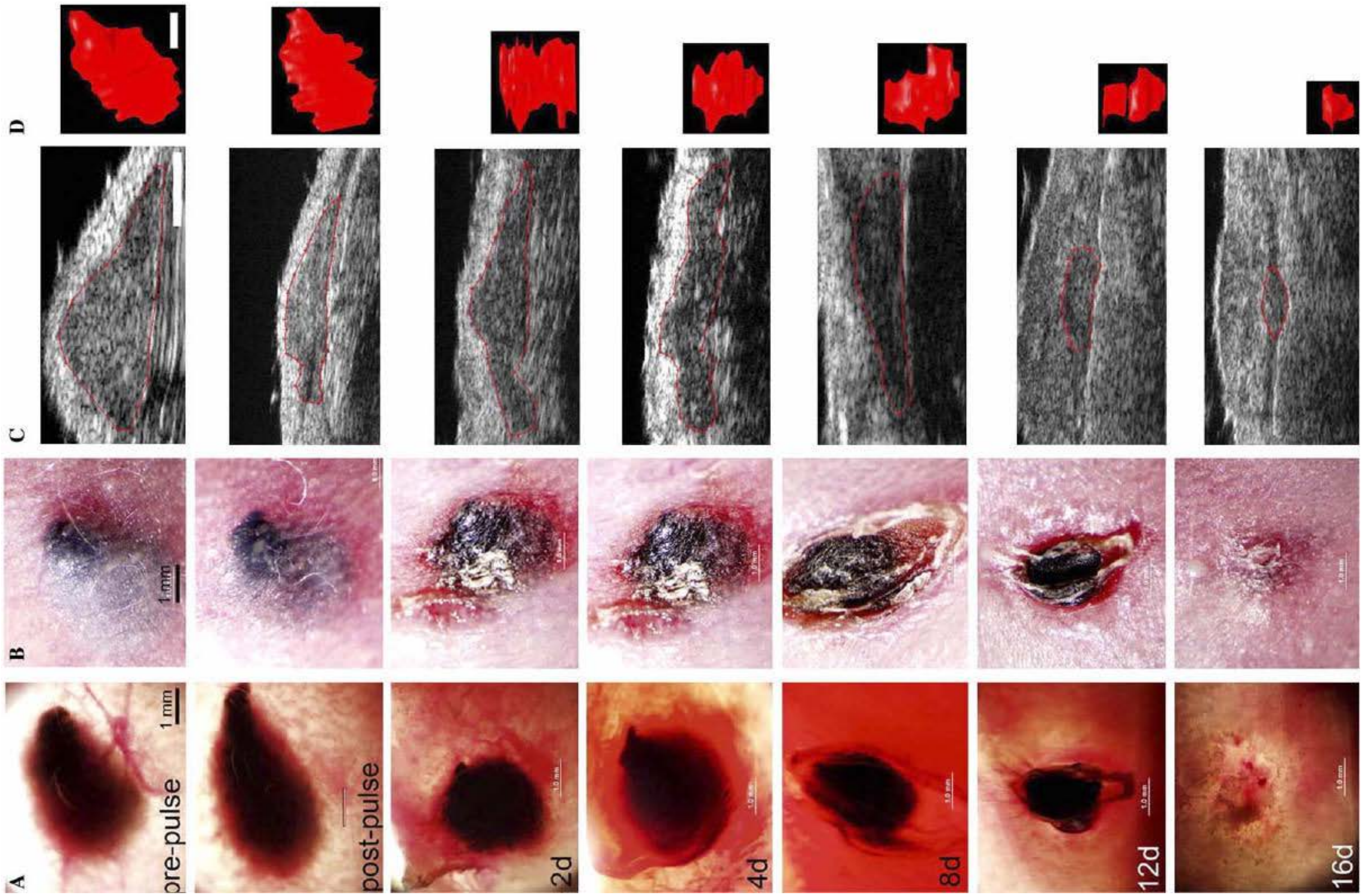
Biomedical applications of low temperature plasma





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**

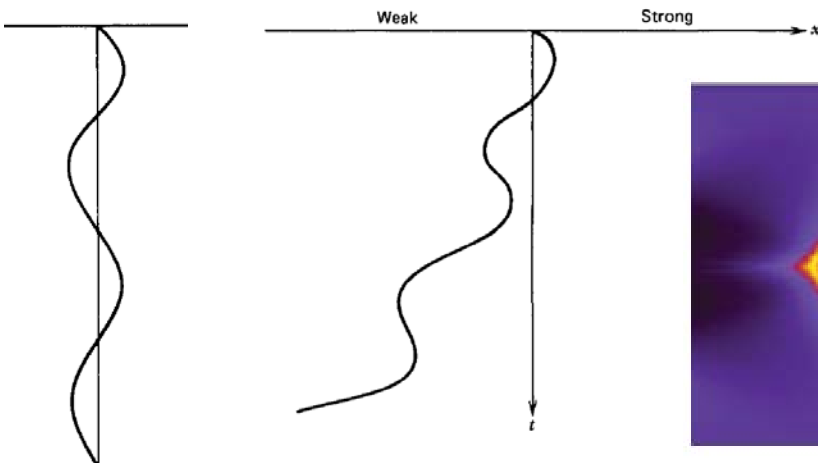
Biochem Biophys Res Commun. 2006 May 5; 343(2): 351–360.

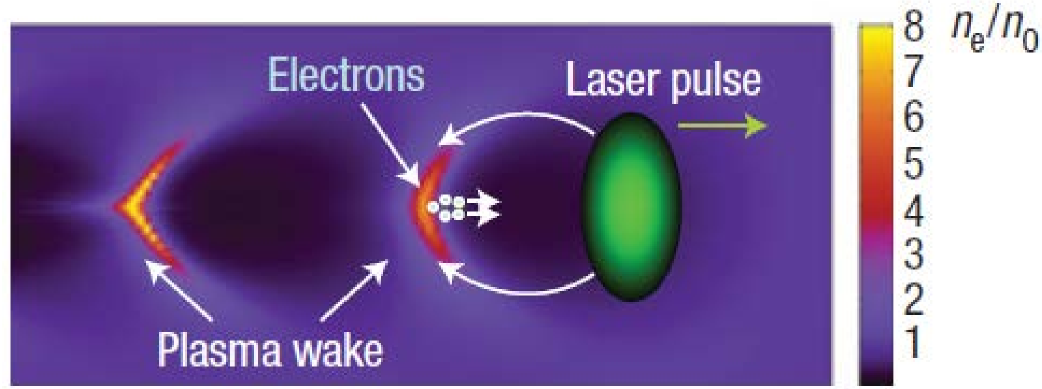
Applications of plasma

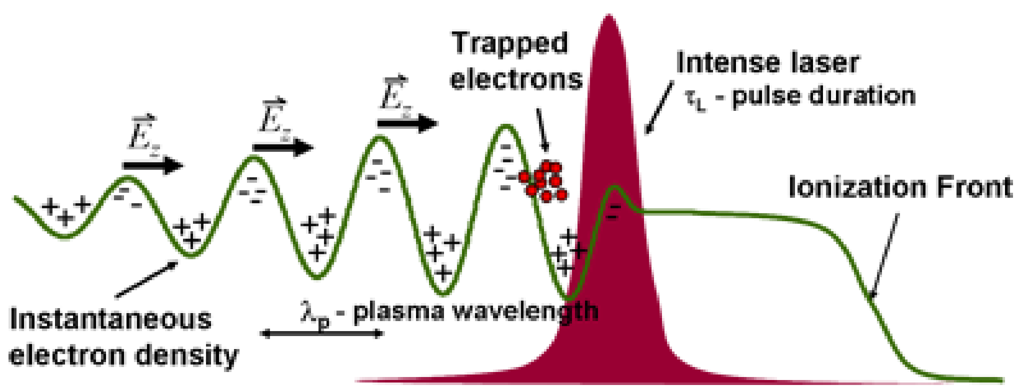
1. Material Processing
2. Plasma in space
3. Biomedical application
4. **High energy particle accelerator**
5. Electric propulsion
6. Controlled thermonuclear fusion

