

Application of Plasma Phenomena



Po-Yu Chang

Institute of Space and Plasma Sciences, National Cheng Kung University

Lecture 6

2025 fall semester

Thursday 9:00-12:00

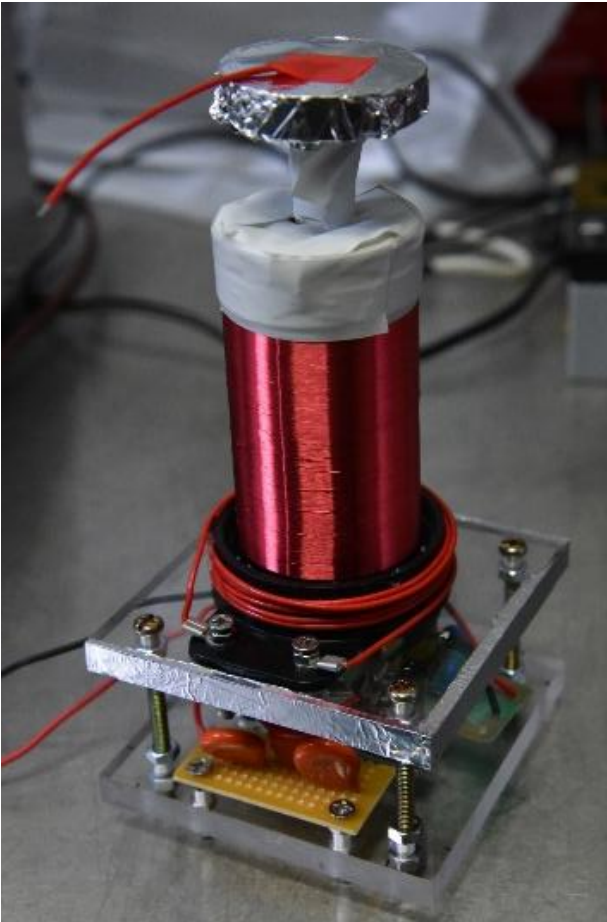
Materials:

<https://capst.ncku.edu.tw/PGS/index.php/teaching/>

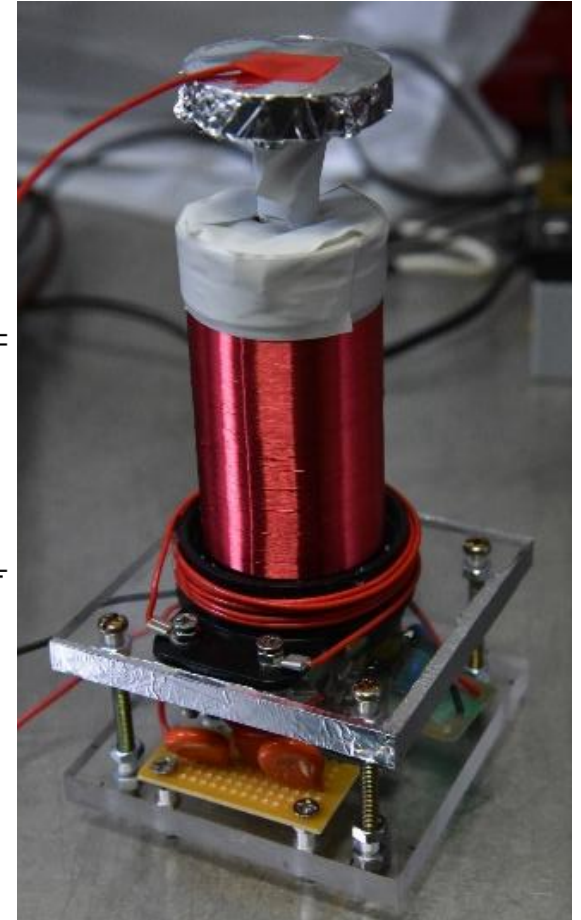
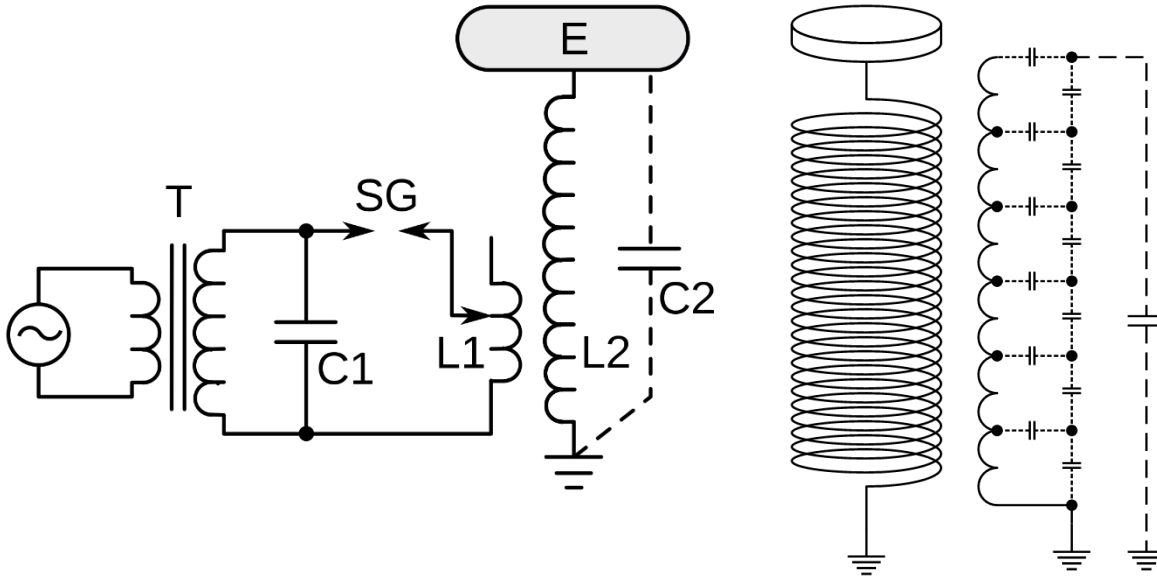
Online courses:

<https://nckucc.webex.com/nckucc/j.php?MTID=m50e2008a7e216ef32c42db2d027415ec>

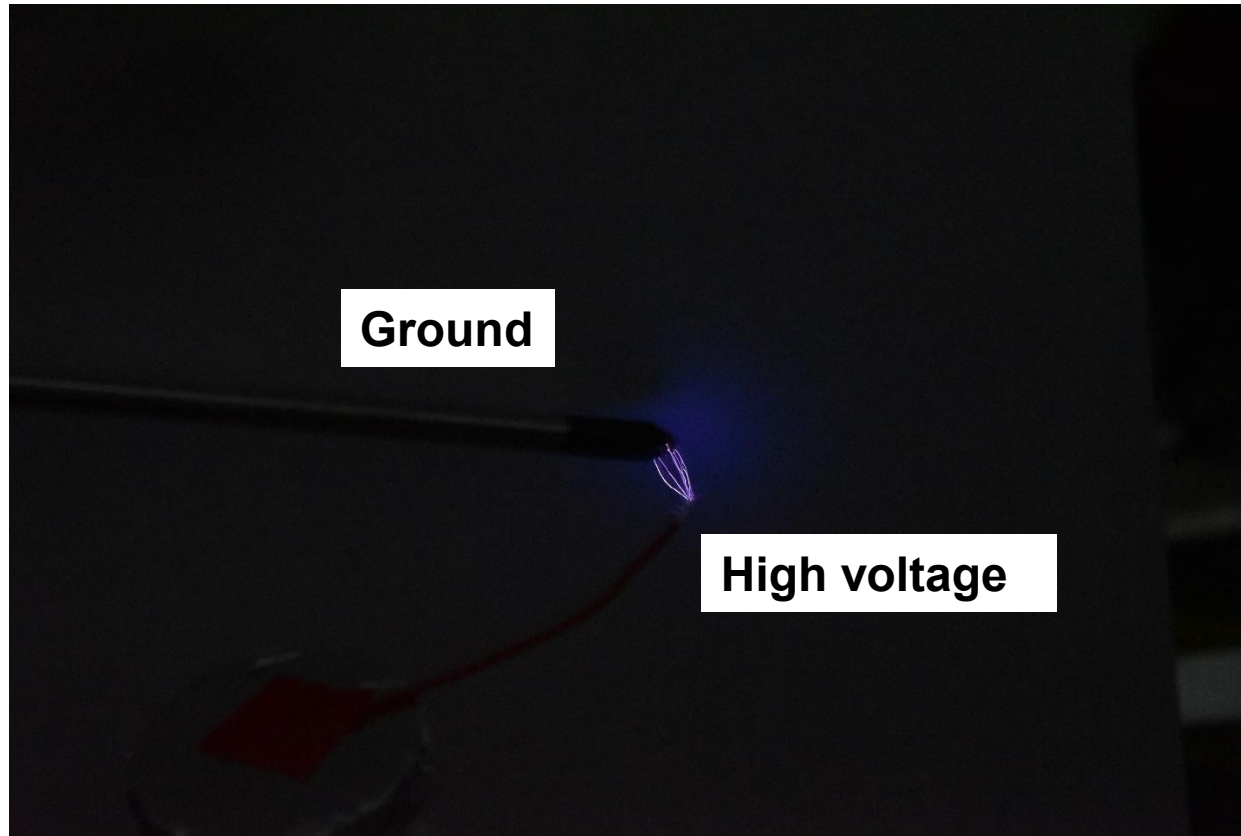
Tesla coil can generate high voltage



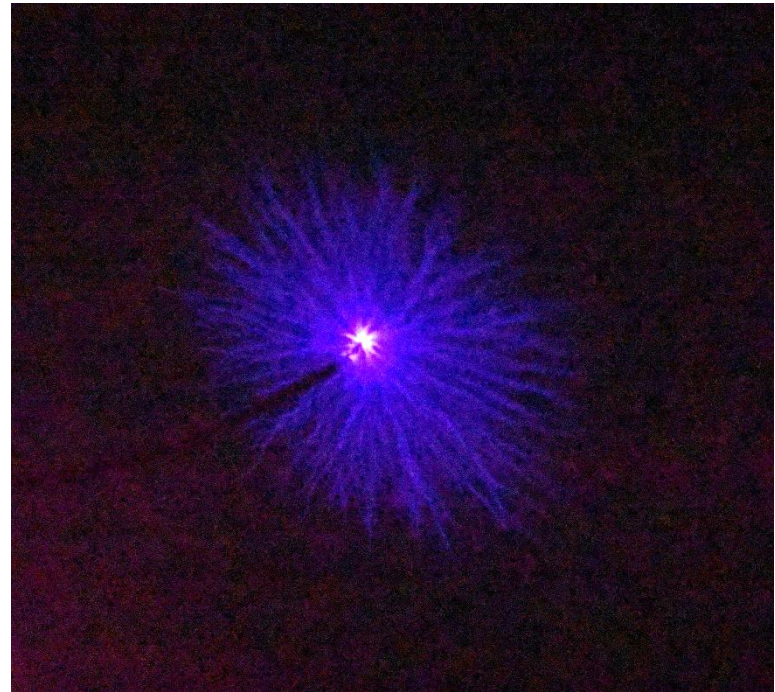
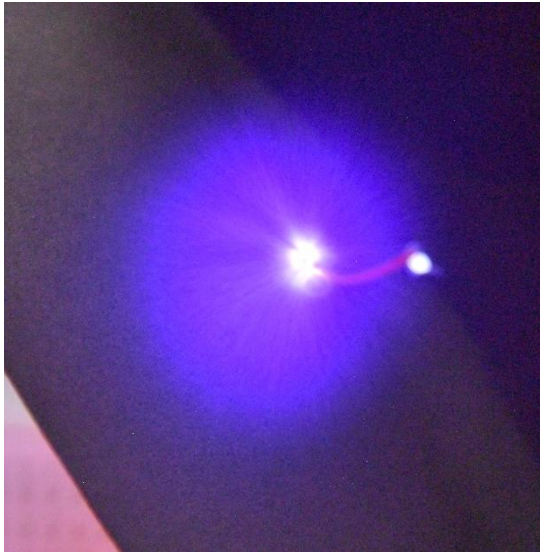
The high voltage is generated by two resonant LC circuits



Arc discharge occur between the high voltage and a grounded electrode



Corona discharge occurs when the electric field drops below a certain value



Methods of plasma production



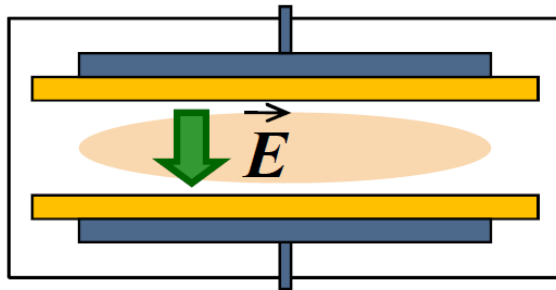
- **DC electrical discharges**
 - Dark electrical discharges in gases
 - DC electrical glow discharges in gases
 - DC electrical arc discharges in gases
- **AC electrical discharges**
 - **RF electrical discharges in gases**
 - Microwave electrical discharges in gases
 - Dielectric-barrier discharges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

RF can interact with plasma inductively or capacitively

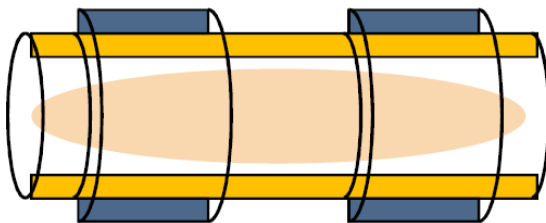


Capacitively coupled

planar

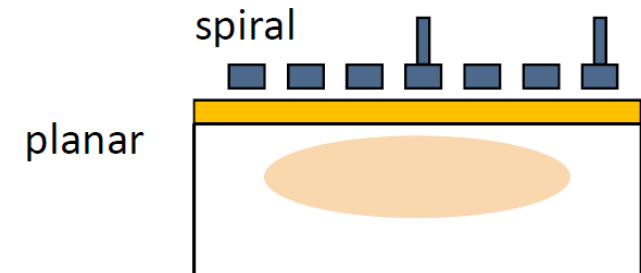
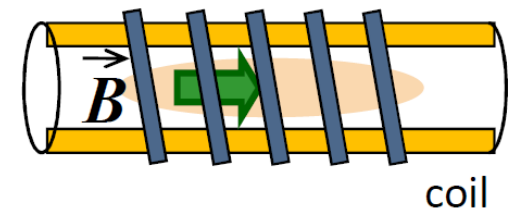


coaxial

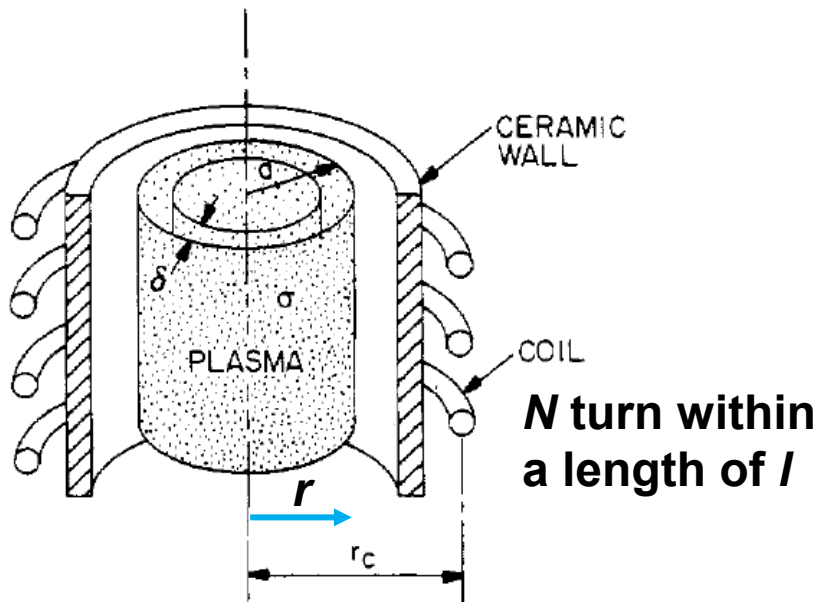


Inductively coupled

coaxial



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



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

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

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

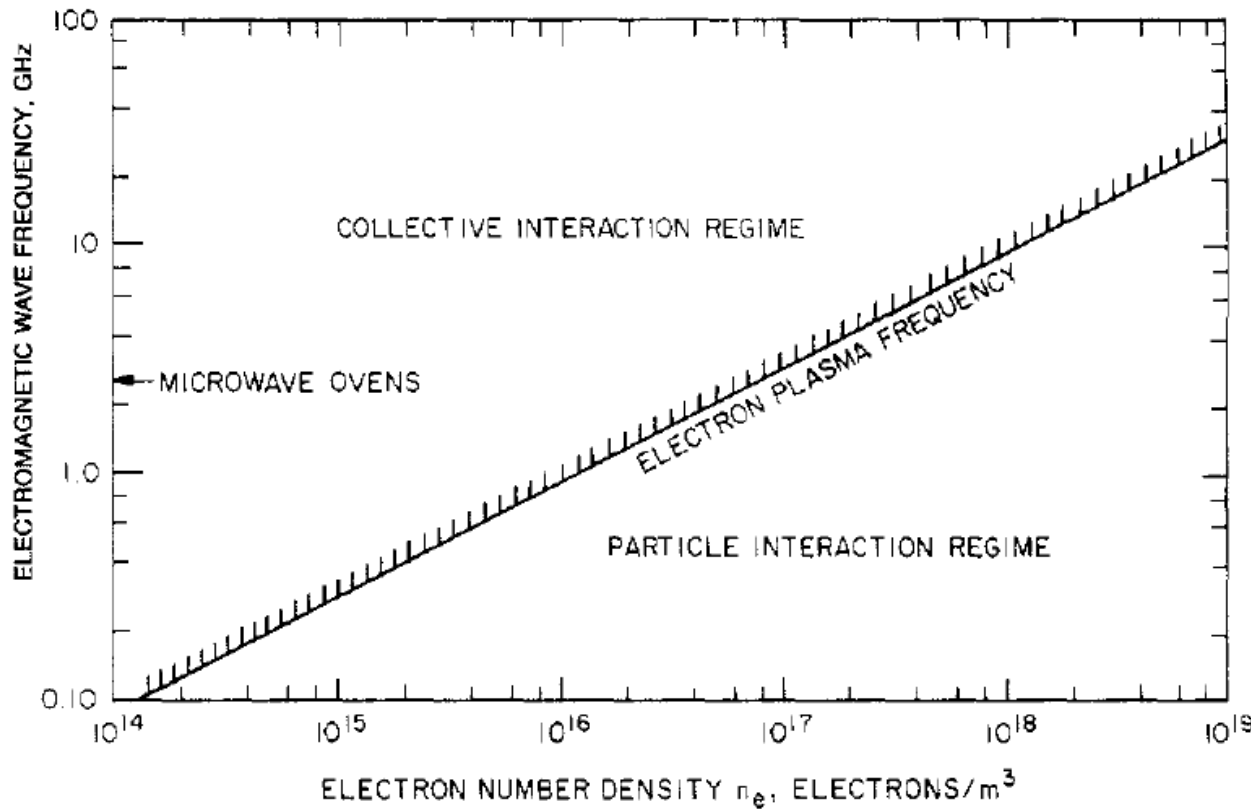
$$E = -\frac{r}{2} \frac{\partial B}{\partial t}$$

$$B \times l = \mu_0 N I$$

$$E = -\frac{r}{2} \mu_0 \frac{N}{l} \frac{\partial I}{\partial t}$$

$$|E| = \frac{r}{2} \mu_0 \frac{N}{l} \omega I$$

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



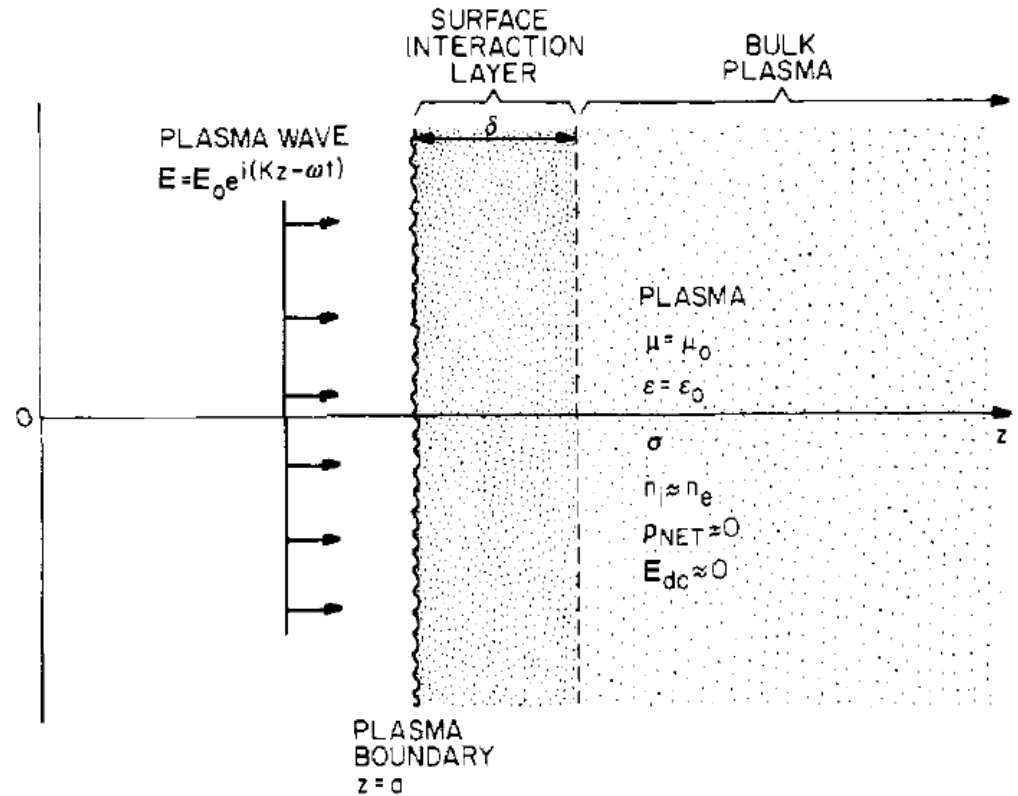
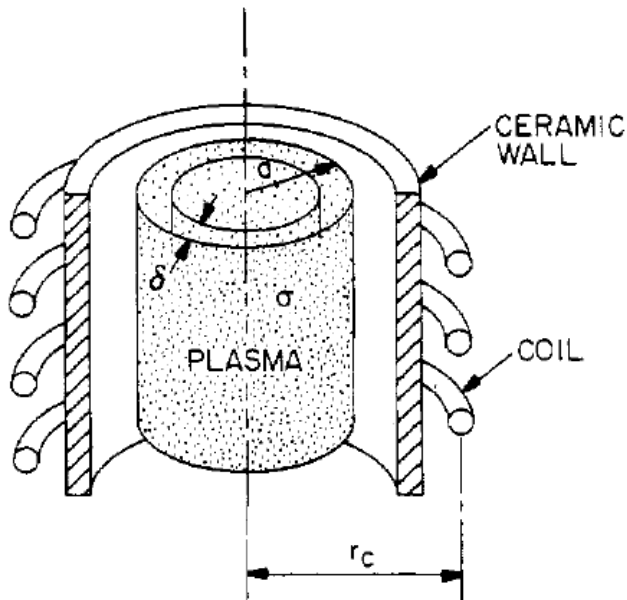
$$\omega_{pe} = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}} \text{ (rad/s)}$$

$$n_{cri} = \frac{\epsilon_0 m_e}{e^2} \omega_{pe}^2 (m^{-3})$$

$$n_{760 \text{ Torr} / 300K} = 2.45 \times 10^{25} m^{-3}$$

$$n_{0.1 \text{ Torr}, 1 \% \text{ ionization}} = 3.2 \times 10^{19} m^{-3}$$

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



Skin depth is calculated using Maxwell's equations



$$\nabla \cdot \vec{E} \approx 0 (\text{quasi-neutral}) \quad \nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad \nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t} \quad \vec{J} = \sigma \vec{E} \text{ (Ohm's law)}$$

$$-\frac{\partial}{\partial t} (\nabla \times \vec{B}) = \nabla \times (\nabla \times \vec{E}) = \nabla (\nabla \cdot \vec{E}) - \nabla^2 \vec{E} \sim -\nabla^2 \vec{E}$$

$$\frac{\partial^2 \vec{E}}{\partial z^2} - \mu_0 \sigma \frac{\partial \vec{E}}{\partial t} - \mu_0 \epsilon_0 \frac{\partial^2 \vec{E}}{\partial t^2} = 0 \quad \vec{E} = \vec{E}_0 \exp[-i(kz - \omega t)] \quad k \equiv \alpha + \frac{i}{\delta}$$

$$(-k^2 + i\omega\mu_0\sigma + \mu_0\epsilon_0\omega^2) \vec{E} = 0 \quad \alpha = \sqrt{\frac{\sigma\mu_0\omega}{2}} \left[\frac{\omega\epsilon_0}{\sigma} + \sqrt{1 + \left(\frac{\omega\epsilon_0}{\sigma}\right)^2} \right]^{1/2}$$
$$\frac{1}{\delta} = \sqrt{\frac{\sigma\mu_0\omega}{2}} \left[\sqrt{1 + \left(\frac{\omega\epsilon_0}{\sigma}\right)^2} - \frac{\omega\epsilon_0}{\sigma} \right]^{1/2}$$

Skin depth is calculated using Maxwell's equations



$$\alpha = \sqrt{\frac{\sigma\mu_0\omega}{2}} \left[\frac{\omega\epsilon_0}{\sigma} + \sqrt{1 + \left(\frac{\omega\epsilon_0}{\sigma}\right)^2} \right]^{1/2} \quad \frac{1}{\delta} = \sqrt{\frac{\sigma\mu_0\omega}{2}} \left[\sqrt{1 + \left(\frac{\omega\epsilon_0}{\sigma}\right)^2} - \frac{\omega\epsilon_0}{\sigma} \right]^{1/2}$$

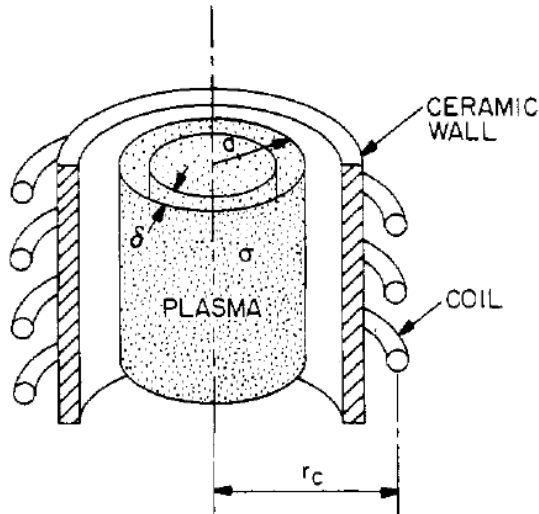
- In most industrial plasma, $\frac{\omega\epsilon_0}{\sigma} \ll 1$. Note that $\sigma = \frac{e^2 n_e}{m_e \nu_c} = \frac{\epsilon_0 \omega_{pe}^2}{\nu_c}$ so $\nu_c \omega \ll \omega_{pe}^2$ is required.

$$\alpha \approx \sqrt{\frac{\sigma\mu_0\omega}{2}} (m^{-1})$$

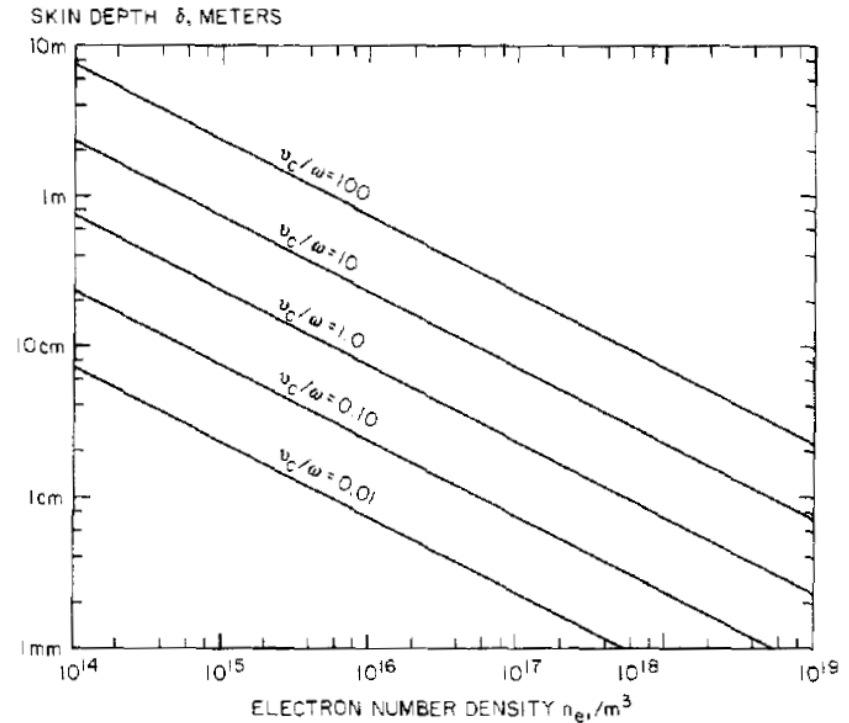
skin depth:
$$\delta \approx \sqrt{\frac{2}{\sigma\mu_0\omega}} = \frac{\sqrt{2}c}{\omega_{pe}} \sqrt{\frac{\nu_c}{\omega}} = \frac{c}{e} \sqrt{\frac{2m_e\epsilon_0}{n_e}} \sqrt{\frac{\nu_c}{\omega}} = \frac{c}{2\pi\nu_{pe}} \sqrt{\frac{\nu_c}{\pi f}} (m)$$

- The skin depth $\delta \sim$ the distance that an electromagnetic wave propagates into a medium during one period of the electron plasma frequency.

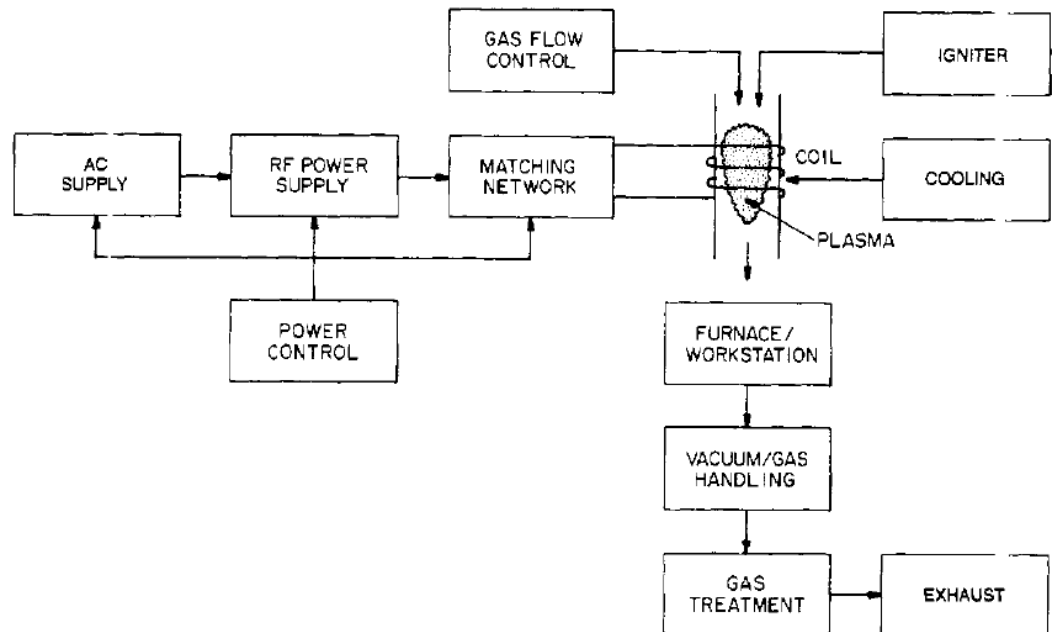
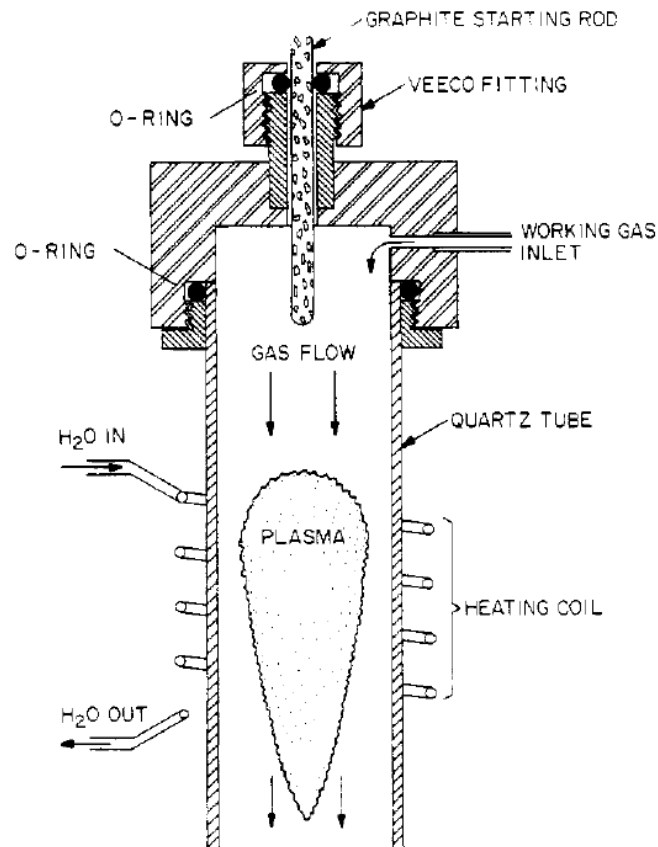
Skin depth needs to be carefully considered in the design of inductive industrial plasma reactors



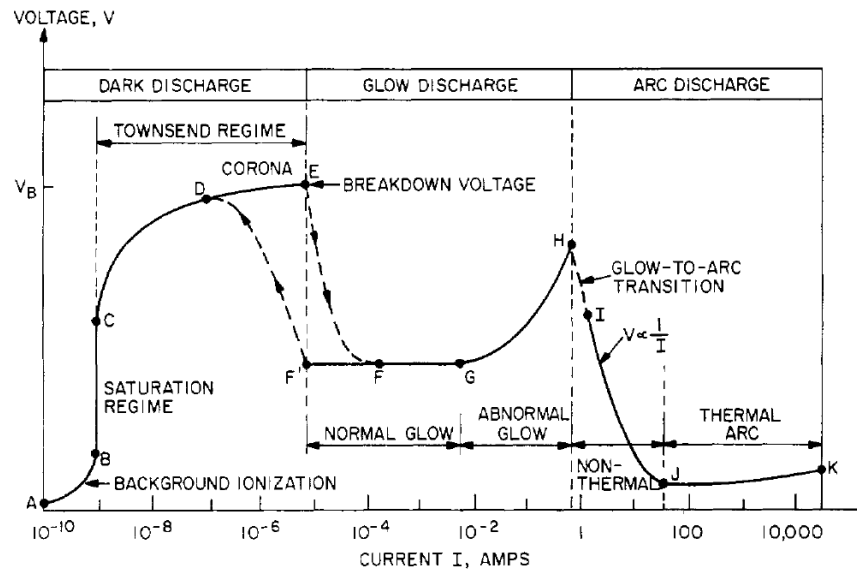
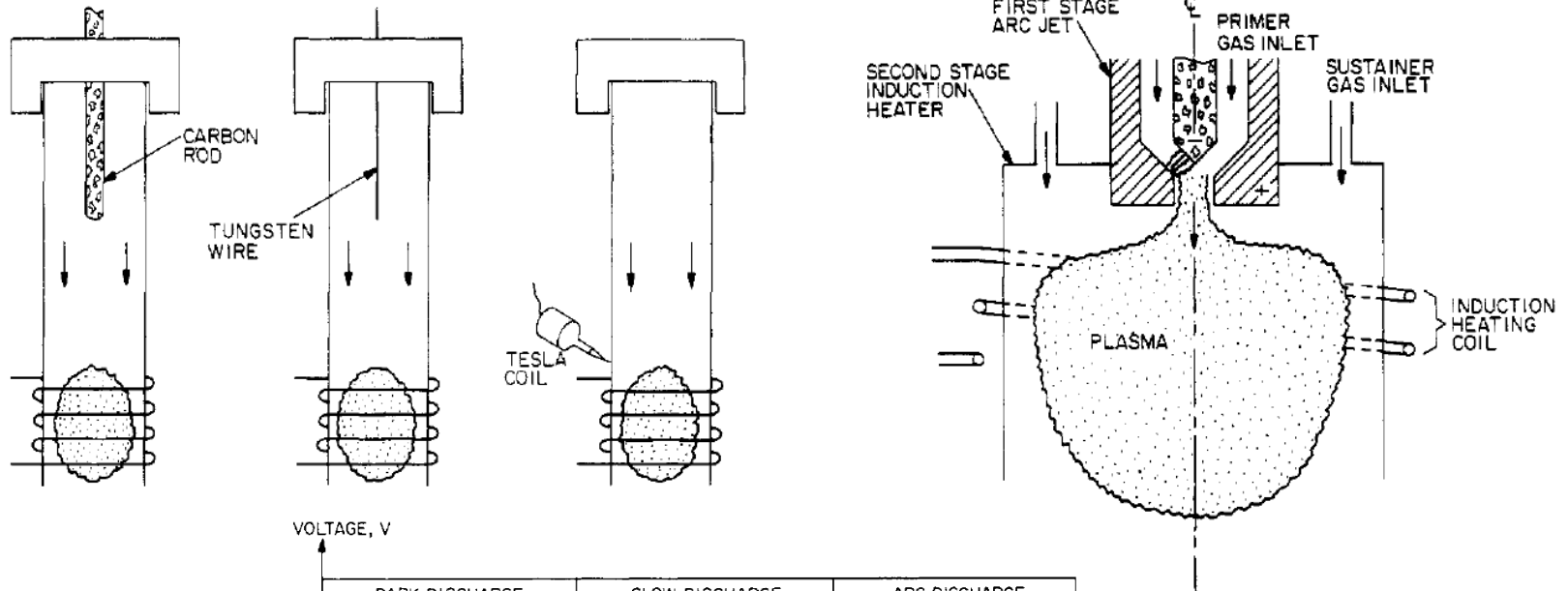
- Boulos et al showed that the energy coupling parameter is maximum when $1.5\delta \leq a \leq 3\delta$. However, it doesn't mean the plasma will be uniformly heated.



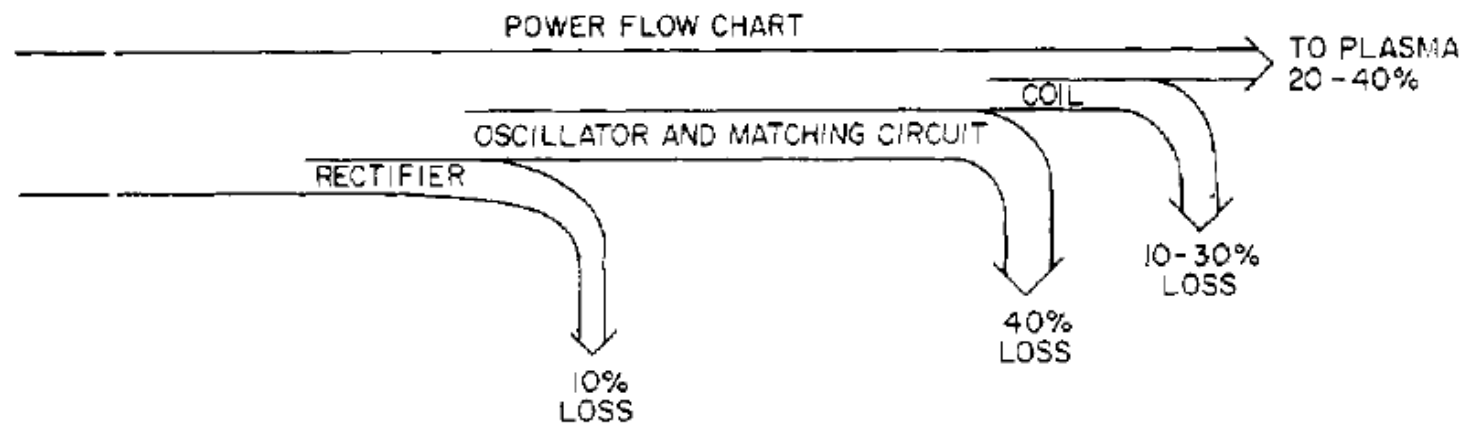
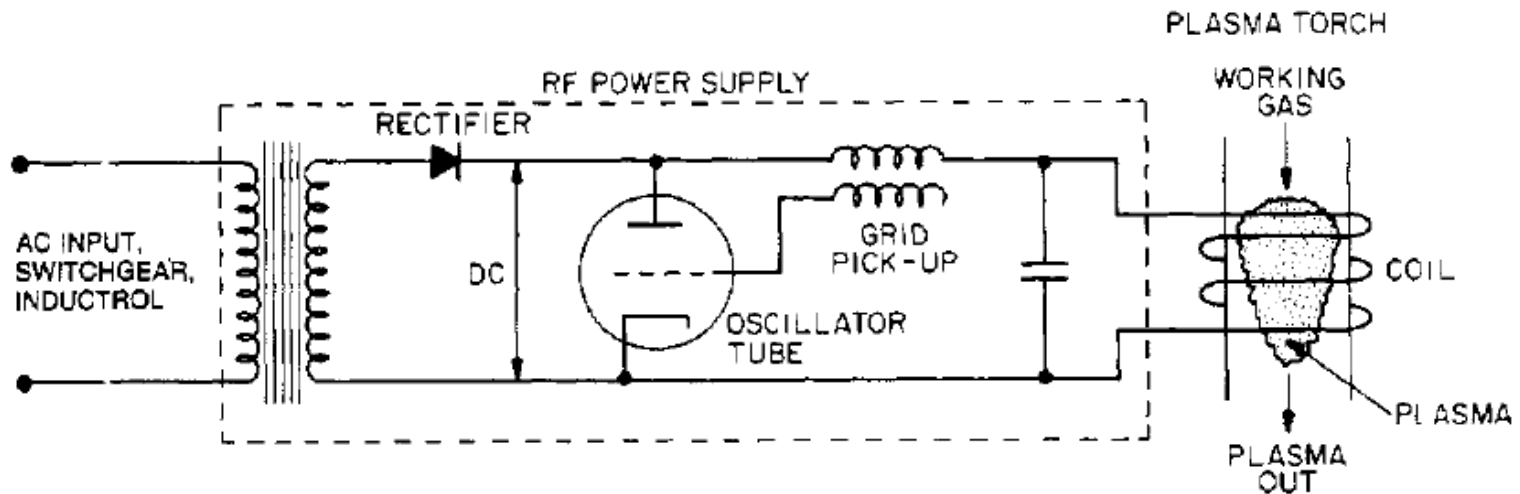
A kilowatt-level inductively coupled plasma torch is shown



High voltage initiation is usually required for inductive RF plasma torches



The power supplies are relatively inefficient

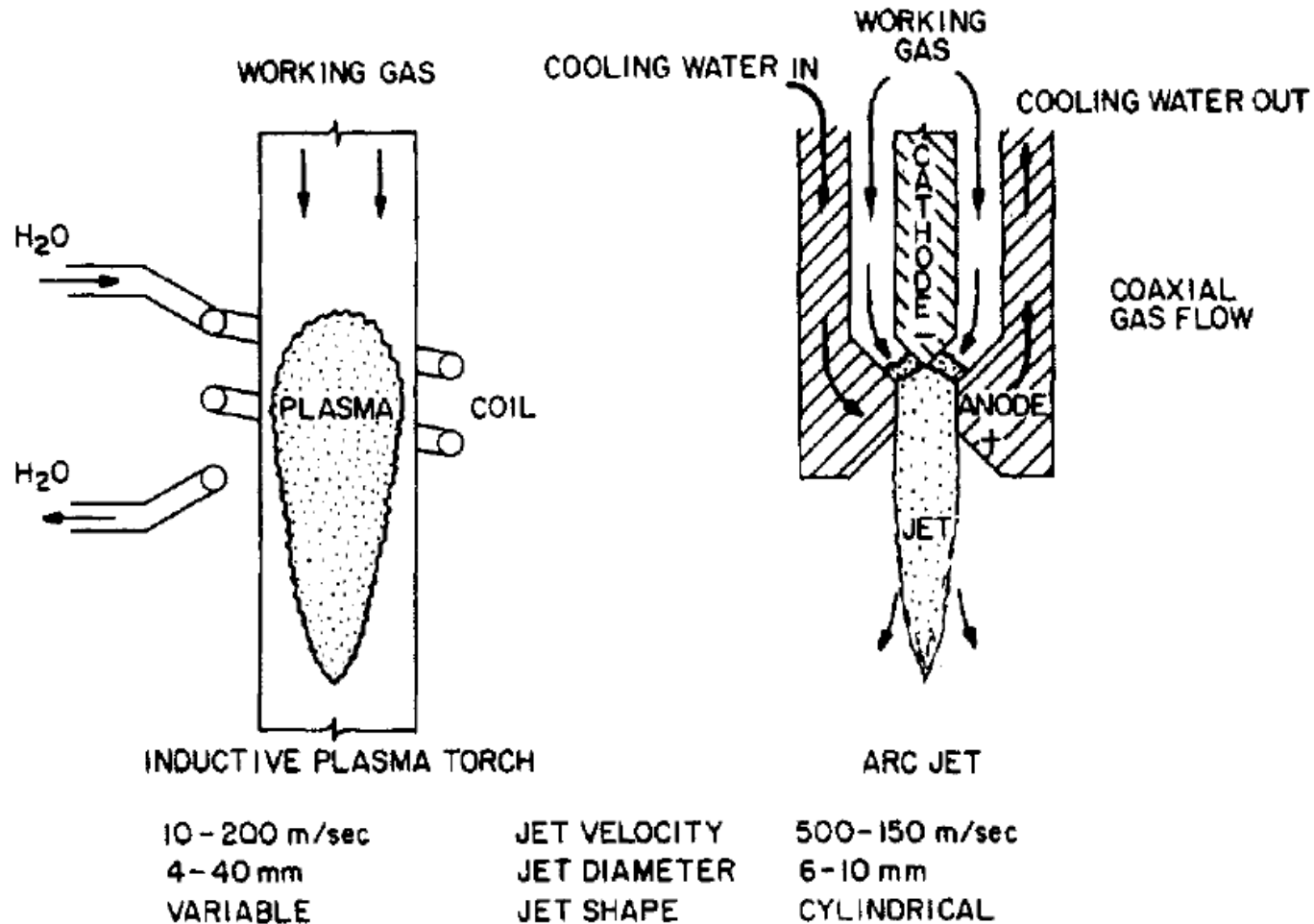


Operating regimes of inductively coupled plasma torches

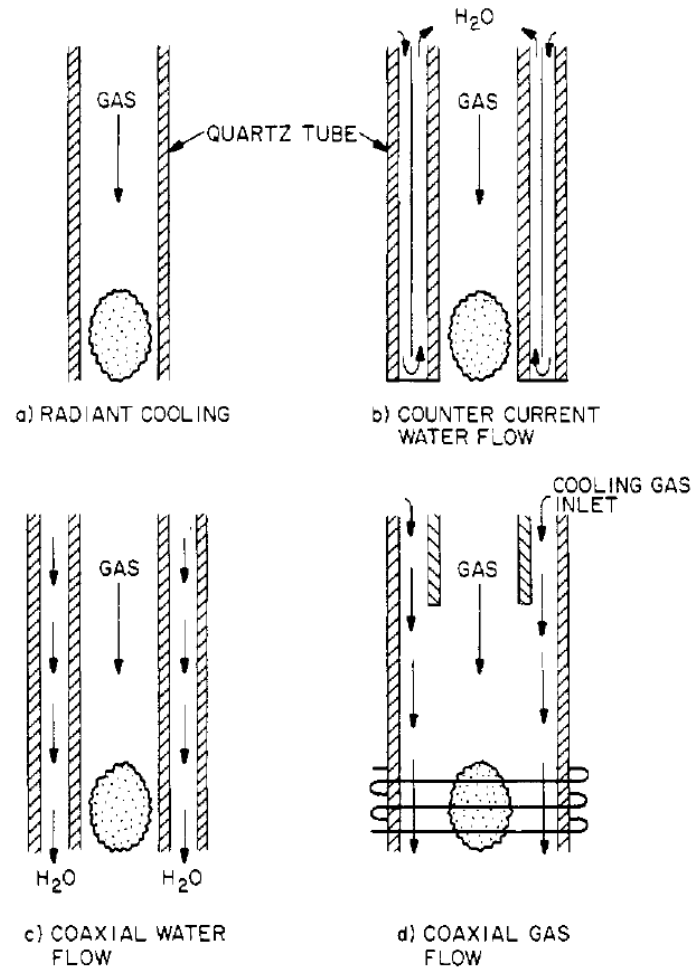


Parameter	Low	Characteristic	High
Frequency	10 kHz	13.56 MHz	100 MHz
Power	1 kW	30 kW	1MW
Efficiency	20%	35%	50%
Pressure	10 Torr	1 atm	10 atm
Gas temperature	1000 K	10^4 K	2×10^4 K

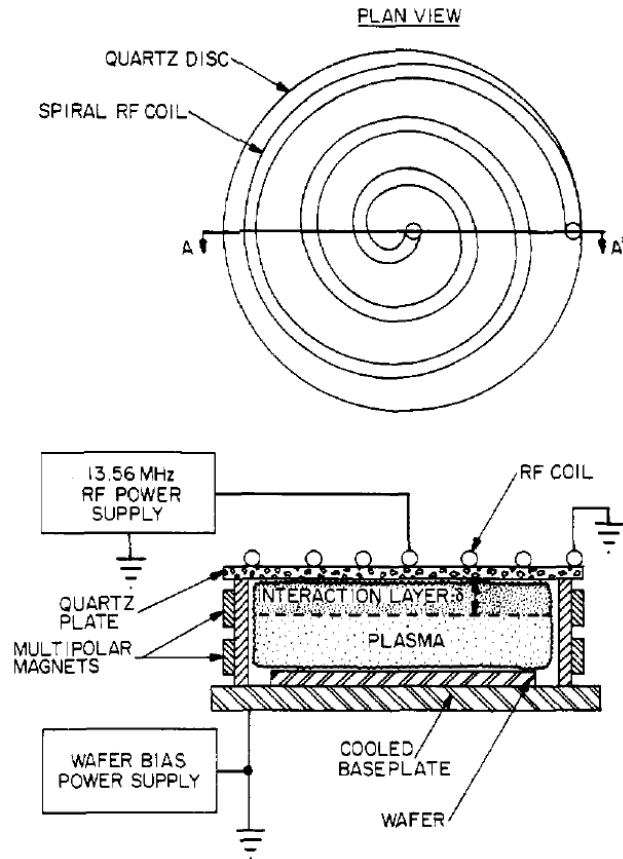
Inductive RF coupling provides a plasma with less contamination from the electrode



Several cooling configurations are shown

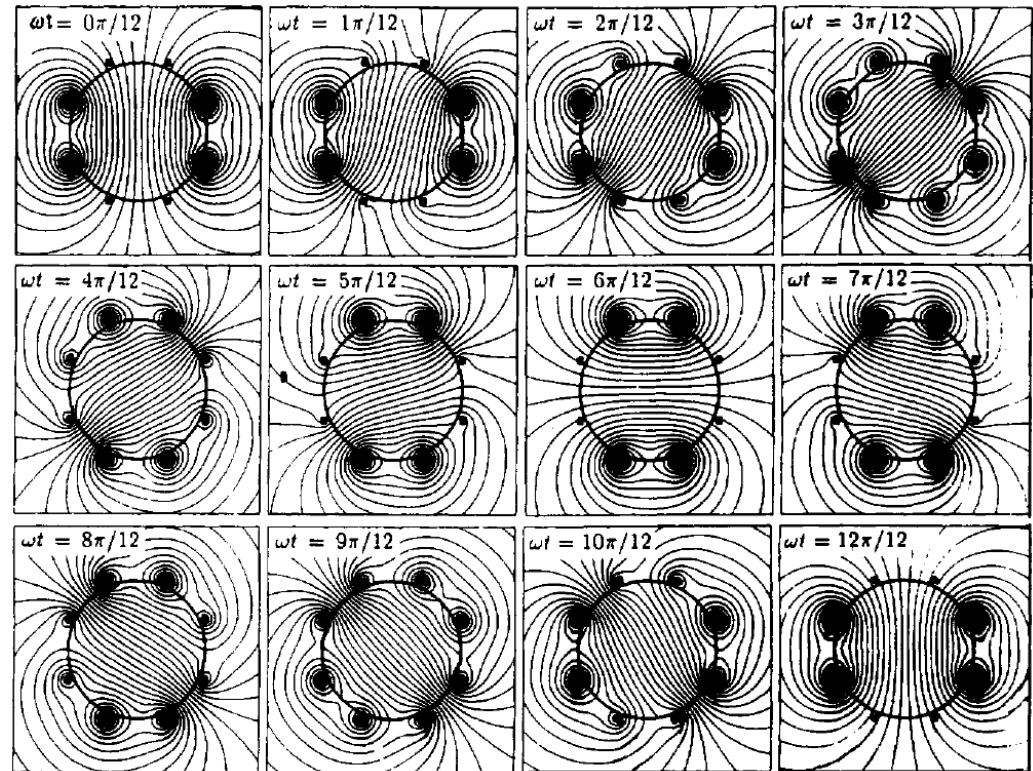
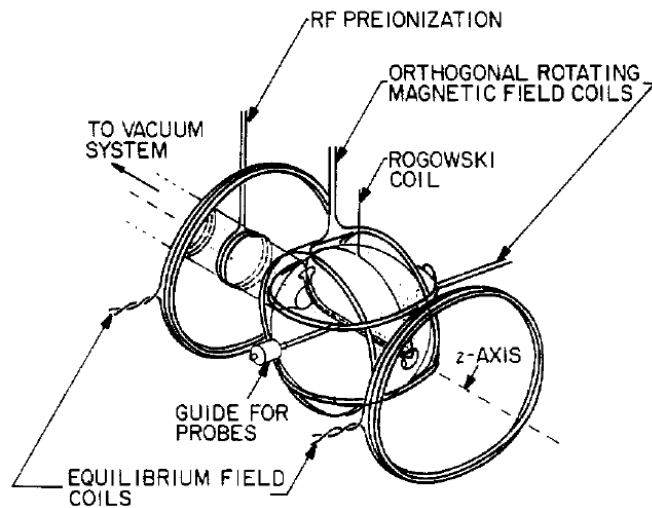


Inductive parallel plate reactor



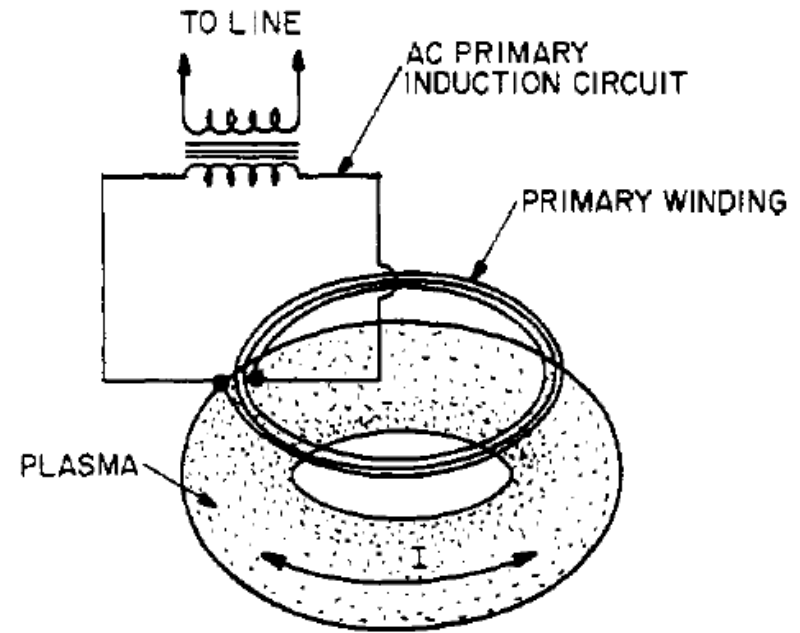
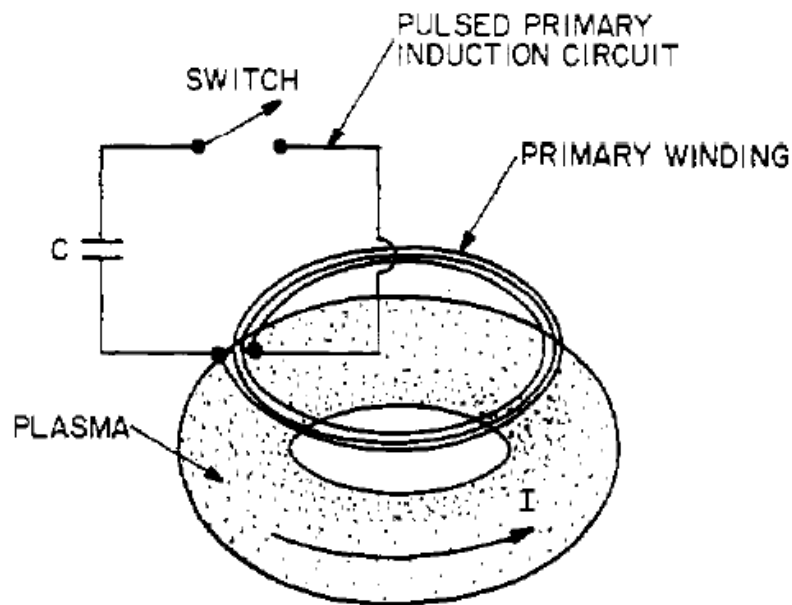
- **Uniform plasma source**
- **Higher power (2 kW) leading to higher plasma density (up to 10^{18} electrons/m³)**
- **Lower gas pressure, i. e., longer mean free paths and little scattering of ions and is desired in deposition and etching applications.**

Rotamak



- The rapidly rotating magnetic field generates large plasma currents, thus heating the plasma to densities and temperatures of interest in many industrial applications

Inductively heated toroidal plasmas



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

Applications of inductive plasma torches



- **High purity materials production**
 - Silica and other refractories
 - Ultrafine powder
 - Spherical fine power
 - Refining/purification
- **High temperature thermal treatment**
 - Heat treatment
 - Plasma sintering
- **Surface treatment**
 - Oxidation
 - Nitriding

Applications of inductive plasma torches



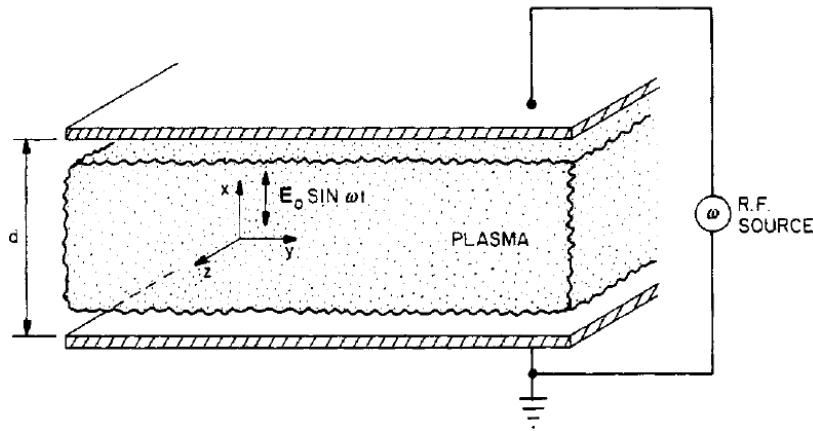
- **Surface coating**
 - Plasma flame spraying
 - Surface coating of powder
- **Chemical vapor deposition (CVD)**
 - At atmospheric pressure
 - At reduced pressure
- **Chemical synthesis and processing**
- **Experimental applications**
 - Laboratory furnace
 - High intensity light source
 - Spectroscopic analysis
 - Isotope separation
 - Ion source
 - High power density plasma source

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
 - **Capacitive RF electrical discharges**
 - Microwave electrical discharges
 - Dielectric-barrier discharges (DBDs)
- Other mechanism
 - Laser produced plasma
 - Pulsed-power generated plasma

Capacitive RF coupling plasma without magnetic fields



$$\vec{F} = m \vec{a} = -\nu_c m \vec{v} - e \vec{E}$$

$$m \frac{dv_y}{dt} + m\nu_c v_y = 0$$

$$v_y(t) = v_{y0} \exp(-\nu_c t)$$

$$m \frac{d^2 x}{dt^2} + m\nu_c \frac{dx}{dt} = eE_0 \sin(\omega t)$$

$$x = C_1 \sin(\omega t) + C_2 \cos(\omega t)$$

$$C_1 = -\frac{eE_0}{m} \frac{1}{\omega^2 + \nu_c^2}$$

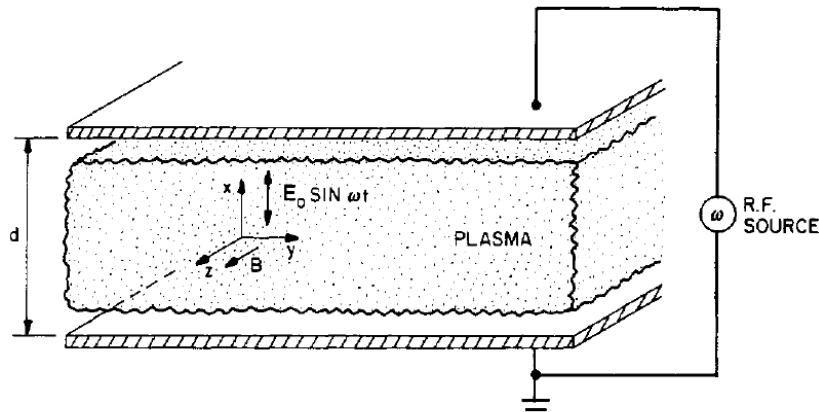
$$C_2 = -\frac{\nu_c eE_0}{\omega m} \frac{1}{\omega^2 + \nu_c^2}$$

$$v_x(t) = -\frac{eE_0 \omega}{m(\omega^2 + \nu_c^2)} \left[\cos(\omega t) - \frac{\nu_c}{\omega} \sin(\omega t) \right]$$

$$P = \frac{dW}{dt} = eE_0 \sin(\omega t) v_x$$

$$\bar{P}_{\text{tot}} = n_e \bar{P} = \frac{1}{4} \epsilon_0 E_0^2 \frac{2n_e e^2}{m \epsilon_0} \frac{\nu_c}{\omega^2 + \nu_c^2}$$

Capacitive RF coupling plasma with magnetic fields



$$\begin{aligned} \frac{d^2x}{dt^2} + \nu_c \frac{dx}{dt} + \omega_c \frac{dy}{dt} &= -\frac{eE_0}{m} \sin(\omega t) \\ \frac{d^2y}{dt^2} + \nu_c \frac{dy}{dt} - \omega_c \frac{dx}{dt} &= 0 \quad \omega_c = \frac{eB}{m} \end{aligned}$$

$$\vec{F} = m \vec{a} = -\nu_c m \vec{v} - e(\vec{v} \times \vec{B}) - e \vec{E}$$

$$m \frac{d^2x}{dt^2} + m\nu_c \frac{dx}{dt} + eB \frac{dy}{dt} = -eE_0 \sin(\omega t)$$

$$m \frac{dv_y}{dt} + m\nu_c v_y - eB \frac{dx}{dt} = 0$$

$$m \frac{dv_z}{dt} + m\nu_c v_z = 0$$

$$v_z(t) = v_{z0} \exp(-\nu_c t)$$

$$x = C_1 \sin(\omega t) + C_2 \cos(\omega t)$$

$$y = C_3 \sin(\omega t) + C_4 \cos(\omega t)$$

$$C_1 = -\frac{eE_0}{2m} \left[\frac{\omega + \omega_c}{(\omega + \omega_c)^2 + \nu_c^2} + \frac{\omega - \omega_c}{(\omega - \omega_c)^2 + \nu_c^2} \right]$$

$$C_2 = -\frac{\nu_c eE_0}{2\omega m} \left[\frac{1}{(\omega + \omega_c)^2 + \nu_c^2} + \frac{1}{(\omega - \omega_c)^2 + \nu_c^2} \right]$$

$$C_3 = \frac{\omega_c (C_1 \nu_c + C_2 \omega)}{\omega^2 + \nu_c^2} \quad C_4 = -\frac{\omega_c (C_1 \omega - C_2 \nu_c)}{\omega^2 + \nu_c^2}$$

The coupling efficient for capacitive RF with magnetic fields is less than DC electrical discharge



$$P = \frac{dW}{dt} = eE_0 \sin(\omega t) v_x$$

$$\begin{aligned} \bar{P}_{\text{tot}} = n_e \bar{P} &= \frac{1}{4} \epsilon_0 E_0^2 \frac{n_e e^2}{m \epsilon_0} v_c \left[\frac{1}{(\omega + \omega_c)^2 + v_c^2} + \frac{1}{(\omega - \omega_c)^2 + v_c^2} \right] \\ &= \frac{1}{4} \epsilon_0 E_0^2 \times \omega_{pe}^2 v_c \left[\frac{1}{(\omega + \omega_c)^2 + v_c^2} + \frac{1}{(\omega - \omega_c)^2 + v_c^2} \right] \end{aligned}$$

- DC, unmagnetized discharge ($\omega = \omega_c = 0$): $v_{*0} = \frac{2\omega_{pe}^2}{v_c}$
- Low collisionality ($\omega_c \gg v_c$):

$$v_* \approx v_{*0} v_c^2 \left[\frac{\omega^2 + \omega_c^2}{(\omega^2 - \omega_c^2)^2} \right] \rightarrow v_{*0} \frac{v_c^2}{\omega_c^2} \ll v_{*0} \quad (\omega, v_c \ll \omega_c)$$
- High collisionality ($\omega_c \ll v_c$):

$$v_* \approx v_{*0} \frac{v_c^2}{\omega^2 + v_c^2} \approx v_{*0} (\omega, \omega_c \ll v_c)$$
- Resonant ($\omega = \omega_c$):

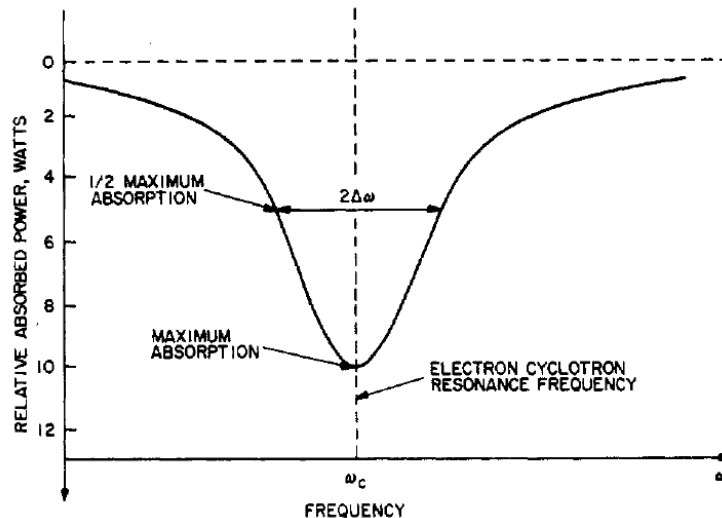
$$v_* = v_{*0} \frac{2\omega_c^2 + v_c^2}{4\omega_c^2 + v_c^2} \rightarrow \frac{1}{2} v_{*0} (\omega = \omega_c \gg v_c)$$

Collision frequency can be measured using capacitive RF electrical discharges



$$\bar{P}(\omega_c) = \frac{1}{4} \epsilon_0 E_0^2 \times v_{*0} \frac{2 + (v_c/\omega_c)^2}{4 + (v_c/\omega_c)^2} = \frac{1}{4} \epsilon_0 E_0^2 \times v_{*0} \frac{2 + \epsilon^2}{4 + \epsilon^2}$$

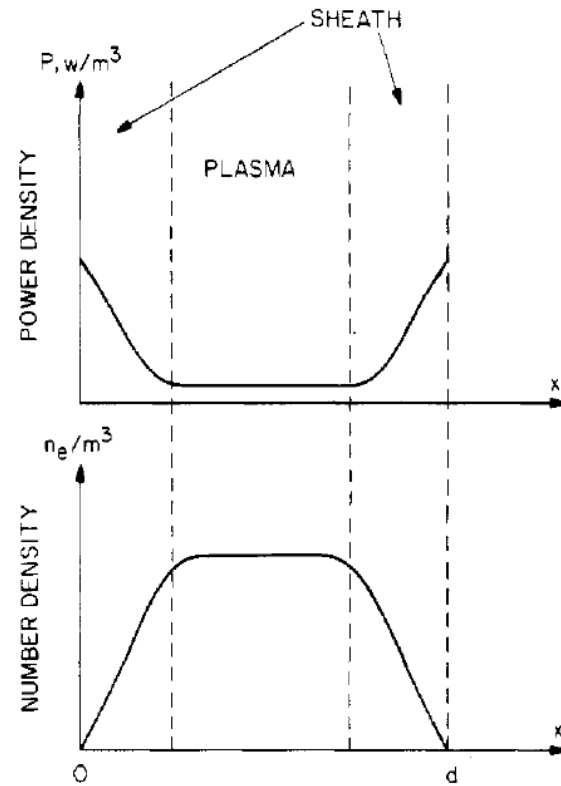
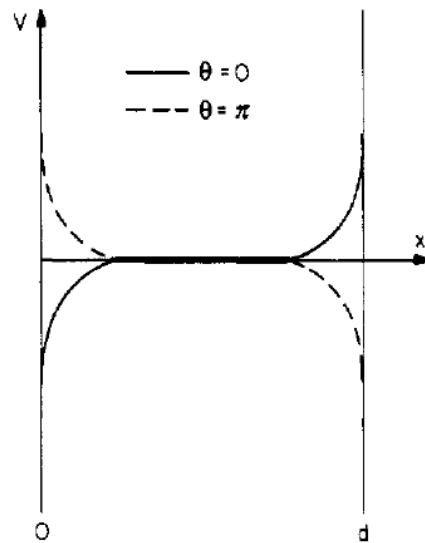
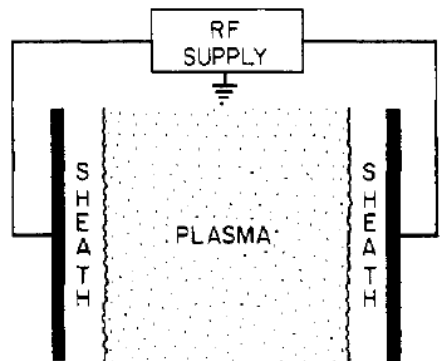
$$\begin{aligned} \bar{P}(\omega_c \pm \Delta\omega) &= \frac{1}{4} \epsilon_0 E_0^2 \times \frac{v_{*0}}{2} \left(\frac{v_c}{\omega_c} \right)^2 \left[\frac{1}{(2 \pm \Delta\omega/\omega_c)^2 + (v_c/\omega_c)^2} + \frac{1}{(\Delta\omega/\omega_c)^2 + (v_c/\omega_c)^2} \right] \\ &= \frac{1}{4} \epsilon_0 E_0^2 \times \frac{v_{*0}}{2} \epsilon^2 \left[\frac{1}{(2 \pm \delta)^2 + \epsilon^2} + \frac{1}{\delta^2 + \epsilon^2} \right] \quad \text{where } \delta \equiv \frac{\Delta\omega}{\omega_c}, \epsilon \equiv \frac{v_c}{\omega_c} \end{aligned}$$



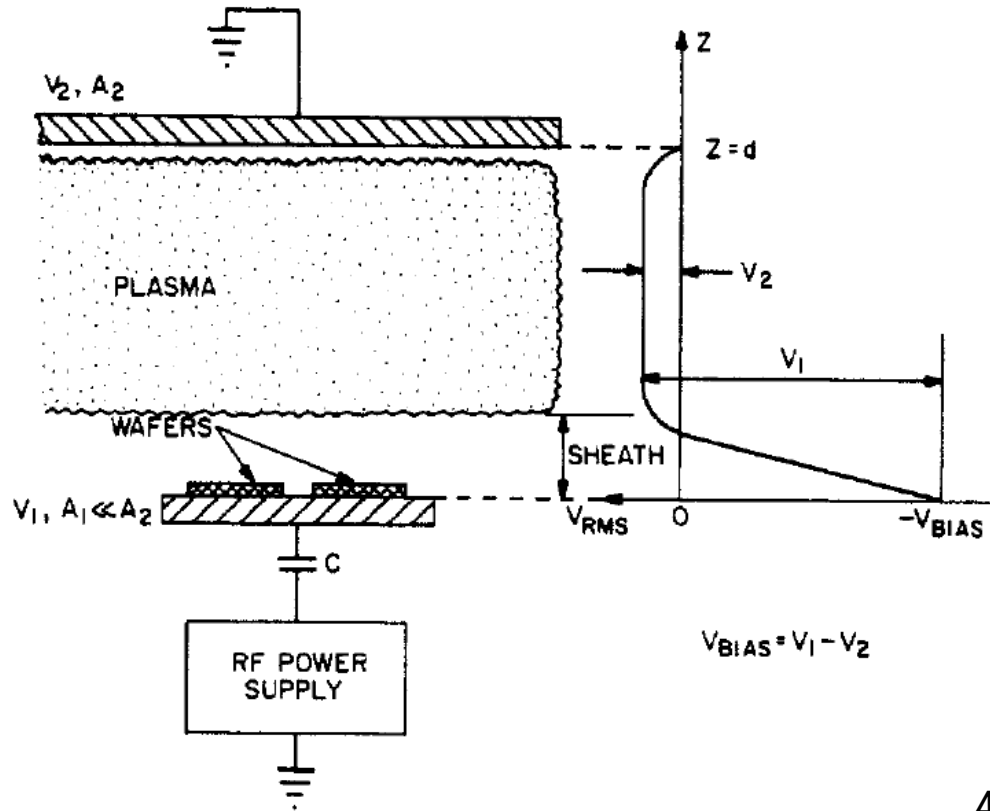
For $\delta \approx \epsilon \ll 1$,

$$\bar{P}(\omega_c \pm v_c) = \frac{1}{2} \bar{P}(\omega_c)$$

Symmetrical capacitive RF discharge model



Empirical scaling of electrode voltage drop



$$I_1 = A_1 J_1 = A_1 e n_{i1} \bar{v}_{i1}$$

$$I_2 = A_2 J_2 = A_2 e n_{i2} \bar{v}_{i2}$$

$$\bar{v}_{i1} = \sqrt{\left(\frac{2eV_1}{m_i}\right)}$$

$$\bar{v}_{i2} = \sqrt{\left(\frac{2eV_2}{m_i}\right)}$$

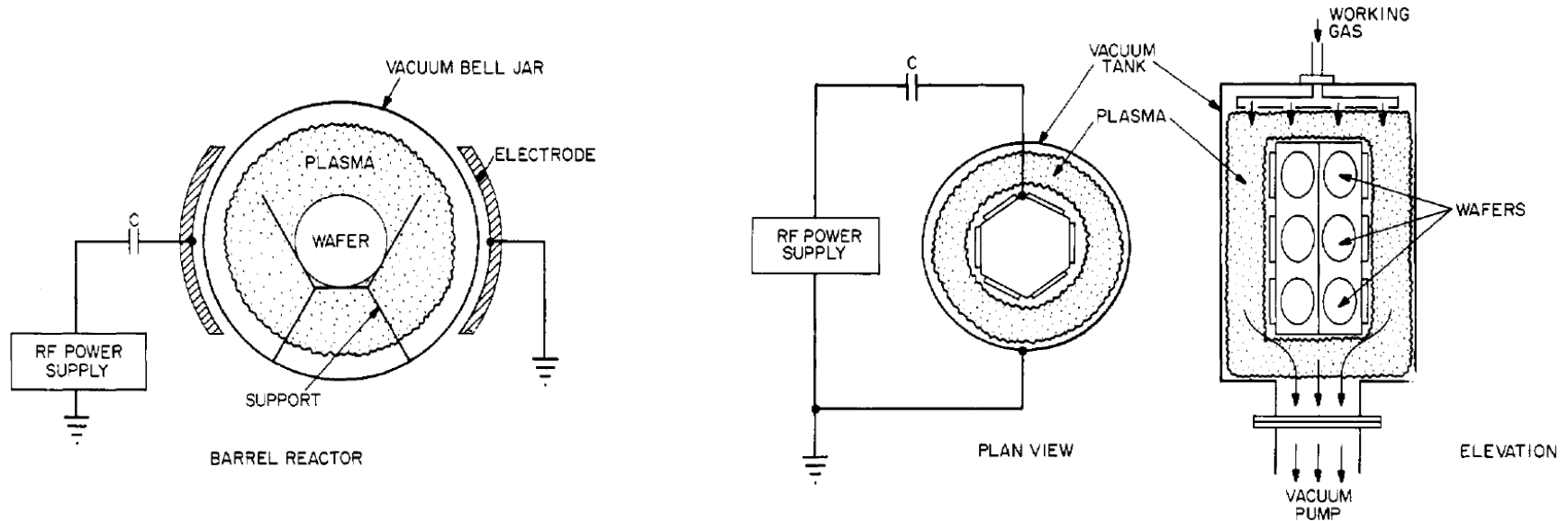
Assuming: $I_1 = I_2$ $n_{i1} = n_{i2}$

$$A_1 e n_{i1} \sqrt{\left(\frac{2eV_1}{m_i}\right)} = A_2 e n_{i2} \sqrt{\left(\frac{2eV_2}{m_i}\right)}$$

$$\frac{V_1}{V_2} = \left(\frac{A_2}{A_1}\right)^q \text{ where } 1.0 \leq q \leq 2.5$$

$$\frac{V_1}{V_2} = \left(\frac{A_2}{A_1}\right)^2$$

Example of capacitively coupled RF plasma source 1



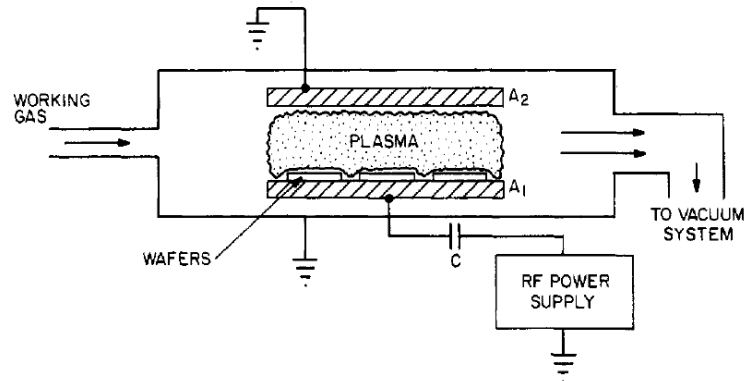
- **Barrier reactor** – the wafers float electrically and have low ion bombardment energies

- **Hexagonal reactor** – the wafers develop a DC bias which leads to a relatively anisotropic, vertical etch.

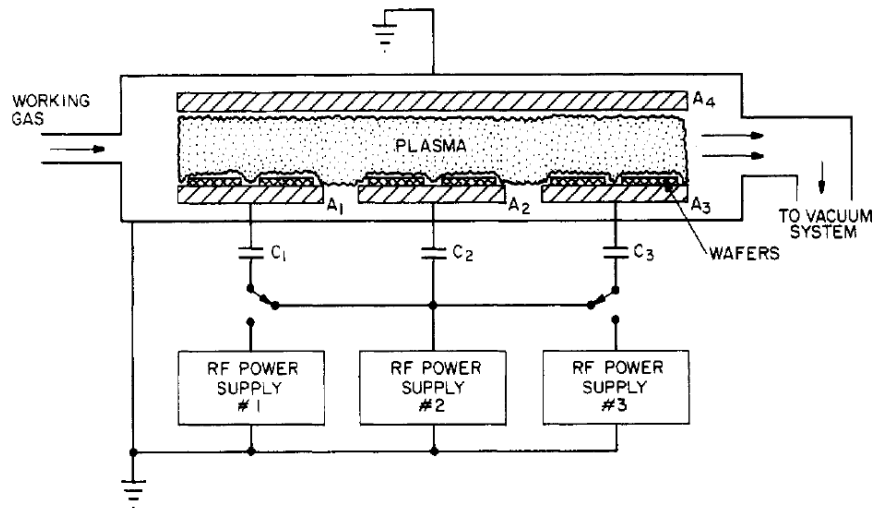
Example of capacitively coupled RF plasma source 2



- Plane parallel reactor



- Multiple electrode system



Operating regimes of capacitively coupled plasma reactors used for plasma processing



Parameter	Low value	Typical value	High value
Frequency	1 kHz	13.56 MHz	100 MHz
Gas pressure	3 mTorr	300 mTorr	5 Torr
Power level	50 W	≈ 200 W	500 W
rms electrode voltage	100 V	≈ 300 V	1000 V
Current density	0.1 mA/cm ²	≈ 3 mA/cm ²	10 mA/cm ²
Electron temperature, T_e	3 eV	≈ 5 eV	8 eV
Electron density, n_e	10 ¹⁵ /m ³	$\approx 5 \times 10^{15}$ /m ³	3×10^{17} /m ³
Ion energy, $\mathcal{E}_i$	5 eV	50 eV	500 eV
Electrode separation, d	0.5 cm	4 cm	30 cm

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



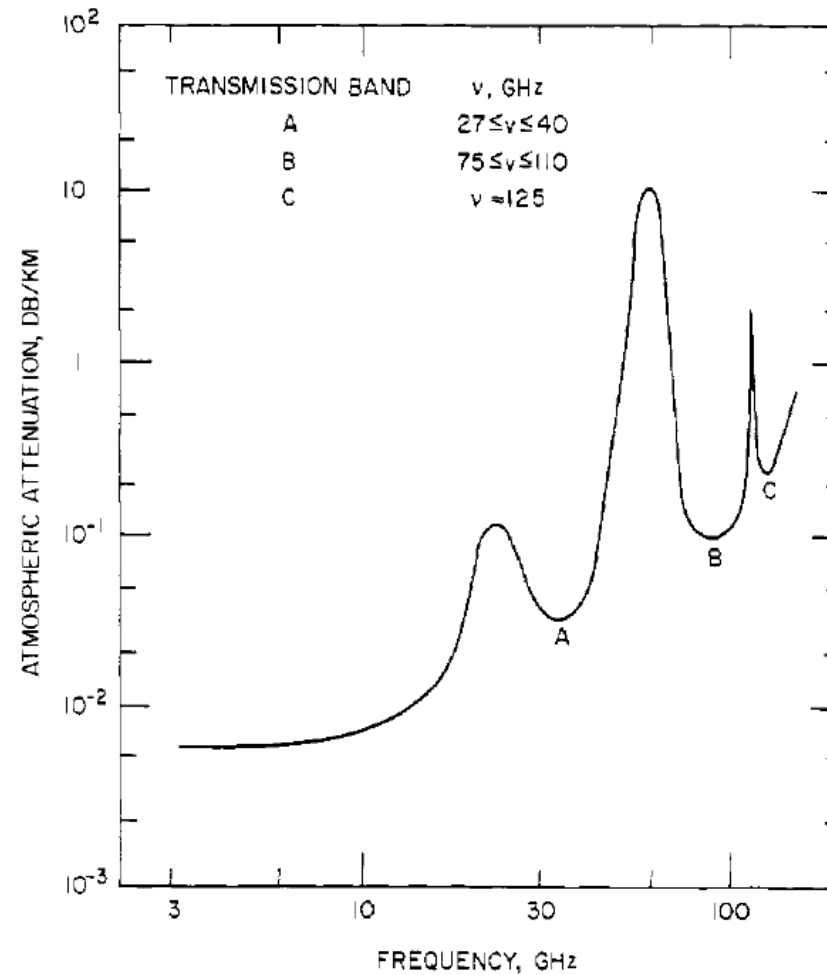
- DC electrical discharge – a true current in the form of a flow of ions or electrons to the electrodes.
- AC electrical discharge – the power supply interacts with the plasma by displacement current.
 - Inductive radio frequency (RF) electrical discharges
 - Capacitive RF electrical discharges
 - **Microwave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

Advantage of using microwave electrical discharges

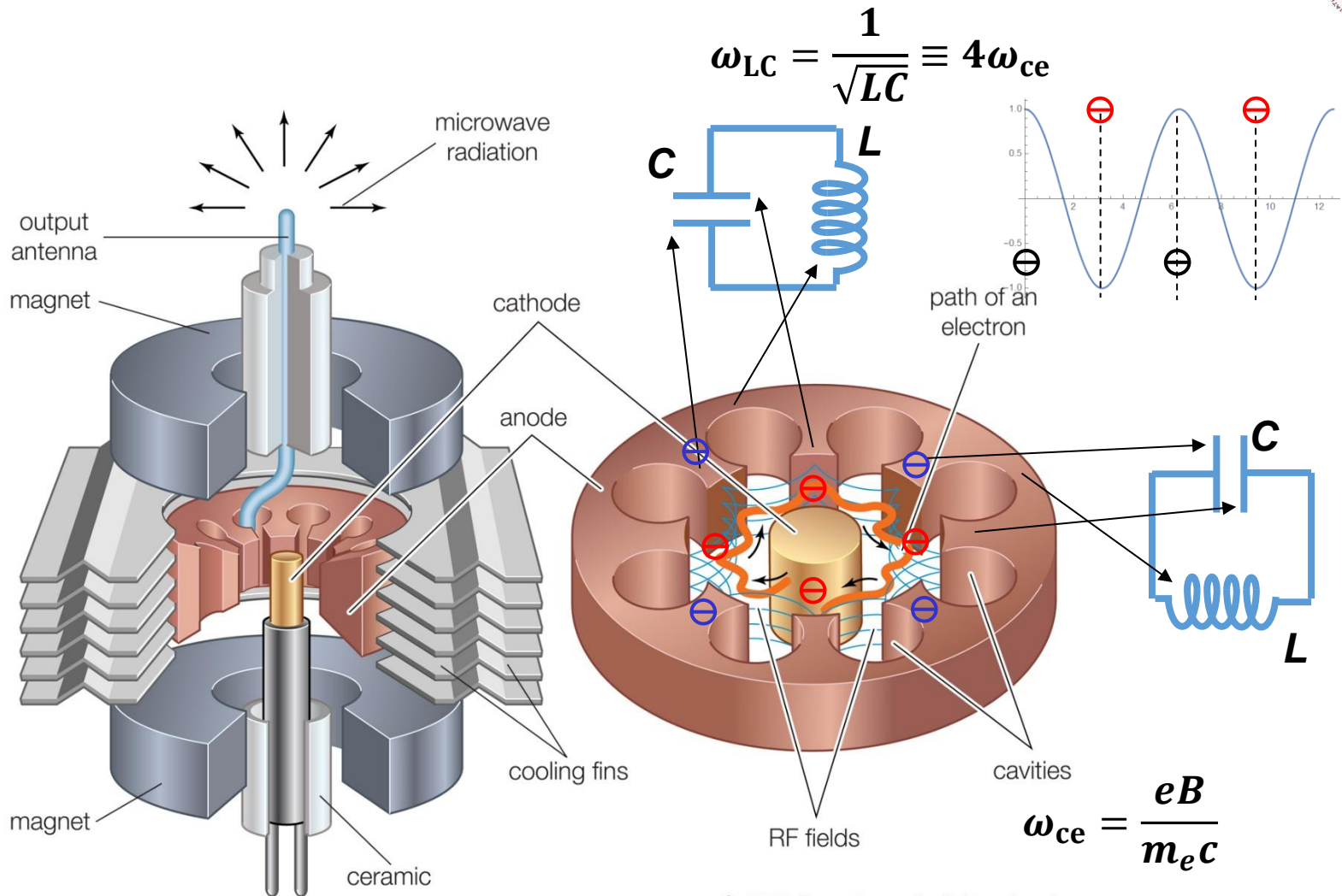


- The wavelength of the microwave is in centimeters range. In contrast, the wavelength is 22 m for RF frequency $f = 13.6$ MHz.
- The electron number density can approach the critical number density. ($7 \times 10^{16} \text{ m}^{-3}$) at a frequency of 2.45 GHz.
- The plasma in microwave discharges is quasi-optical to microwave.
- Microwave-generated plasmas have a higher electron kinetic temperature (5 ~ 15 eV) than DC or low frequency RF-generated plasmas (1 or 2 eV).
- Capable of providing a higher fraction of ionization.
- Do not have a high voltage sheath.
- No internal electrodes.

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

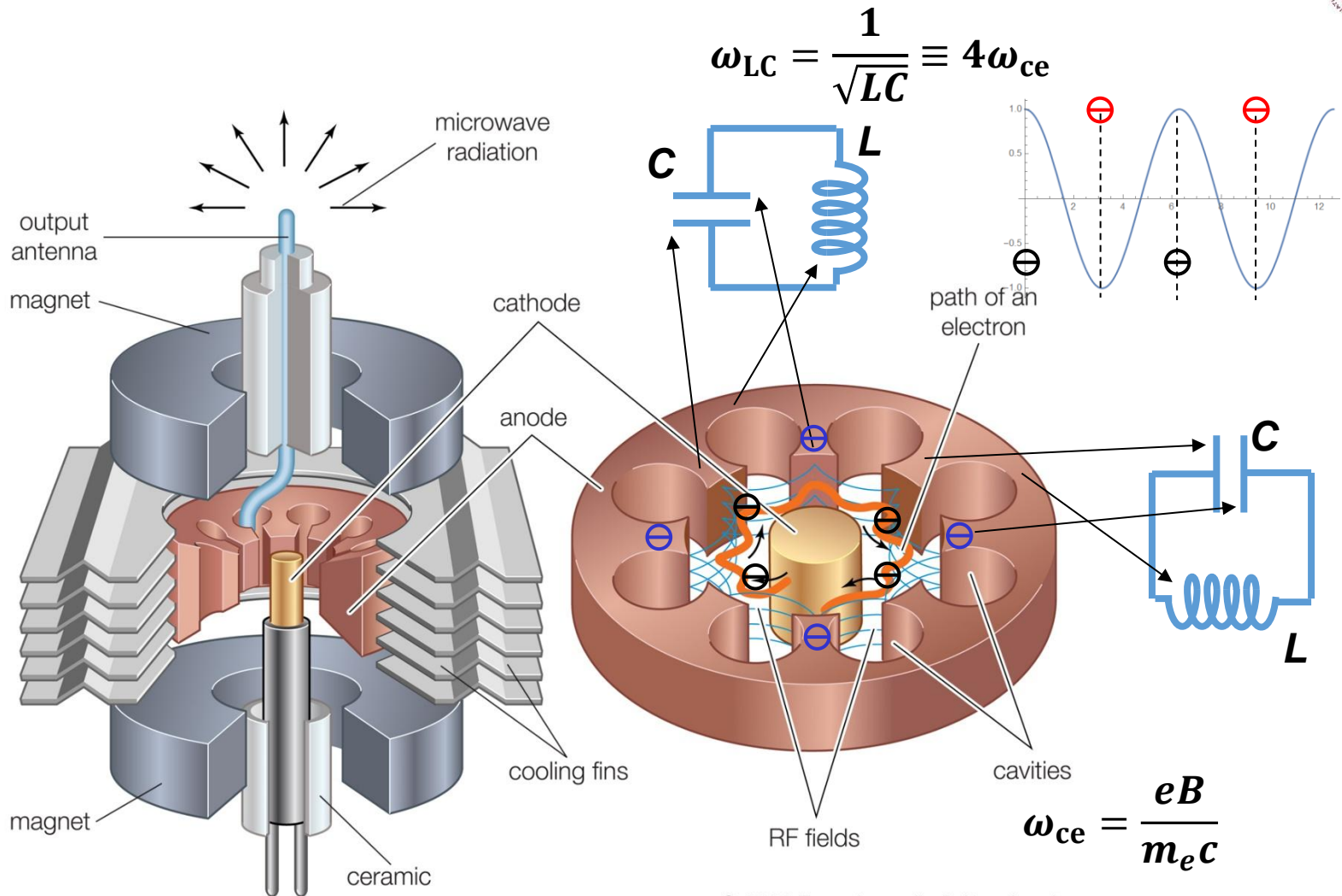


Internal of a magnetron



© 2010 Encyclopædia Britannica, Inc.

Internal of a magnetron

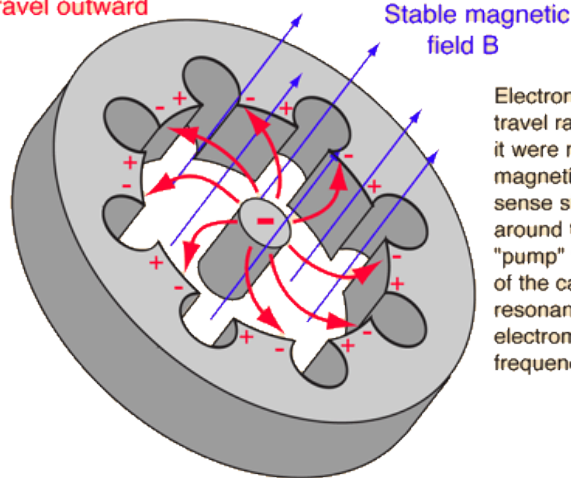


© 2010 Encyclopædia Britannica, Inc.

Magnetron is a forced oscillation driven by electrons between the gap

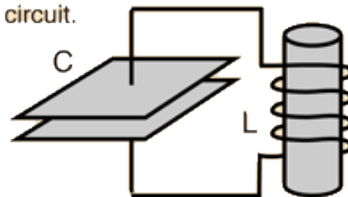


Hot cathode emits electrons which travel outward



Electrons from a hot filament would travel radially to the outside ring if it were not for the magnetic field. The magnetic force deflects them in the sense shown and they tend to sweep around the circle. In so doing, they "pump" the natural resonant frequency of the cavities. The currents around the resonant cavities cause them to radiate electromagnetic energy at that resonant frequency.

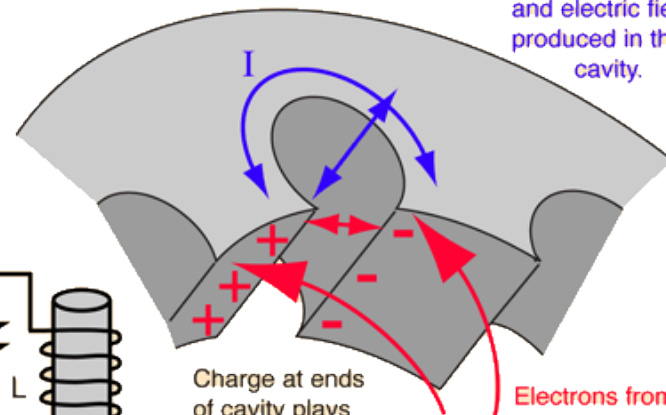
The cavity exhibits a resonance analogous to a parallel resonant circuit.



$$f_{\text{resonance}} \approx \frac{1}{2\pi} \sqrt{\frac{1}{LC}}$$

Current around the cavity plays the role of an inductor.