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

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

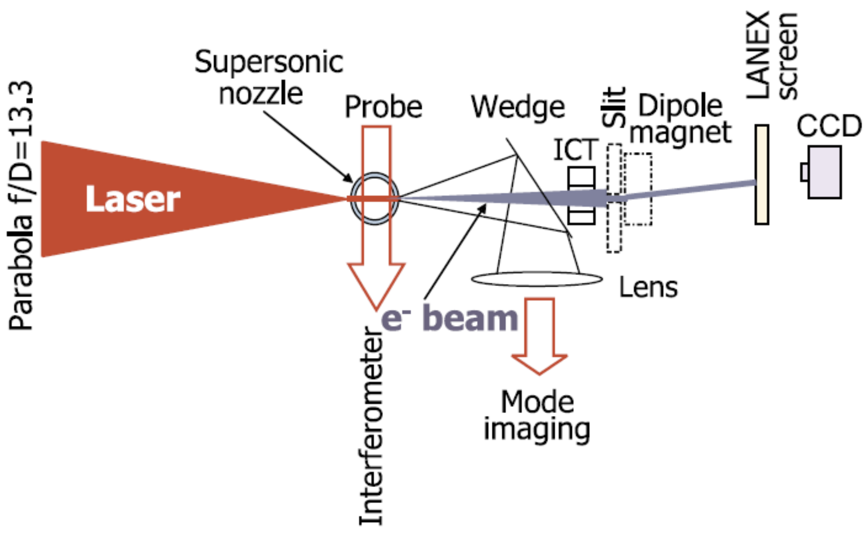


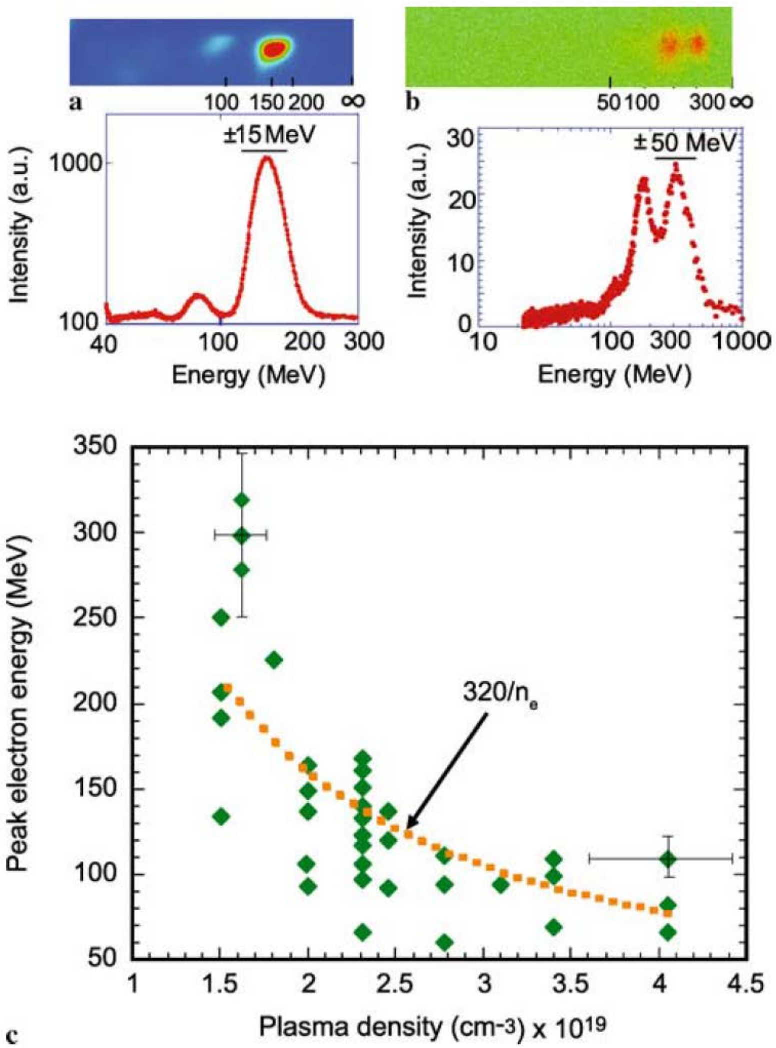




V. Malka, *et al.*, Nature Physics **4**, 447 (2008)
http://cuos.engin.umich.edu/researchgroups/hfs/research/laser-wakefield-acceleration/
https://i.ytimg.com/vi/CA-SDf1wvTQ/maxresdefault.jpg

Electrons with a maximum energy of 320 MeV are generated





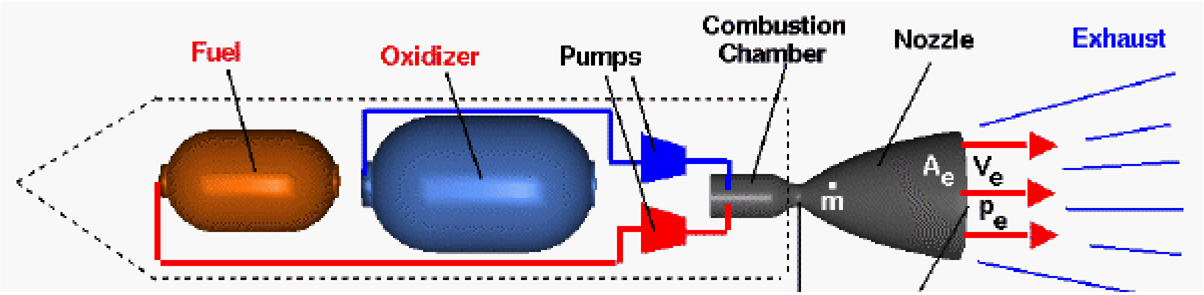
A. Maksimchuk, *et al.*, Appl. Phys. B **89**, 201 (2007)

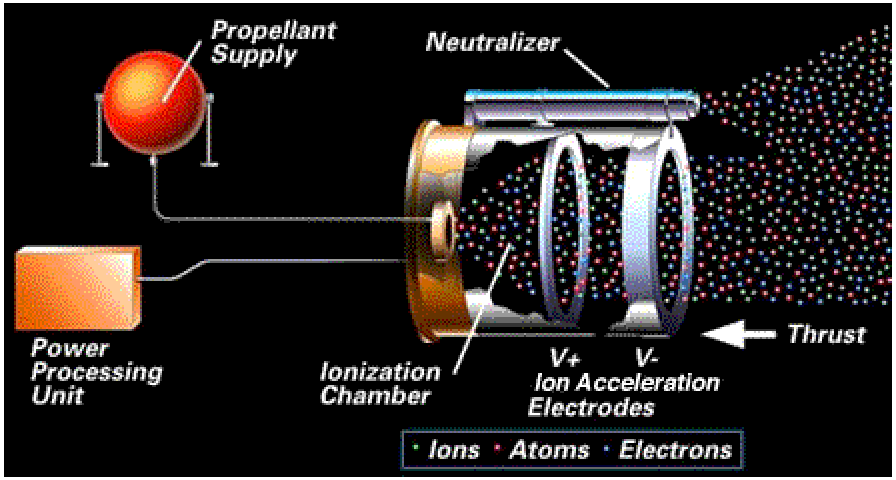
Applications of plasma

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



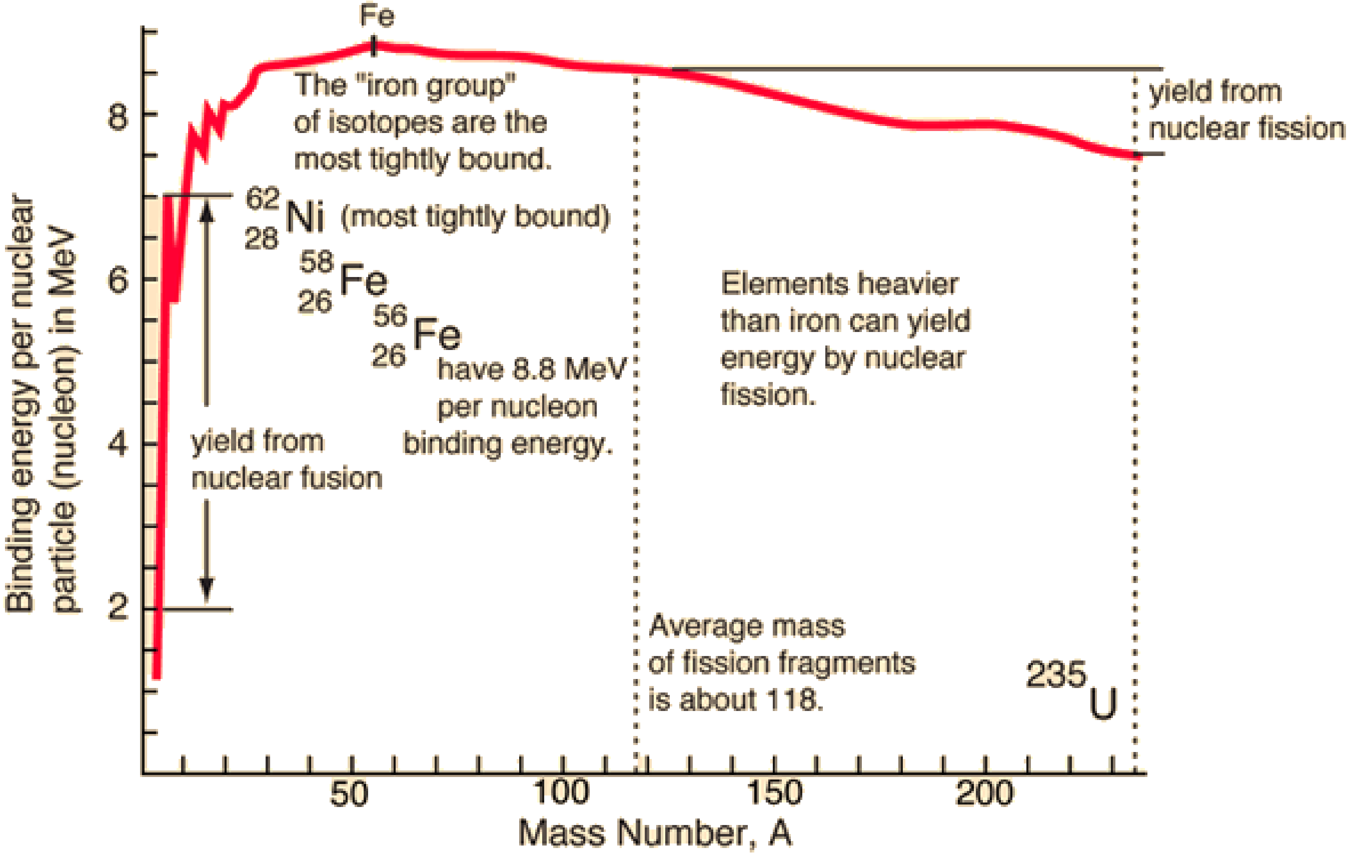


https://www.grc.nasa.gov/WWW/K-12/airplane/lrockth.html
https://defence.pk/pdf/threads/isro-to-test-electric-propulsion-on-satellites.411176/

Applications of plasma

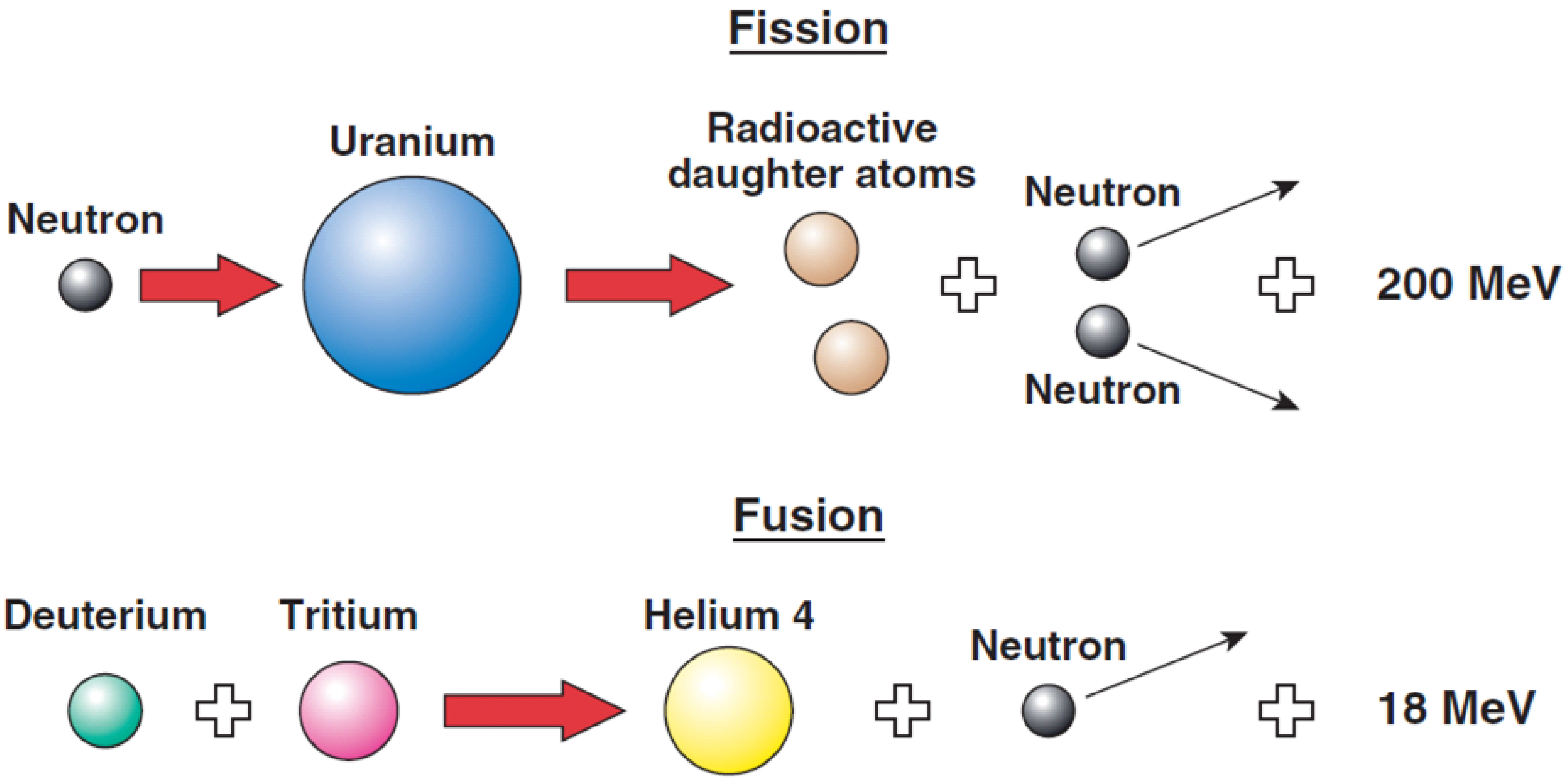
1. Material Processing
2. Plasma in space
3. biomedical application
4. high energy particle accelerator
5. Electric propulsion
6. **Controlled thermonuclear fusion**