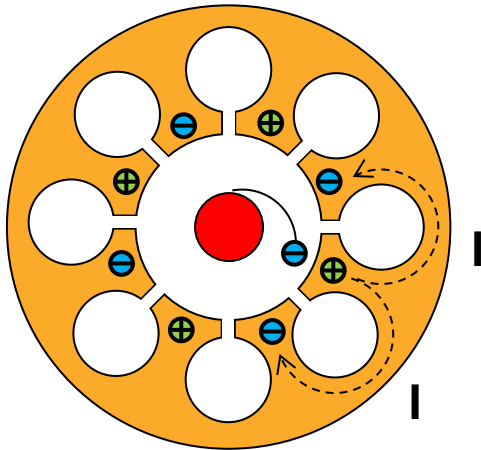
Oscillating magnetic and electric fields produced in the cavity.



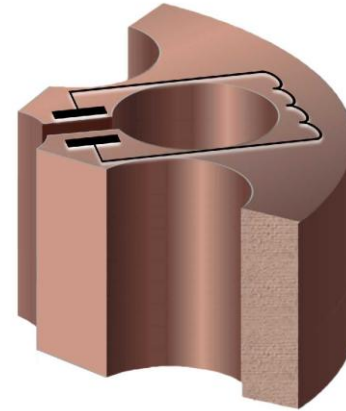
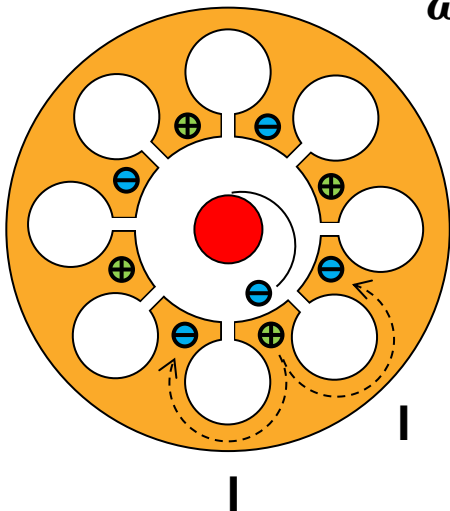
Charge at ends of cavity plays the role of a capacitor.

Electrons from the hot center cathode arriving at a negatively charged region tend to drive it back around the cavity, "pumping" the natural resonant frequency.

Strong oscillation occurs when the electron cyclotron frequency match the LC oscillation frequency



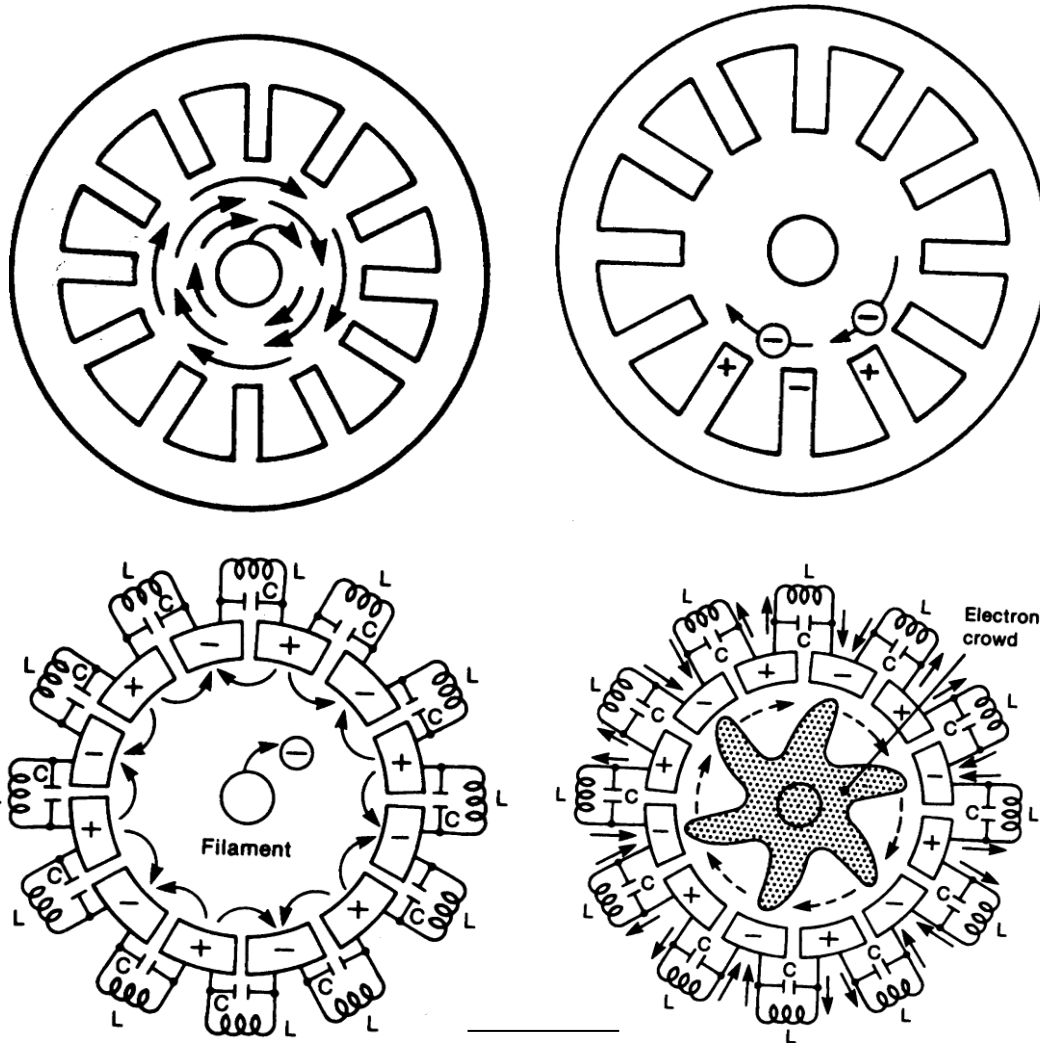
$$\omega_{\text{CE}} = \frac{eB}{mc}$$



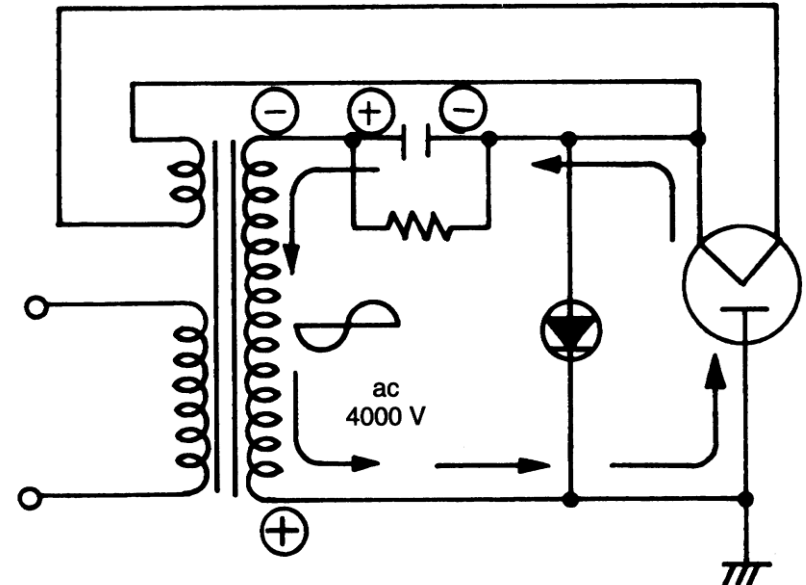
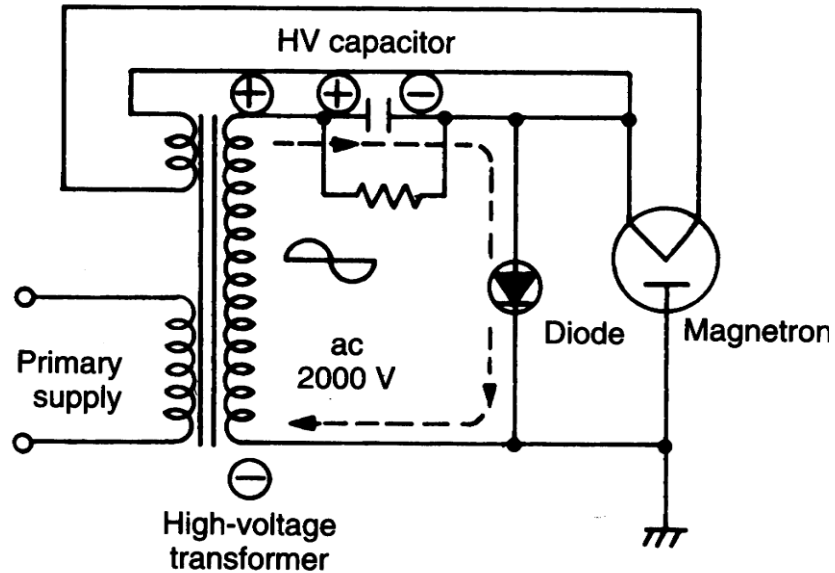
$$\omega = \frac{1}{\sqrt{LC}}$$

Resonance condition: $\omega_{\text{CE}} = \omega$

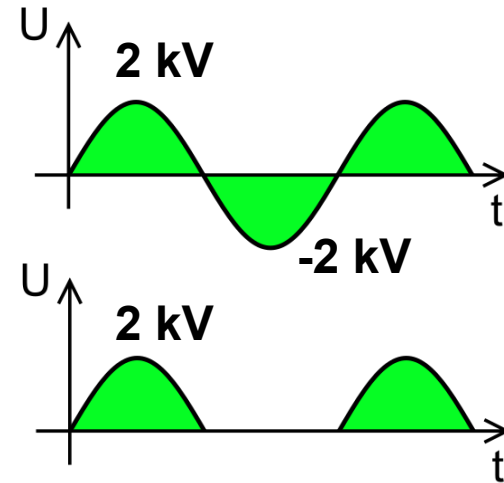
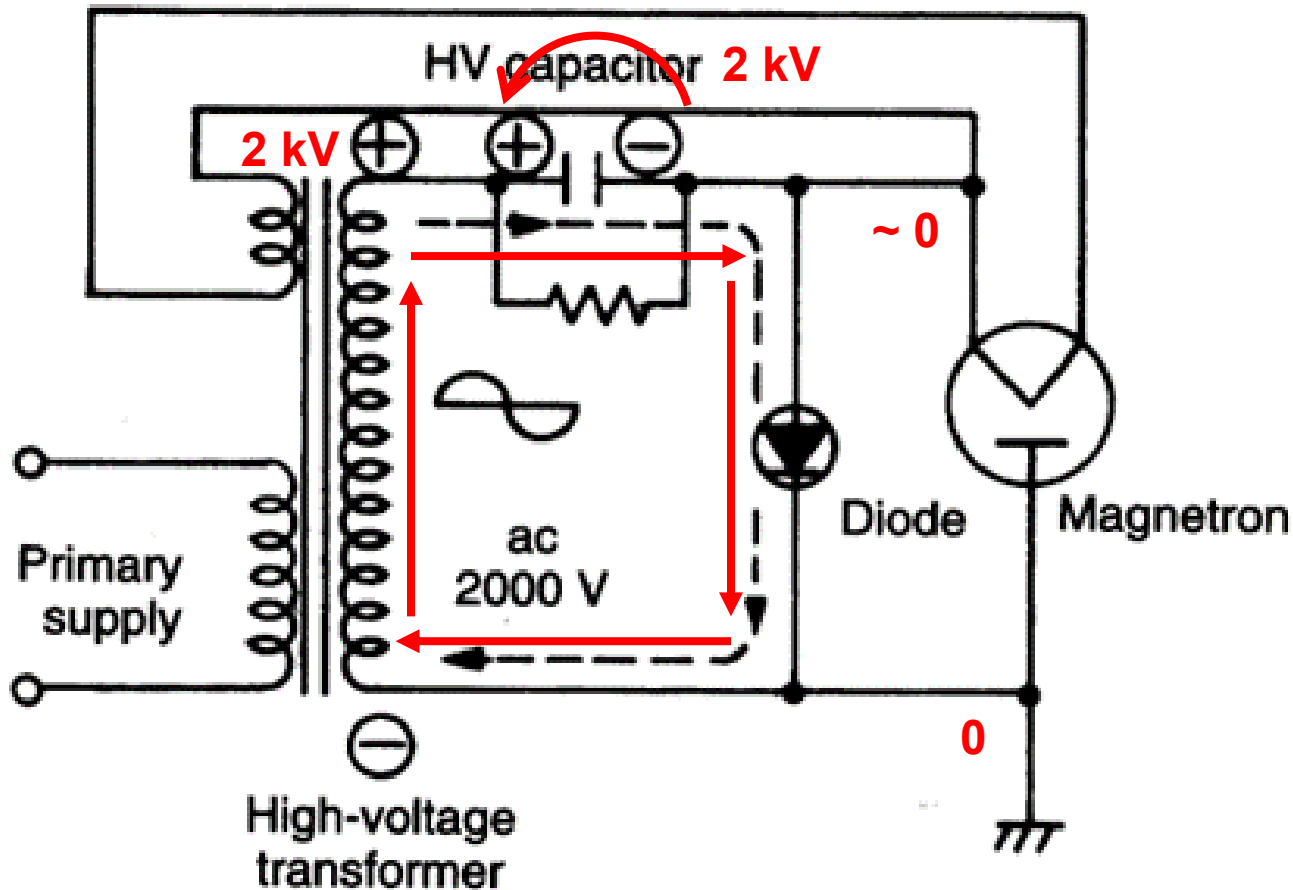
Resonance in a magnetron



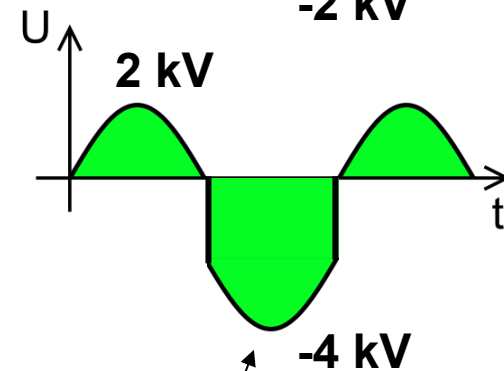
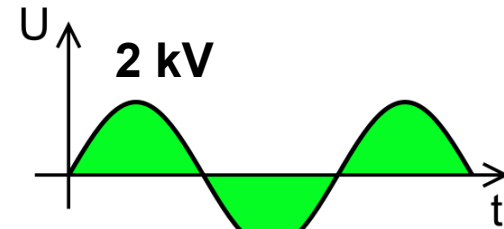
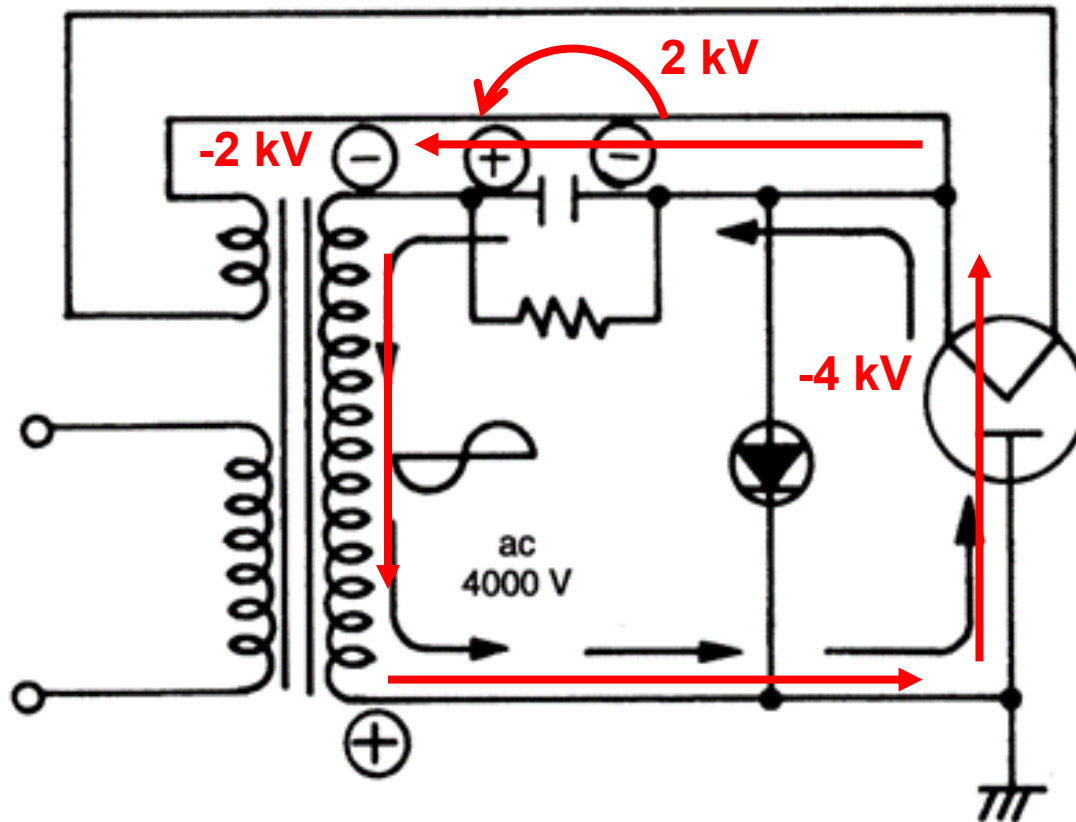
Magnetron schematic diagram



Magnetron schematic diagram

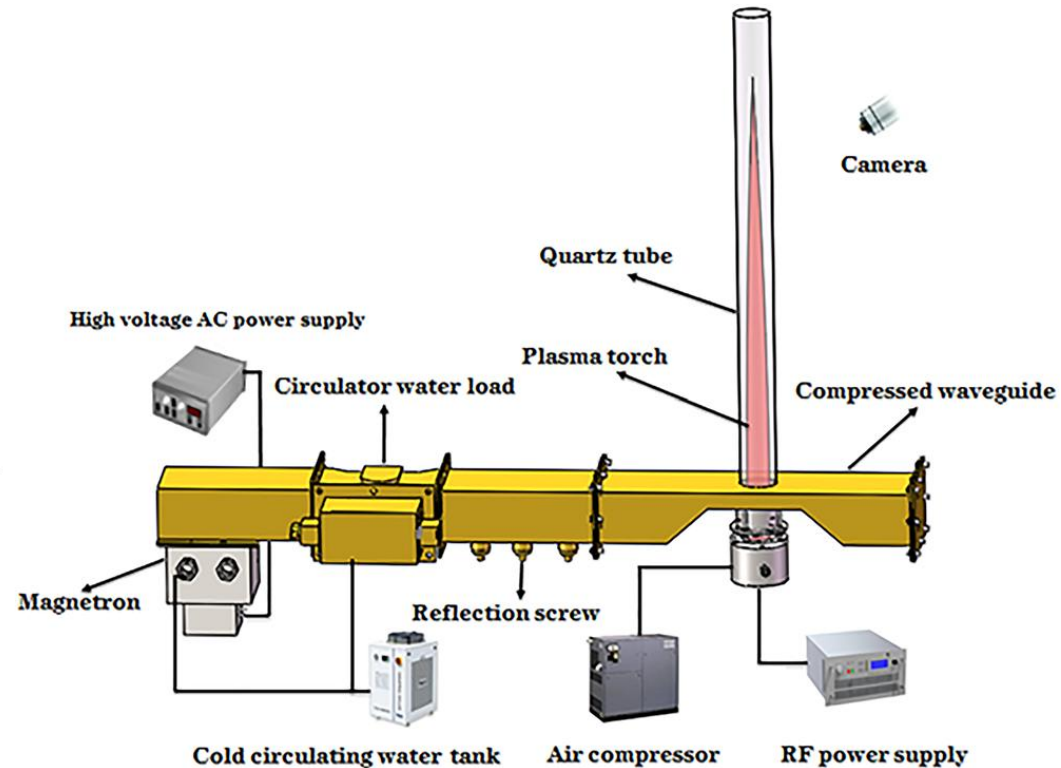
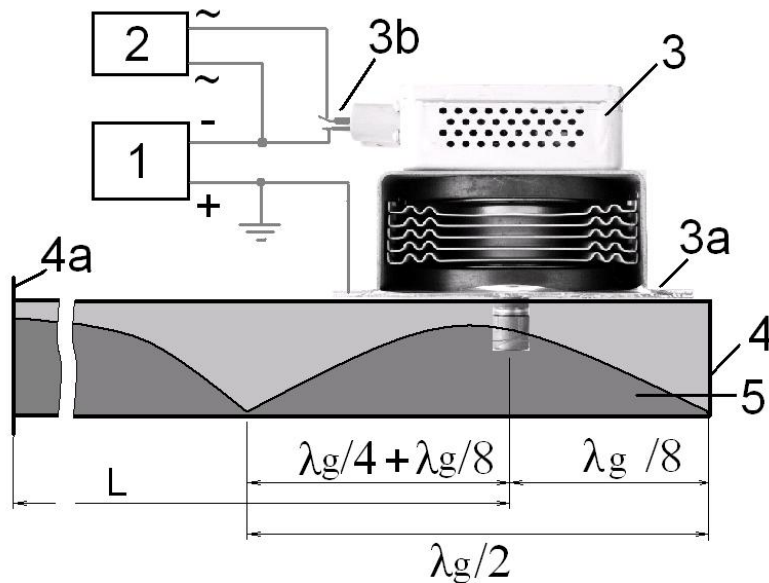


Magnetron schematic diagram

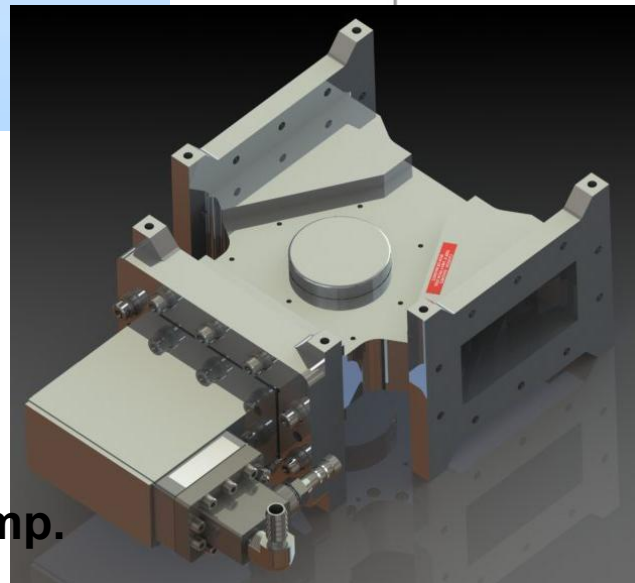
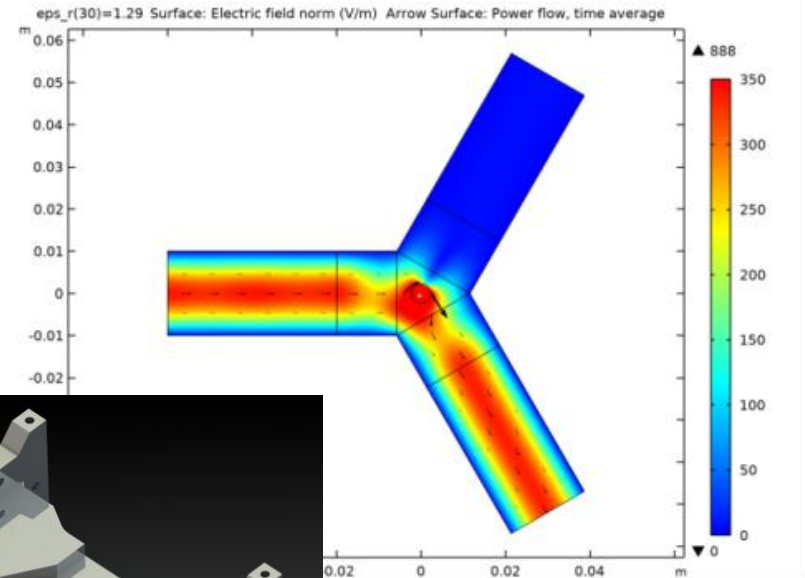
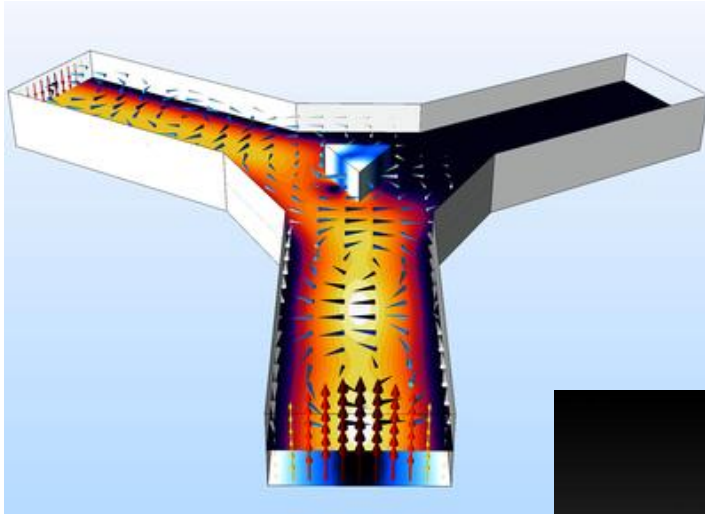


Microwave is generated.

The electrode of the microwave source is located at the location with the highest electric field



A 3-port circulator combining with a dump can be used as a isolator



Water load as a dump.

<https://cn.comsol.com/model/impedance-matching-of-a-lossy-ferrite-3-port-circulator-10302>

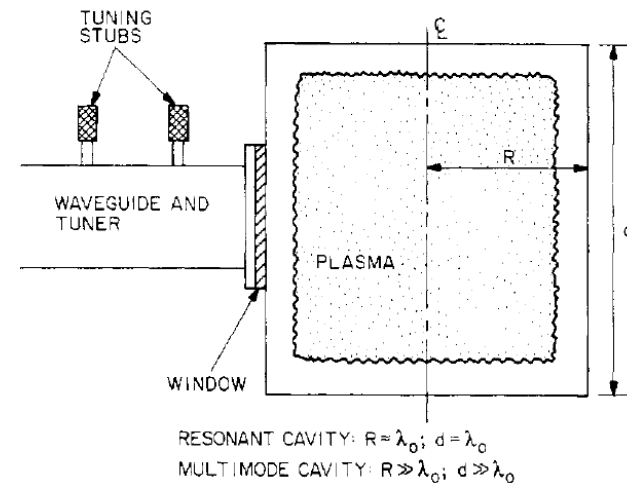
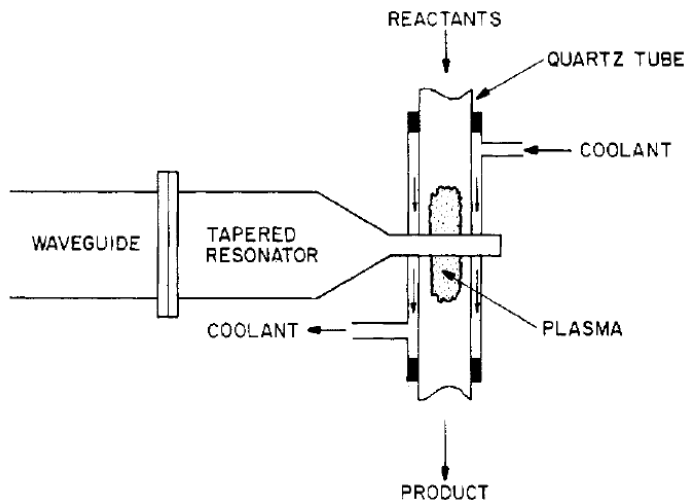
<https://doc.comsol.com/6.0/doc/com.comsol.help.models.rf.circulator/circulator.html>

<https://ferriteinc.com/high-power-microwave-circulators-isolators/wr340-waveguide-s-band/>

Microwave plasma reactor configurations



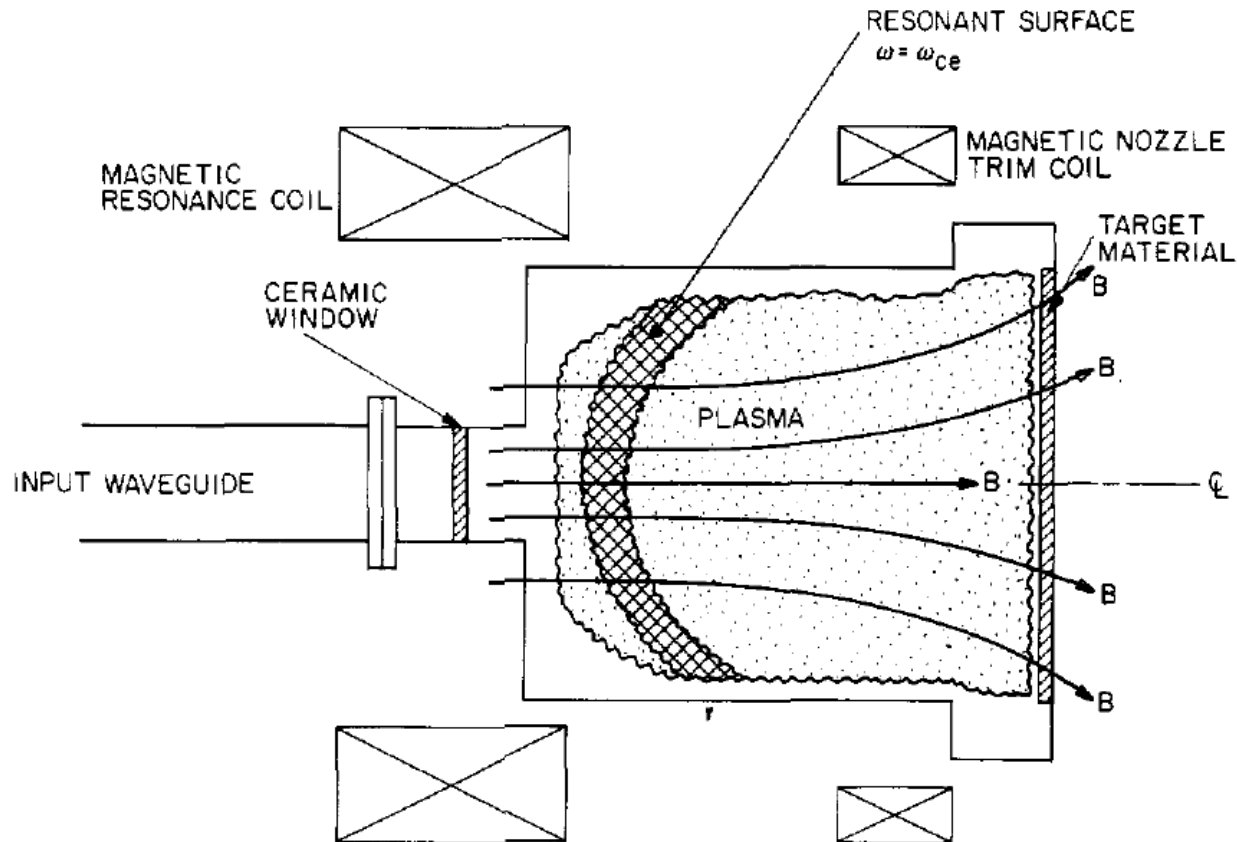
- **Waveguide coupled reactor**
- **Resonant or multimode cavity –**
if the impedance matching is good, more energy can be fed into the cavity.



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



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

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

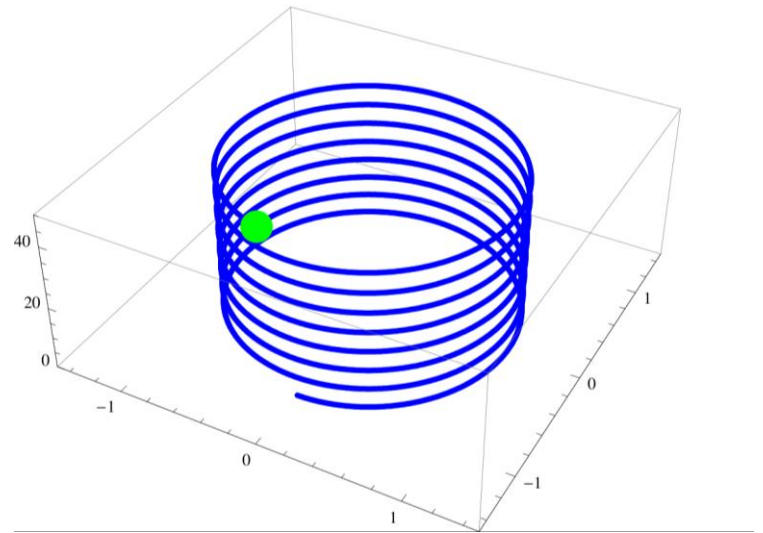
$$\begin{aligned} m_e \dot{v}_x &= -\frac{e}{c} B v_y & m_e \dot{v}_z &= 0 \\ m_e \dot{v}_y &= \frac{e}{c} B v_x \end{aligned}$$

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

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

- Therefore

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



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



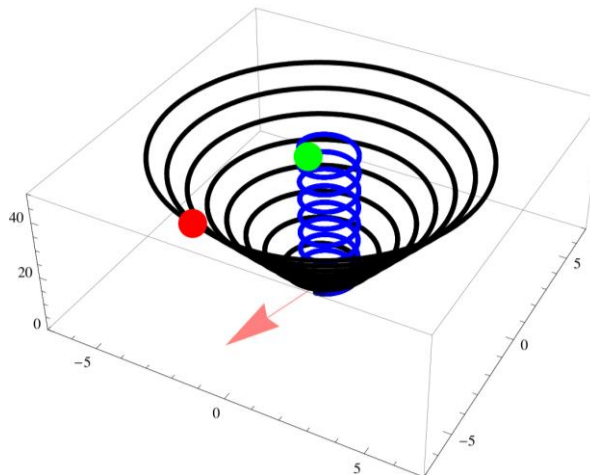
$$m_e \frac{d\vec{v}}{dt} = -\frac{e}{c} \vec{v} \times \vec{B} - e \vec{E} \quad \vec{B} = B_0 \hat{z} \quad \vec{E} = E_0 [\hat{x} \cos(\omega t) + \hat{y} \sin(\omega t)]$$

$$m_e \dot{v}_x = -\frac{e}{c} B v_y + E_0 \cos(\omega t) \quad m_e \dot{v}_y = \frac{e}{c} B v_x + E_0 \sin(\omega t) \quad m_e \dot{v}_z = 0$$

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

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

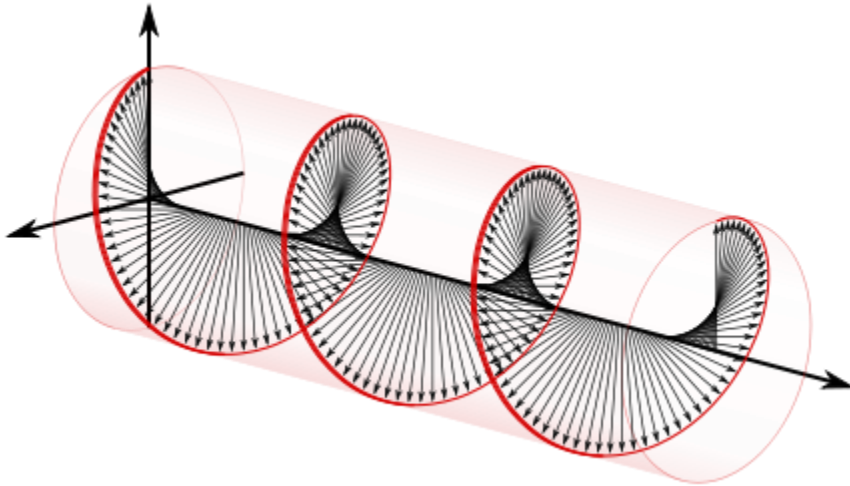
$$\omega_{ce} = \frac{eB}{m_e c}$$



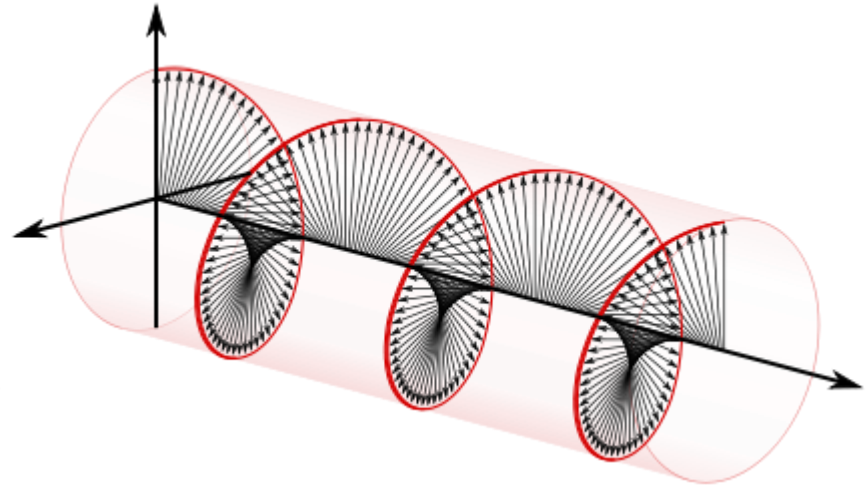
Electric field in a circular polarized electromagnetic wave keeps rotating as the wave propagates



- Right-handed polarization



- Left-handed polarization

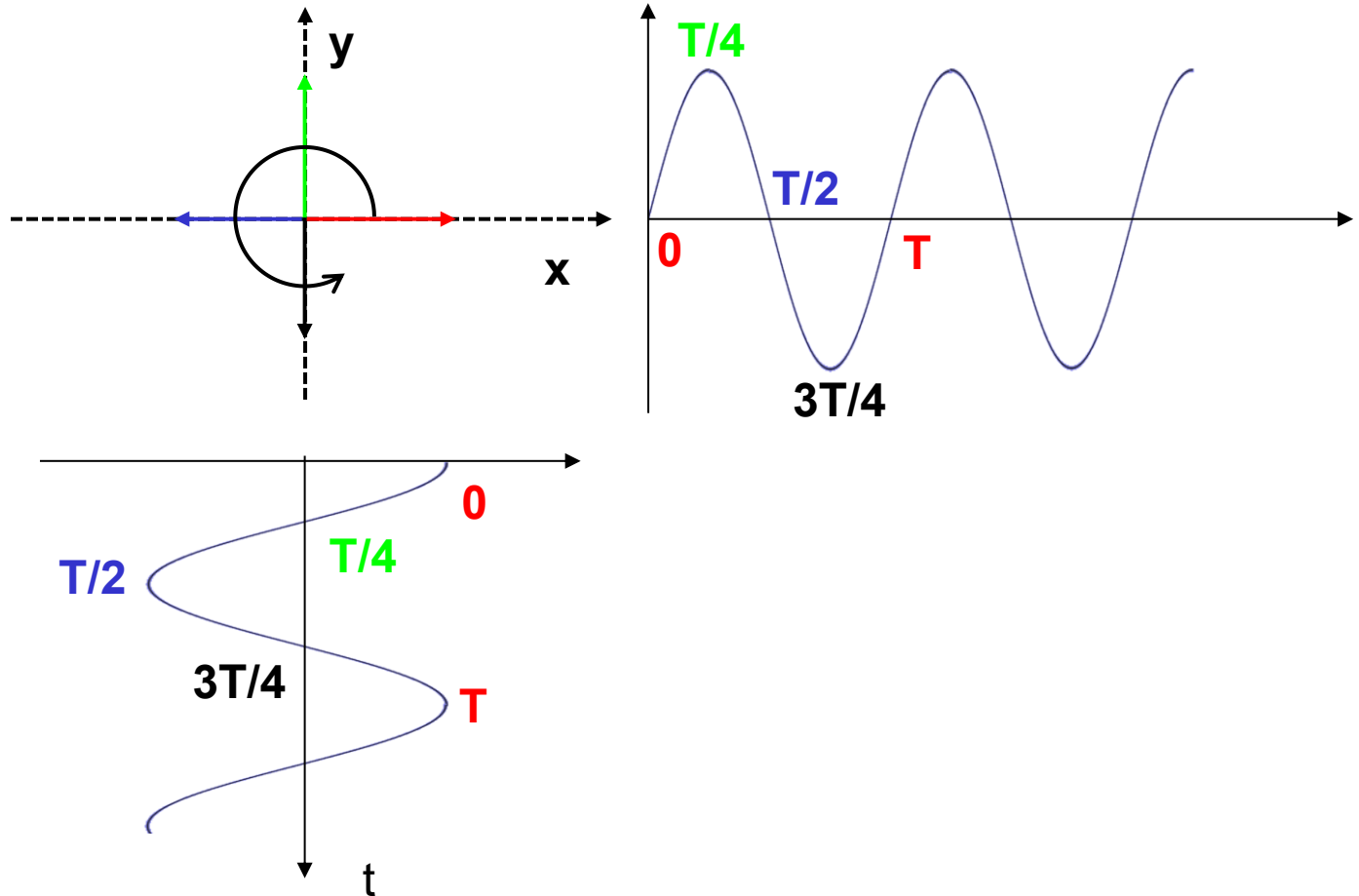


Electric field rotates in a circular polarization



$$E_x = E_0 \exp(-i\omega t)$$

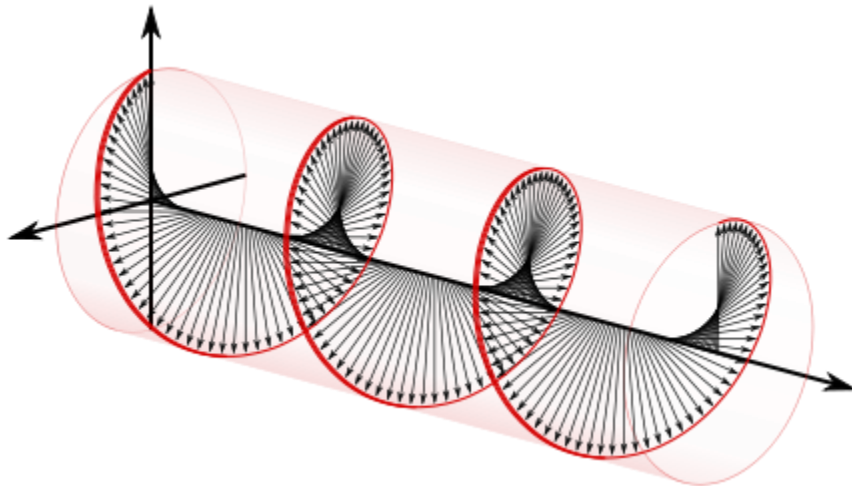
$$E_y = \pm i E_x = i E_0 \exp(-i\omega t) = E_0 \exp\left(\pm i \frac{\pi}{2}\right) \exp(-i\omega t) = E_0 \exp\left[-i\left(\omega t \pm \frac{\pi}{2}\right)\right]$$



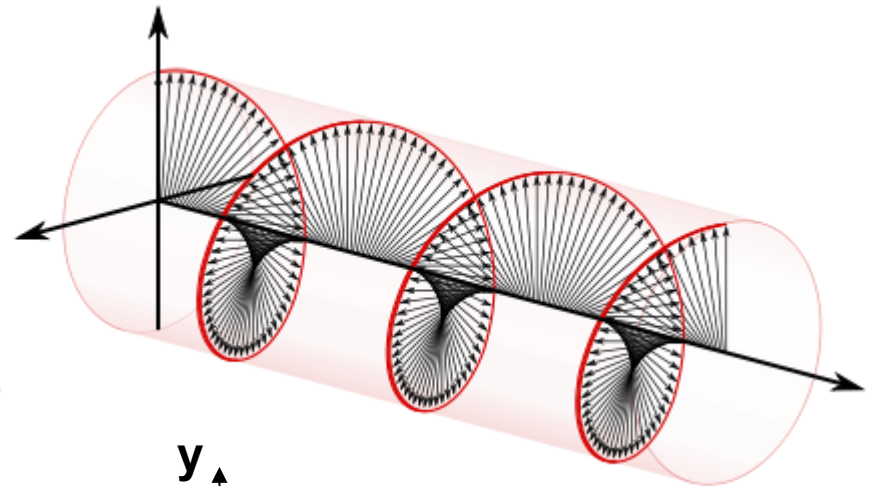
A linear polarized wave can be decomposed by a left-handed and a right-handed polarized wave



- Right-handed polarization



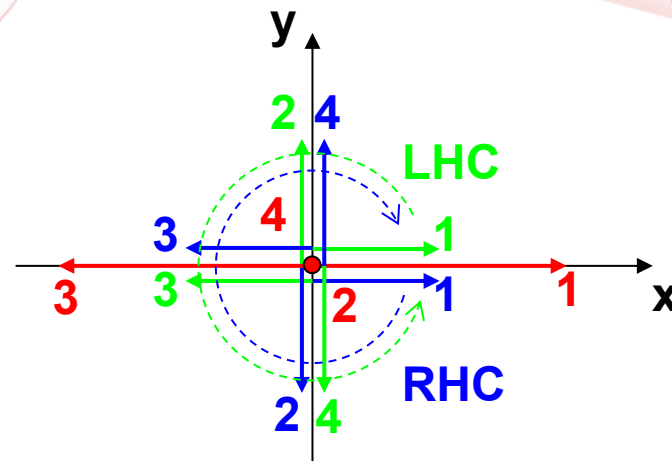
- Left-handed polarization



$$\vec{E} = E_0 \hat{x} = \frac{E_0}{2} [(\hat{x} + i\hat{y}) + (\hat{x} - i\hat{y})]$$

RHC

LHC



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

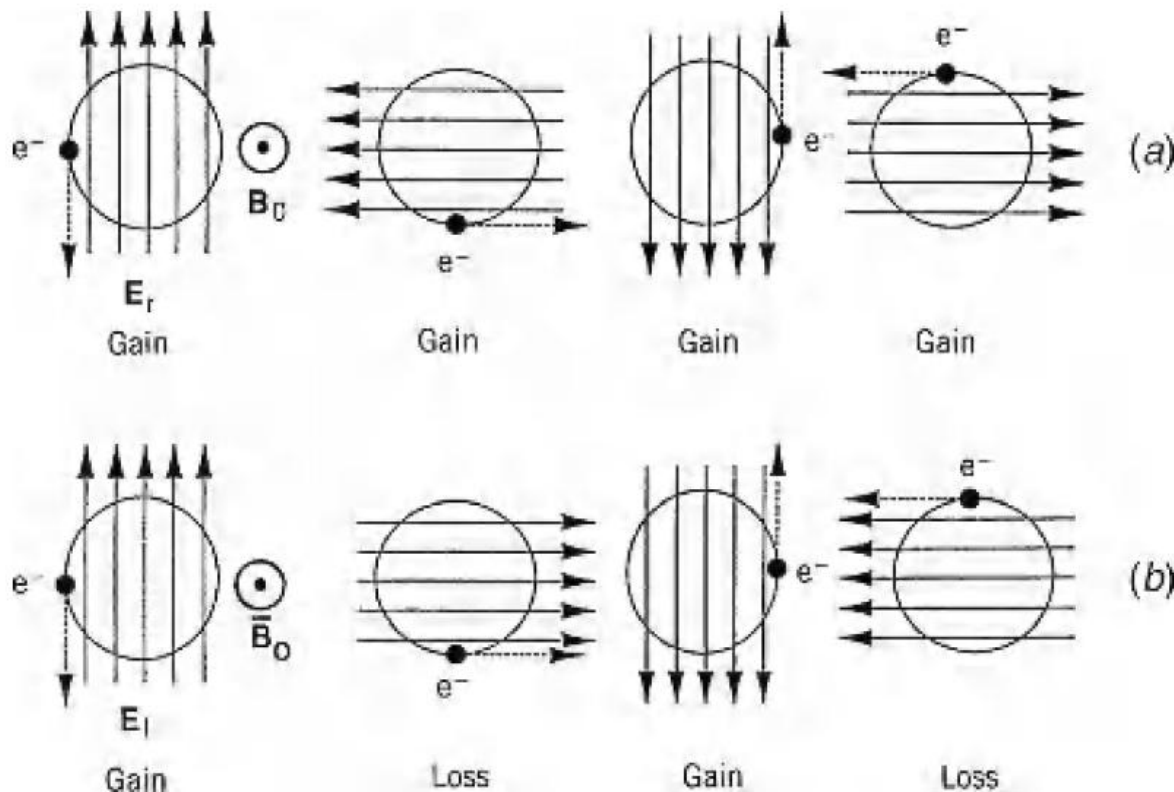
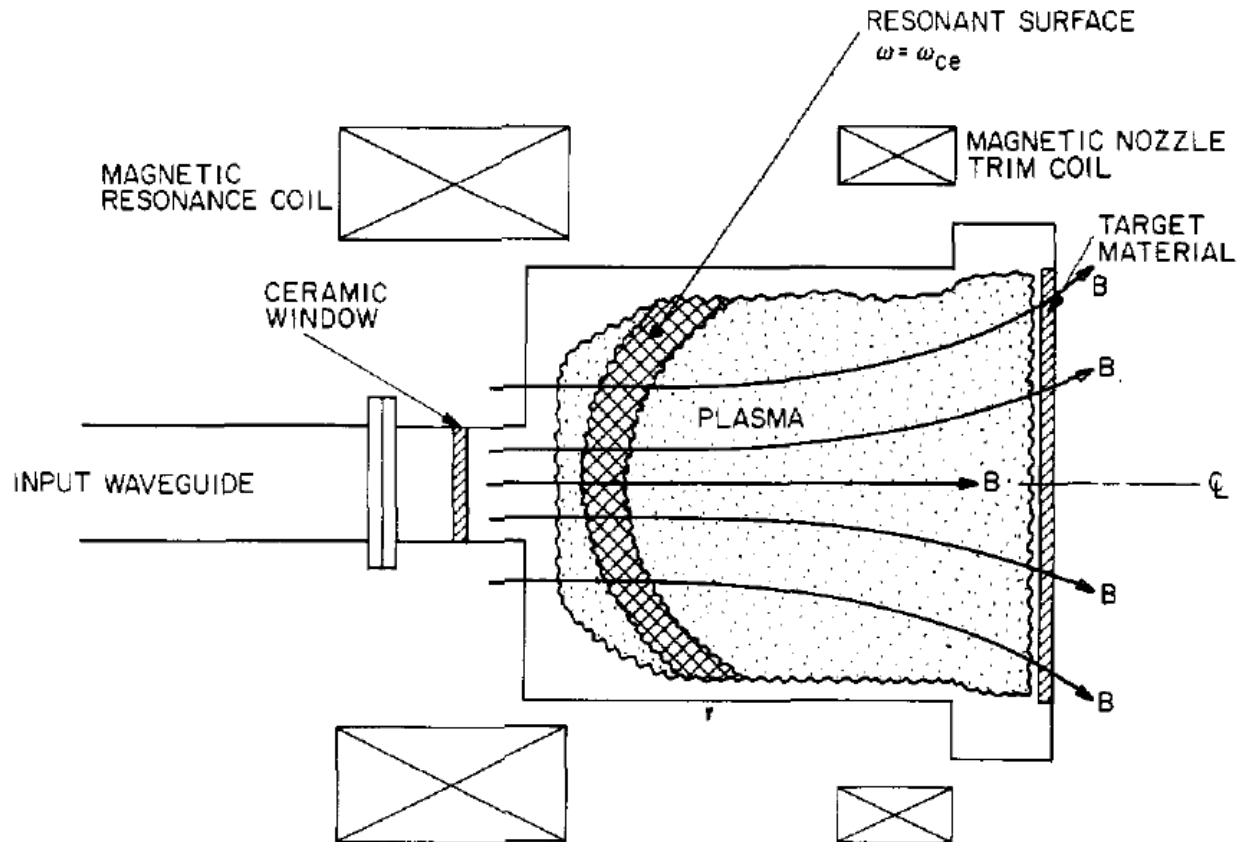


FIGURE 13.5. Basic principle of ECR heating: (a) continuous energy gain for right-hand polarization; (b) oscillating energy for left-hand polarization (after Lieberman and Gottscho, 1994).

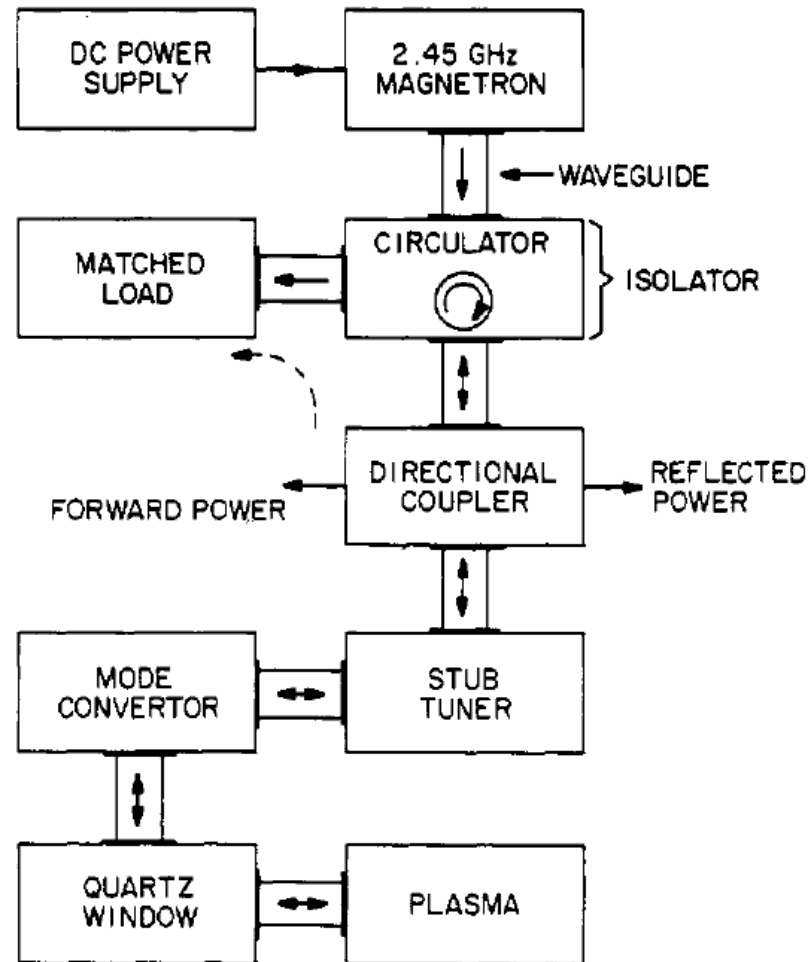
Strong absorption occurs when the frequency matches the electron cyclotron frequency



- Electron cyclotron resonance (ECR) plasma reactor



Electron cyclotron resonance (ECR) microwave systems

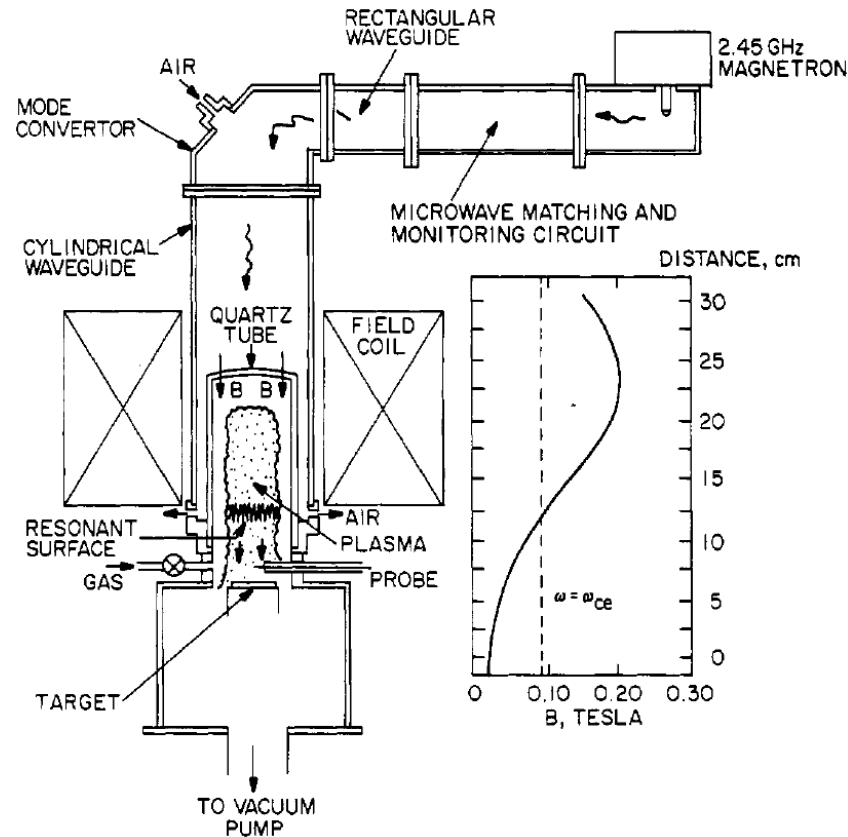


microwave systems

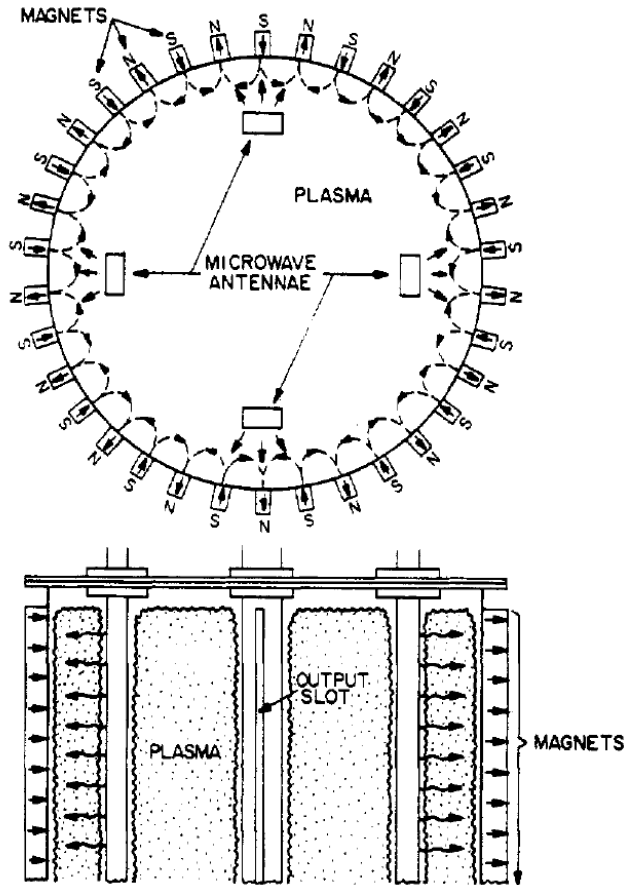
Immersed ECR plasma source



- High particle fluxes on targets for diamond or other thin film deposition
- The ions in the plasma flux can be used for etching.

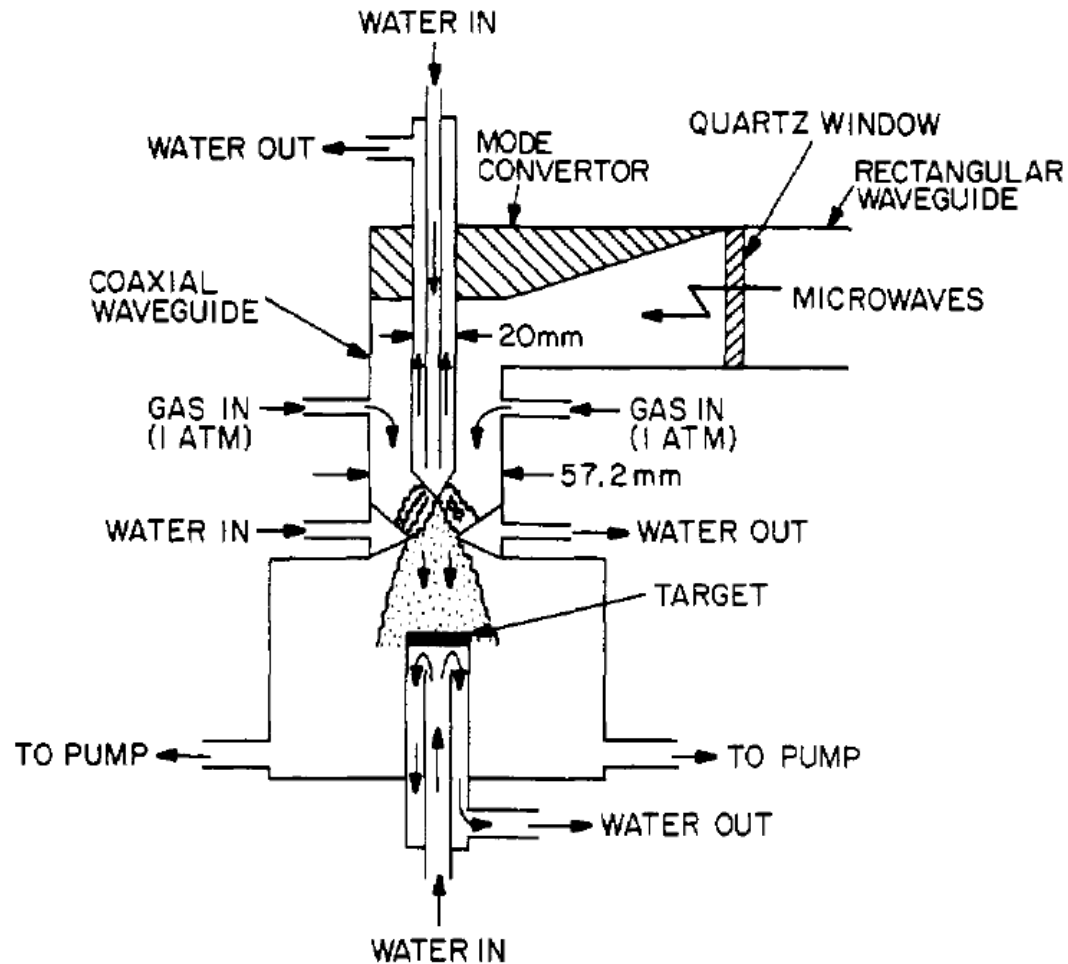


Distributed ECR system



- **Function of the multipolar magnetic field at the tank boundary:**
 - Provide a resonant surface for ECR absorption
 - Improve the confinement of the plasma

Microwave plasma torch deposit a much faster rate than other types of plasma source for diamond film deposition



Microwave-generated plasmas have the capability of filling very large volumes with moderately high density



- **Advantages**

- Lower neutral gas pressure, i.e., longer ion and neutral mean free paths.
- Higher fraction ionize.
- Higher electron density.

- **Disadvantages**

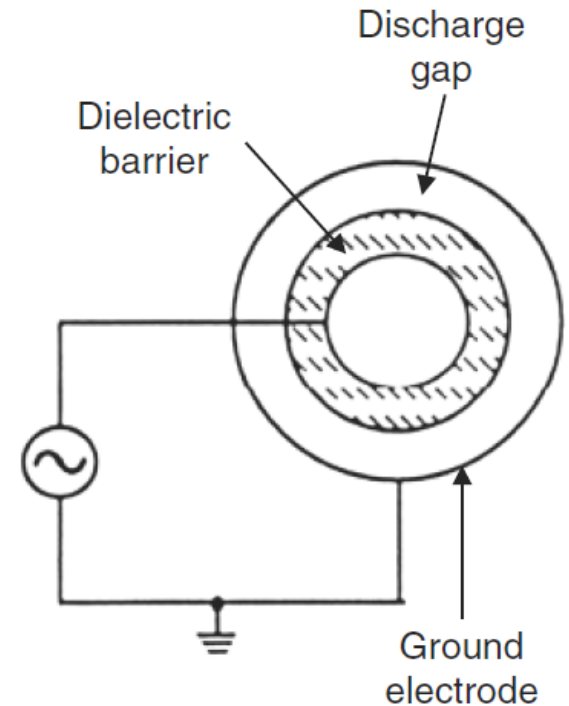
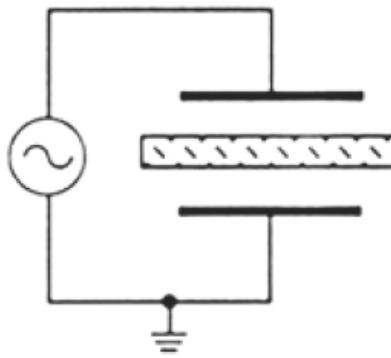
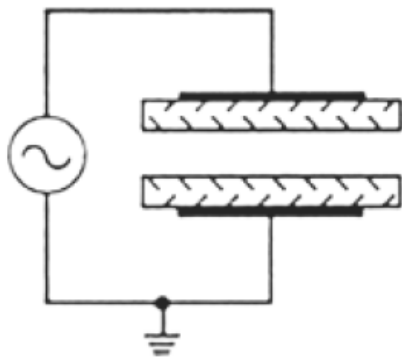
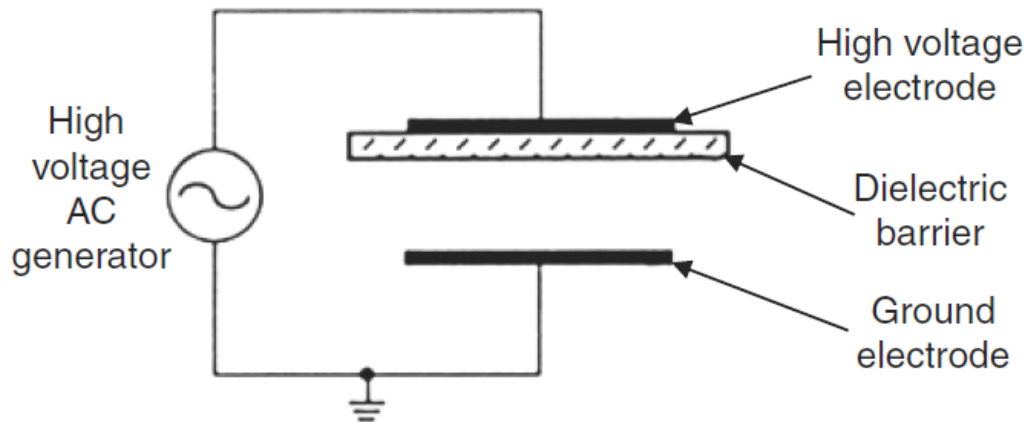
- Lower ion bombardment energies.
- Less control of the bombarding ion energy.
- Difficult in tuning up and achieving efficient coupling.
- Much more difficult and expensive to make uniform over a large area.
- More expensive.

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

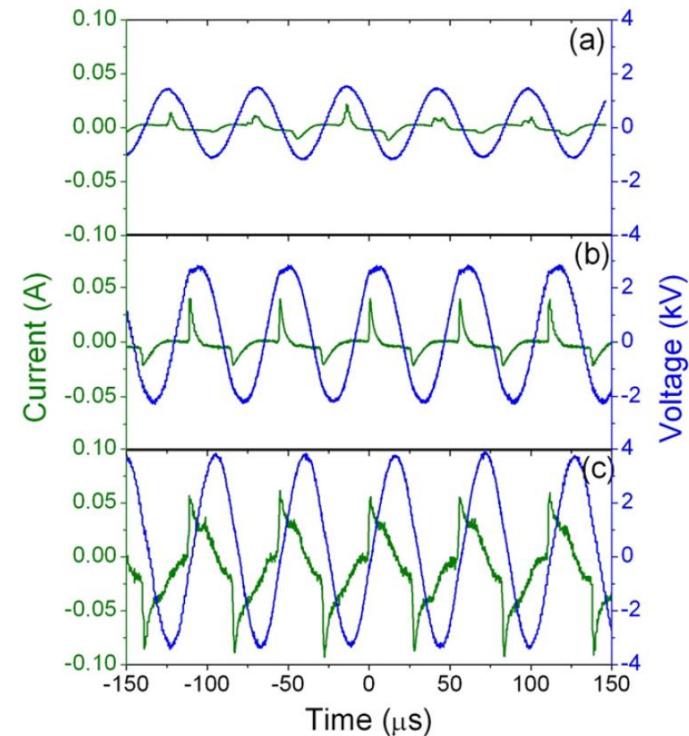
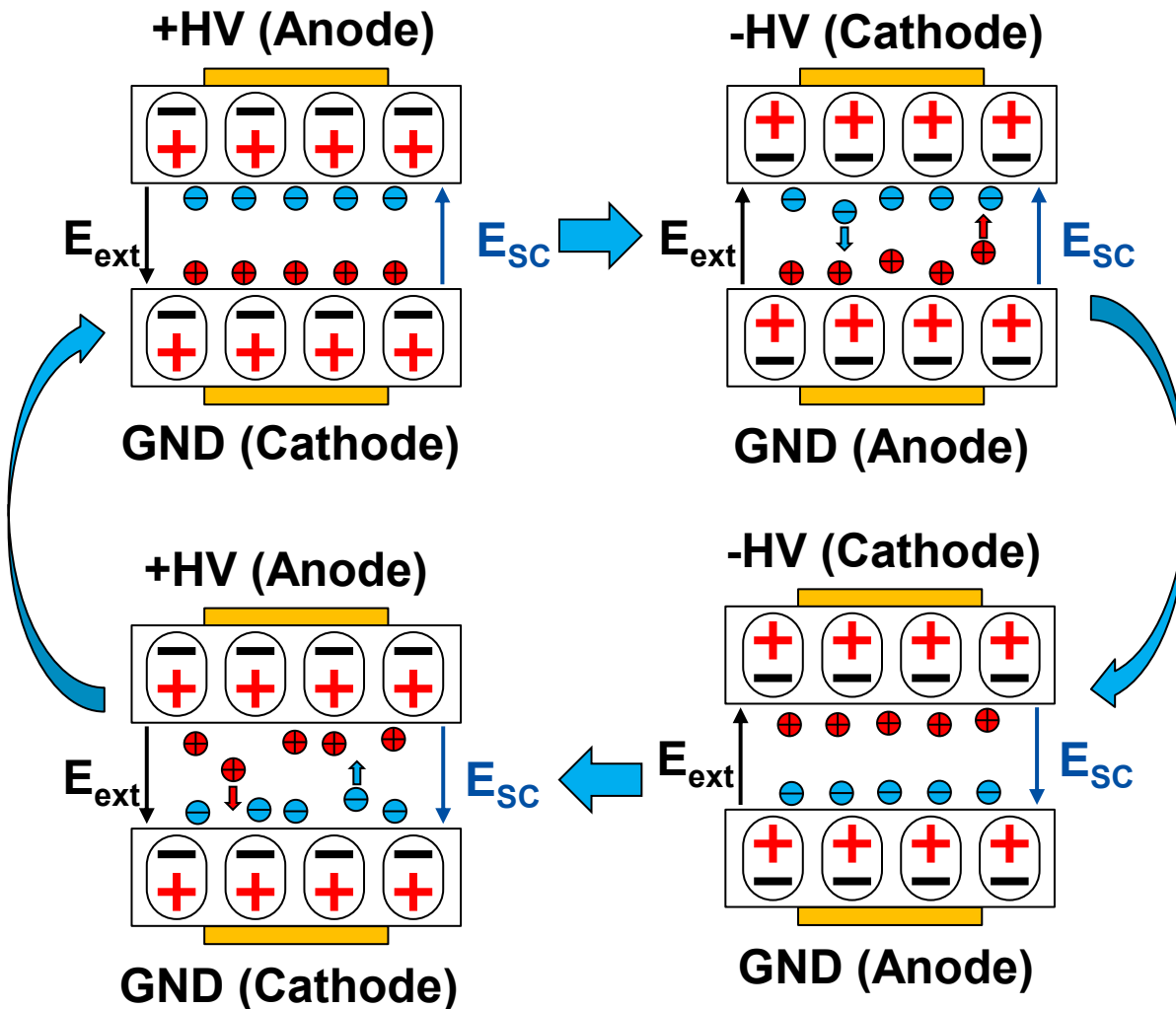


- DC electrical discharge – a true current in the form of a flow of ions or electrons to the electrodes.
- AC electrical discharge – the power supply interacts with the plasma by displacement current.
 - Inductive radio frequency (RF) electrical discharges
 - Capacitive RF electrical discharges
 - Microwave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

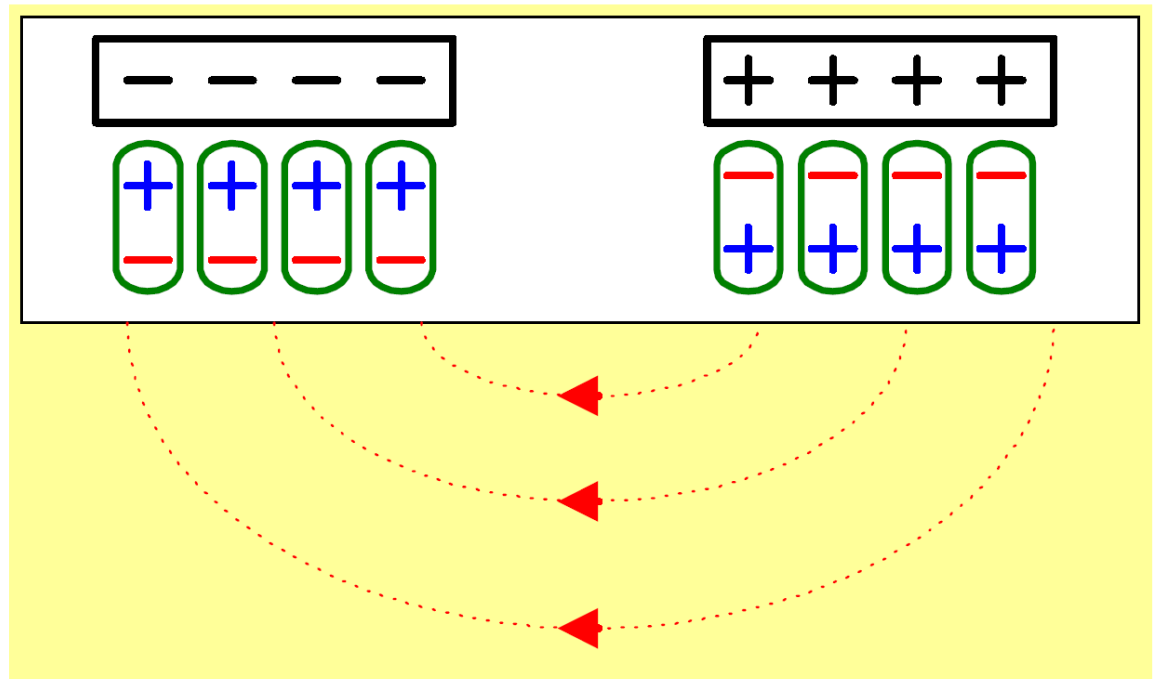
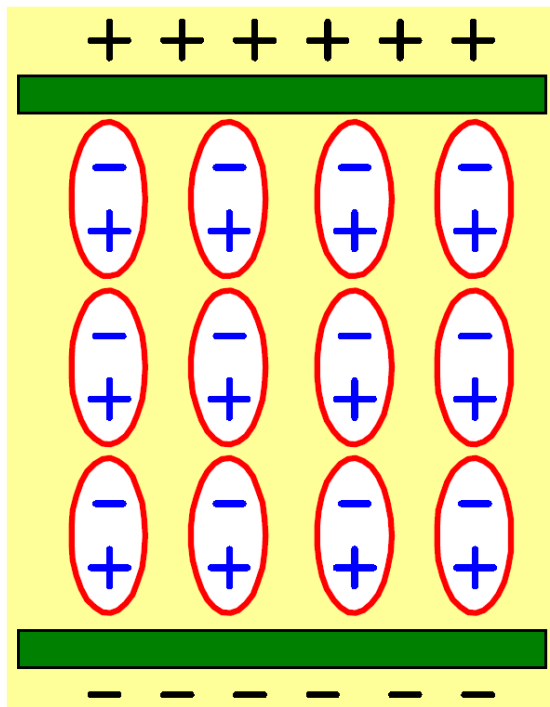
Dielectric-barrier discharges (DBDs)



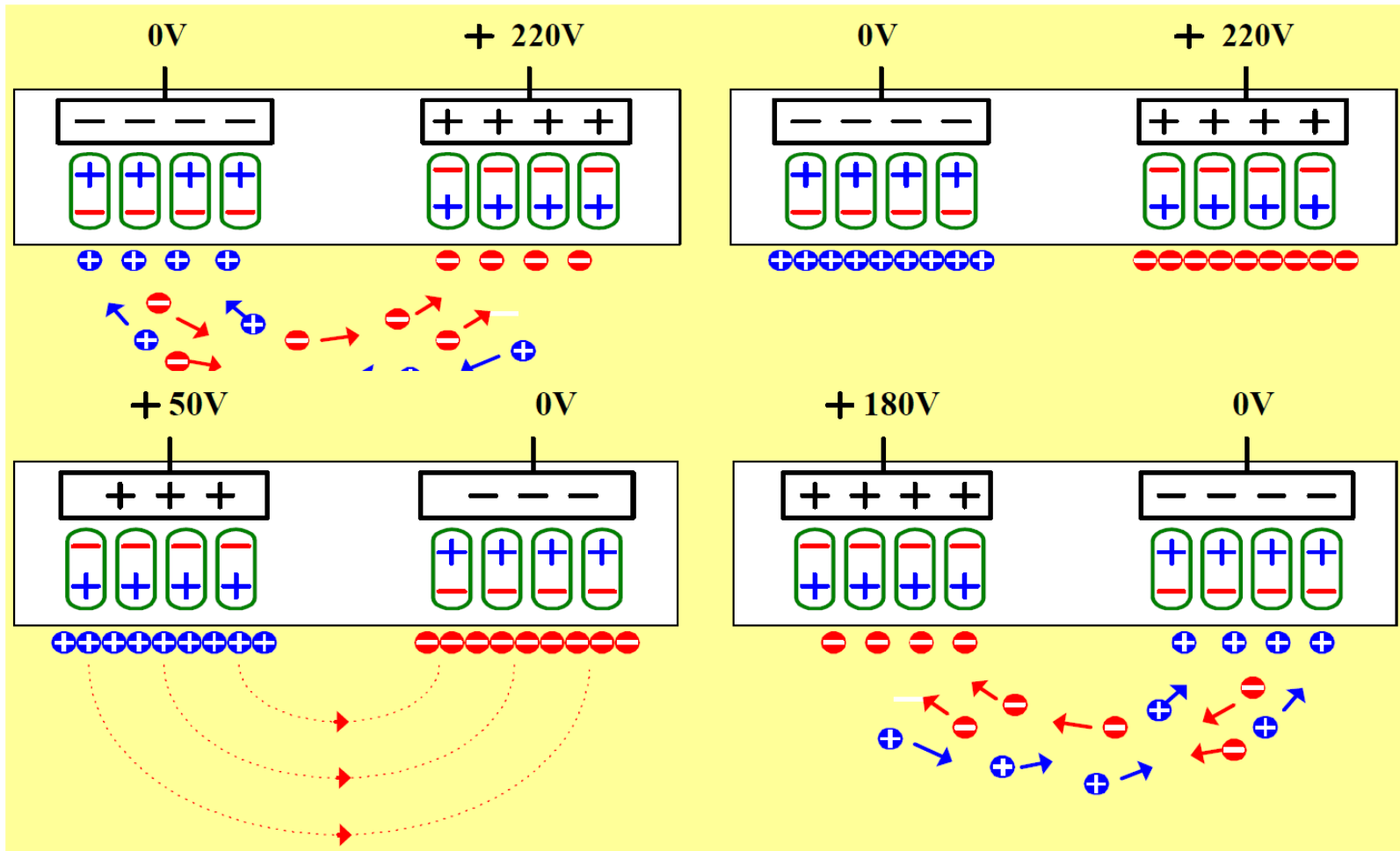
Space charge effect enhance the electric field



The foundation of AC discharge in plasma display panel

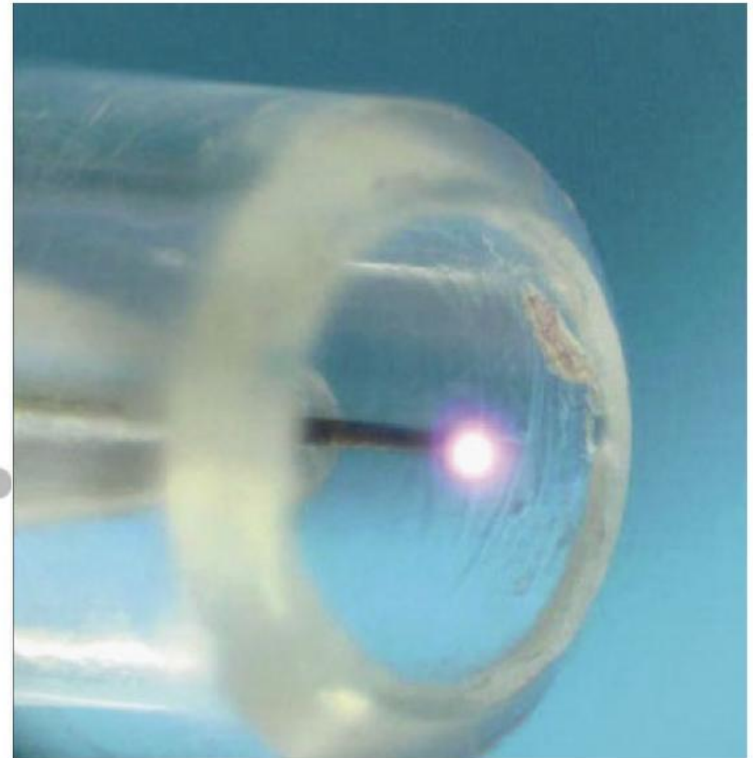
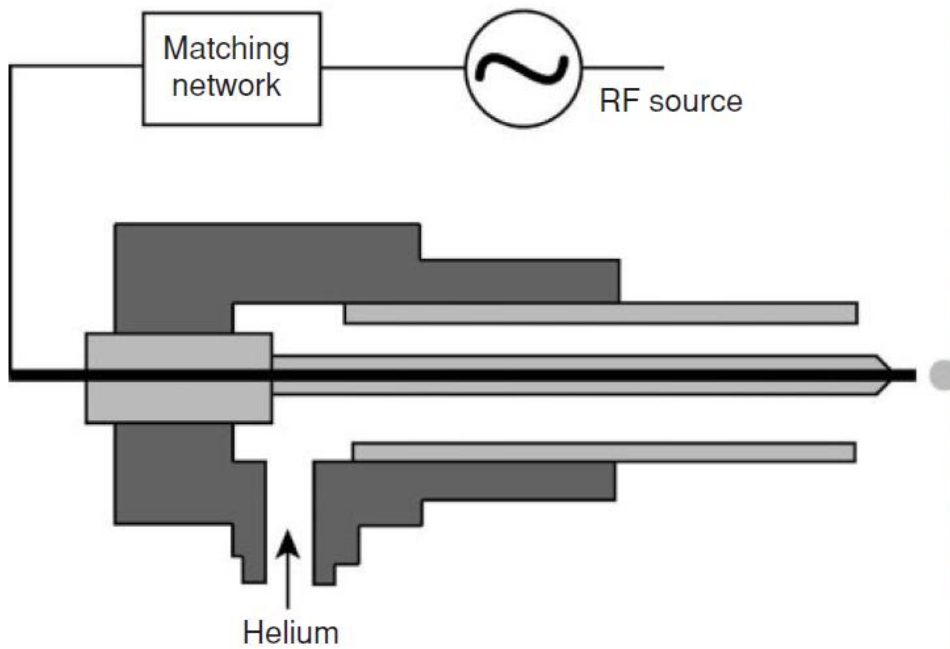


The plasma can be sustained using ac discharged in plasma display panel

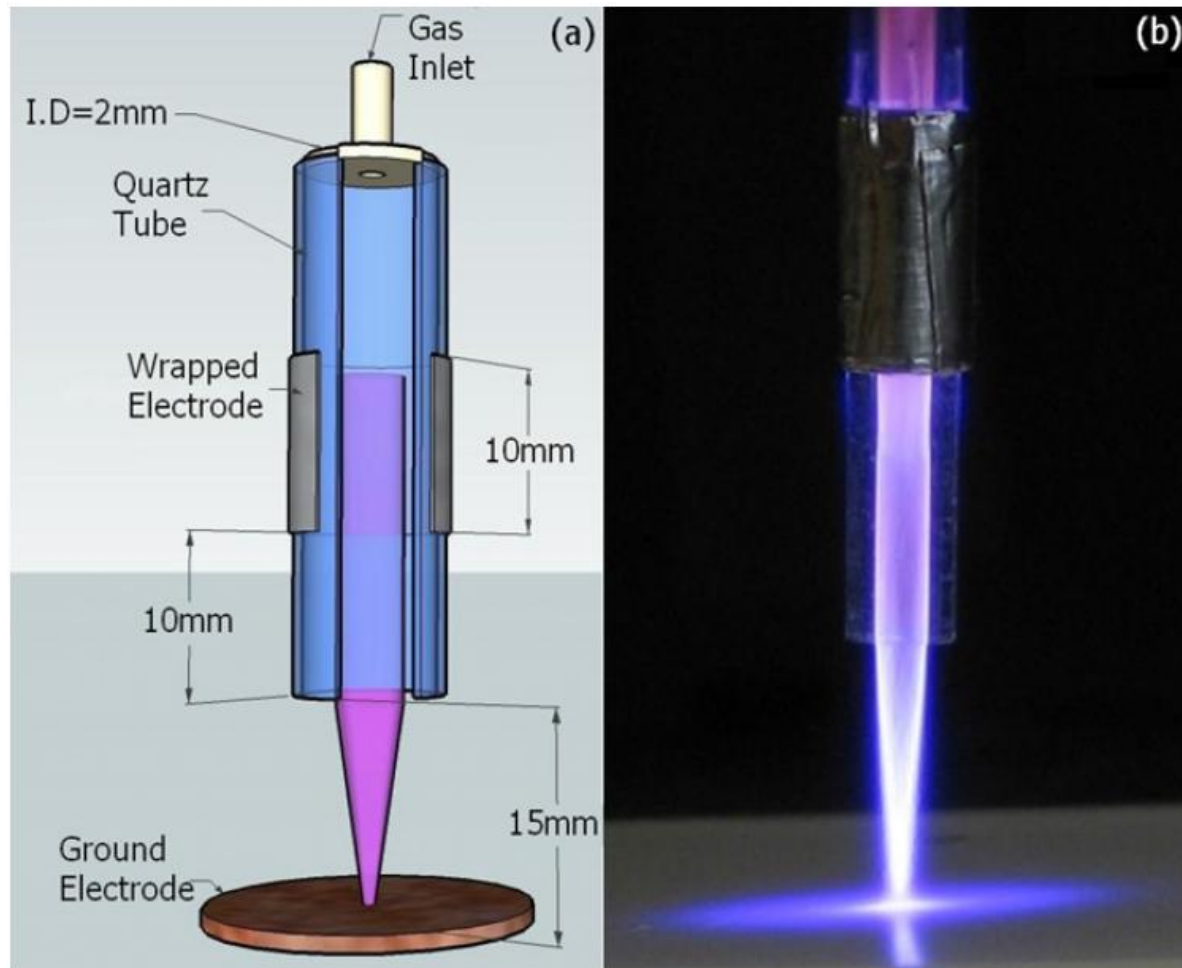


- **Wall discharge reduced the required discharge voltage**

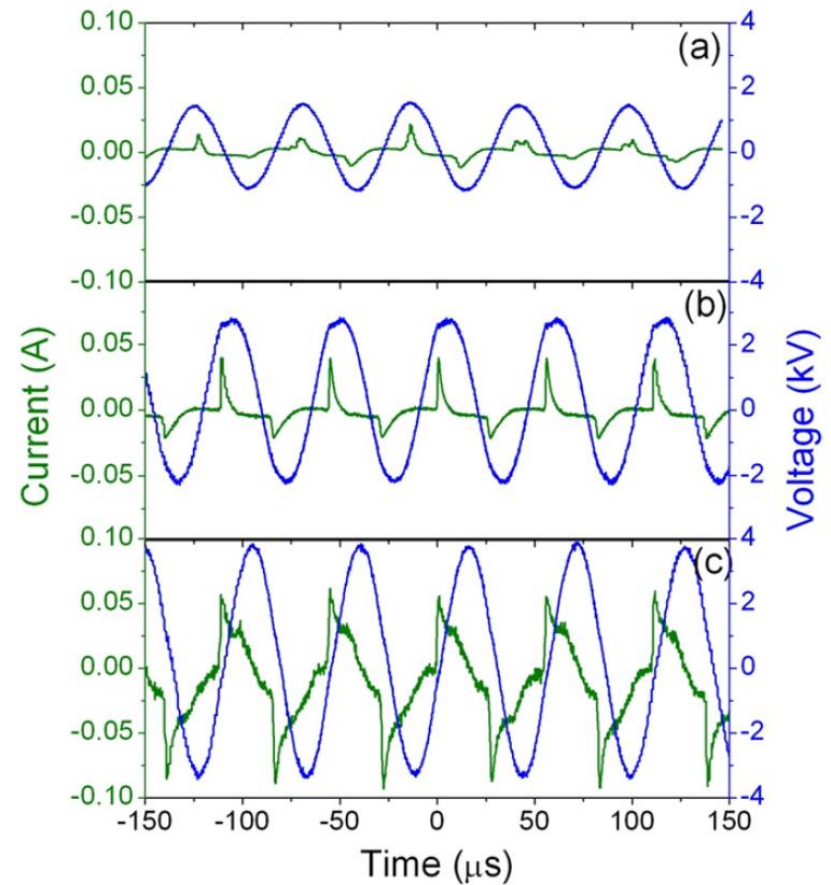
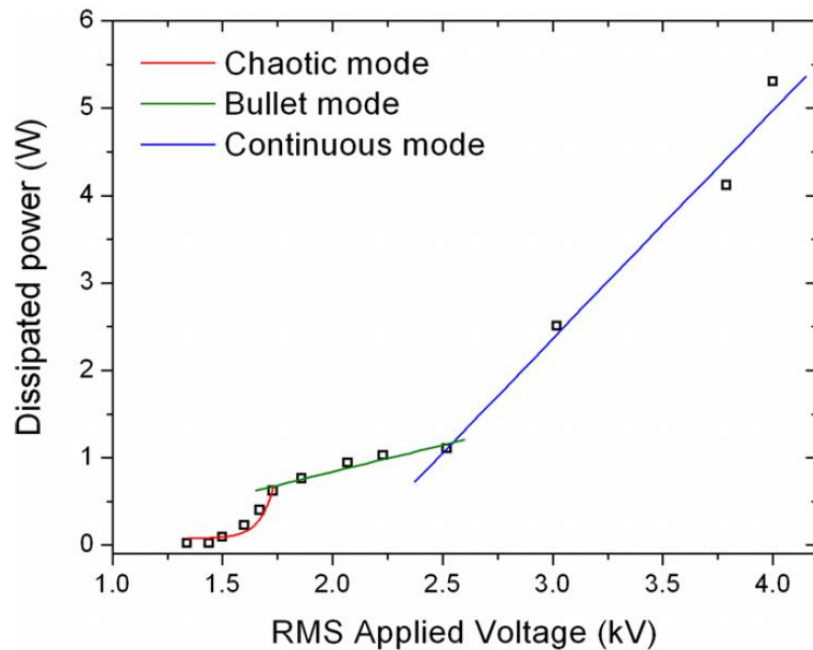
Plasma-needle discharge



Atmospheric-pressure cold helium microplasma jets



There are three different modes: chaotic, bullet, and continuous mode



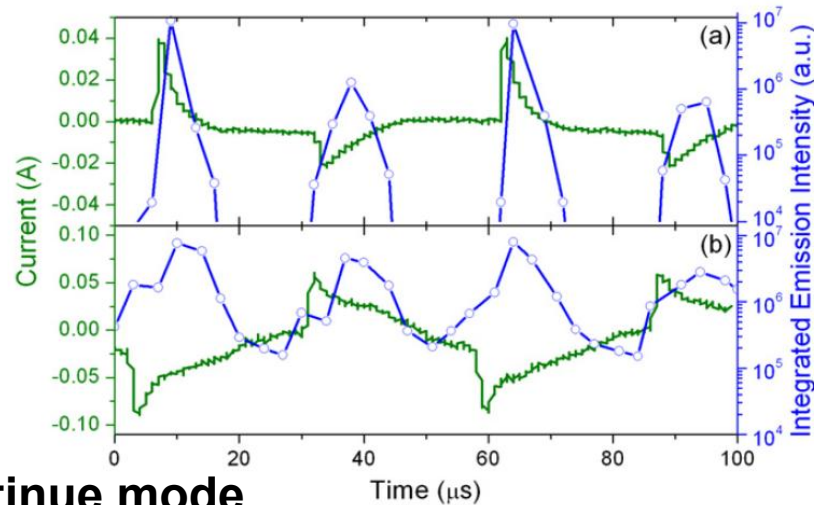
In bullet mode, the plasma jet comes out as a pulse



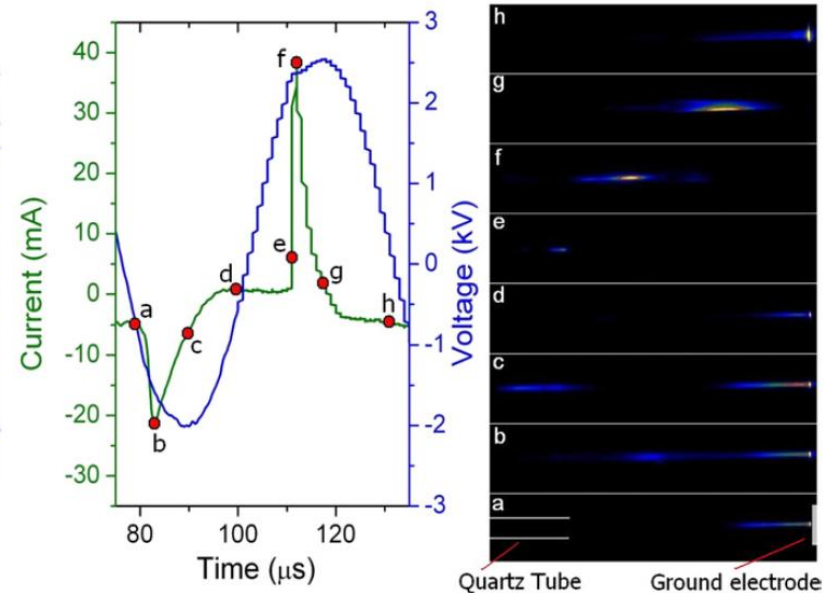
- wavelength-integrated optical emission signal (350–800 nm)