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



(3.5MeV) (14.1MeV)

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

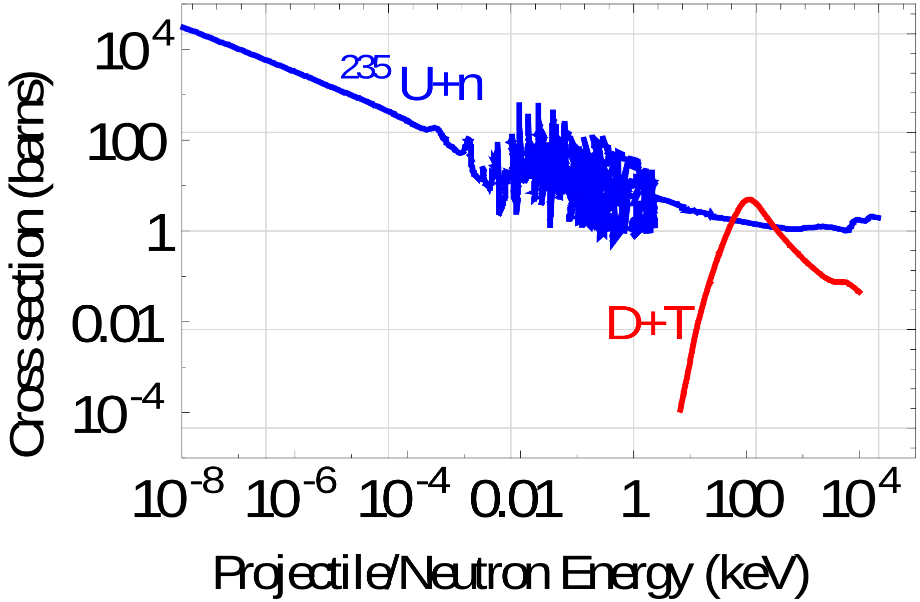
Fusion of $^2H + ^3H$: $$\frac{Q}{A} = \frac{17.6\ MeV}{(3+2)\ amu} = 3.5\ \frac{MeV}{amu}$$

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

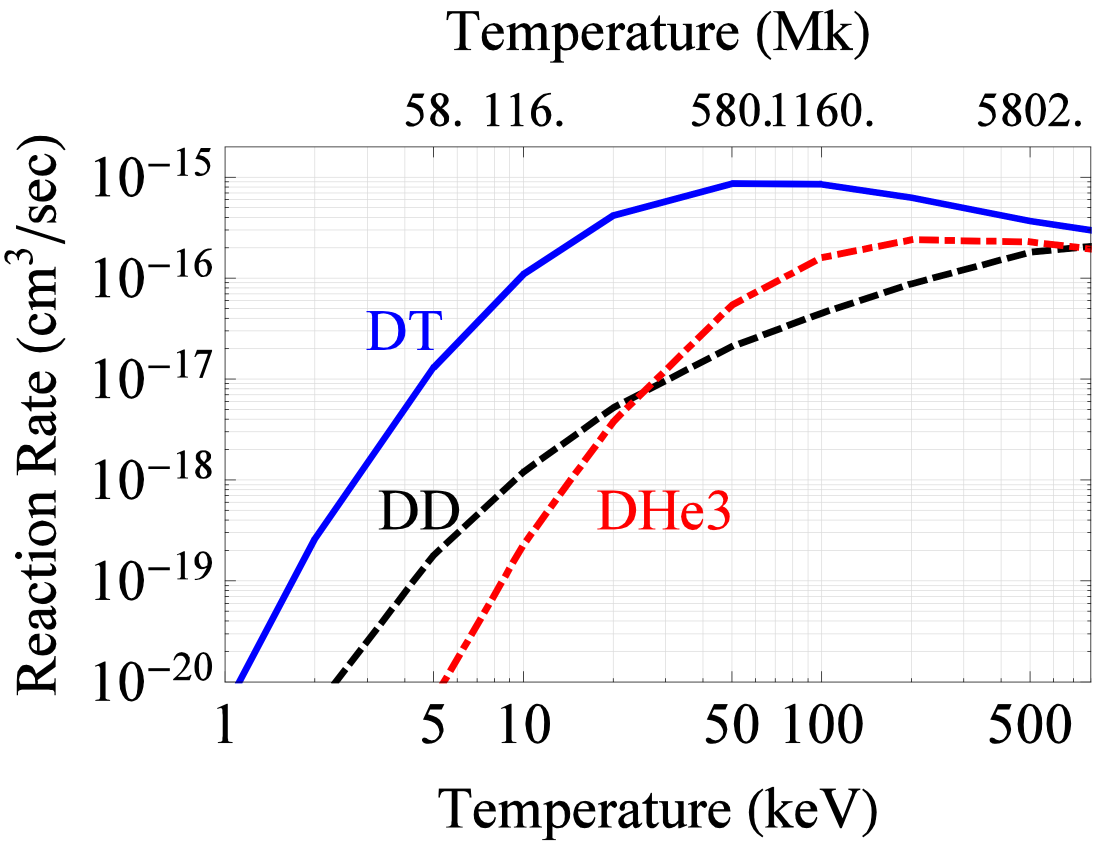
	Half-life (years)
U235	7.04×10^8
U238	4.47×10^9
…	
Tritium	12.3