- Images of bullet mode

Bullet mode



Continue mode



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

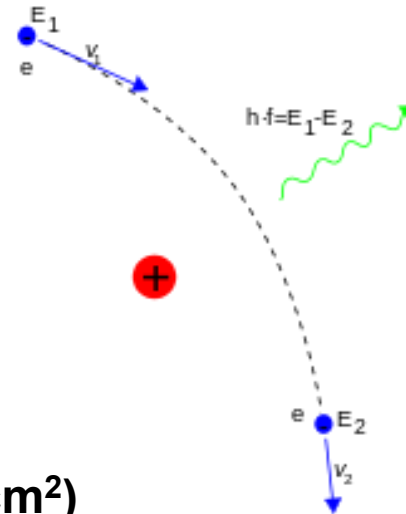


- DC electrical discharge – a true current in the form of a flow of ions or electrons to the electrodes.
- AC electrical discharge – the power supply interacts with the plasma by displacement current.
 - Inductive radio frequency (RF) electrical discharges
 - Capacitive RF electrical discharges
 - Microwave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

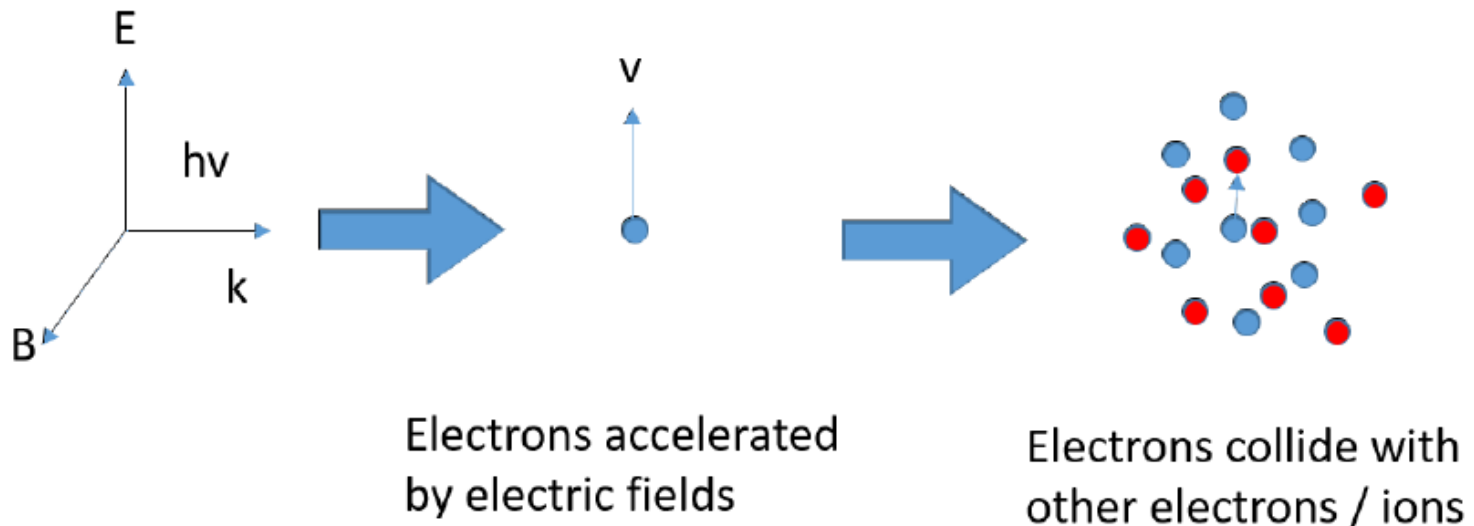
Laser is absorbed in underdense plasma through collisional process called inverse bremsstrahlung



- Bremsstrahlung



- Inverse bremsstrahlung (For $I < 10^{18} \text{ w/cm}^2$)

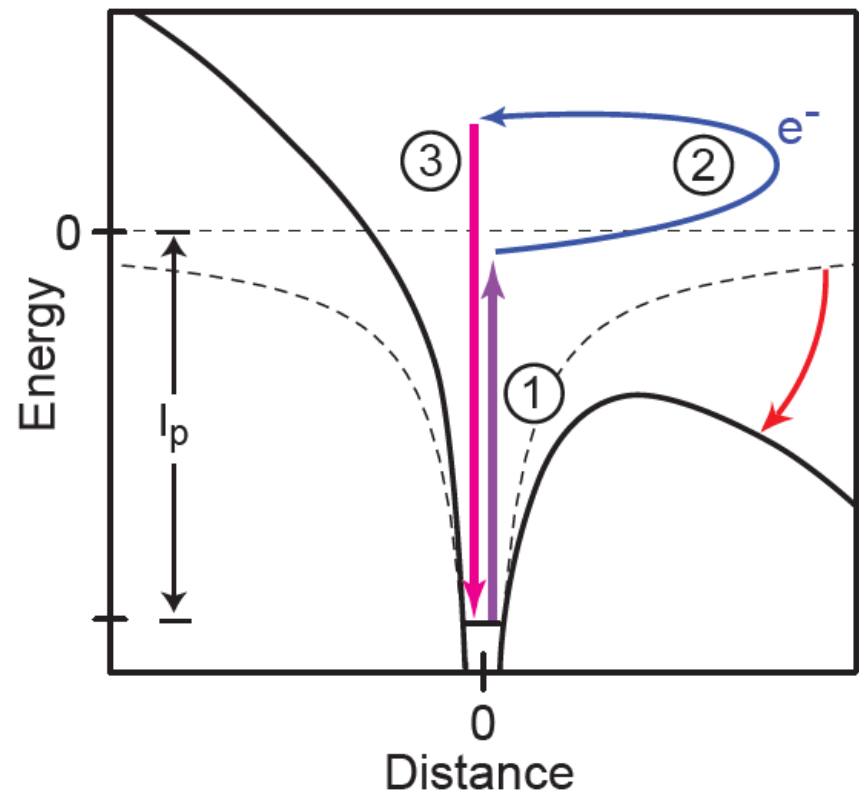
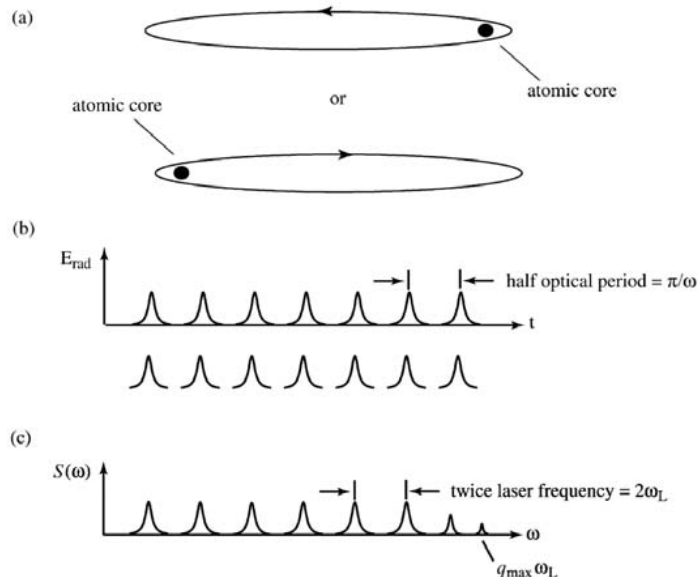
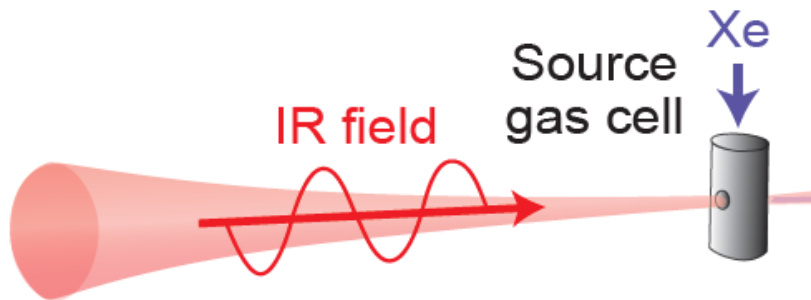


Electric field of a high-power laser can perturb the potential of a nuclear and thus ionize the atom directly



- For $I \sim 10^{14} \sim 10^{16} \text{ W/cm}^2$

$$E_{\text{cutoff}} \approx I_p + 3.17U_p \quad I_p : \text{ionization potential} \quad U_p : \text{ponderomotive energy}$$



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



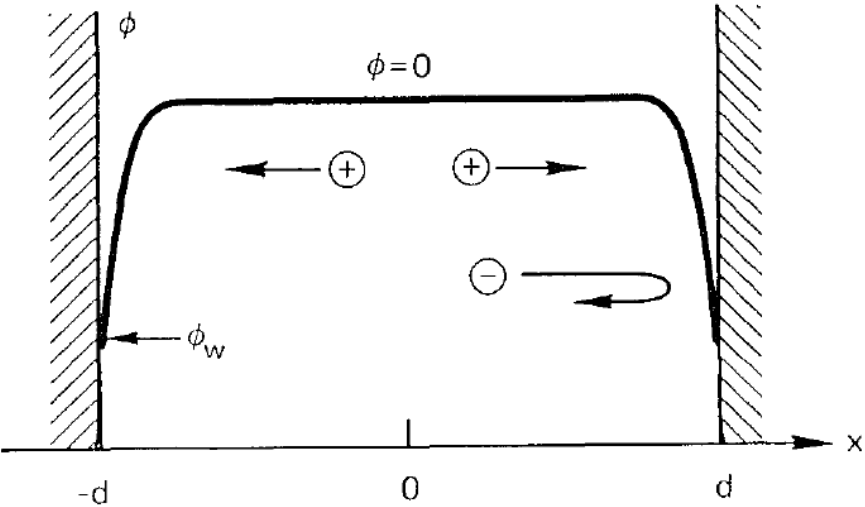
- DC electrical discharge – a true current in the form of a flow of ions or electrons to the electrodes.
- AC electrical discharge – the power supply interacts with the plasma by displacement current.
 - Inductive radio frequency (RF) electrical discharges
 - Capacitive RF electrical discharges
 - Microwave electrical discharges
 - Dielectric-barrier discharges (DBDs)
- Other mechanism
 - Laser produced plasma
 - Pulsed-power generated plasma – it will be introduced later.

Diagnostics



- Single/double Langmuir probe – n_e , T_e
- Interferometer – n_e
- Schlieren – dn_e/dx
- Faraday rotator – B
- Bdot probe – B
- Charged particle – B
- Spectroscopy – T_e , n_e
- Thomson scattering – T_e , n_e , T_i , n_i
- Faraday cup – dn_i/dt
- Retarding Potential Analyzer - v_i
- Intensified CCD – 2D image
- Framing camera – 2D image
- Streak camera – 1D image
- VISAR – shock velocity
- Neutron time of flight (NToF)
 - Neutron yield, T_i
- Thomson parabola – e/m
- Stimulated brillouin scattering
 - Laser pulse compression

All plasmas are separated from the walls surrounding them by a sheath



- When ions and electrons hit the wall, they recombine and are lost.
- Since electrons have much higher thermal velocities than ions, they are lost faster and leave the plasma with a net positive charge.
- Debye shielding will confine the potential variation to a layer of the order of several Debye lengths in thickness.
- A potential barrier is formed to confine electrons electrostatically.
- The flux of electrons is just equal to the flux of ions reaching the wall.

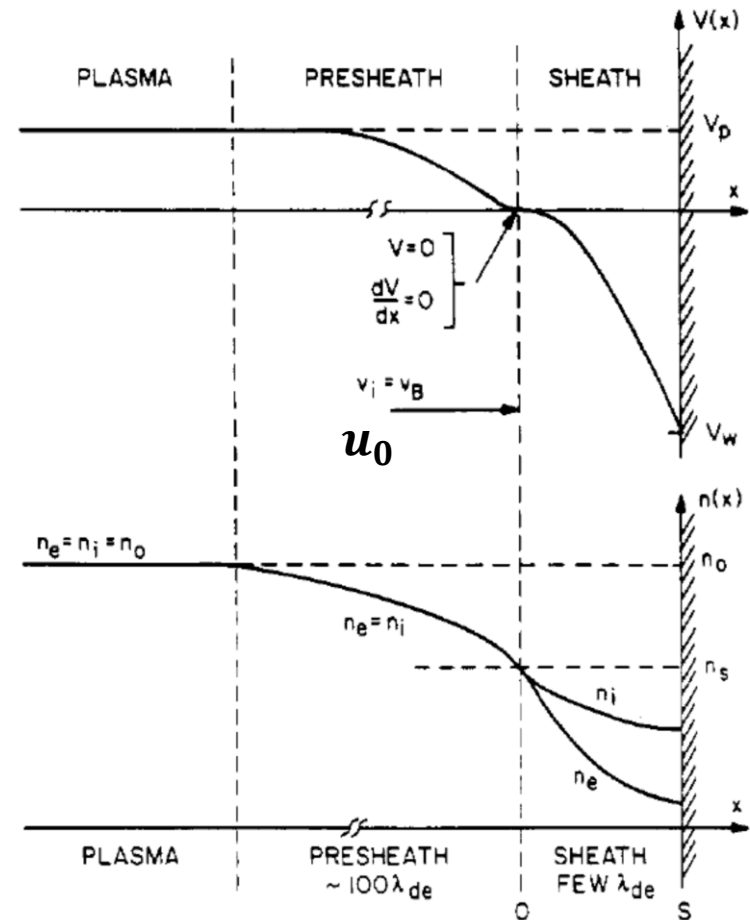
The potential variation in a plasma-wall system can be divided into three parts



- Sheath:
 - ~Debye length, n_e is appreciable.
 - A dark layers where no electrons were present to excite atoms to emission.
 - It has been measured by the electrostatic deflection of a thin electron beam shot parallel to a wall
- Presheath: ions are accelerated to the required velocity u_0 by a potential drop

$$|\phi| \geq \frac{1}{2} \frac{KT_e}{e}$$

$$\frac{1}{2} m u_0^2 = |e\phi|, m u_0^2 > K T_e$$



Electrostatic probes



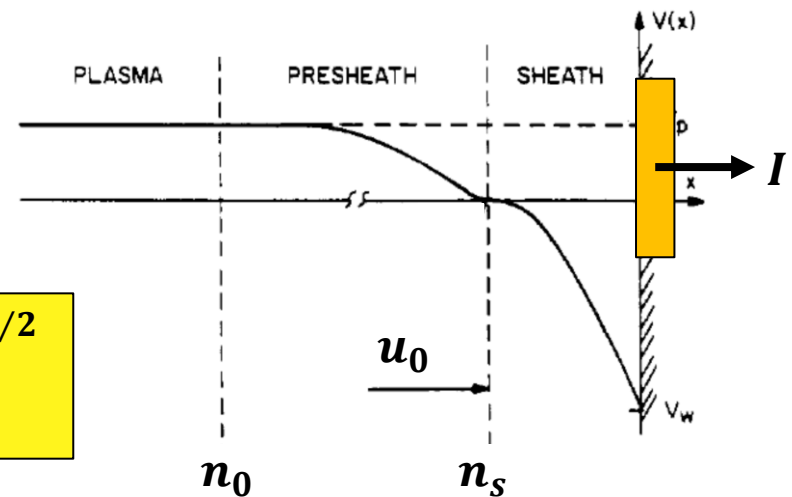
- The electron current can be neglected if the probe is sufficiently negative relative to the plasma to repel most electrons.

$$mu_0^2 > KT_e \quad J = enu \quad I = n_s e A \left(\frac{KT_e}{m} \right)^{1/2}$$

$$|\phi| \simeq \frac{1}{2} \frac{KT_e}{e}$$

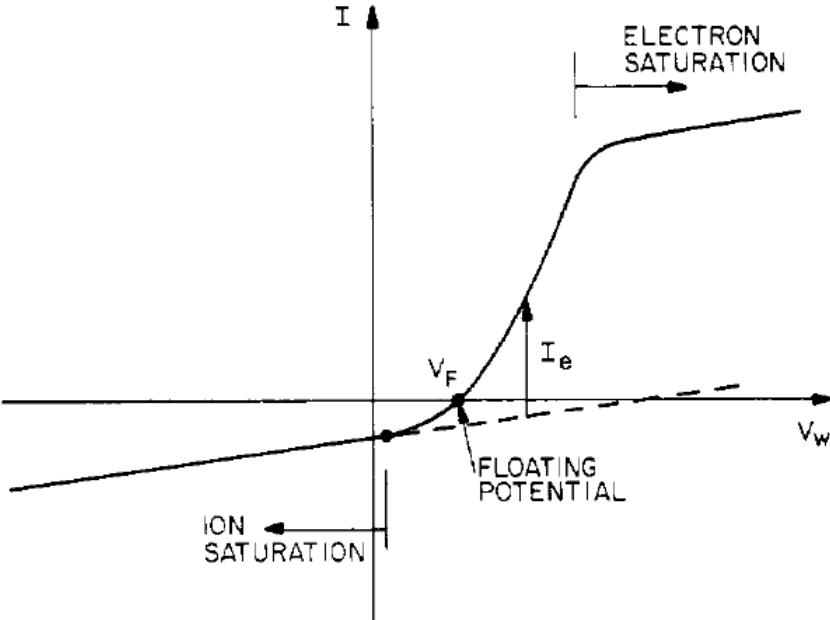
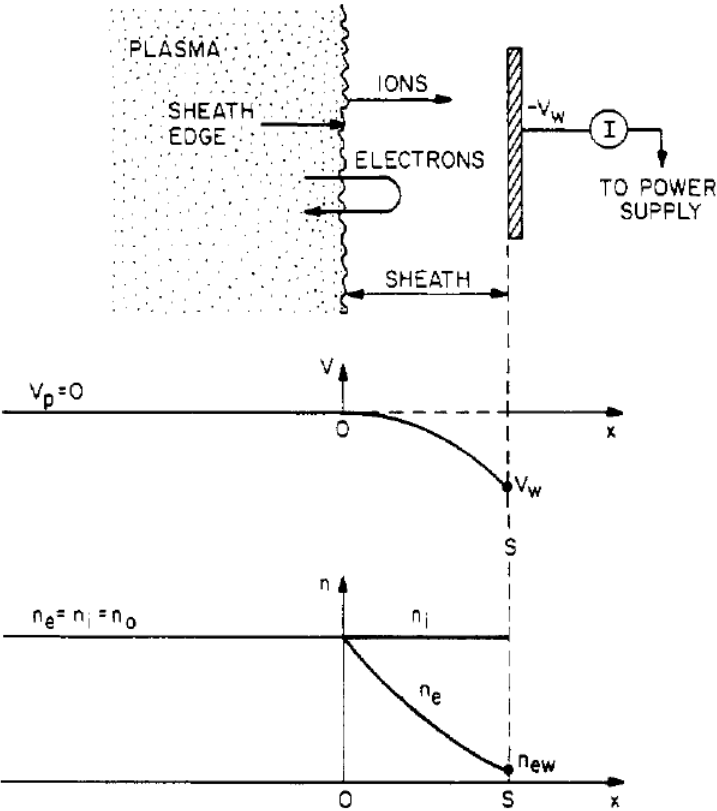
$$n_s = n_0 \exp\left(\frac{e\phi}{KT_e}\right) = n_0 e^{-1/2} = 0.61 n_0$$

Bohm current: $I_B \simeq 0.5 n_0 e A \left(\frac{KT_e}{m} \right)^{1/2}$



- The plasma density can be obtained once the temperature is known.

A plasma sheath is formed when plasma is contact to a surface



Floating voltage is determined when ion flux is balanced by electron flux



- Wall flux of ions:

$$\Gamma_i = \frac{1}{4} n_0 \bar{v}_i = n_0 \sqrt{\frac{8KT_i}{\pi m_i}}$$

- Wall flux of electrons due to random motion:

$$n_{ew} = n_0 \exp\left(\frac{e\Phi_w}{KT_e}\right) \quad (\text{Boltzman equation})$$

$$\Gamma_e = \frac{1}{4} n_{ew} \bar{v}_e = n_0 \exp\left(\frac{e\Phi_w}{KT_e}\right) \sqrt{\frac{8KT_e}{\pi m_e}}$$

- Balance between electron and ion flux (current)

$$I = eA(\Gamma_i - \Gamma_e) = 0$$

$$\Phi_w = -\frac{KT_e}{2e} \ln\left(\frac{m_i T_e}{m_e T_i}\right)$$

Floating voltage can also be calculated using Bohm's velocity



- Wall flux of ions using Bohm's velocity:

$$u_0 = \sqrt{\frac{KT_e}{m_i}} \quad \Gamma_i = n_s u_0$$

- Wall flux of electrons due to random motion:

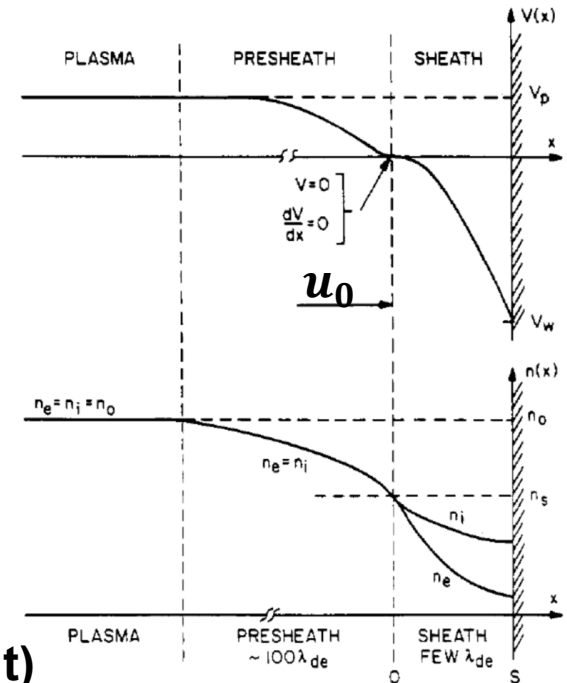
$$n_{ew} = n_s \exp\left(\frac{e\Phi_w}{KT_e}\right)$$

$$\Gamma_e = \frac{1}{4} n_w \bar{v}_e = \frac{1}{4} n_s \exp\left(\frac{e\Phi_w}{KT_e}\right) \sqrt{\frac{8KT_e}{\pi m_e}}$$

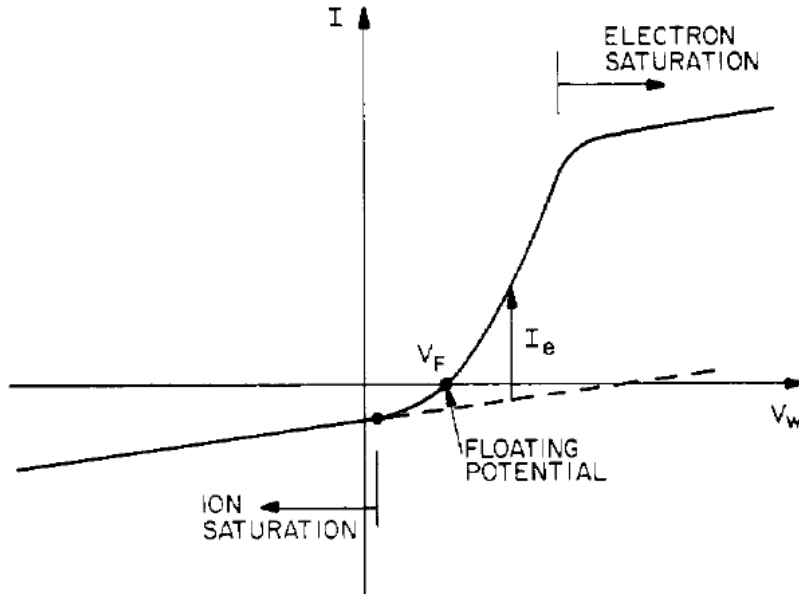
- Balance between electron and ion flux (current)

$$I = eA(\Gamma_i - \Gamma_e) = 0$$

$$\Phi_{wB} = -\frac{KT_e}{2e} \ln\left(\frac{m_i}{2\pi m_e}\right) \quad \longleftrightarrow \quad \Phi_w = -\frac{KT_e}{2e} \ln\left(\frac{m_i T_e}{m_e T_i}\right)$$



Electron temperature can be determined by the slope of the I-V curve between ion and electron saturation



- Ion saturation current:

$$\begin{aligned} I_{is} &= A J_{is} = e A \Gamma_{is} \\ &= e A \frac{1}{4} n_i \bar{v}_i \\ &= \frac{e A n_i}{4} \sqrt{\frac{8 K T_i}{\pi m_i}} \end{aligned}$$

$$n_i = \frac{4 I_{is}}{e A} \sqrt{\frac{\pi m_i}{8 K T_i}}$$

- Total current: $I = I_{is} + I_e = I_{is} + \frac{1}{4} n_s \exp\left(\frac{eV}{K T_e}\right) \bar{v}_e e A \quad V \equiv \Phi$

Assuming: $\frac{dI_{is}}{dV} \ll \frac{dI}{dV}$

$$\begin{aligned} \frac{dI}{dV} &= \frac{dI_{is}}{dV} + \frac{1}{4} \frac{e}{K T_e} n_s \exp\left(\frac{eV}{K T_e}\right) \bar{v}_e e A = \frac{dI_{is}}{dV} + \frac{e}{K T_e} I_e = \frac{dI_{is}}{dV} + \frac{e}{K T_e} (I - I_{is}) \\ &\approx \frac{e}{K T_e} (I - I_{is}) \end{aligned}$$

$$T_e = \frac{e(I - I_{is})}{dI/dV}$$

Electron temperature can be obtained alternatively by finding the slope of I-V curve in Log-Linear plot

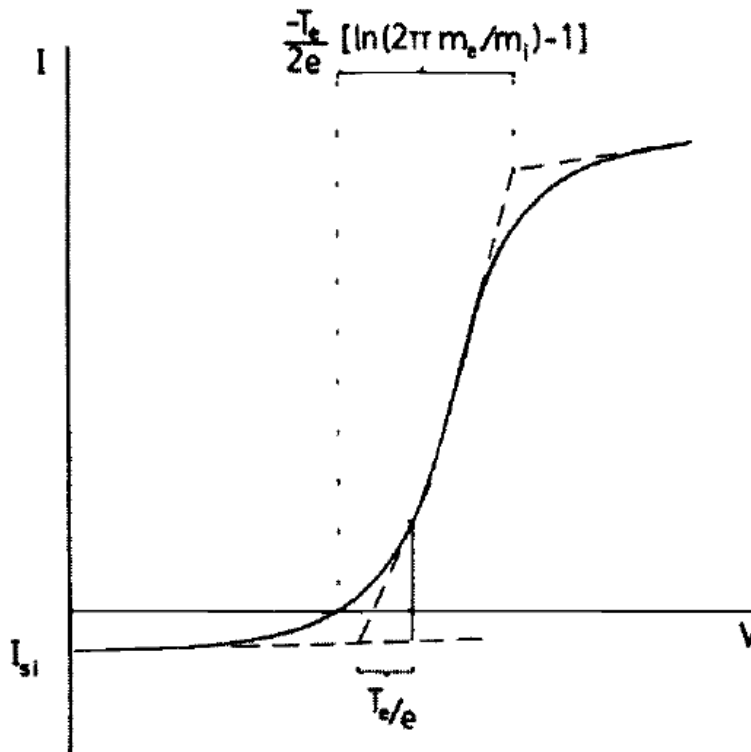


- Electron saturation

$$V = V_p \quad I_{es} = \frac{1}{4} n_s \exp\left(\frac{eV_p}{KT_e}\right) \bar{v}_e eA$$

$$\begin{aligned} I &= I_e + I_{is} \approx I_{es} = \frac{1}{4} n_s \exp\left(\frac{eV}{KT_e}\right) \bar{v}_e eA \\ &= \frac{1}{4} n_s \exp\left(\frac{eV - eV_p + eV_p}{KT_e}\right) \bar{v}_e eA \\ &= \frac{1}{4} n_s \exp\left(\frac{eV_p}{KT_e}\right) \exp\left(e \frac{V - V_p}{KT_e}\right) \bar{v}_e eA \\ &= I_{es} \exp\left(e \frac{V - V_p}{KT_e}\right) \end{aligned}$$

$$T_e = \frac{e(V - V_p)}{K(\ln I_{es} - \ln I)}$$



Plasma density can be obtained by finding the electron saturation current

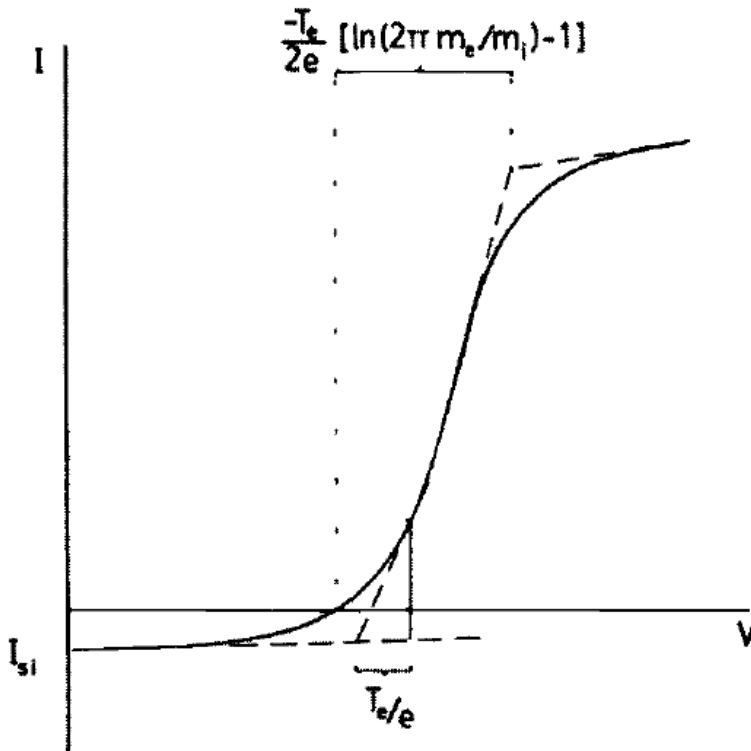


- Electron saturation current:

$$I_{es} = \frac{1}{4} n_s \exp\left(\frac{eV_p}{KT_e}\right) \bar{v}_e eA$$

$$= \frac{1}{4} n_0 eA \sqrt{\frac{8KT_e}{\pi m_e}}$$

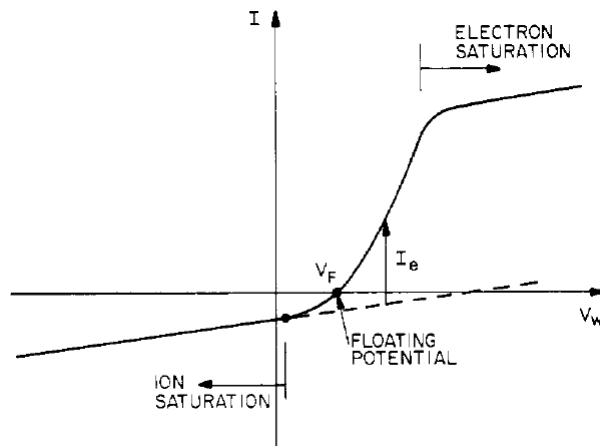
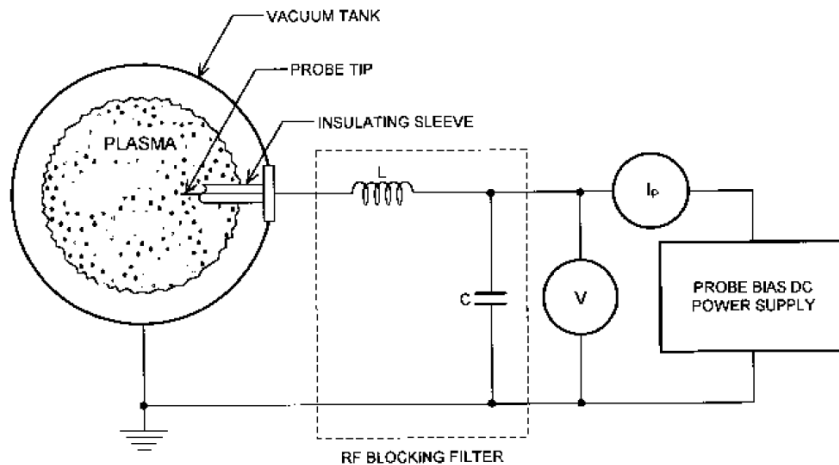
$$n_0 = \frac{4I_{es}}{eA} \sqrt{\frac{\pi m_e}{8KT_e}}$$



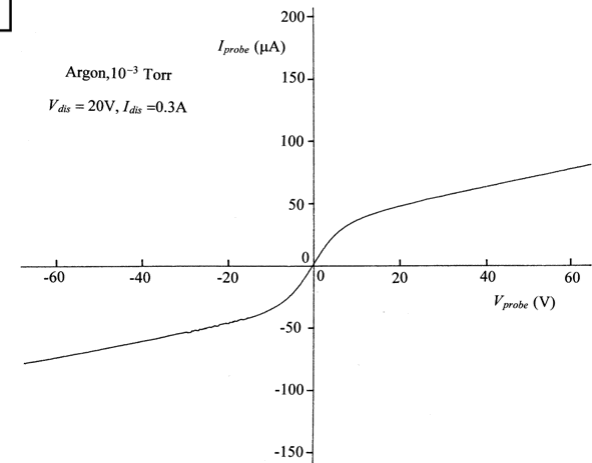
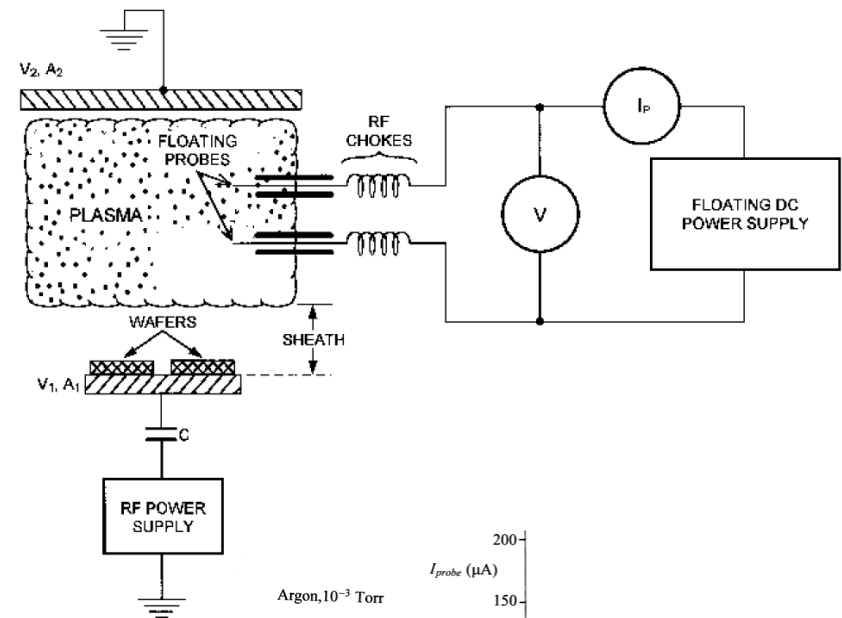
Two Langmuir probes can be operated simultaneously



Single Probe



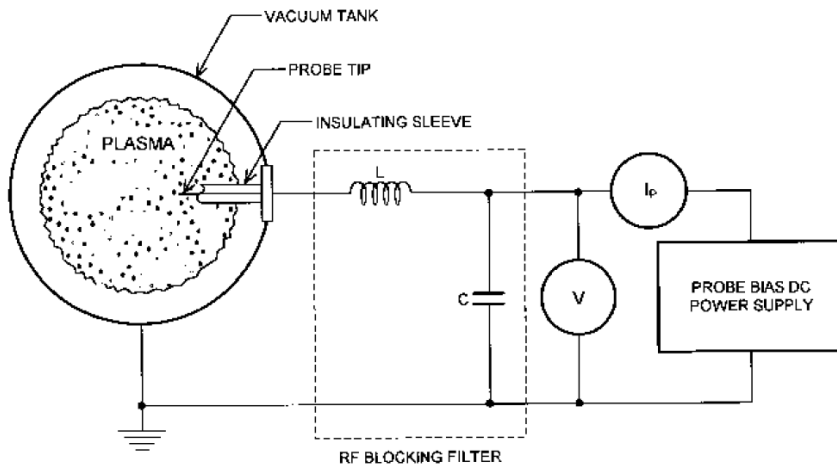
Double Probe



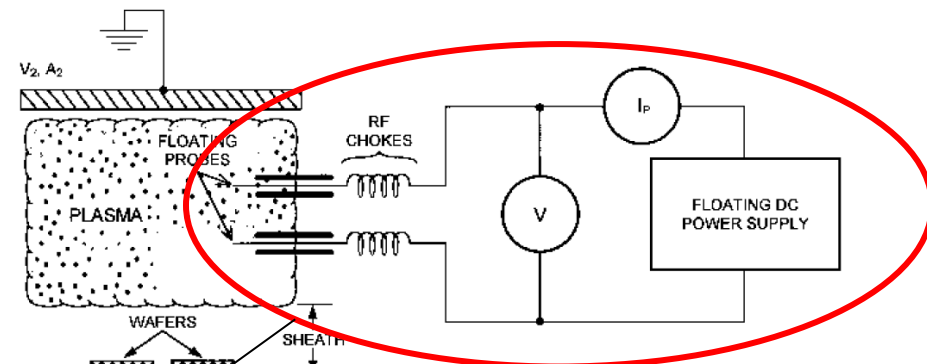
Two Langmuir probes can be operated simultaneously



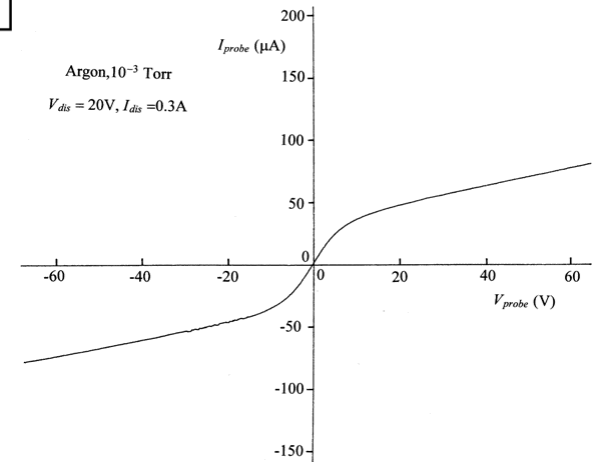
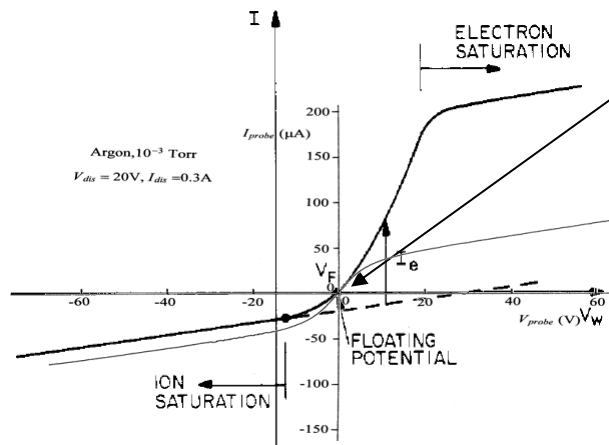
Single Probe



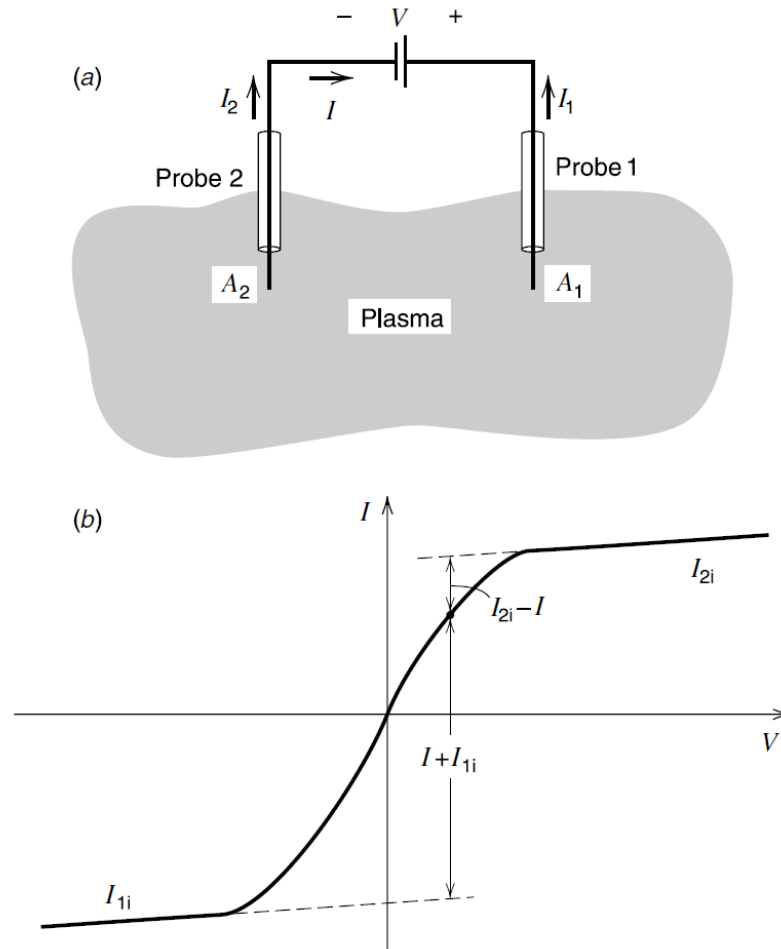
Double Probe



**~Single Probe @
floating potential**



Double Langmuir probe is not disturbed by the discharge



$$I = I_{1e} - I_{1i} = I_{2i} - I_{2e}$$

$$I_{1e} = A_1 \frac{\bar{v}_e e}{4} n_s \exp\left(\frac{eV_1}{KT_e}\right)$$

$$I_{2e} = A_2 \frac{\bar{v}_e e}{4} n_s \exp\left(\frac{eV_2}{KT_e}\right)$$

$$I_{1e} = I + I_{1i} \quad I_{2e} = I_{2i} - I$$

$$\frac{I + I_{1i}}{I_{2i} - I} = \frac{A_1}{A_2} \exp\left(\frac{e(V_1 - V_2)}{KT_e}\right)$$

$$= \frac{A_1}{A_2} \exp\left(\frac{eV}{KT_e}\right)$$

$$I = I_i \tanh\left(\frac{eV}{2KT_e}\right) \quad \left.\frac{dI}{dV}\right|_{V=0} = \frac{eI_i}{2KT_e}$$

- The net current never exceeds the ion saturation current, minimizing the disturbance to the discharge.