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

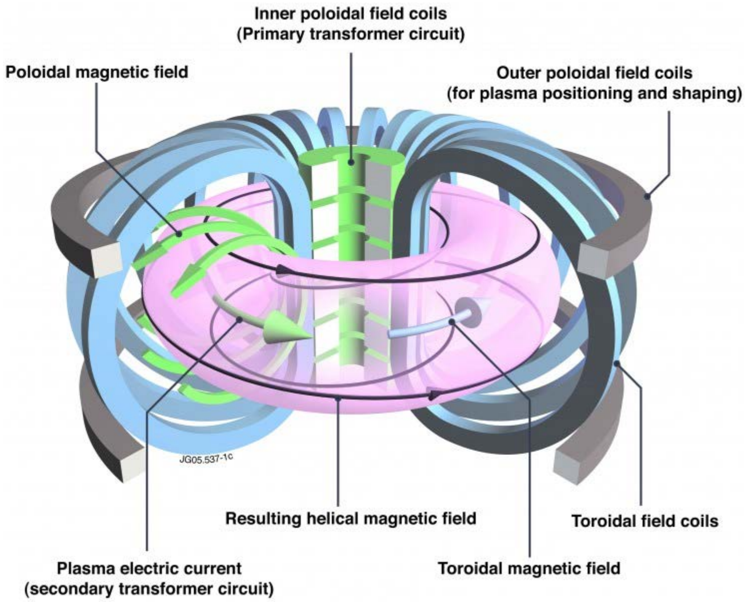


*NRL Plasma Formulary, Naval Research Laboratory, Washington, DC 203785-5320

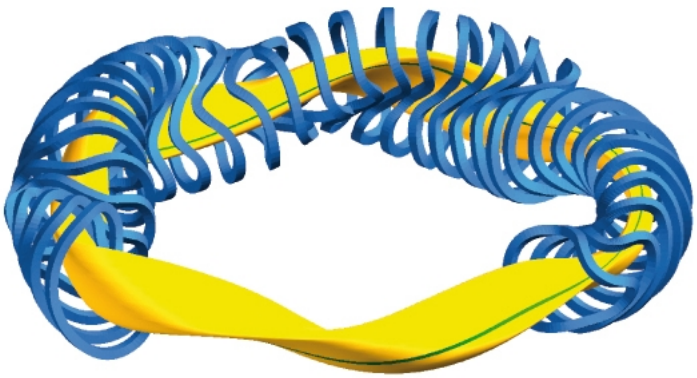
The plasma is too hot to be contained

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

Tokamak



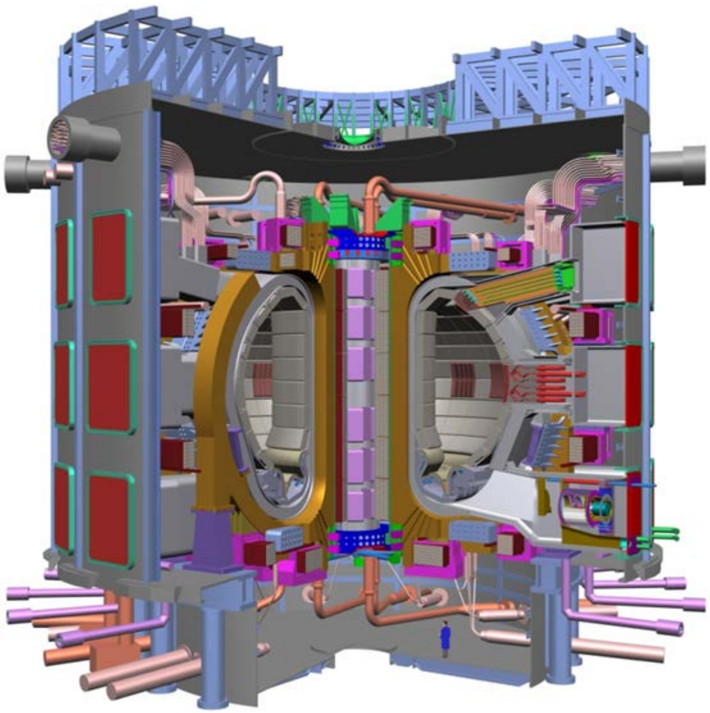
Stellarator



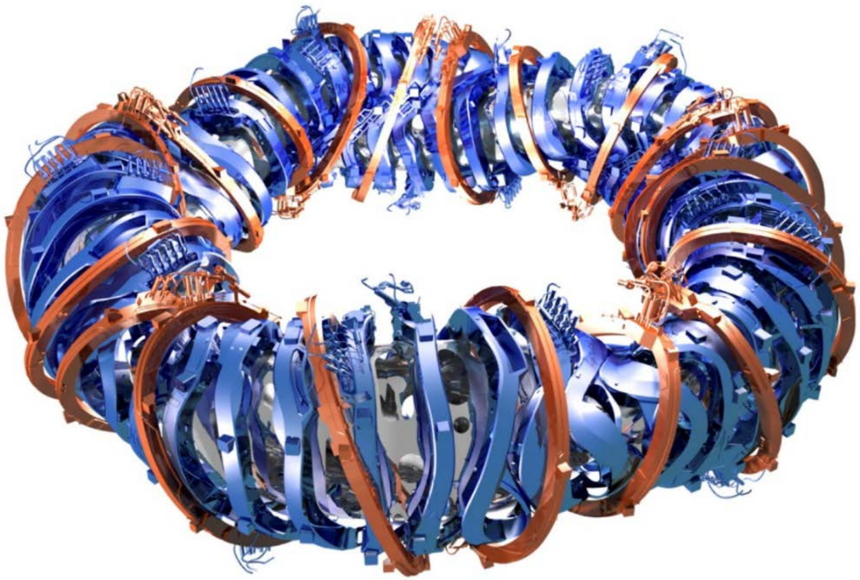
https://www.euro-fusion.org/2011/09/tokamak-principle-2/
https://en.wikipedia.org/wiki/Stellarator

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

- **ITER**

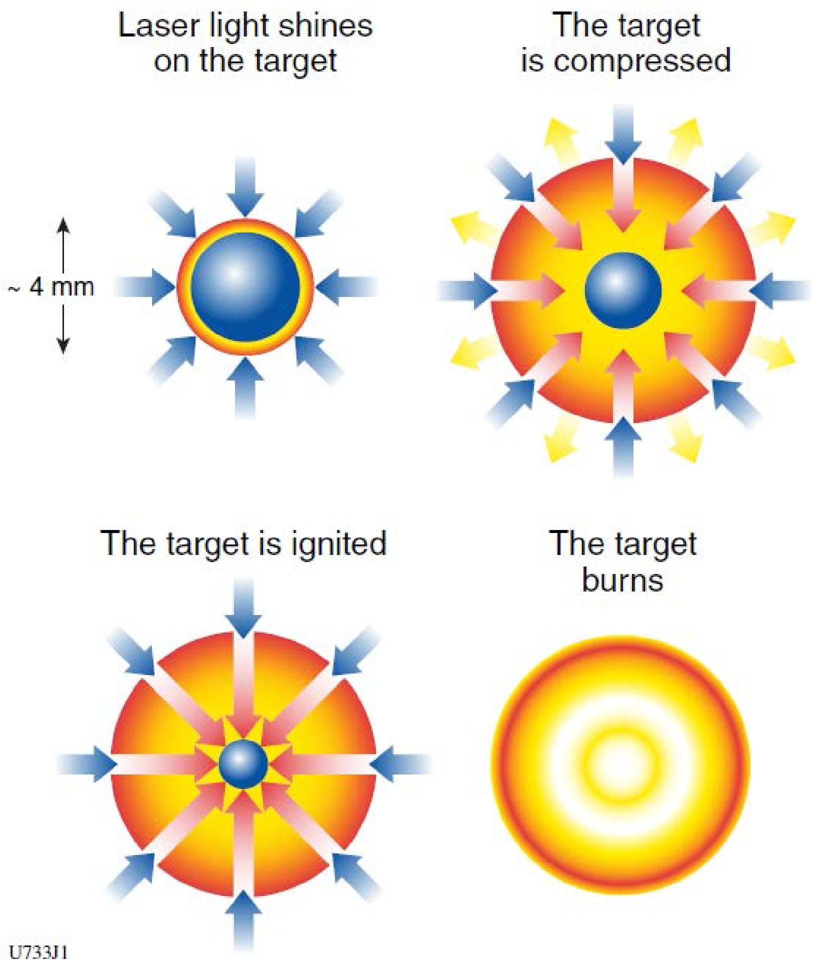


- **Wendelstein 7-X**

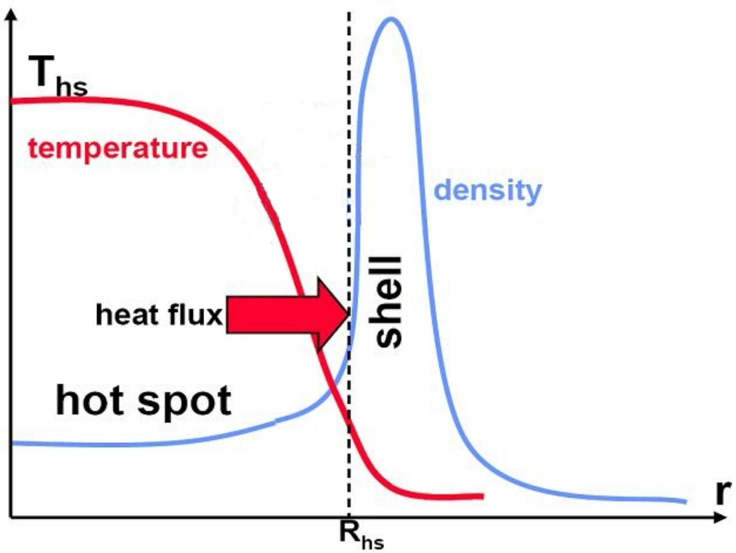


- **Schedule of ITER:**
  - **Dec 2025** **First Plasma**
  - **2035** **Deuterium-Tritium Operation begins**