An electromagnetic wave is described using Maxwell's equation



$$\begin{cases} \nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\ \nabla \times \vec{B} &= \mu_0 \vec{j} + \epsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t} \end{cases}$$

$$\nabla \times \left(\nabla \times \vec{E} \right) = -\frac{\partial}{\partial t} \left(\nabla \times \vec{B} \right) = -\frac{\partial}{\partial t} \left(\mu_0 \vec{j} + \epsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t} \right)$$

Conductivity: $\vec{j} = \overleftrightarrow{\sigma} \cdot \vec{E}$

$$\nabla \times \left(\nabla \times \vec{E} \right) = -\frac{\partial}{\partial t} \left(\nabla \times \vec{B} \right) = -\frac{\partial}{\partial t} \left(\mu_0 \overleftrightarrow{\sigma} \cdot \vec{E} + \epsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t} \right)$$

Plane wave: $\vec{E} = \vec{E} \exp \left[i \left(\vec{k} \cdot \vec{x} - \omega t \right) \right]$

$$i \vec{k} \times \left(i \vec{k} \times \vec{E} \right) = i \omega \left(\mu_0 \overleftrightarrow{\sigma} \cdot \vec{E} - i \omega \epsilon_0 \mu_0 \vec{E} \right)$$

An electromagnetic wave is described using Maxwell's equation



$$\begin{cases} \nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\ \nabla \times \vec{B} &= \mu_0 \vec{j} + \epsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t} \end{cases}$$

$$\nabla \times \left(\nabla \times \vec{E} \right) = -\frac{\partial}{\partial t} \left(\nabla \times \vec{B} \right) = -\frac{\partial}{\partial t} \left(\mu_0 \vec{j} + \epsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t} \right)$$

Conductivity: $\vec{j} = \overleftrightarrow{\sigma} \cdot \vec{E}$

$$\nabla \times \left(\nabla \times \vec{E} \right) = -\frac{\partial}{\partial t} \left(\nabla \times \vec{B} \right) = -\frac{\partial}{\partial t} \left(\mu_0 \overleftrightarrow{\sigma} \cdot \vec{E} + \epsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t} \right)$$

Plane wave: $\vec{E} = \vec{E} \exp \left[i \left(\vec{k} \cdot \vec{x} - \omega t \right) \right]$

$$i \vec{k} \times \left(i \vec{k} \times \vec{E} \right) = i \omega \left(\mu_0 \overleftrightarrow{\sigma} \cdot \vec{E} - i \omega \epsilon_0 \mu_0 \vec{E} \right)$$

Dispersion relation is determined by the determinant of the matrix of coefficient



$$-\vec{k} \times (\vec{k} \times \vec{E}) = -\left[(\vec{k} \cdot \vec{E}) \vec{k} - (\vec{k} \cdot \vec{k}) \vec{E}\right] = -(\vec{k} : \vec{k}) \vec{E} + k^2 \vec{E}$$

$$\begin{aligned} i\omega \left(\mu_0 \overleftrightarrow{\sigma} \cdot \vec{E} - i\omega\epsilon_0\mu_0\vec{E} \right) &= i\omega \left(\mu_0 \overleftrightarrow{\sigma} \cdot \vec{E} - \frac{i\omega}{c^2} \vec{E} \right) = \frac{\omega^2}{c^2} \left[-\frac{c^2}{i\omega} \mu_0 \overleftrightarrow{\sigma} \cdot \vec{E} + \vec{E} \right] \\ &= \frac{\omega^2}{c^2} \left(\overleftrightarrow{1} + \frac{i}{\omega\epsilon_0} \overleftrightarrow{\sigma} \right) \vec{E} \equiv \frac{\omega^2}{c^2} \overleftrightarrow{\epsilon} \vec{E} \end{aligned}$$

Dielectric tensor: $\overleftrightarrow{\epsilon} \equiv \overleftrightarrow{1} + \frac{i}{\omega\epsilon_0} \overleftrightarrow{\sigma}$

$$i\vec{k} \times (i\vec{k} \times \vec{E}) = i\omega \left(\mu_0 \overleftrightarrow{\sigma} \cdot \vec{E} - i\omega\epsilon_0\mu_0\vec{E} \right)$$

 $\left(\vec{k} : \vec{k} - k^2 \overleftrightarrow{1} + \frac{\omega^2}{c^2} \overleftrightarrow{\epsilon} \right) \vec{E} = 0$

$$\det \left(\vec{k} : \vec{k} - k^2 \overleftrightarrow{1} + \frac{\omega^2}{c^2} \overleftrightarrow{\epsilon} \right) = 0$$

Two mode can propagate in the plasma



$$\det \left(\vec{k} : \vec{k} - k^2 \overleftrightarrow{1} + \frac{\omega^2}{c^2} \overleftrightarrow{\epsilon} \right) = 0$$

Assuming the wave propagates along the z direction and isotropic medium:

$$\begin{aligned} \vec{k} &= k \hat{z} \\ \overleftrightarrow{\epsilon} &= \epsilon \overleftrightarrow{1} \end{aligned} \quad \left(\begin{array}{ccc} -k^2 + \frac{\omega^2}{c^2} \epsilon & 0 & 0 \\ 0 & -k^2 + \frac{\omega^2}{c^2} \epsilon & 0 \\ 0 & 0 & \frac{\omega^2}{c^2} \epsilon \end{array} \right) = 0$$

$$\left(-k^2 + \frac{\omega^2}{c^2} \epsilon \right)^2 \frac{\omega^2}{c^2} \epsilon = 0$$

$$\frac{\omega^2}{c^2} \epsilon = 0$$

Longitudinal wave

$$\left(-k^2 + \frac{\omega^2}{c^2} \epsilon \right)^2 = 0$$

Transverse wave

The reflective index is determined by the dielectric



- **Longitudinal wave:**

$$\frac{\omega^2}{c^2} \varepsilon = 0$$

$$\begin{pmatrix} -k^2 + \frac{\omega^2}{c^2} \varepsilon & 0 & 0 \\ 0 & -k^2 + \frac{\omega^2}{c^2} \varepsilon & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = 0 = \begin{pmatrix} \left(-k^2 + \frac{\omega^2}{c^2} \varepsilon \right) E_x \\ \left(-k^2 + \frac{\omega^2}{c^2} \varepsilon \right) E_y \\ 0 \end{pmatrix}$$

$$E_x = E_y = 0$$

- **Transverse wave:**

$$\left(-k^2 + \frac{\omega^2}{c^2} \varepsilon \right)^2 = 0$$

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{\omega^2}{c^2} \varepsilon \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = 0$$

$$E_z = 0$$

Reflective index: $n \equiv \frac{kc}{\omega} = \varepsilon^{1/2}$

Conductivity tensor can be determined from equation of motion for electron

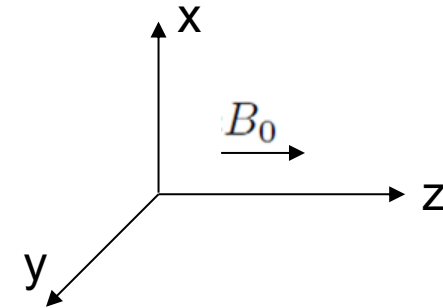


$$m_e \frac{\partial \vec{v}}{\partial t} = -e \left(\vec{E} + \vec{v} \times \vec{B} \right)$$

$$\vec{v} = \vec{v} \exp \left[i \left(\vec{k} \cdot \vec{x} - \omega t \right) \right]$$

$$\begin{cases} -i\omega m_e v_x = -eE_x - eB_0 v_y \\ -i\omega m_e v_y = -eE_y + eB_0 v_x \\ -i\omega m_e v_z = -eE_z \end{cases}$$

$$\Omega \equiv \frac{eB_0}{m_e}$$



$$\begin{cases} v_x = -\frac{ie}{\omega m_e} \frac{1}{1 - \Omega^2/\omega^2} \left(E_x - i\frac{\Omega}{\omega} E_y \right) \\ v_y = -\frac{ie}{\omega m_e} \frac{1}{1 - \Omega^2/\omega^2} \left(i\frac{\Omega}{\omega} E_x + E_y \right) \\ v_z = -\frac{ie}{\omega m_e} E_z \end{cases}$$

$$\vec{j} = -en_e \vec{v}_e \equiv \overleftrightarrow{\sigma} \vec{E}$$

$$\begin{aligned} \overleftrightarrow{\sigma} &= -en_e \left(\frac{-ie}{\omega m_e} \right) \frac{1}{1 - \Omega^2/\omega^2} \begin{pmatrix} 1 & -i\frac{\Omega}{\omega} & 0 \\ i\frac{\Omega}{\omega} & 1 & 0 \\ 0 & 0 & 1 - \frac{\Omega^2}{\omega^2} \end{pmatrix} \\ &= i \frac{n_e e^2}{\omega m_e} \frac{1}{1 - \Omega^2/\omega^2} \begin{pmatrix} 1 & -i\frac{\Omega}{\omega} & 0 \\ i\frac{\Omega}{\omega} & 1 & 0 \\ 0 & 0 & 1 - \frac{\Omega^2}{\omega^2} \end{pmatrix} \end{aligned}$$

Dielectric tensor is obtained from conductivity tensor



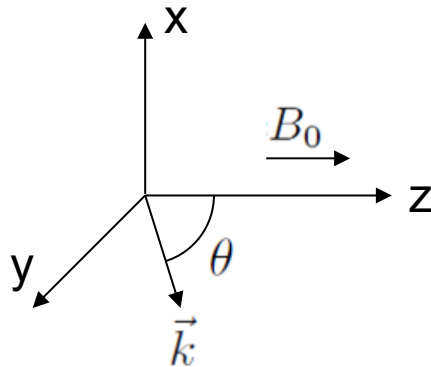
$$\begin{aligned}
 \frac{i}{\omega \epsilon_0} \overleftrightarrow{\sigma} &= -\frac{n_e e^2}{\epsilon_0 m_e} \frac{1}{\omega^2} \frac{1}{1 - \Omega^2/\omega^2} \begin{pmatrix} 1 & -i\frac{\Omega}{\omega} & 0 \\ i\frac{\Omega}{\omega} & 1 & 0 \\ 0 & 0 & 1 - \frac{\Omega^2}{\omega^2} \end{pmatrix} \\
 &= -\frac{\omega_p^2}{\omega^2 - \Omega^2} \begin{pmatrix} 1 & -i\frac{\Omega}{\omega} & 0 \\ i\frac{\Omega}{\omega} & 1 & 0 \\ 0 & 0 & 1 - \frac{\Omega^2}{\omega^2} \end{pmatrix} \quad \omega_p^2 = \frac{n_e e^2}{\epsilon_0 m_e} \\
 &= \begin{pmatrix} -\frac{\omega_p^2}{\omega^2 - \Omega^2} & i\frac{\Omega}{\omega} \frac{\omega_p^2}{\omega^2 - \Omega^2} & 0 \\ -i\frac{\Omega}{\omega} \frac{\omega_p^2}{\omega^2 - \Omega^2} & -\frac{\omega_p^2}{\omega^2 - \Omega^2} & 0 \\ 0 & 0 & -\frac{\omega_p^2}{\omega^2} \end{pmatrix}
 \end{aligned}$$

$$\overleftrightarrow{\epsilon} = \overleftrightarrow{1} + \frac{i}{\omega \epsilon_0} \overleftrightarrow{\sigma} = \begin{pmatrix} 1 - \frac{\omega_p^2}{\omega^2 - \Omega^2} & i\frac{\Omega}{\omega} \frac{\omega_p^2}{\omega^2 - \Omega^2} & 0 \\ -i\frac{\Omega}{\omega} \frac{\omega_p^2}{\omega^2 - \Omega^2} & 1 - \frac{\omega_p^2}{\omega^2 - \Omega^2} & 0 \\ 0 & 0 & 1 - \frac{\omega_p^2}{\omega^2} \end{pmatrix}$$

Assuming the wave is on the yz plane



let $X \equiv \frac{\omega_p^2}{\omega^2}$ $Y \equiv \frac{\Omega}{\omega}$ $\overleftrightarrow{\epsilon} = \begin{pmatrix} 1 - \frac{X}{1-Y^2} & i\frac{XY}{1-Y^2} & 0 \\ -i\frac{XY}{1-Y^2} & 1 - \frac{X}{1-Y^2} & 0 \\ 0 & 0 & 1-X \end{pmatrix}$



$$\vec{k} = k (0, \sin \theta, \cos \theta)$$

$$k_i = 0, \quad k_j = k \sin \theta, \quad k_k = k \cos \theta$$

$$\vec{k} : \vec{k} = \begin{pmatrix} 0 \\ k \sin \theta \\ k \cos \theta \end{pmatrix} \cdot \begin{pmatrix} 0 & k \sin \theta & k \cos \theta \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sin^2 \theta & \sin \theta \cos \theta \\ 0 & \sin \theta \cos \theta & \cos^2 \theta \end{pmatrix}$$

$$n \equiv \frac{kc}{\omega} \quad \frac{\omega^2}{c^2} \overleftrightarrow{\epsilon} = \frac{k^2 \omega^2}{k^2 c^2} \overleftrightarrow{\epsilon} = \frac{k^2}{n^2} \overleftrightarrow{\epsilon}$$

$$\det \left(\vec{k} : \vec{k} - k^2 \overleftrightarrow{1} + \frac{\omega^2}{c^2} \overleftrightarrow{\epsilon} \right) = 0$$

Reflective index



$$\begin{vmatrix} -k^2 + \frac{k^2}{n^2} \left(1 - \frac{X}{1-Y^2}\right) & i \frac{k^2}{n^2} \frac{XY}{1-Y^2} & 0 \\ -i \frac{k^2}{n^2} \frac{XY}{1-Y^2} & k^2 \sin^2 \theta - k^2 + \frac{k^2}{n^2} \left(1 - \frac{X}{1-Y^2}\right) & k^2 \sin \theta \cos \theta \\ 0 & k^2 \sin \theta \cos \theta & k^2 \cos^2 \theta - k^2 + \frac{k^2}{n^2} (1 - X) \end{vmatrix} = 0$$

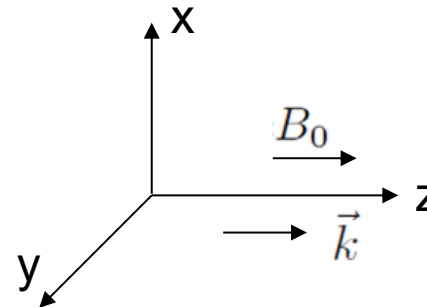
$$\begin{vmatrix} -n^2 + 1 - \frac{X}{1-Y^2} & i \frac{XY}{1-Y^2} & 0 \\ -i \frac{XY}{1-Y^2} & -n^2 \cos^2 \theta + 1 - \frac{X}{1-Y^2} & n^2 \sin \theta \cos \theta \\ 0 & n^2 \sin \theta \cos \theta & -n^2 \sin^2 \theta + 1 - X \end{vmatrix} = 0$$

$$n^2 = 1 - \frac{X(1-X)}{1 - X - \frac{1}{2}Y^2 \sin^2 \theta \pm \left[\left(\frac{1}{2}Y^2 \sin^2 \theta \right)^2 + (1-X)^2 Y^2 \cos^2 \theta \right]^{1/2}}$$

Wave is circular polarized propagating along the magnetic field



- **Parallel to B_0** ($\theta = 0$)



$$n^2 = 1 - \frac{X(1-X)}{1-X \pm [(1-X)^2 Y^2]^{1/2}} = 1 - \frac{X}{1 \pm Y} = 1 - \frac{\omega_p^2/\omega^2}{1 \pm \Omega/\omega} = 1 - \frac{\omega_p^2}{\omega(\omega \pm \Omega)}$$

$$\begin{pmatrix} -n^2 + 1 - \frac{X}{1-Y^2} & i\frac{XY}{1-Y^2} & 0 \\ -i\frac{XY}{1-Y^2} & -n^2 \cos^2 \theta + 1 - \frac{X}{1-Y^2} & 0 \\ 0 & 0 & 1-X \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = 0$$

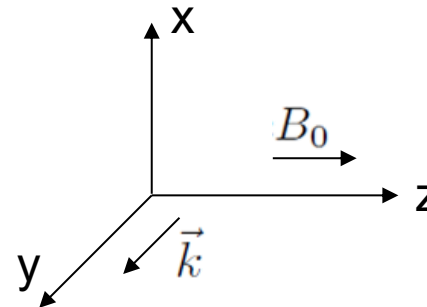
$$\left(-n^2 + 1 - \frac{X}{1-Y^2}\right) E_x + i\frac{XY}{1-Y^2} E_y = \frac{\mp XY}{1-Y^2} E_x + i\frac{XY}{1-Y^2} E_y = 0$$

$$\frac{E_x}{E_y} = \pm i \quad \text{Left hand circular (LHC) or right hand circular (RHC) polarized.}$$

Electric field is not necessary parallel to the propagating direction which is perpendicular to B_0



- Perpendicular to B_0 ($\theta = \frac{\pi}{2}$)



$$n^2 = 1 - \frac{X(1-X)}{1-X-\frac{1}{2}Y^2 \pm \frac{1}{2}Y^2} = 1-X \text{ or } 1 - \frac{X(1-X)}{1-X-Y^2}$$

$$\begin{pmatrix} -n^2 + 1 - \frac{X}{1-Y^2} & i\frac{XY}{1-Y^2} & 0 \\ -i\frac{XY}{1-Y^2} & 1 - \frac{X}{1-Y^2} & 0 \\ 0 & 0 & -n^2 + 1 - X \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = 0$$

$$n^2 = 1 - \frac{\omega_p^2}{\omega^2} \quad E_x = E_y = 0 \quad \text{Ordinary wave (O-wave)}$$

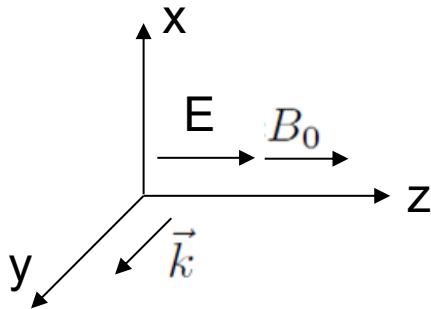
$$n^2 = 1 - \frac{\omega_p^2(1 - \omega_p^2/\omega^2)}{\omega^2 - \omega_p^2 - \Omega^2} \quad \frac{E_x}{E_y} = -i\omega \left(\frac{\omega^2 - \omega_p^2 - \Omega^2}{\omega_p^2\Omega} \right) \quad E_z = 0$$

Extraordinary wave (E-wave)

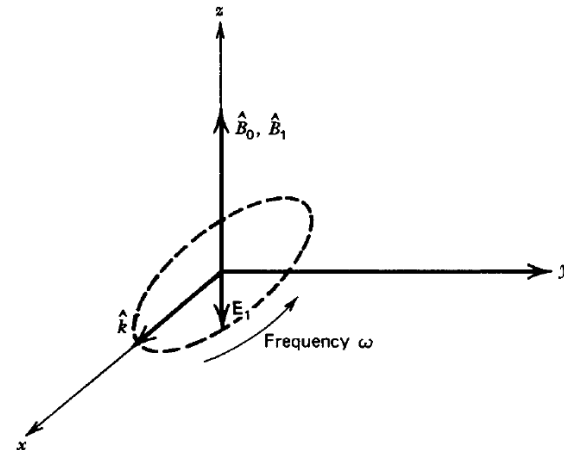
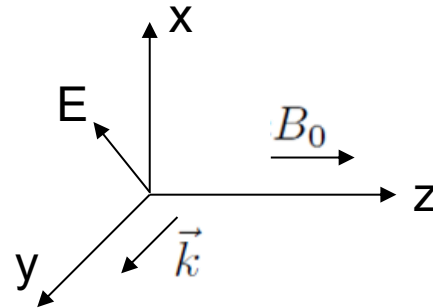
The electric field of an extraordinary wave rotates elliptically



Ordinary wave (O-wave)



Extraordinary wave (E-wave)



Electromagnetic wave can be used to measure the density or the magnetic field in the plasma



- **Nonmagnetized isotropic plasma (interferometer needed):**

$$n^2 = 1 - \frac{X(1-X)}{1 - X - \frac{1}{2}Y^2 \sin^2 \theta \pm \left[\left(\frac{1}{2}Y^2 \sin^2 \theta \right)^2 + (1-X)^2 Y^2 \cos^2 \theta \right]^{1/2}}$$
$$= 1 - X = 1 - \frac{\omega_p^2}{\omega^2} = 1 - \frac{n_e}{n_{cr}} \quad \left(Y \equiv \frac{\Omega}{\omega} \equiv 0 \right)$$

Note: $\omega_p^2 = \frac{n_e e^2}{\epsilon_0 m_e}$ $n_{cr} = \frac{\epsilon_0 m_e \omega^2}{e^2}$

- **Magnetized isotropic plasma (Polarization detected needed):**

Parallel to B_0

$$n^2 = 1 - \frac{\omega_p^2}{\omega(\omega \pm \Omega)} \quad \frac{E_x}{E_y} = \pm i \quad \Omega \equiv \frac{eB_0}{m_e}$$

Faraday rotation: linear polarization rotation caused by the difference between the speed of LHC and RHC polarized wave.

Electromagnetic wave can be used to measure the density or the magnetic field in the plasma



- Nonmagnetized isotropic plasma (interferometer needed):

$$n^2 = 1 - \frac{X(1-X)}{1-X - \frac{1}{2}Y^2 \sin^2 \theta \pm \left[\left(\frac{1}{2}Y^2 \sin^2 \theta \right)^2 + (1-X)^2 Y^2 \cos^2 \theta \right]^{1/2}}$$
$$= 1 - X = 1 - \frac{\omega_p^2}{\omega^2} = 1 - \frac{n_e}{n_{cr}} \quad \left(Y \equiv \frac{\Omega}{\omega} \equiv 0 \right)$$

Note: $\omega_p^2 = \frac{n_e e^2}{\epsilon_0 m_e}$ $n_{cr} = \frac{\epsilon_0 m_e \omega^2}{e^2}$

- Magnetized isotropic plasma (Polarization detected needed):

Parallel to B_0

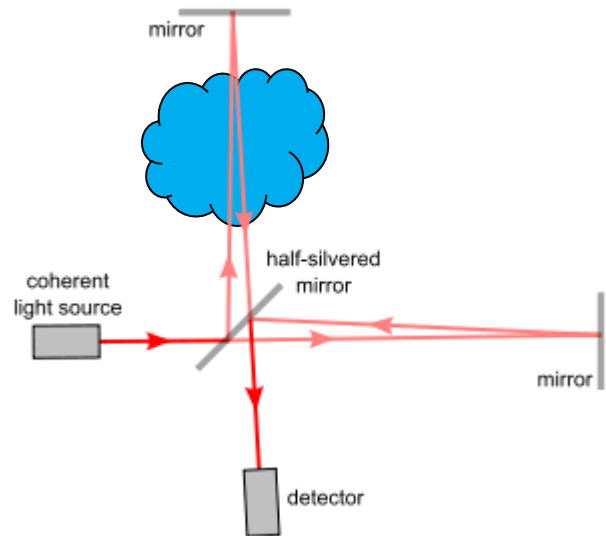
$$n^2 = 1 - \frac{\omega_p^2}{\omega(\omega \pm \Omega)} \quad \frac{E_x}{E_y} = \pm i \quad \Omega \equiv \frac{eB_0}{m_e}$$

Faraday rotation: linear polarization rotation caused by the difference between the speed of LHC and RHC polarized wave.

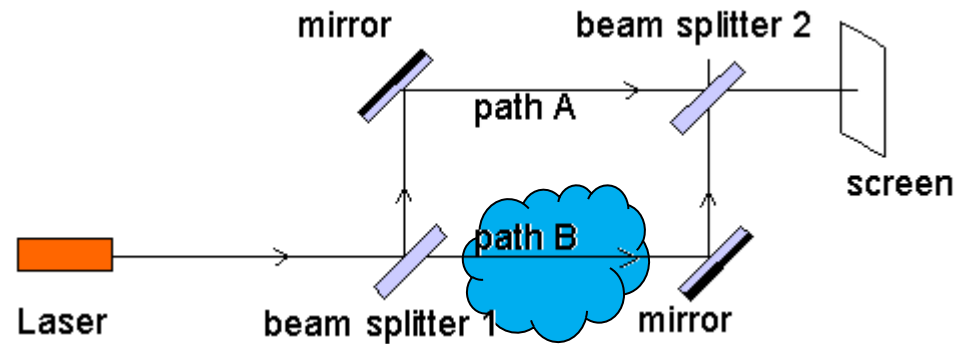
There are two main style of interferometer



Michelson interferometer



Mach-zehnder interferometer

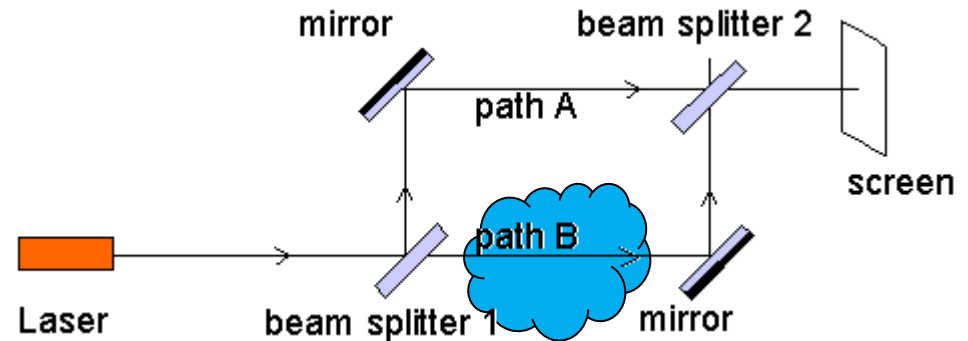


Interference pattern are due to the phase difference between two different path



$$E_1 = E_1 \exp(-i\omega t)$$

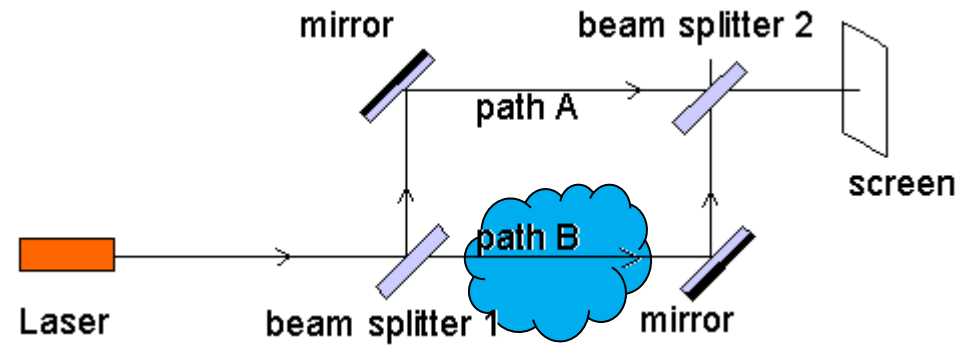
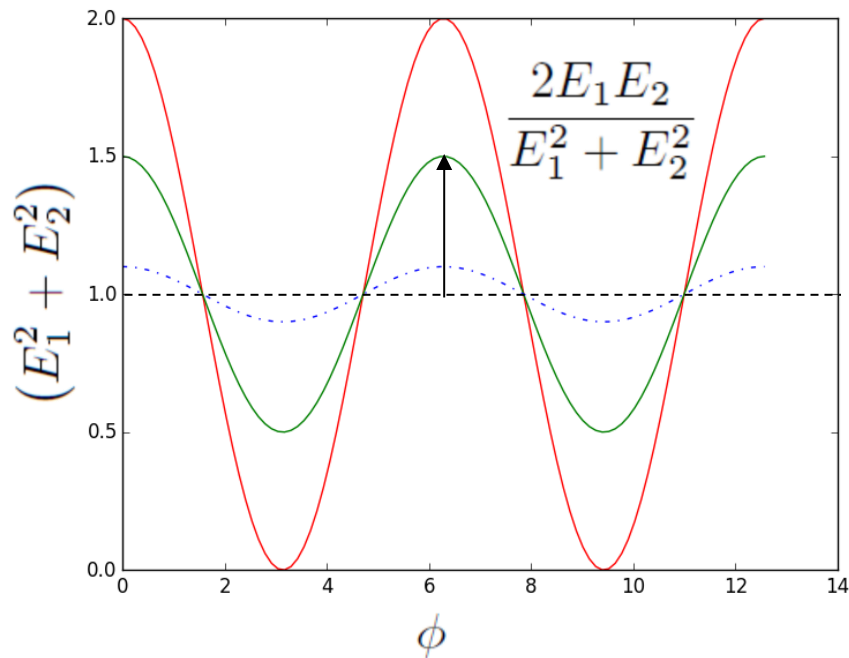
$$E_2 = E_2 \exp(-i\omega t + i\phi)$$



$$E = E_1 + E_2 = [E_1 + E_2 \exp(i\phi)] \exp(-i\omega t)$$

$$\begin{aligned} I &= |E|^2 = E^* E = [E_1 + E_2 \exp(-i\phi)] \exp(i\omega t) [E_1 + E_2 \exp(i\phi)] \exp(-i\omega t) \\ &= E_1^2 + E_2^2 + E_1 E_2 \exp(i\phi) + E_1 E_2 \exp(-i\phi) \\ &= E_1^2 + E_2^2 + 2E_1 E_2 \cos \phi \\ &= (E_1^2 + E_2^2) \left(1 + \frac{2E_1 E_2}{E_1^2 + E_2^2} \cos \phi \right) \end{aligned}$$

The intensity on screen depends on the phase different between two paths



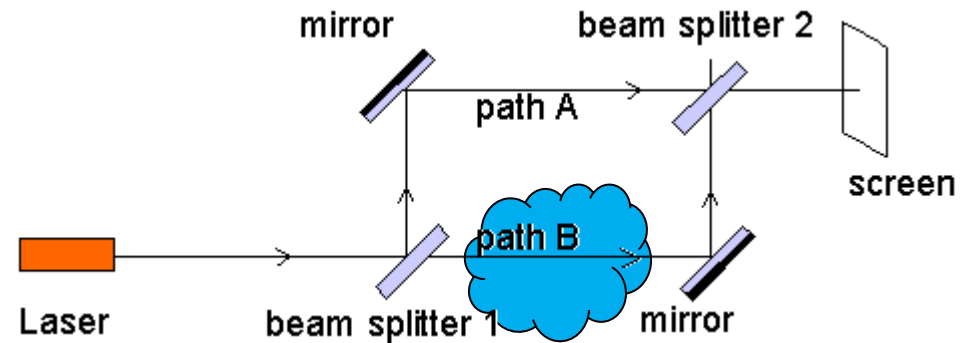
$$I = (E_1^2 + E_2^2) \left(1 + \frac{2E_1E_2}{E_1^2 + E_2^2} \cos \phi \right)$$

The phase different depends on the line integral of the electron density along the path



$$\phi = \int k dl = \int n \frac{\omega}{c} dl$$

$$n^2 = 1 - \frac{n_e}{n_{cr}} \quad n_{cr} = \frac{\epsilon_0 m_e \omega^2}{e^2}$$

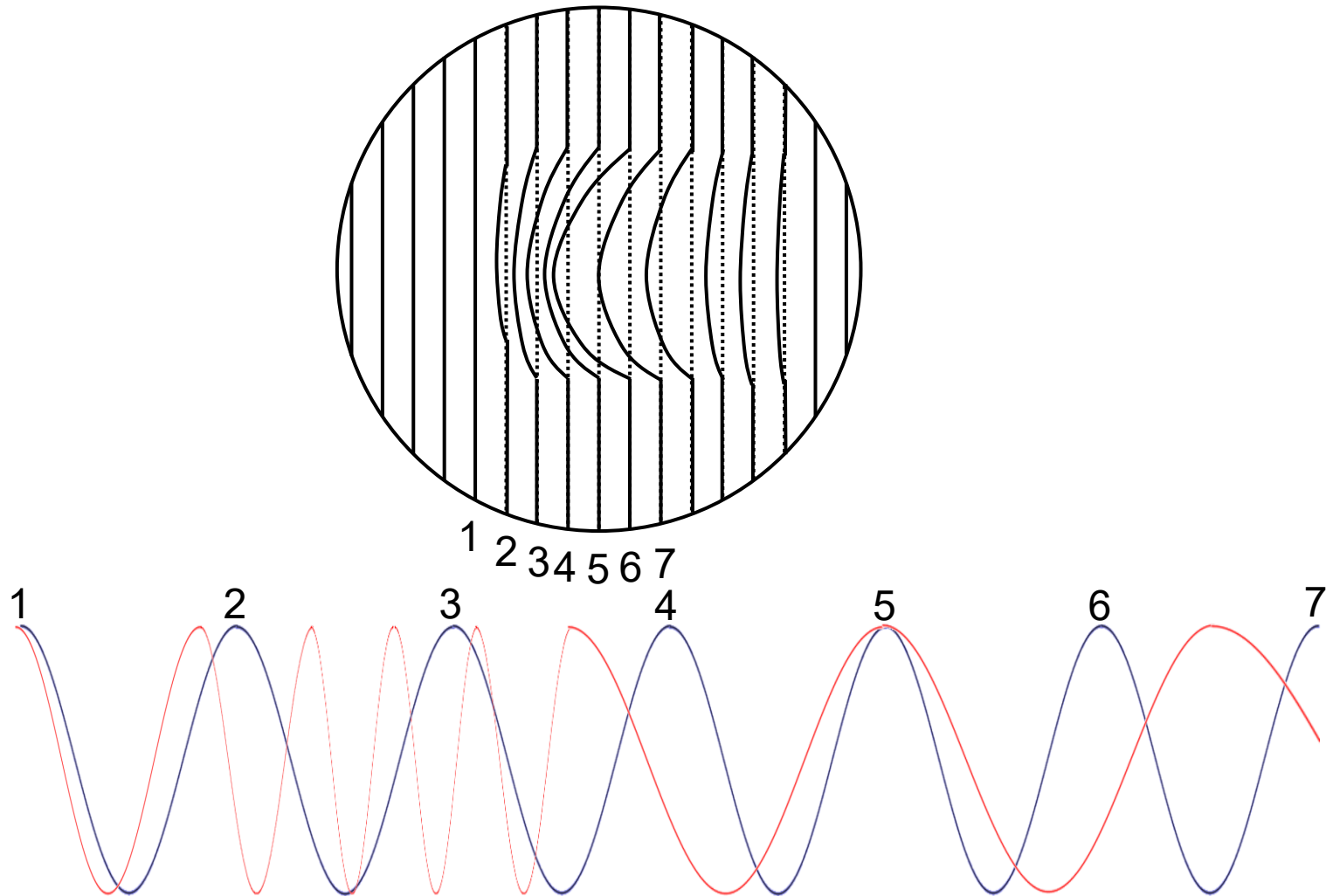


$$\begin{aligned} \Delta\phi &= \int (k_{\text{plasma}} - k_0) dl = \frac{\omega}{c} \int (n - 1) dl \\ &= \frac{\omega}{c} \int \left(\sqrt{1 - \frac{n_e}{n_{cr}}} - 1 \right) dl \approx \frac{\omega}{c} \int \left(1 - \frac{1}{2} \frac{n_e}{n_{cr}} - 1 \right) dl \\ &= -\frac{\omega}{2cn_{cr}} \int n_e dl \end{aligned}$$

Note that $n_e \ll n_{cr}$ is assumed,

$$\sqrt{1 - \frac{n_e}{n_{cr}}} \approx 1 - \frac{1}{2} \frac{n_e}{n_{cr}}$$

The phase is determined by comparing to the pattern without the phase shift



Fourier transform can be used to retrieve the data from the interferometer image



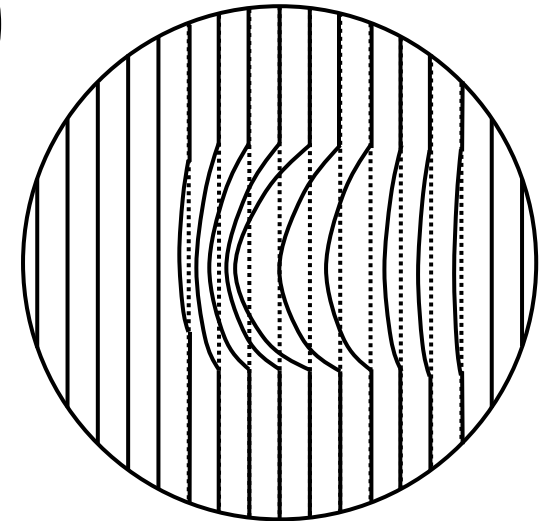
$$\begin{aligned}
 I(x, y) &= I_0(x, y) + m(x, y) \cos[2\pi\nu_0 x + \phi(x, y)] & \cos(x) &= \frac{e^{ix} + e^{-ix}}{2} \\
 &= I_0(x, y) + \frac{1}{2} m(x, y) (e^{i[2\pi\nu_0 x + \phi(x, y)]} + e^{-i[2\pi\nu_0 x + \phi(x, y)]}) \\
 &= I_0(x, y) + \frac{1}{2} m(x, y) e^{i\phi(x, y)} e^{i2\pi\nu_0 x} + \frac{1}{2} m(x, y) e^{-i\phi(x, y)} e^{-i2\pi\nu_0 x} \\
 &= I_0(x, y) + c(x, y) e^{i2\pi\nu_0 x} + c^*(x, y) e^{-i2\pi\nu_0 x}
 \end{aligned}$$

$$c(x, y) \equiv \frac{1}{2} m(x, y) e^{i\phi(x, y)} \quad \phi(x, y) = \tan^{-1} \left(\frac{\text{Im}[c(x, y)]}{\text{Re}[c(x, y)]} \right)$$

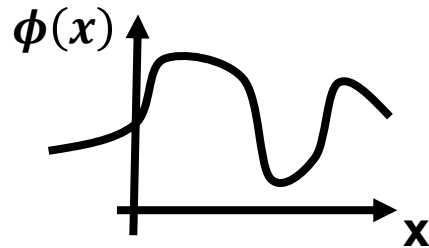
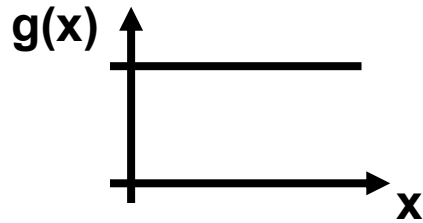
$$\hat{g}(f_x, y) \equiv \text{FT}[g(x, y)]$$

$$\hat{g}(f_x - \nu_0, y) = \text{FT}[g(x, y) e^{i2\pi\nu_0 x}]$$

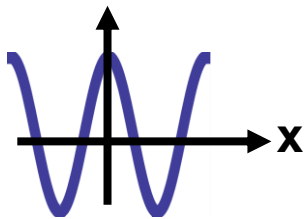
$$\hat{I}(f_x, y) = \hat{I}_0(f_x, y) + \hat{c}(f_x - \nu_0, y) + \hat{c}^*(f_x + \nu_0, y)$$



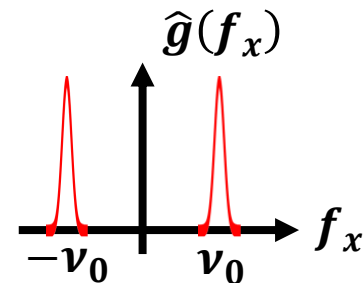
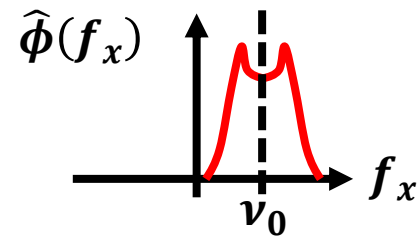
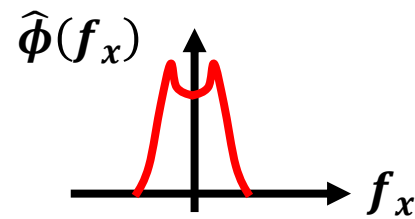
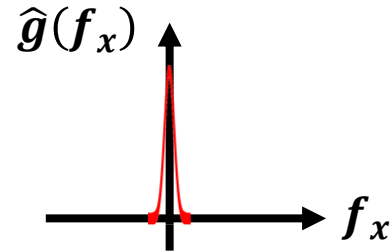
Basic knowledge of Fourier transform



$$h(x) = \phi(x) \times e^{-i2\pi\nu_0 x}$$



$$\begin{aligned} g(x) &= \cos(2\pi\nu_0 x) \\ &= \frac{e^{i2\pi\nu_0 x} + e^{-i2\pi\nu_0 x}}{2} \end{aligned}$$

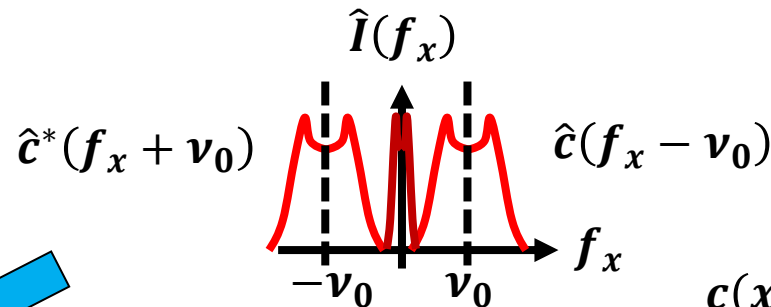
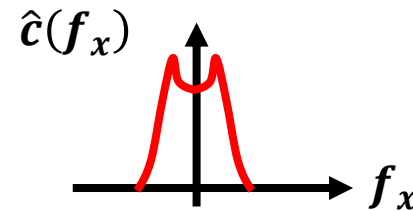
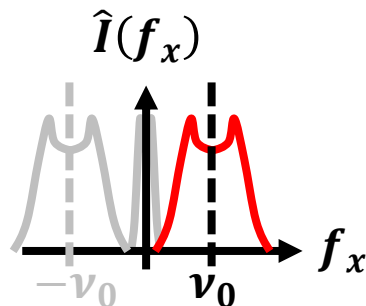
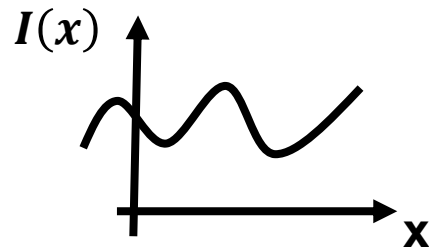
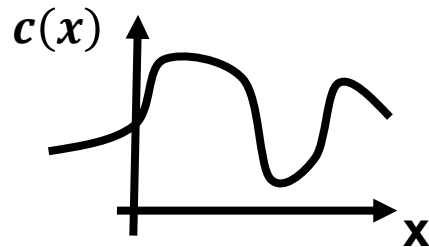


Procedure of retrieving data



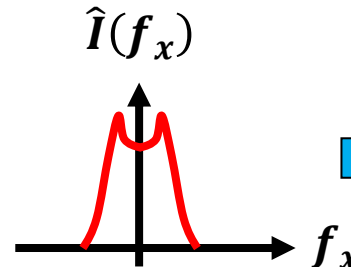
$$\begin{aligned} I(x) &= I_0(x) + m(x)\cos[2\pi\nu_0x + \phi(x)] \\ &\equiv \cos[2\pi\nu_0x + \phi(x)] \\ &= c^*(x, y)e^{i2\pi\nu_0x} + c(x, y)e^{-i2\pi\nu_0x} \end{aligned}$$

$$\hat{I}(f_x) = \hat{c}(f_x - \nu_0) + \hat{c}^*(f_x + \nu_0)$$

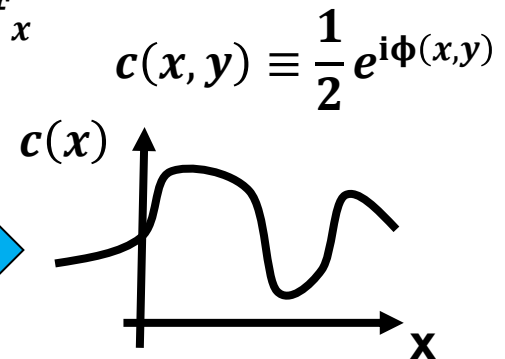


Filter

Shift

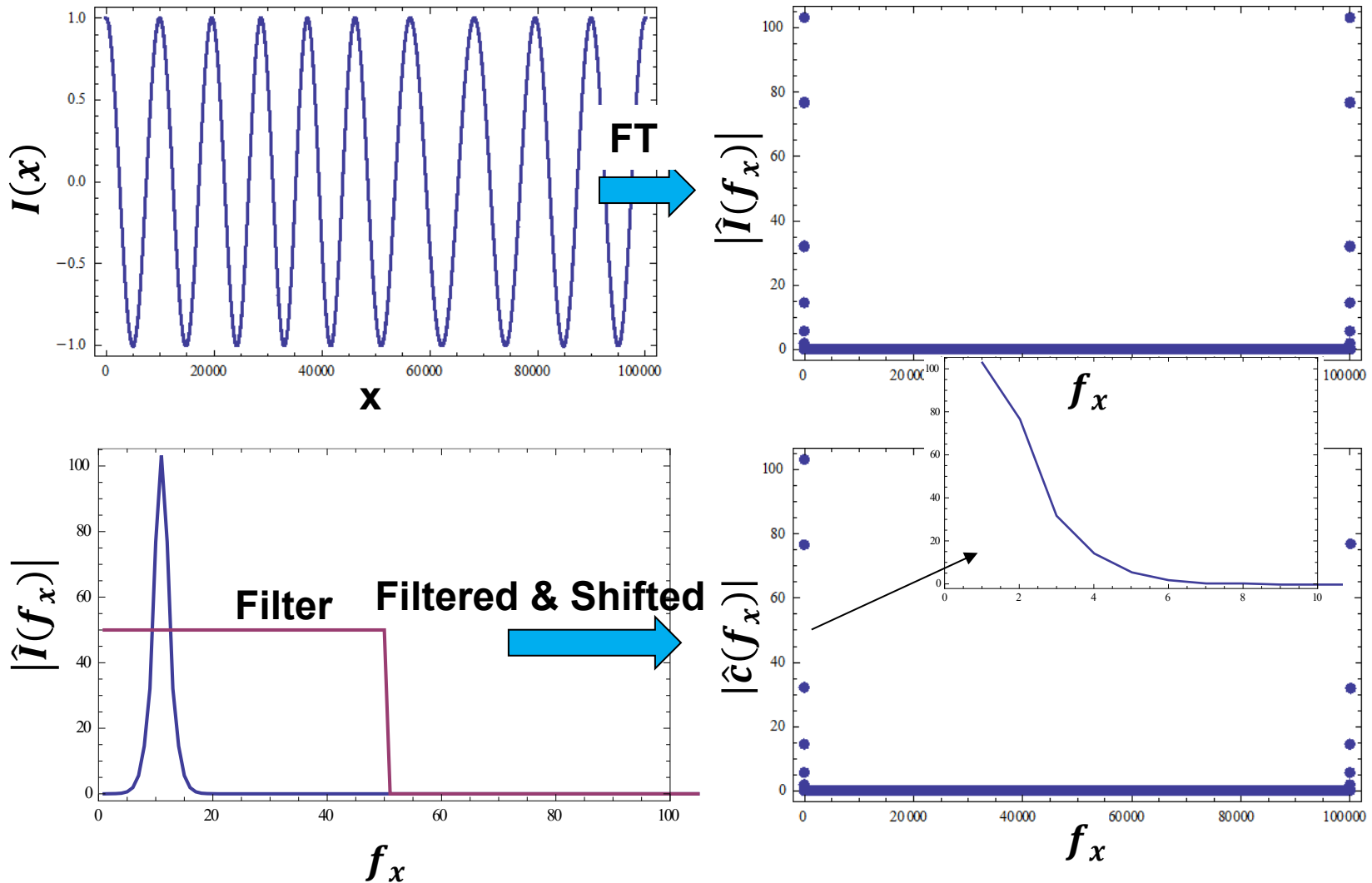


FT⁻¹

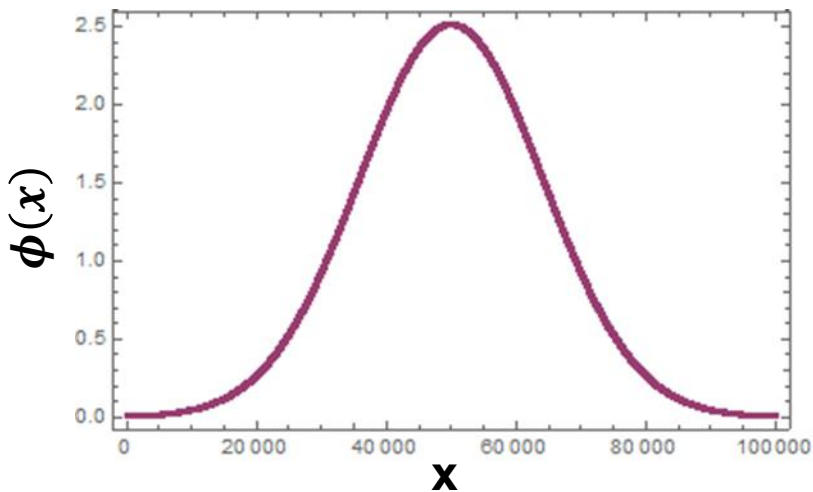
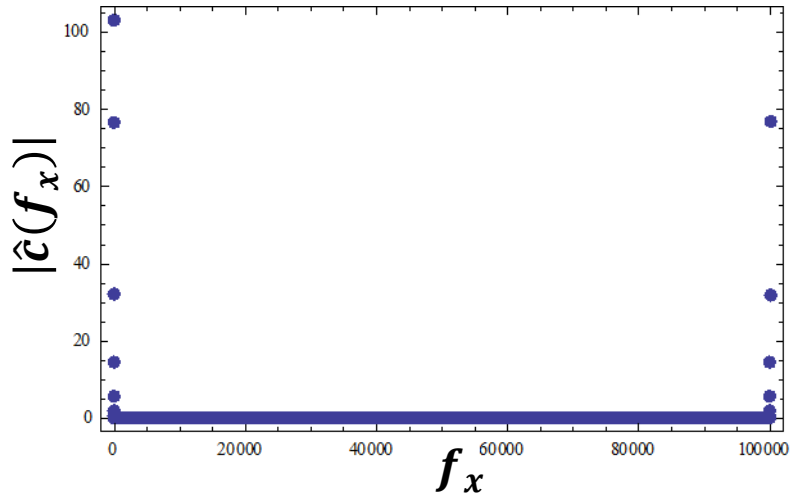


$$c(x, y) \equiv \frac{1}{2} e^{i\phi(x, y)}$$

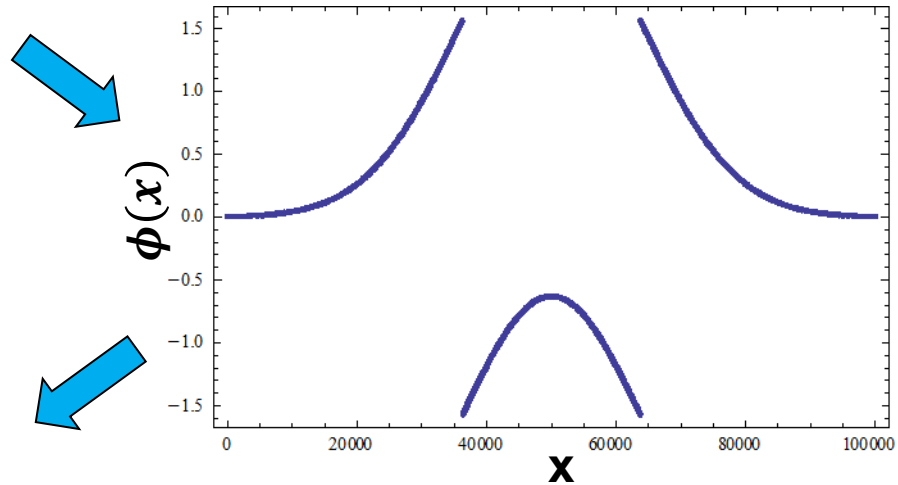
Example of retrieving data from 1D interferometer