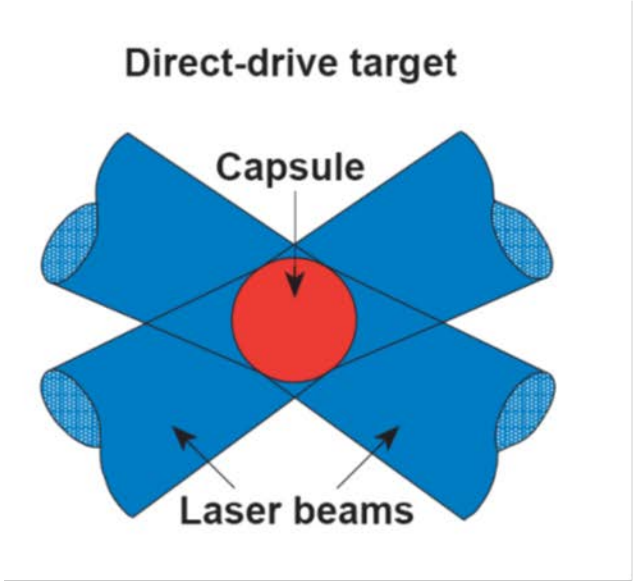
Plasma is confined by its own inertia in inertial confinement fusion (ICF)