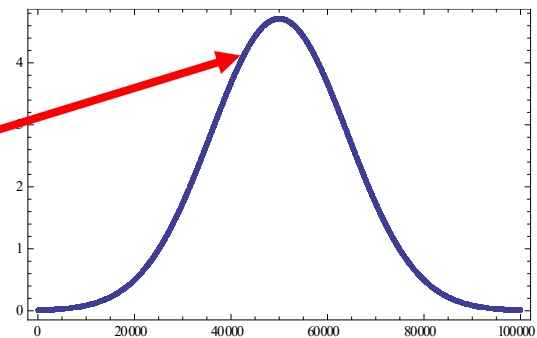
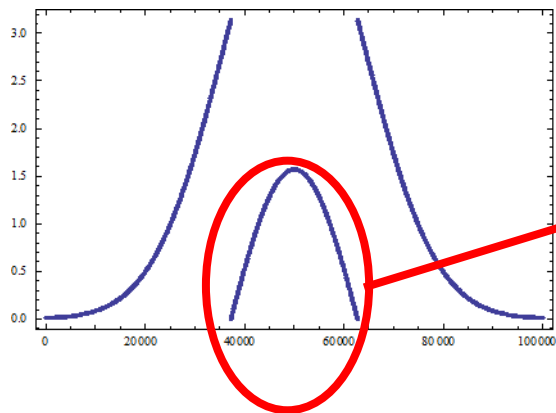
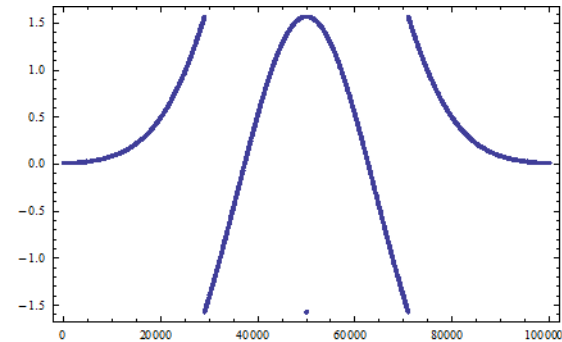
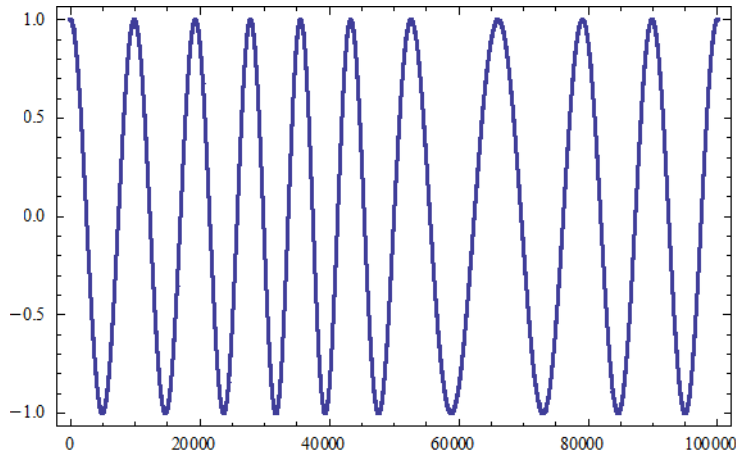
The retrieved data need to be modified if the phase change is too much



$$\text{FT}^{-1} \& \phi(x) = \tan^{-1} \left(\frac{\text{Im}[c(x)]}{\text{Re}[c(x)]} \right)$$



The final phase difference needs to be determined manually since it may exceeds 2π

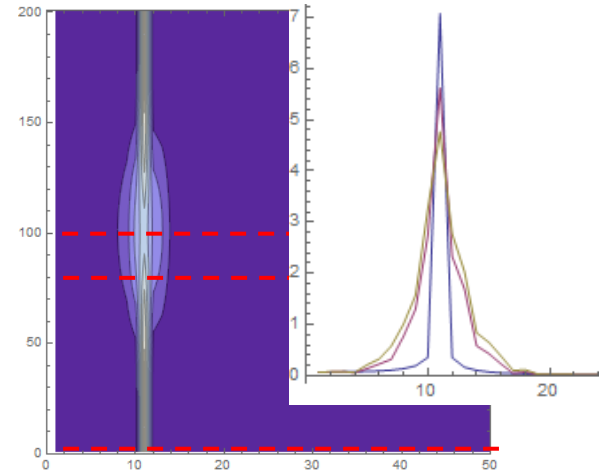
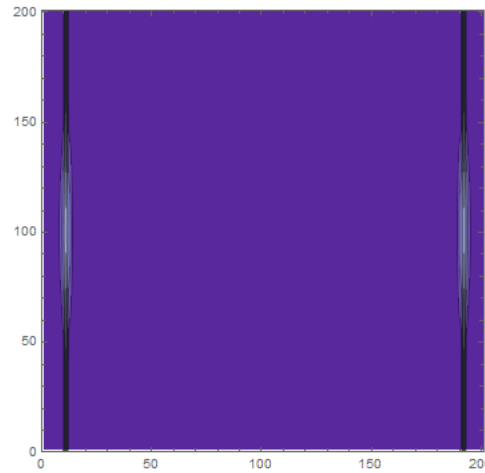
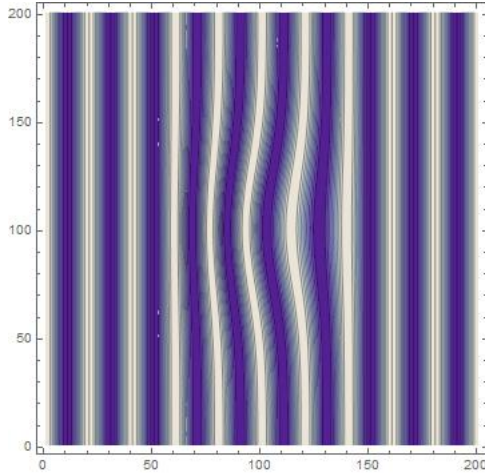


Example of retrieving data from 2D interferometer

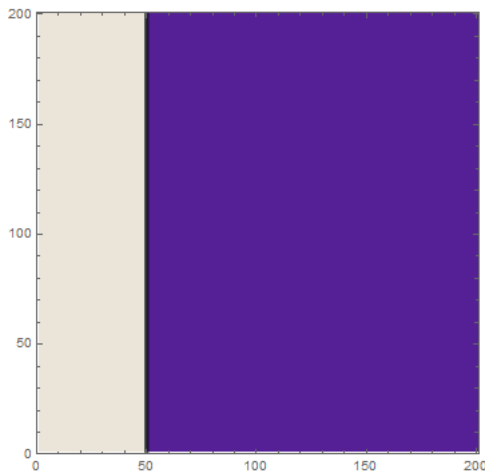


$$I(x, y) = \cos[2\pi\nu_0 x + \phi(x, y)]$$

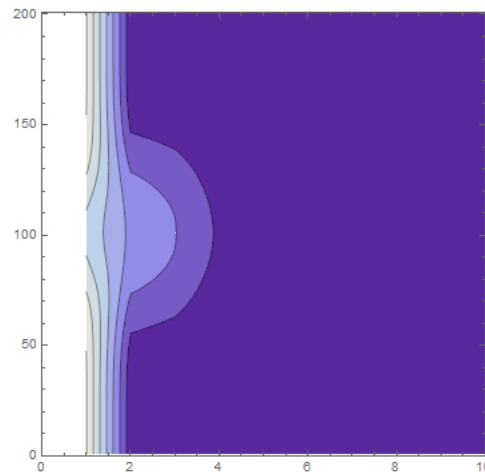
$$\hat{I}(f_x, y) = \hat{c}(f_x - \nu_0, y) + \hat{c}^*(f_x + \nu_0, y)$$



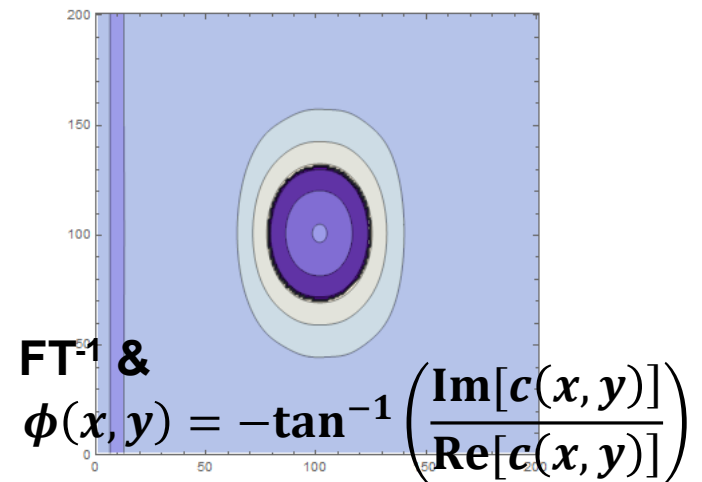
Filter



Filtered & Shifted



Retrieved data

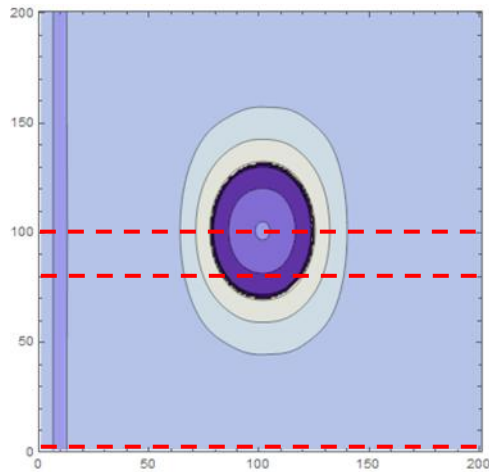


$$\phi(x, y) = -\tan^{-1} \left(\frac{\text{Im}[c(x, y)]}{\text{Re}[c(x, y)]} \right)$$

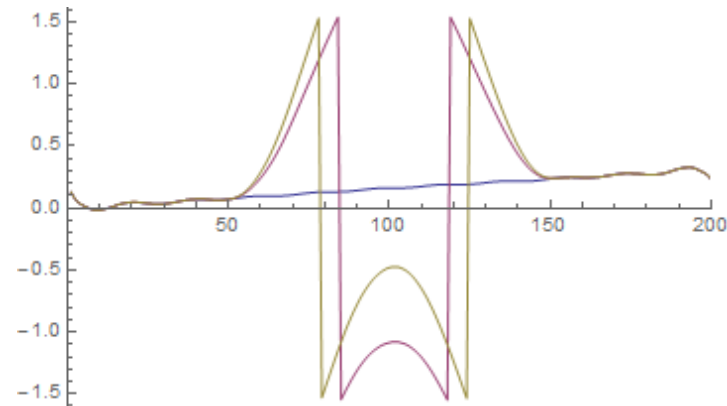
The retrieved data may need to be modified if the phase change is too large



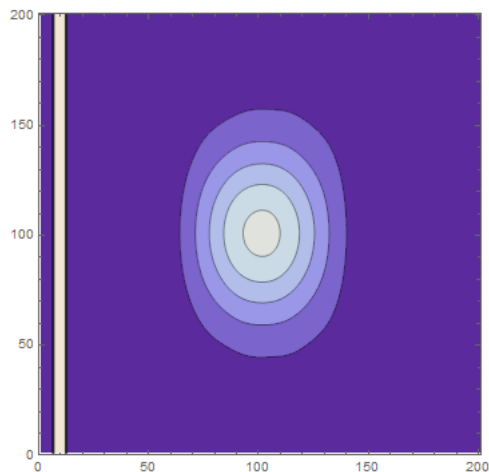
Retrieved data



1D profile

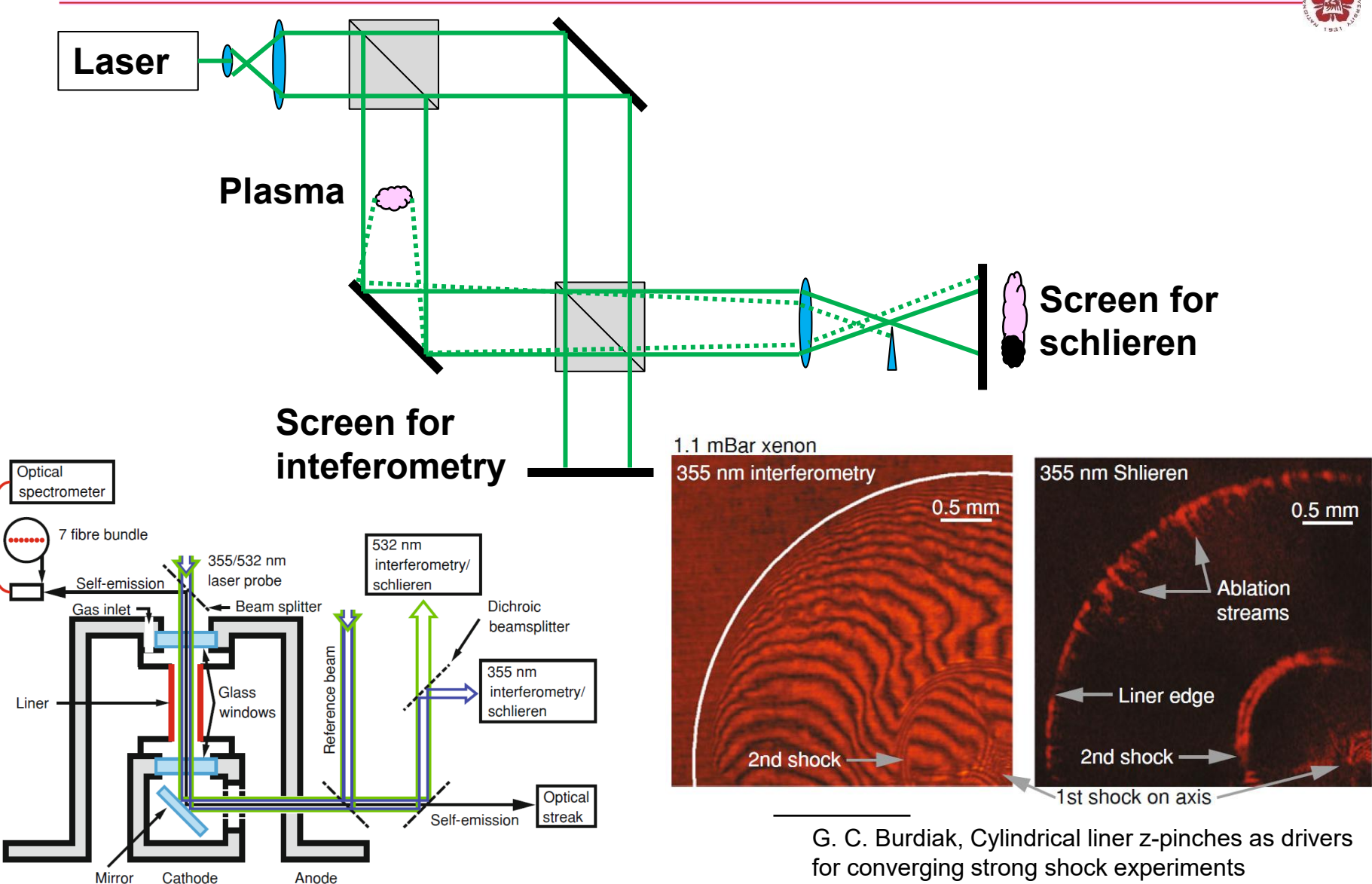


Modified result



- Noise came from low spatial resolution.

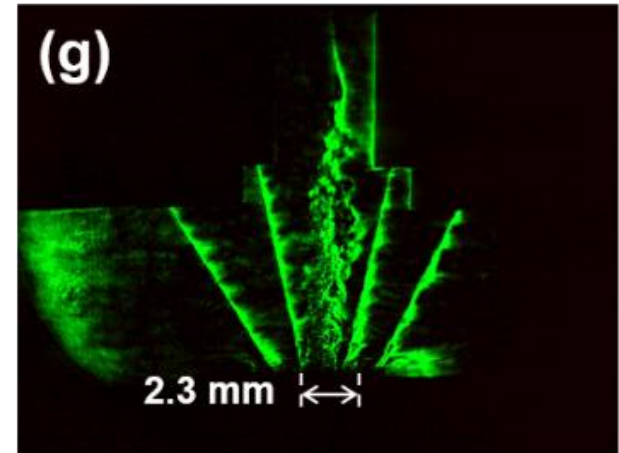
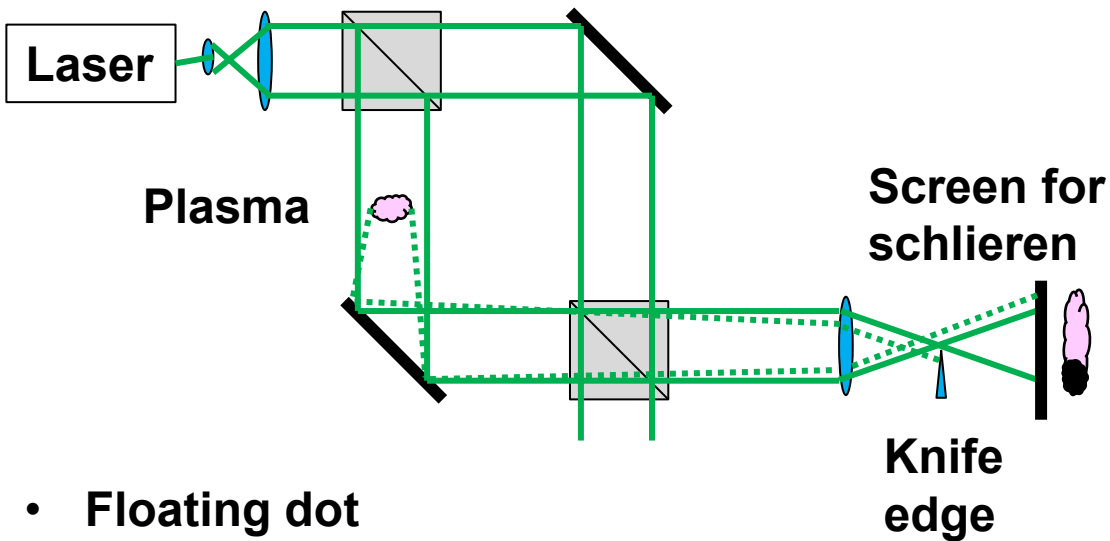
Schlieren imaging system can detect density gradient



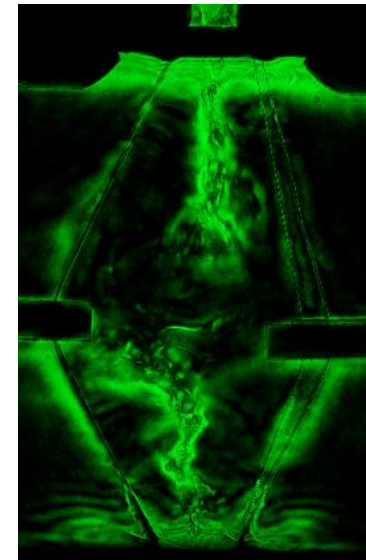
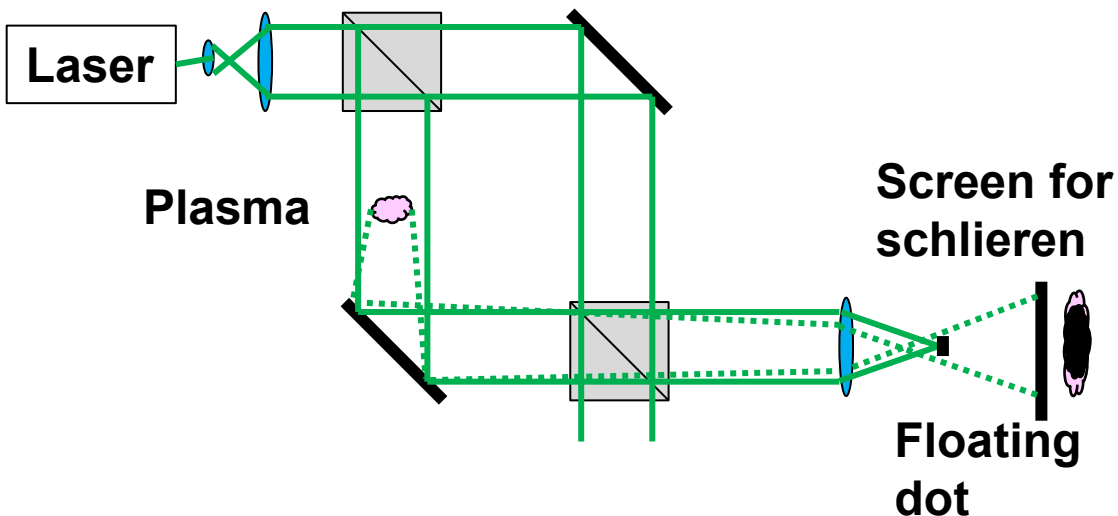
A symmetric Schlieren image can be obtained if the knife edge is replaced by a “floating dot”



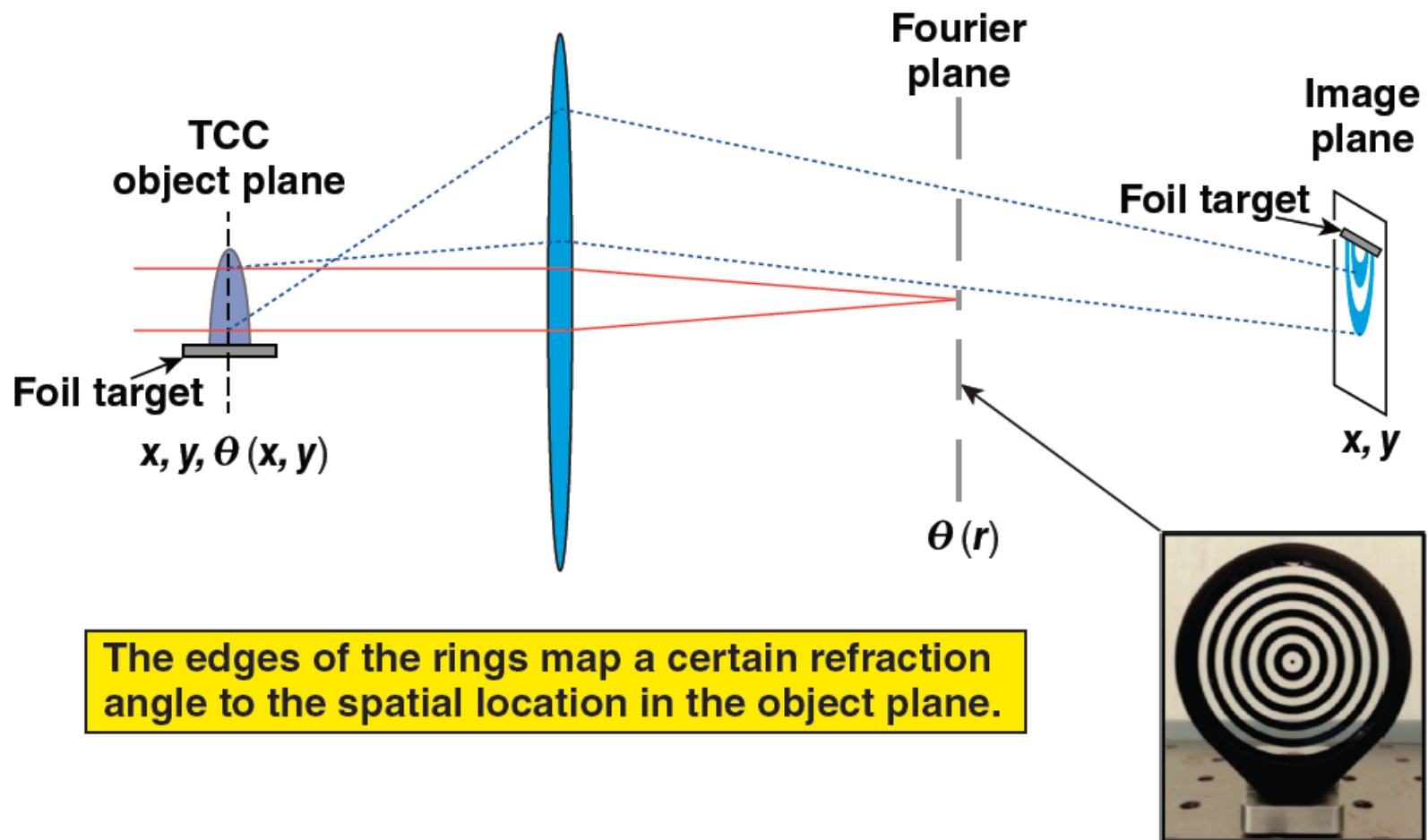
- Knife edge



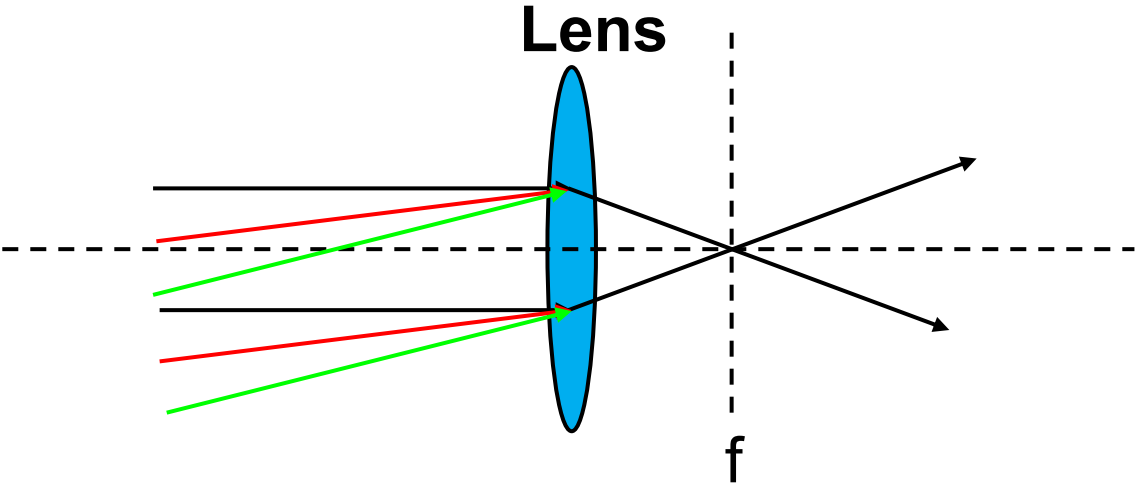
- Floating dot



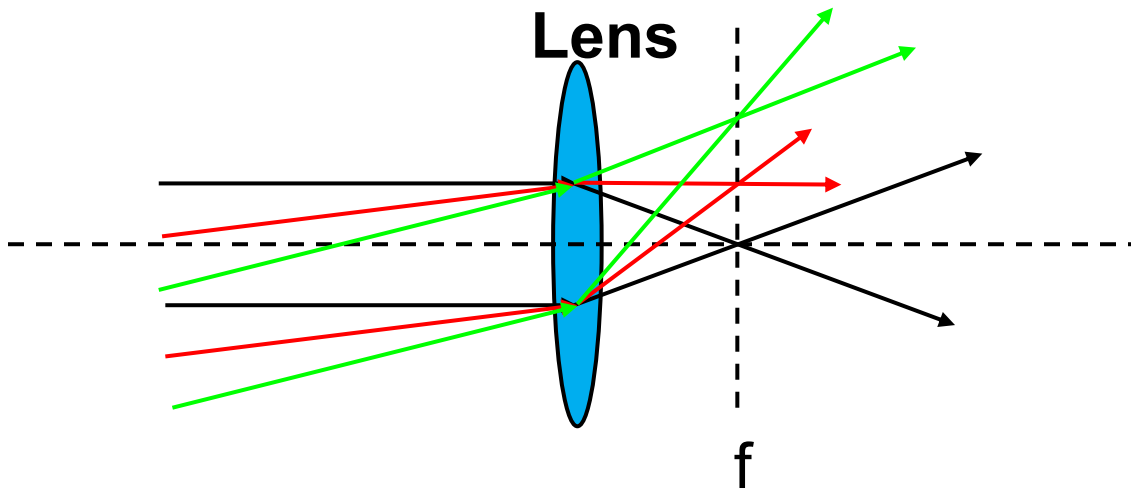
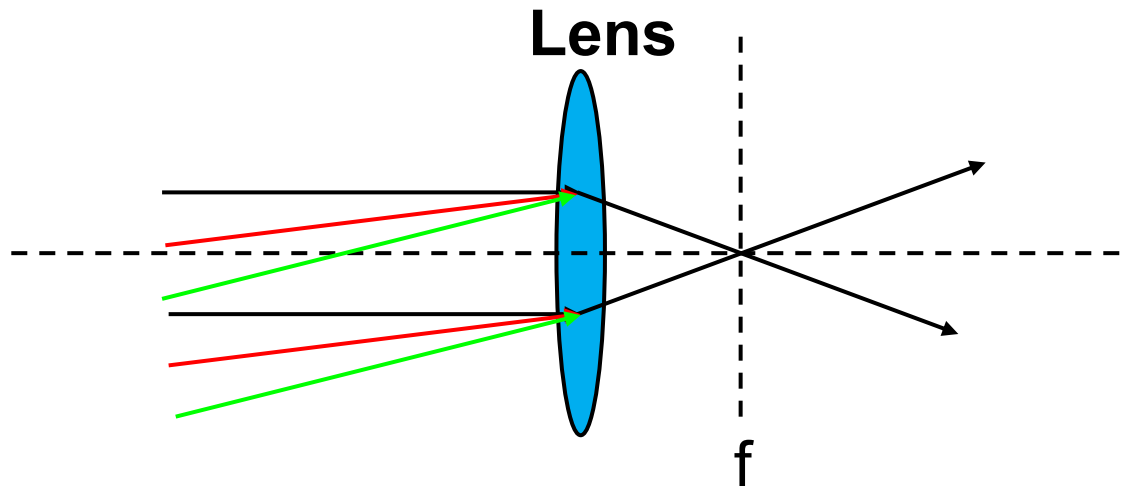
Angular filter refractometry (AFR) maps the refraction of the probe beam at TCC to contours in the image plane



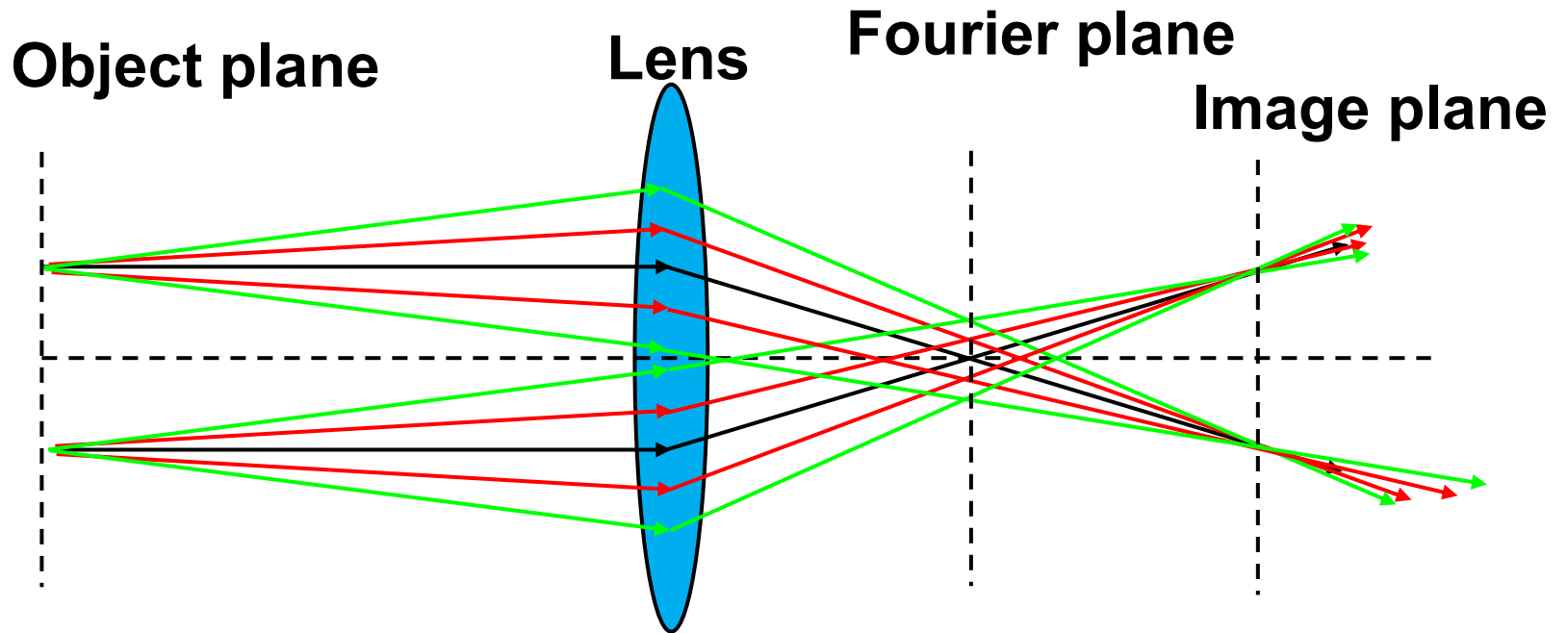
Angular spectrum of plane waves can be used for diagnostic



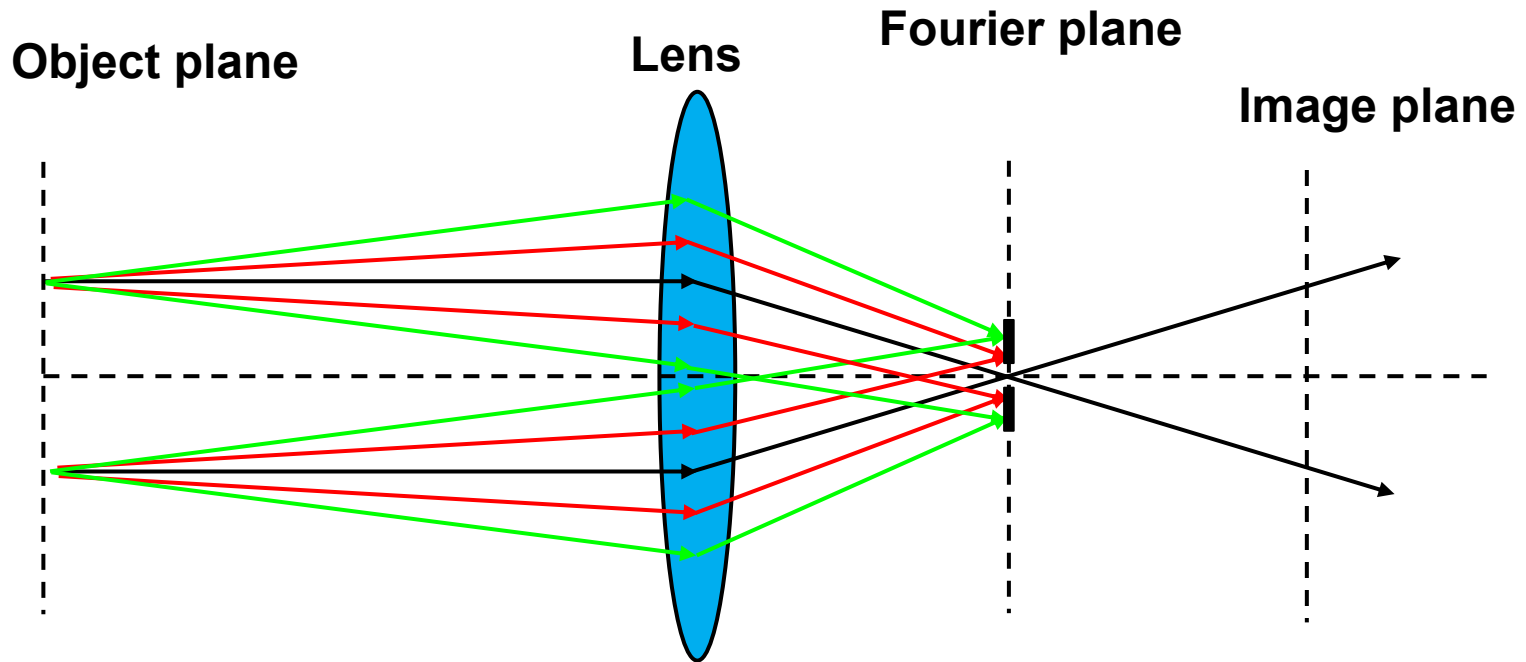
Angular spectrum of plane waves can be used for diagnostic



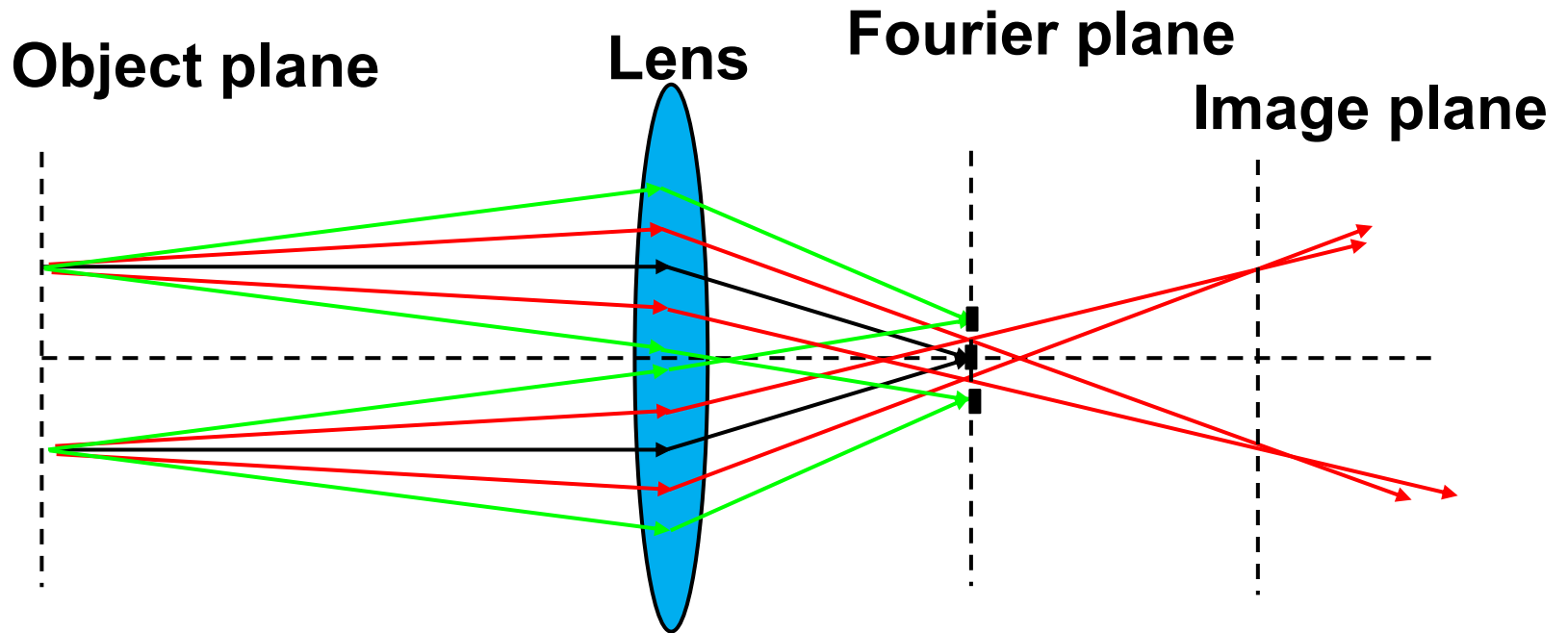
Rays with different angles go through different focal points on the focal points



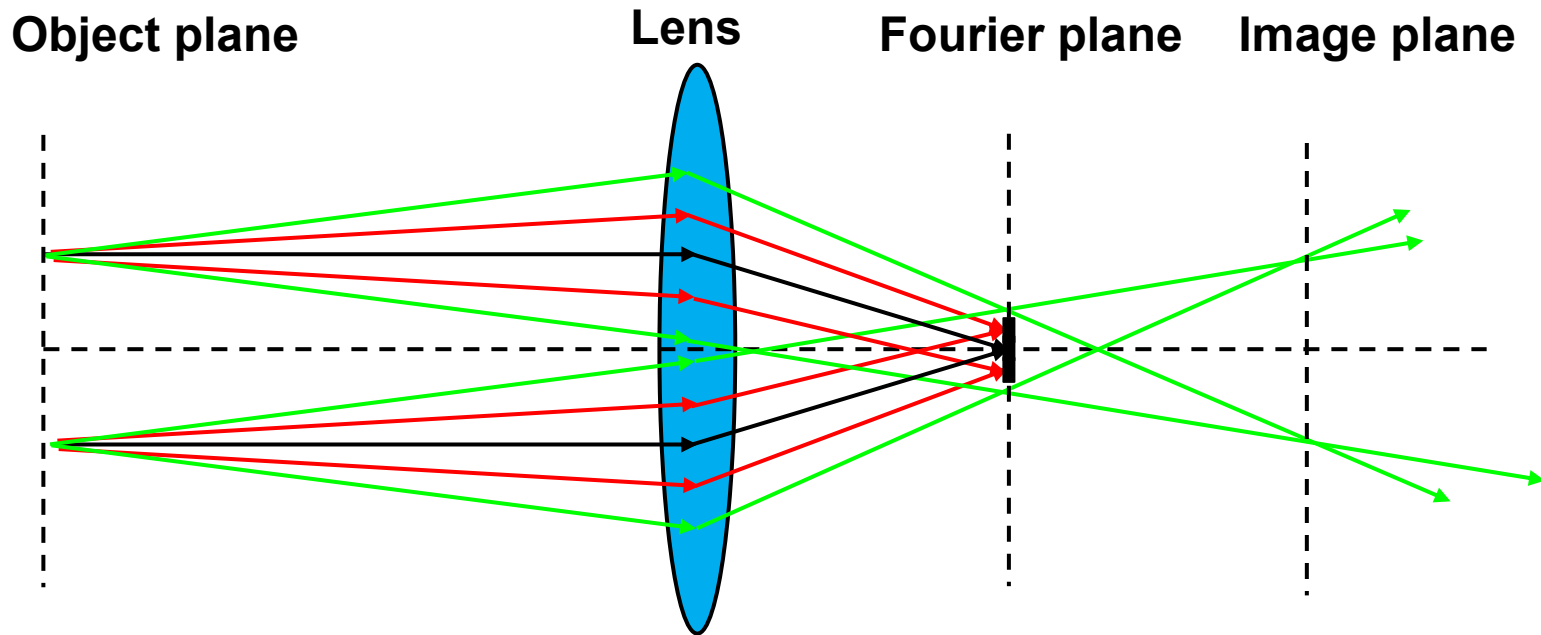
Rays with different angles can be selected by blocking different focal points



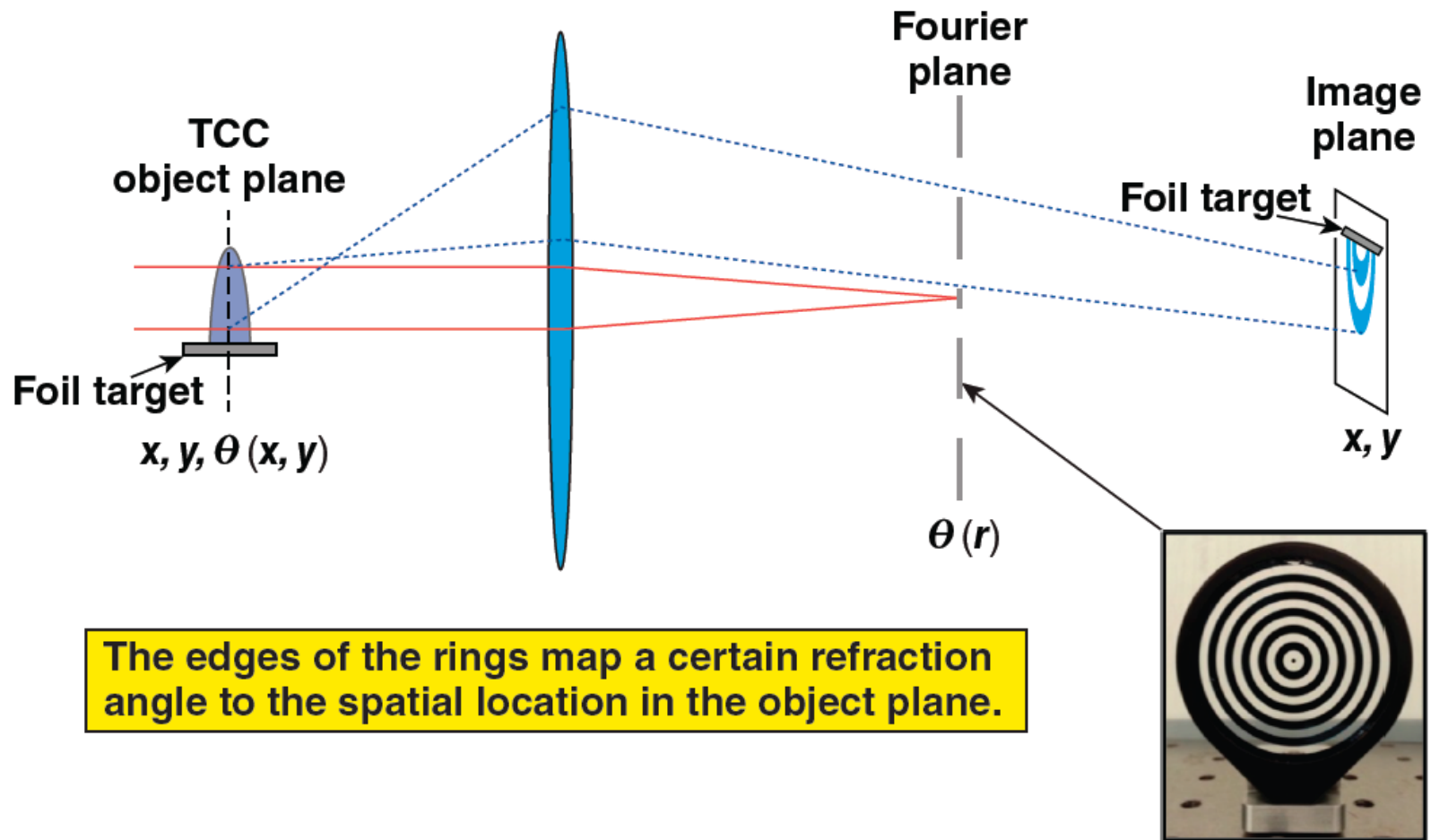
Rays with different angles go through different focal points on the focal points