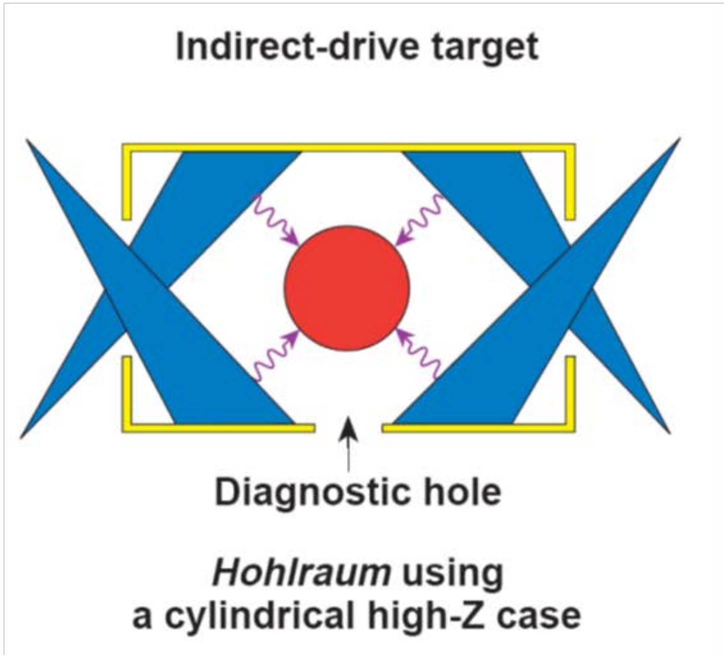


Spatial profile at stagnation



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

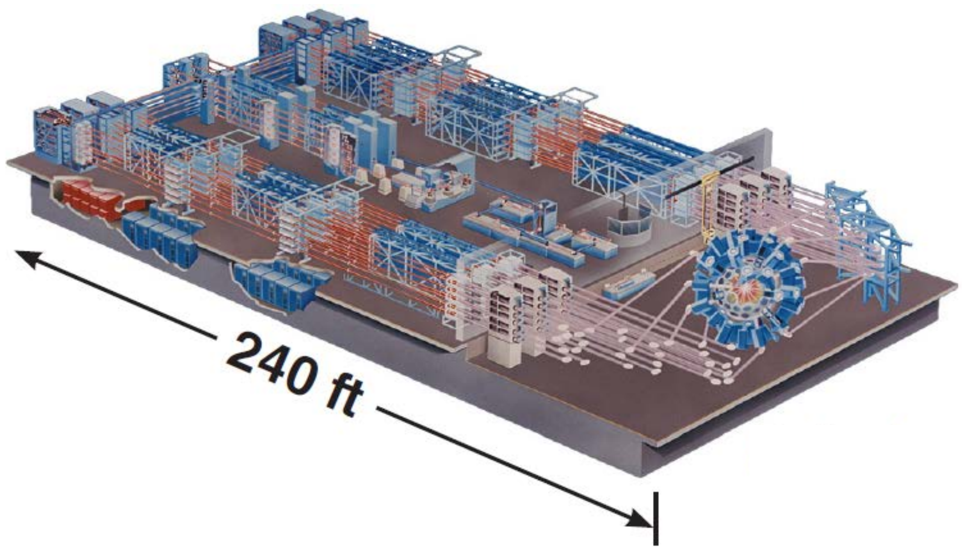


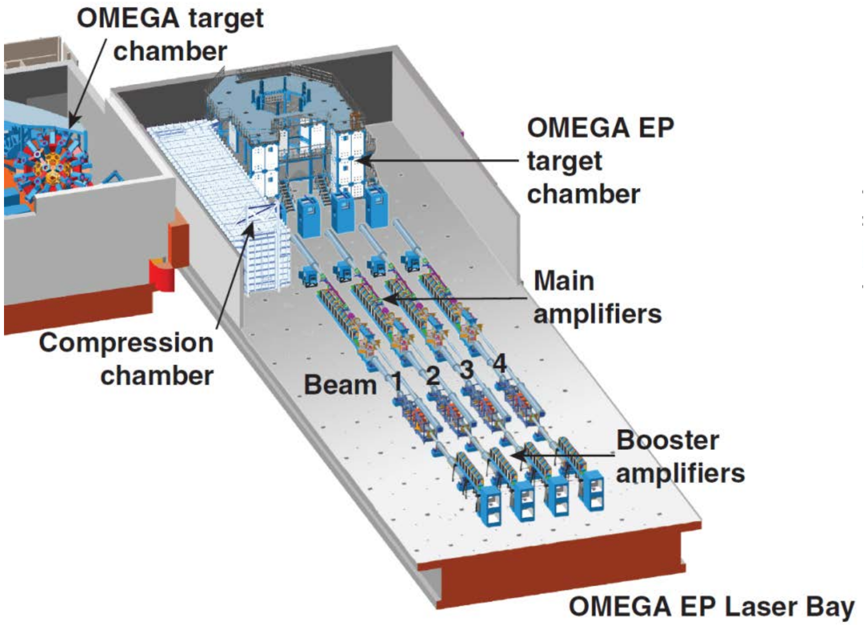


*R. Betti, HEDSA HEDP Summer School, 2015

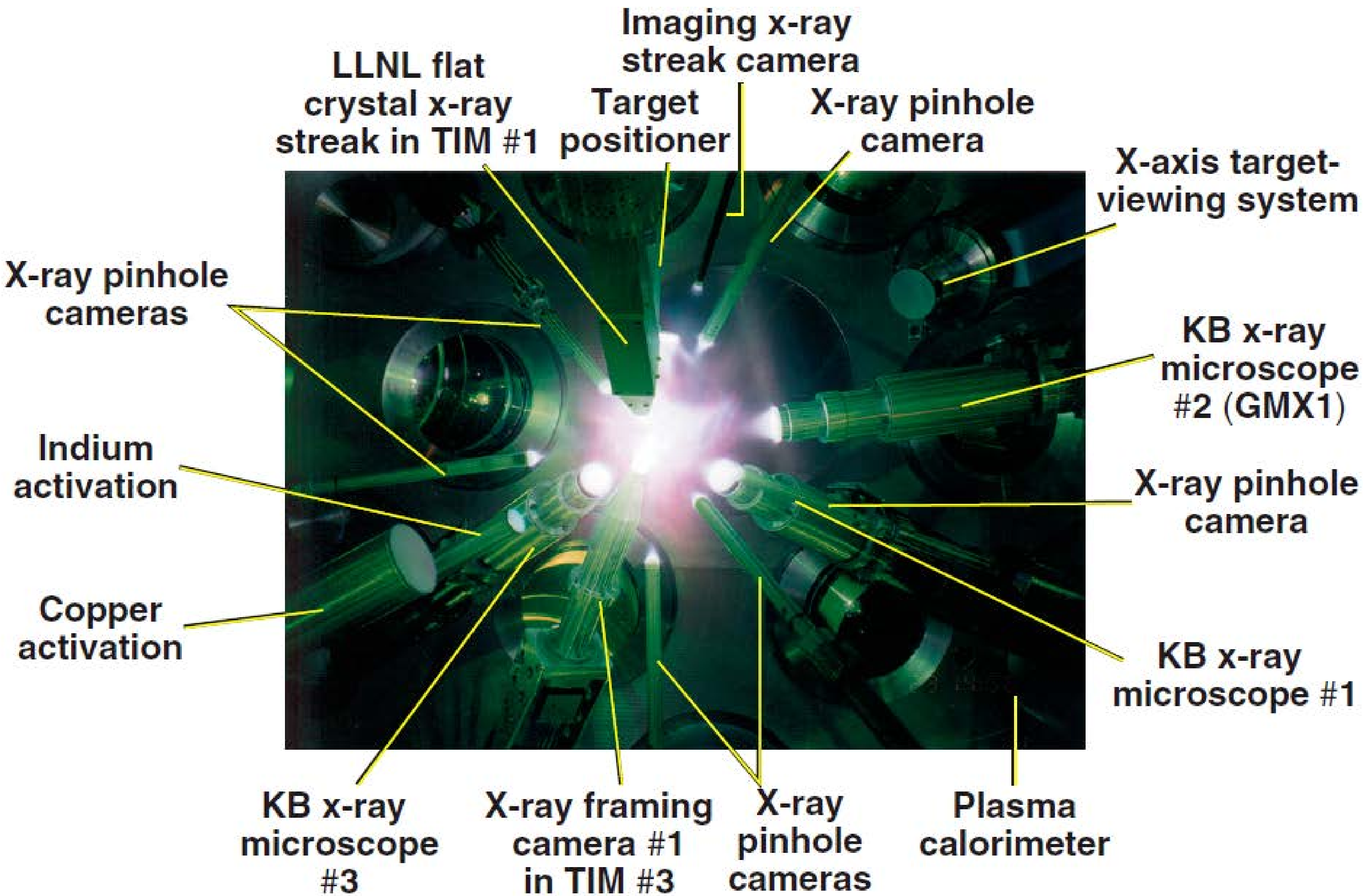
Laboratory for Laser Energetics, University of Rochester is a pioneer in laser fusion

- 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





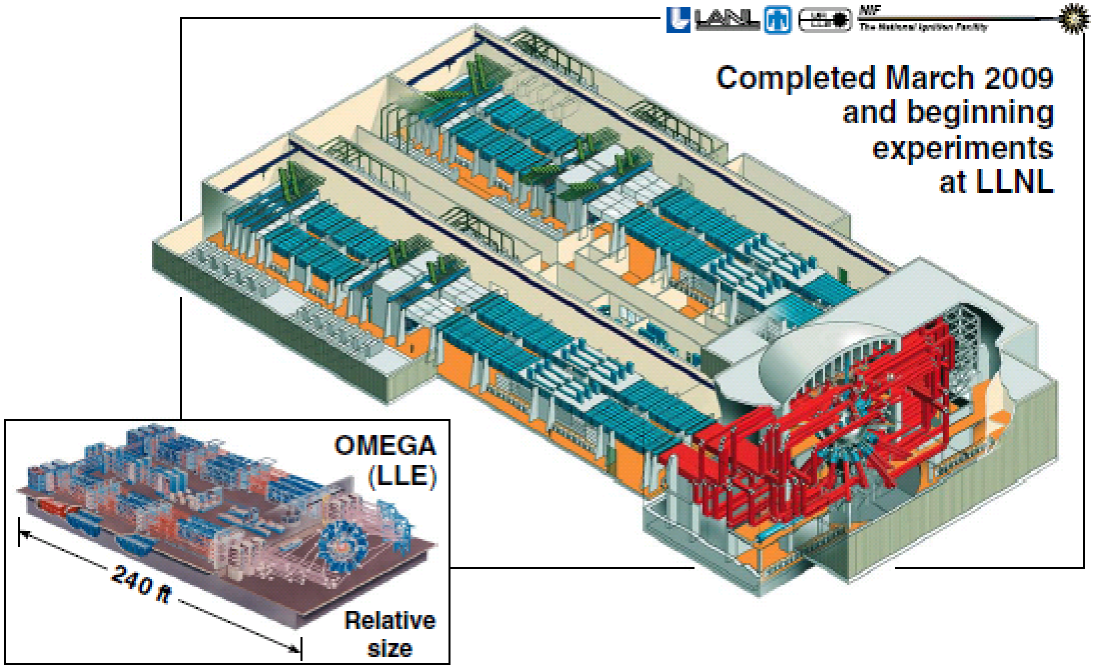
The OMEGA Facility is carrying out ICF experiments using a full suite of target diagnostics



E8012b

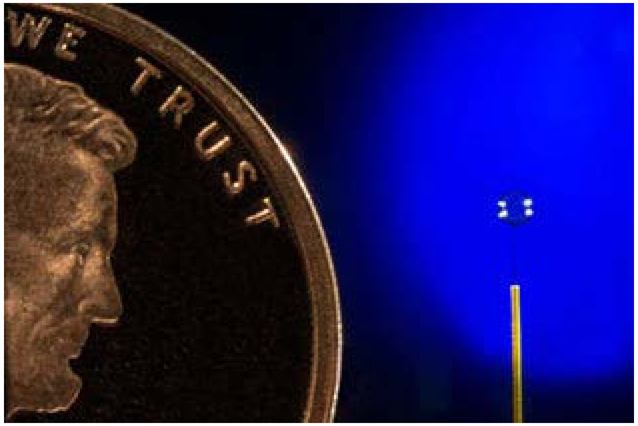
Photo taken from port H11B

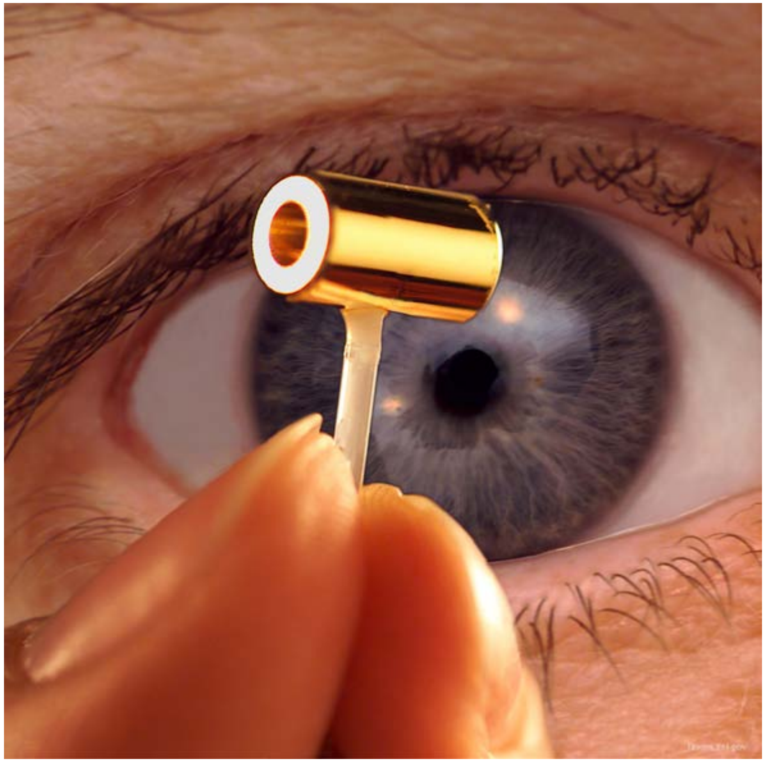
The 1.8-MJ National Ignition Facility (NIF) will demonstrate ICF ignition and modest energy gain



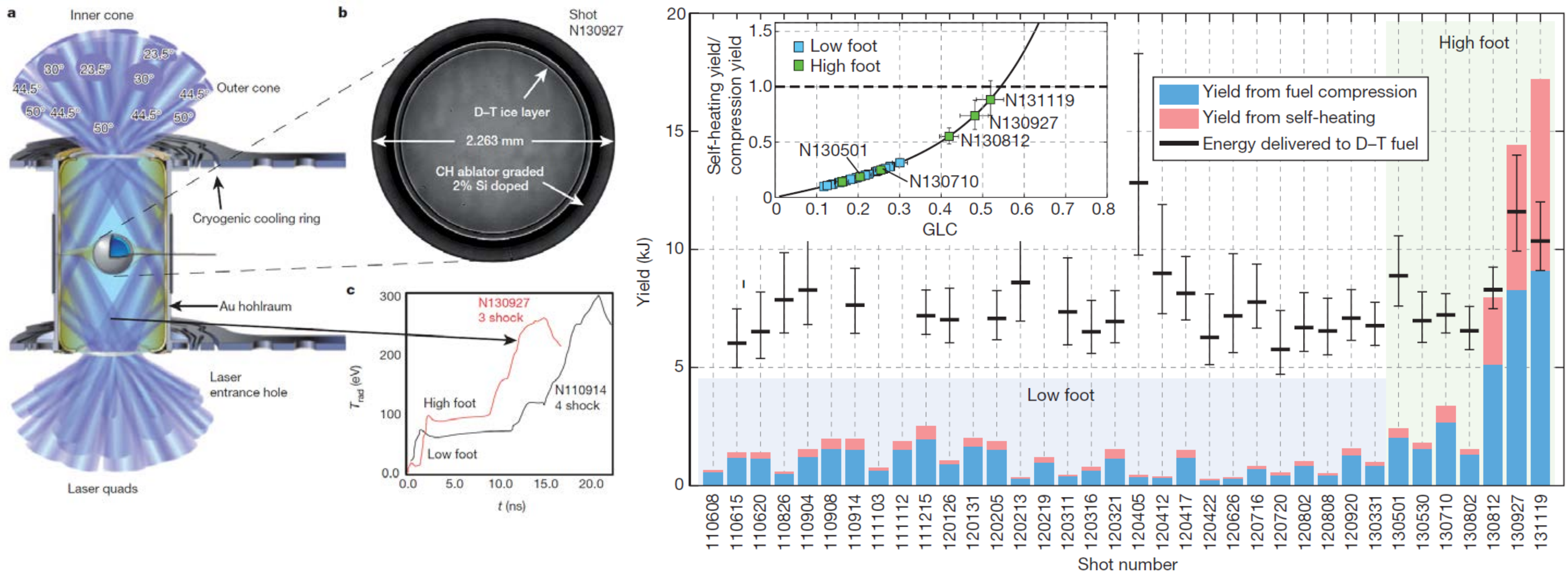
OMEGA experiments are integral to an ignition demonstration on the NIF.

Targets used in ICF





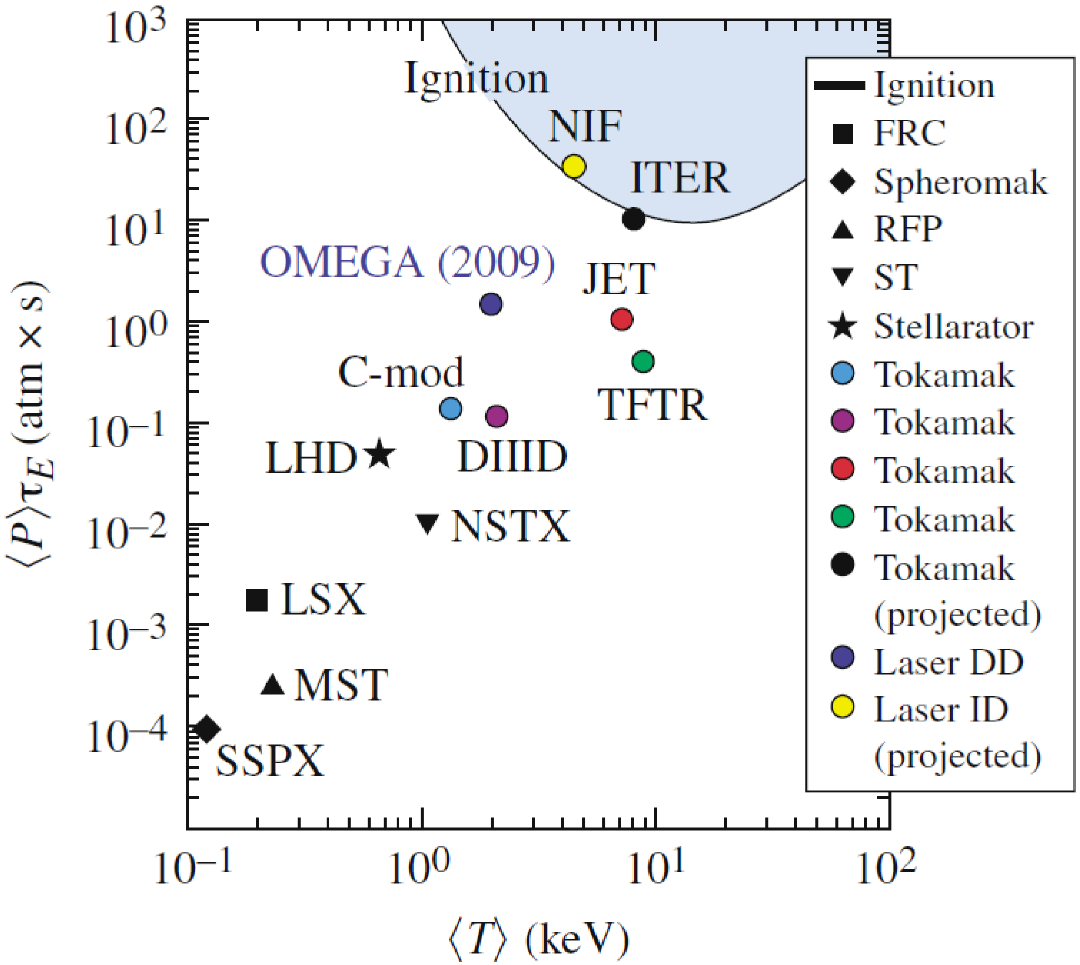
Nature letter “Fuel gain exceeding unity in an inertially confined fusion implosion”



- **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 (items 1–2)

Day 4~5: Experiments (item 3)