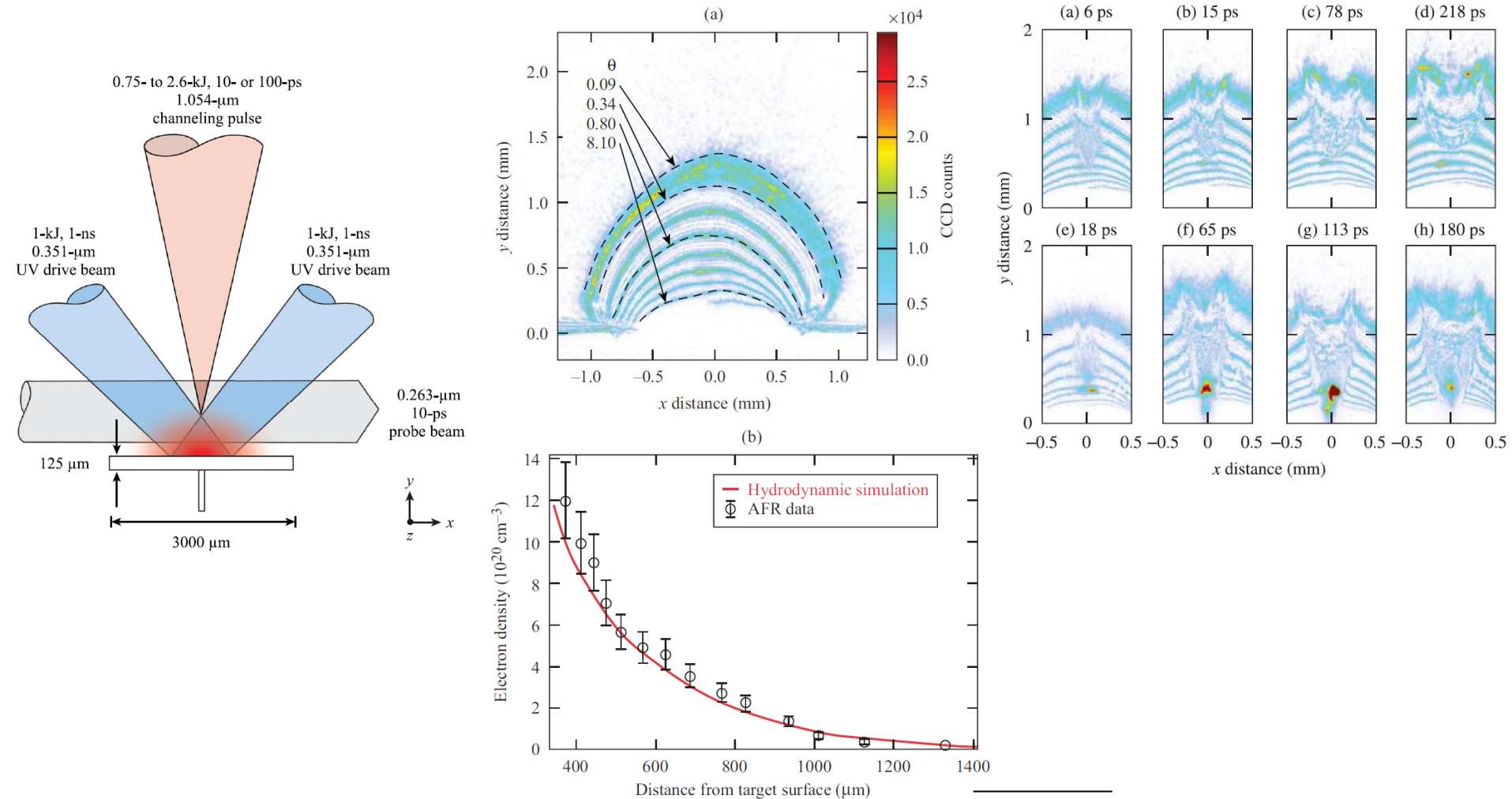
Rays with different angles go through different focal points on the focal points



Angular filter refractometry (AFR) maps the refraction of the probe beam at TCC to contours in the image plane



Channeling of multi-kilojoule high-intensity laser beams in an inhomogeneous plasma was observed using AFR



Electromagnetic wave can be used to measure the density or the magnetic field in the plasma



- Nonmagnetized isotropic plasma (interferometer needed):

$$n^2 = 1 - \frac{X(1-X)}{1-X - \frac{1}{2}Y^2 \sin^2 \theta \pm \left[\left(\frac{1}{2}Y^2 \sin^2 \theta \right)^2 + (1-X)^2 Y^2 \cos^2 \theta \right]^{1/2}}$$
$$= 1 - X = 1 - \frac{\omega_p^2}{\omega^2} = 1 - \frac{n_e}{n_{cr}} \quad \left(Y \equiv \frac{\Omega}{\omega} \equiv 0 \right)$$

Note: $\omega_p^2 = \frac{n_e e^2}{\epsilon_0 m_e}$ $n_{cr} = \frac{\epsilon_0 m_e \omega^2}{e^2}$

- Magnetized isotropic plasma (Polarization detected needed):

Parallel to B_0

$$n^2 = 1 - \frac{\omega_p^2}{\omega(\omega \pm \Omega)} \quad \frac{E_x}{E_y} = \pm i \quad \Omega \equiv \frac{eB_0}{m_e}$$

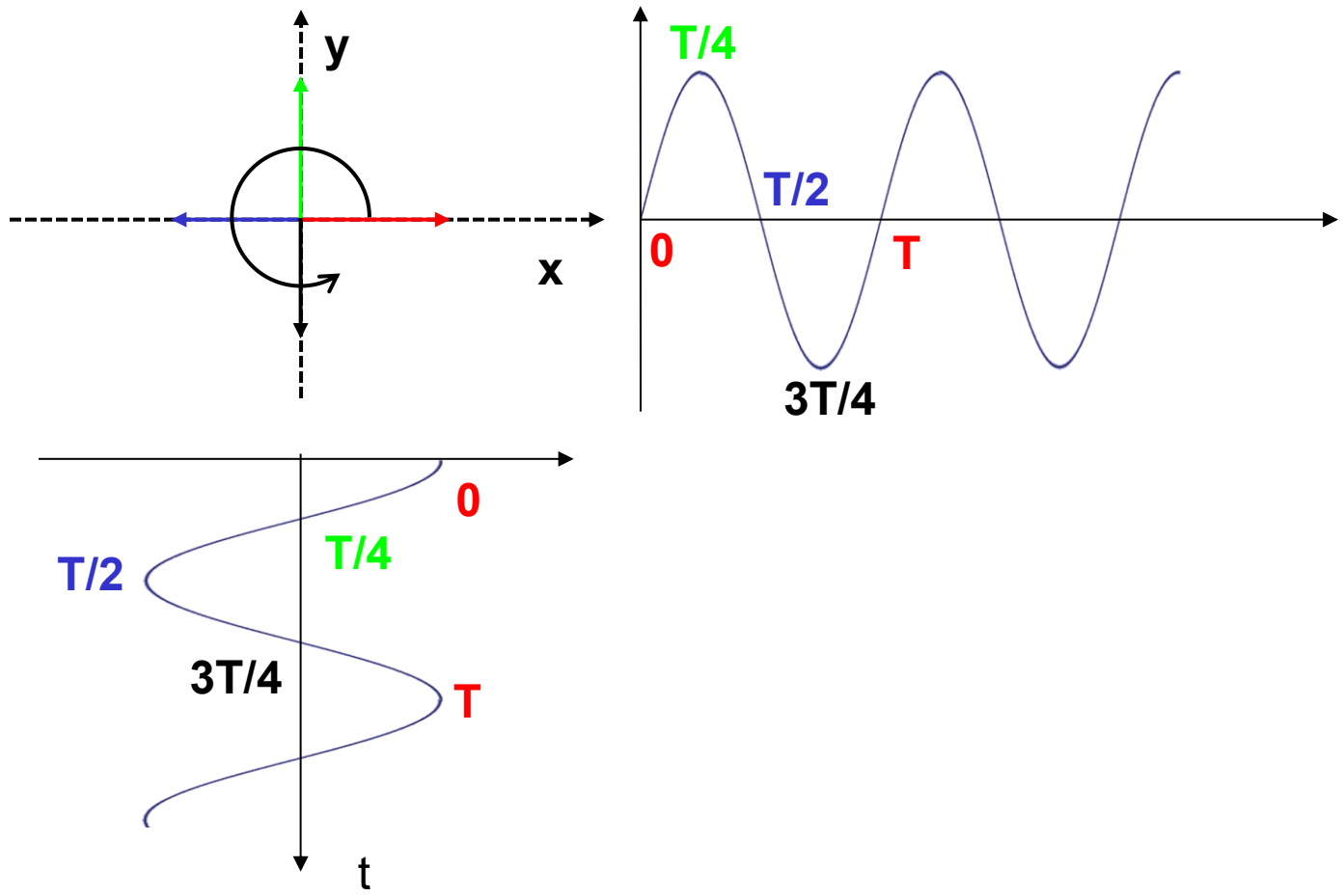
Faraday rotation: linear polarization rotation caused by the difference between the speed of LHC and RHC polarized wave.

Circular polarization



$$E_x = E_0 \exp(-i\omega t)$$

$$E_y = iE_x = iE_0 \exp(-i\omega t) = E_0 \exp\left(i\frac{\pi}{2}\right) \exp(-i\omega t) = E_0 \exp\left[-i\left(\omega t - \frac{\pi}{2}\right)\right]$$



Linear polarization rotates as the wave propagates with different speed in LHC and RHC polarization



$$\vec{E} = E_0 \hat{x} = \frac{E_0}{2} [(\hat{x} + i\hat{y}) + (\hat{x} - i\hat{y})] \quad \vec{E}(z) = \vec{E} \exp(i\phi) \quad \phi_R \neq \phi_L$$

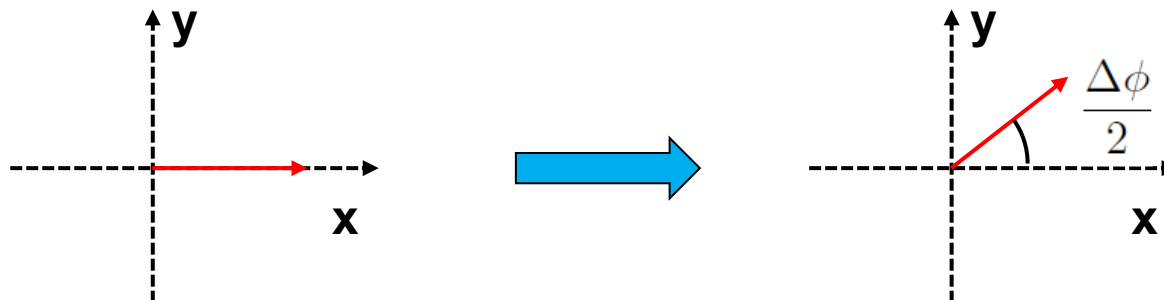
$$\vec{E}(z) = \frac{E_0}{2} [(\hat{x} + i\hat{y})e^{i\phi_R} + (\hat{x} - i\hat{y})e^{i\phi_L}] \quad \bar{\phi} \equiv \frac{\phi_R + \phi_L}{2}, \quad \Delta\phi = \frac{\phi_R - \phi_L}{2}$$

$$= \frac{E_0}{2} [\hat{x}(e^{i\phi_R} + e^{i\phi_L}) + \hat{y}i(e^{i\phi_R} - e^{i\phi_L})]$$

$$= \frac{E_0}{2} [\hat{x}(e^{i(\bar{\phi} + \frac{\Delta\phi}{2})} + e^{i(\bar{\phi} - \frac{\Delta\phi}{2})}) + \hat{y}i(e^{i(\bar{\phi} + \frac{\Delta\phi}{2})} - e^{i(\bar{\phi} - \frac{\Delta\phi}{2})})]$$

$$= E_0 e^{i\bar{\phi}} \left[\hat{x} \left(\frac{e^{i\frac{\Delta\phi}{2}} + e^{-i\frac{\Delta\phi}{2}}}{2} \right) + \hat{y}i \left(\frac{e^{i\frac{\Delta\phi}{2}} - e^{-i\frac{\Delta\phi}{2}}}{2} \right) \right]$$

$$= E_0 e^{i\bar{\phi}} \left[\hat{x} \cos\left(\frac{\Delta\phi}{2}\right) - \hat{y} \sin\left(\frac{\Delta\phi}{2}\right) \right]$$



The rotation angle of the polarization depends on the linear integral of magnetic field and electron density



$$\phi = \int k dl = \int n \frac{\omega}{c} dl \quad \alpha = \frac{\Delta\phi}{2} = \frac{\omega}{2c} \int (n_R - n_L) dl$$

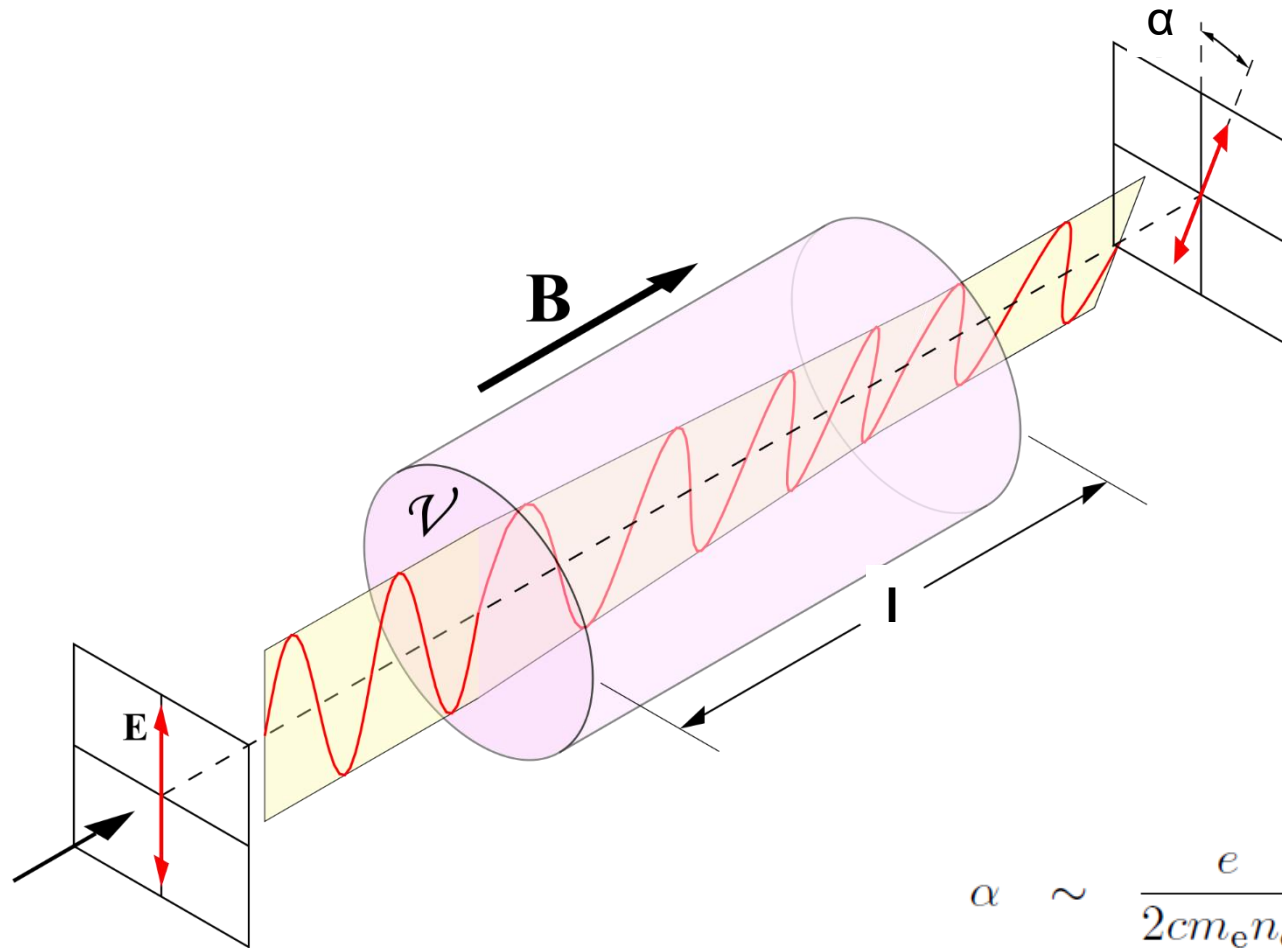
$$n_R = \sqrt{1 - \frac{X}{1+Y}} \sim 1 - \frac{1}{2} \frac{X}{1+Y} \quad X, Y \ll 1$$

$$n_L \sim 1 - \frac{1}{2} \frac{X}{1-Y} \quad \frac{X}{1 \pm Y} \ll 1$$

$$n_R - n_L \sim \frac{X}{2} \left(\frac{1}{1-Y} - \frac{1}{1+Y} \right) = \frac{XY}{1-Y^2} \sim XY$$

$$\begin{aligned} \alpha &\sim \frac{\omega}{2c} \int XY dl = \frac{\omega}{2c} \int \frac{\omega_p^2}{\omega^2} \frac{\Omega}{\omega} dl = \frac{1}{2c} \int \frac{n_e}{n_{cr}} \frac{eB}{m_e} dl \\ &= \frac{e}{2cm_en_{cr}} \int n_e B dl \end{aligned}$$

The rotation angle of the polarization depends on the linear integral of magnetic field and electron density



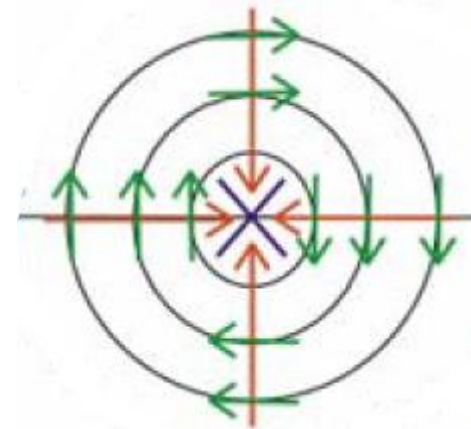
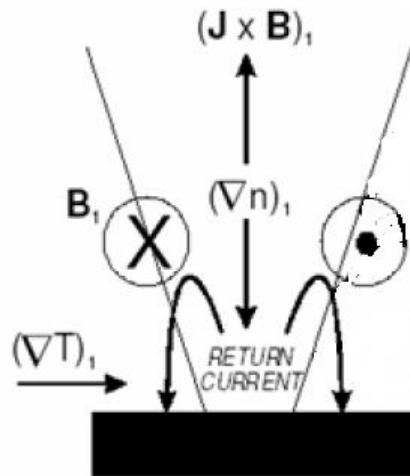
$$\alpha \sim \frac{e}{2cm_en_{cr}} \int n_e B dl$$

Magnetic field can be generated when the temperature and density gradients are not parallel to each other



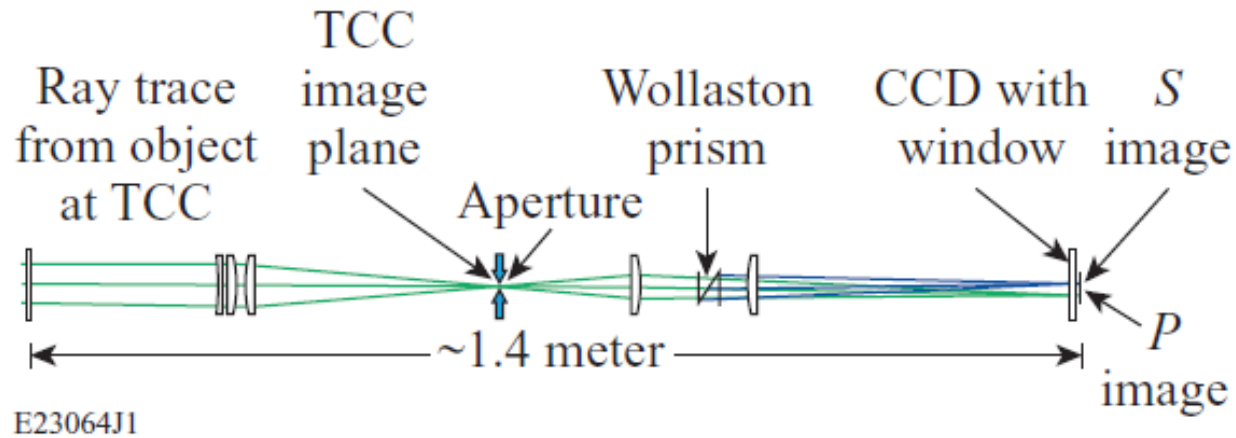
$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left[\underbrace{\vec{u} \times \vec{B}}_{\text{Convection term}} + \underbrace{\frac{1}{\sigma \mu_0} \nabla \times \vec{B}}_{\text{Diffusion term}} + \underbrace{\frac{\nabla p_e}{n_e e}}_{\text{self generated field}} - \underbrace{\frac{1}{\mu_0} \left(\frac{\nabla \times \vec{B}}{n_e e} \times \vec{B} \right)}_{\text{Hall term}} \right]$$

$$\nabla \times \frac{\nabla p_e}{n_e e} = -\frac{k_B}{e} \frac{\nabla n_e \times \nabla T_e}{n_e}$$

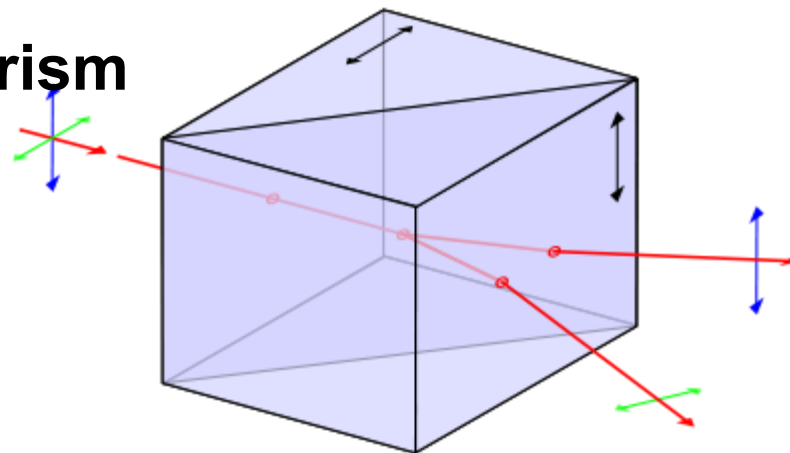


$$(\text{grad } n_e) \times (\text{grad } T_e) \longrightarrow \text{B field} \longrightarrow$$

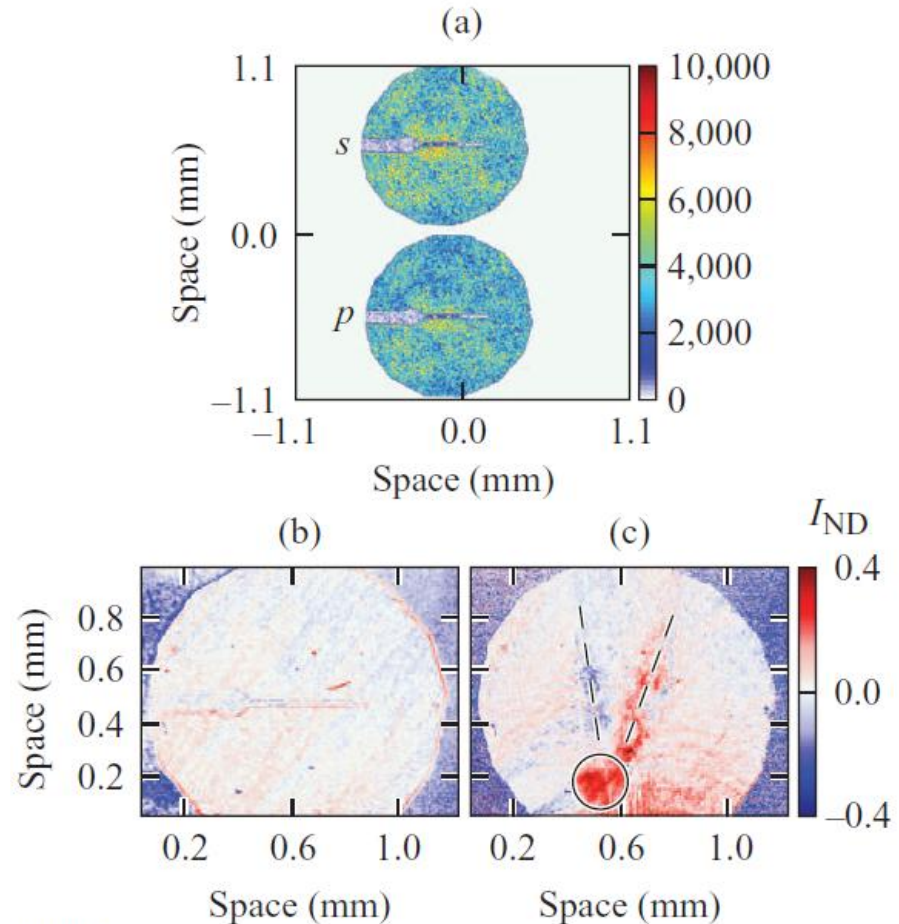
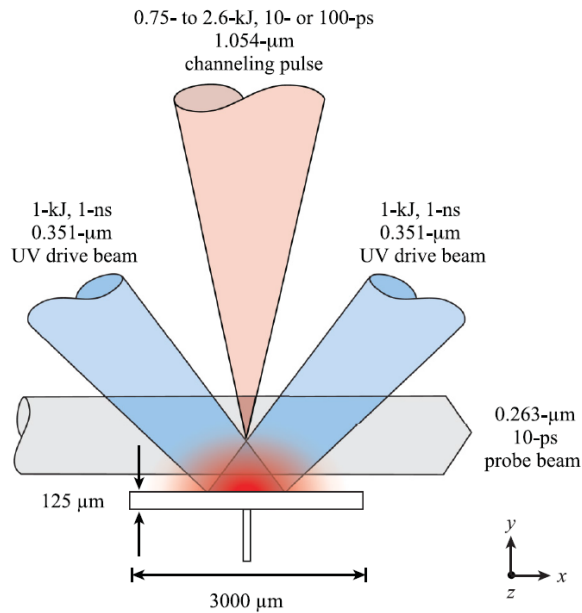
Polarimetry diagnostic can be used to measure the magnetic field



Wollaston prism

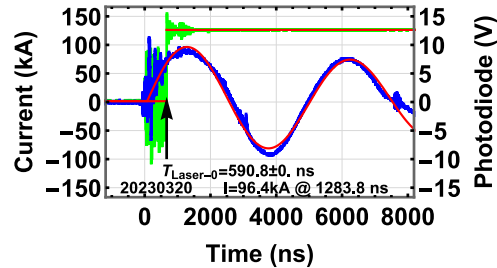


Self-generated field was suggested when multi-kilojoule high-intensity laser beams illuminated on an inhomogeneous plasma

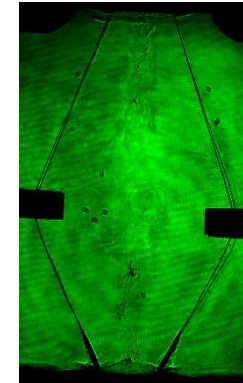
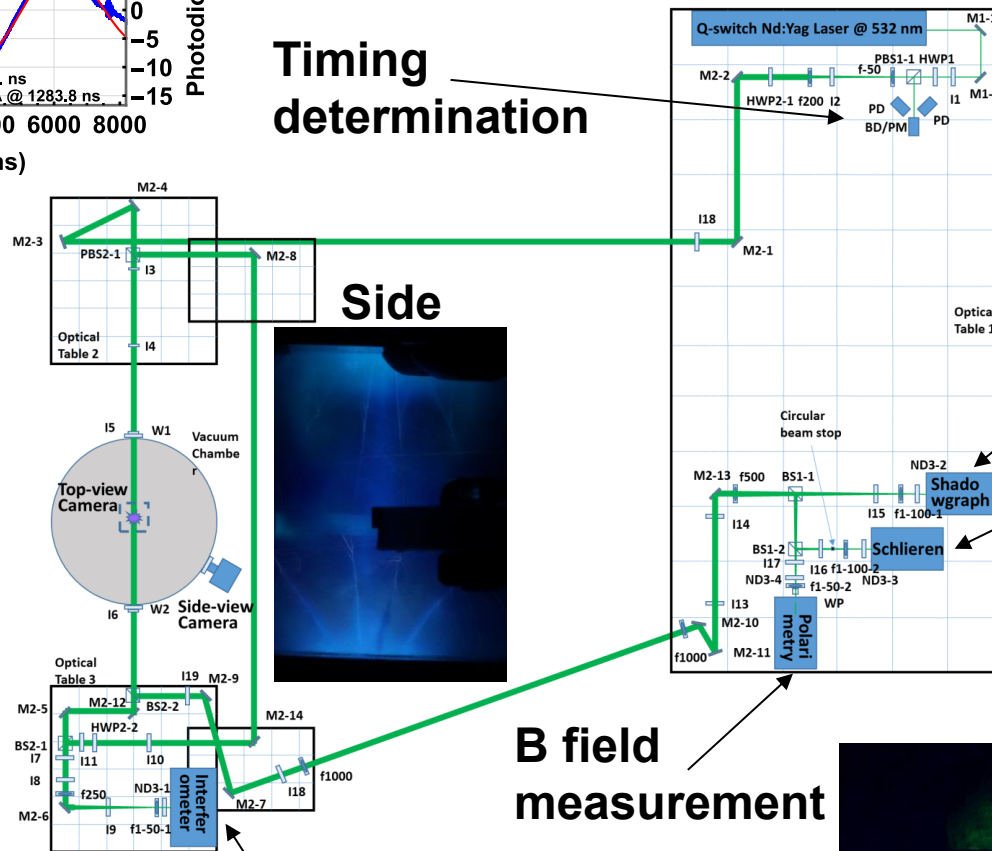


E23066J1

Time-resolved imaging system with temporal resolution in the order of nanoseconds was implemented

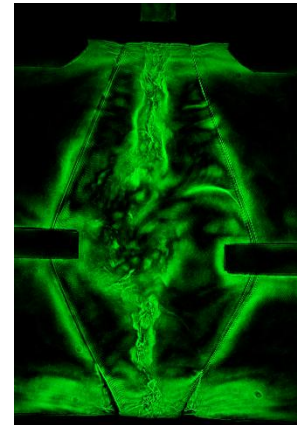


Timing determination

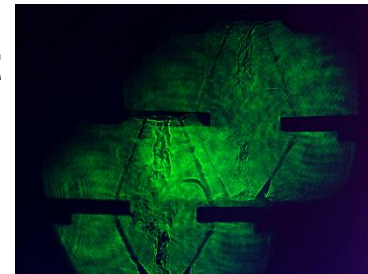


Plasma image

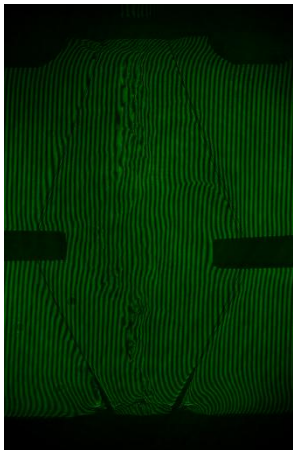
Plasma edge detection



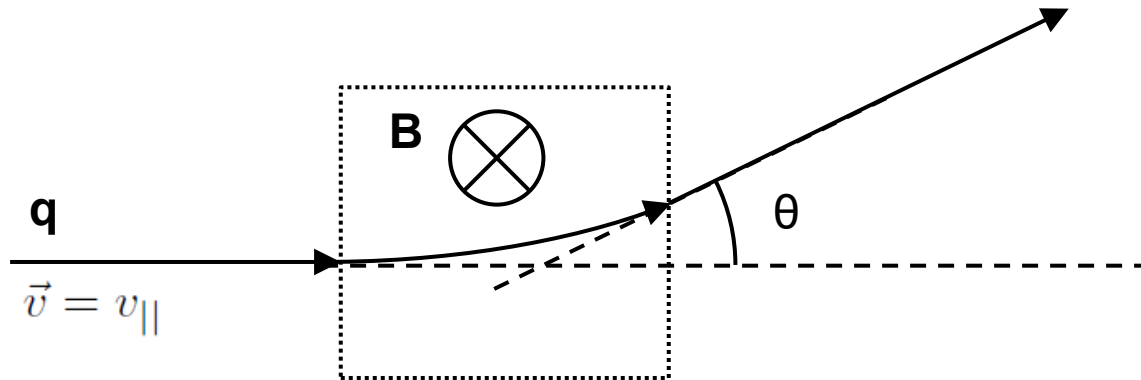
B field measurement



Density measurement



The magnetic field can be measured by measuring the deflected angle of charged particles

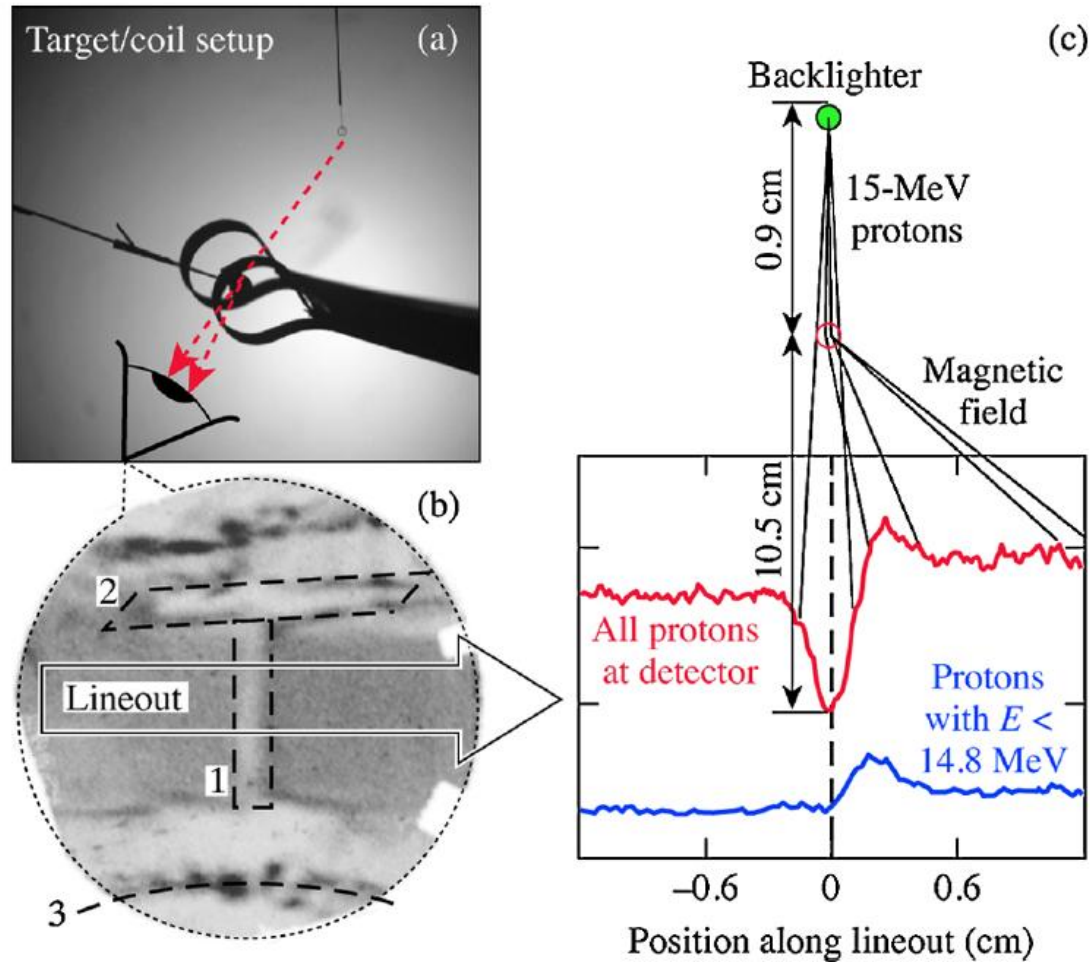


$$F_{\perp} = q\vec{v} \times \vec{B} = qv_{\parallel}B = m\frac{dv_{\perp}}{dt}$$

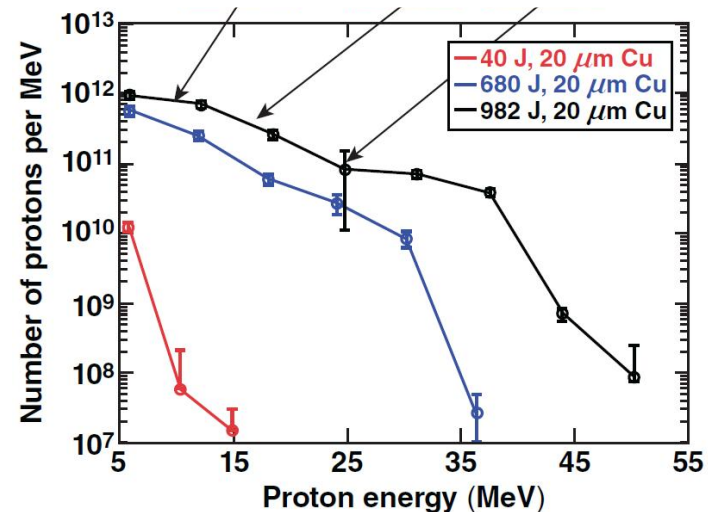
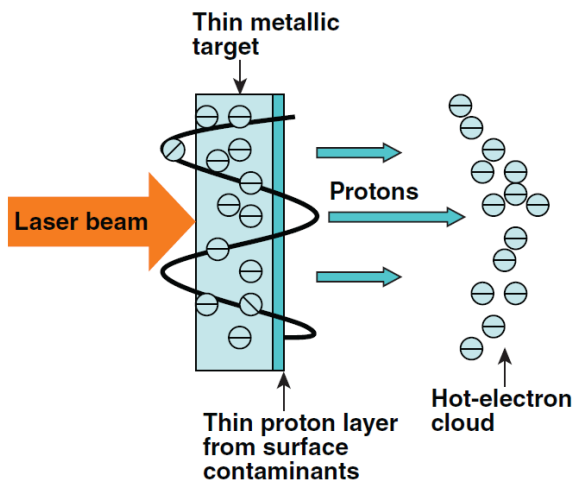
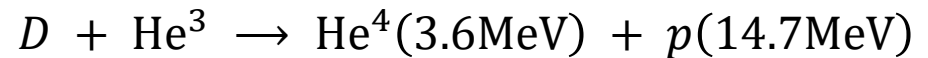
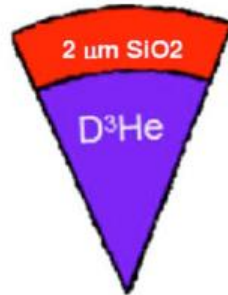
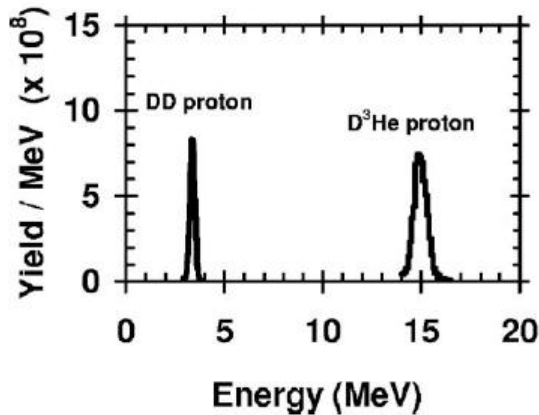
$$v_{\perp} = \int \frac{qv_{\parallel}B}{m} dt = \frac{qv_{\parallel}}{m} \int B dt \frac{dx}{dx} = \frac{qv_{\parallel}}{m} \int \frac{B}{v_{\parallel}} dx = \frac{q}{m} \int B dx$$

$$\tan \theta = \frac{v_{\perp}}{v_{\parallel}} = \frac{q}{mv_{\parallel}} \int B dx = \frac{q}{\sqrt{2mE}} \int B dx \qquad \int B dx = \frac{\sqrt{2mE}}{q} \tan \theta$$

Magnetic field was measured using protons



Protons can be generated from fusion product or copper foil illuminated by short pulse laser



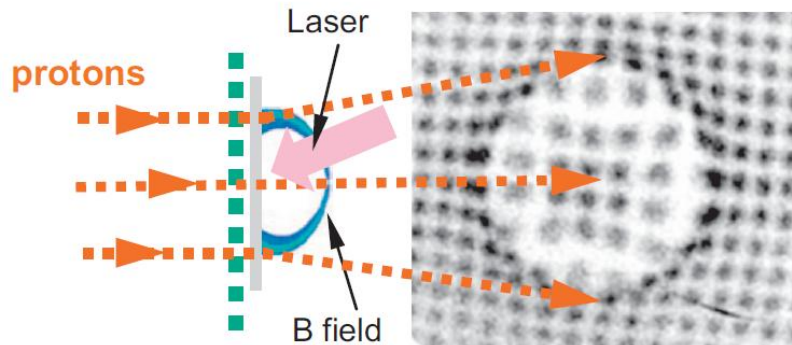
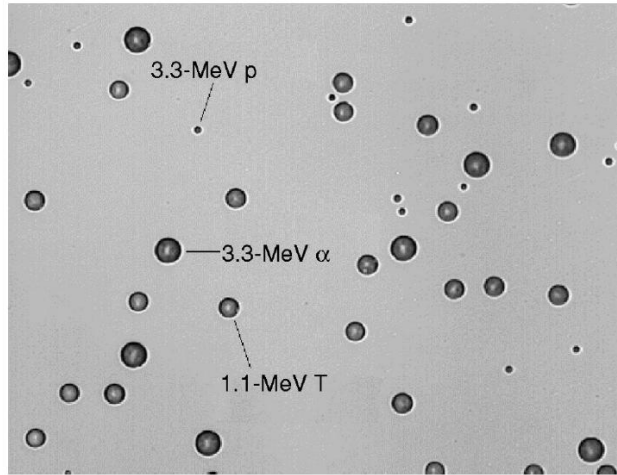
Target normal sheath acceleration (TNSA)

C. K. Li *et al.*, Rev. Sci. Instrum. **77**, 10E725 (2006)
L. Gao, PhD Thesis

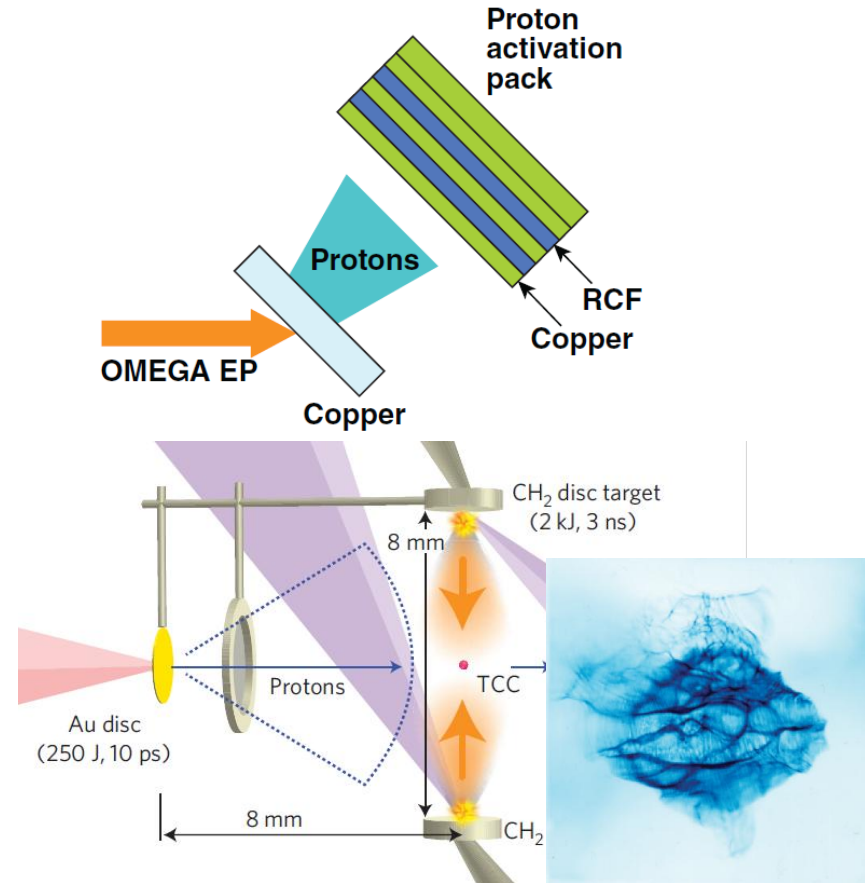
Protons can leave tracks on CR39 or film



CR 39



Radiochromic film pack



- F. H. Seguin *et al.*, Rev. Sci. Instrum. **74**, 975 (2003)
 C. K. Li *et al.*, Phys. Plasmas **16**, 056304 (2009)
 L. Gao, PhD Thesis
 N. L. Kugland *et al.*, Nature Phys. B, 809 (2012)

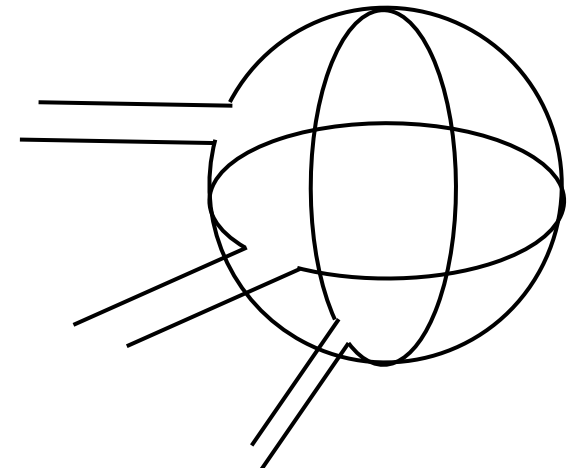
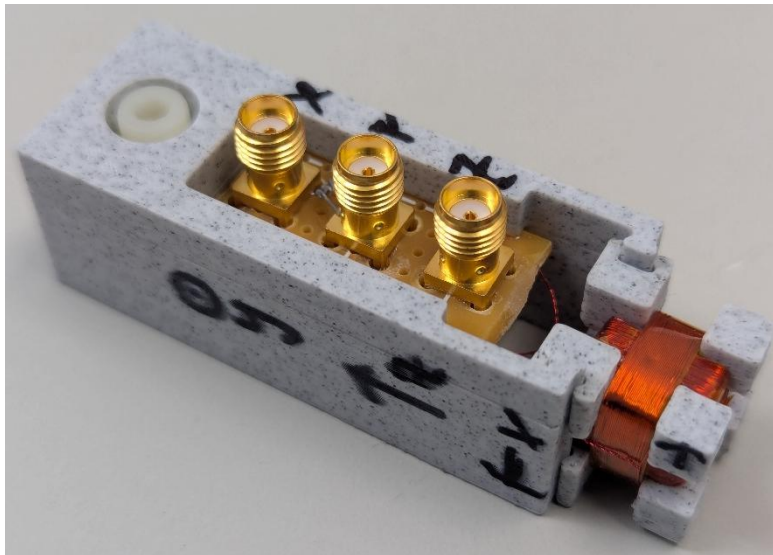
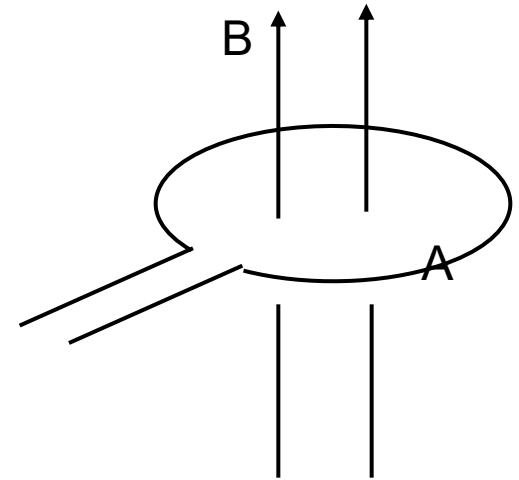
Time dependent magnetic field can be measured using B-dot probe



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

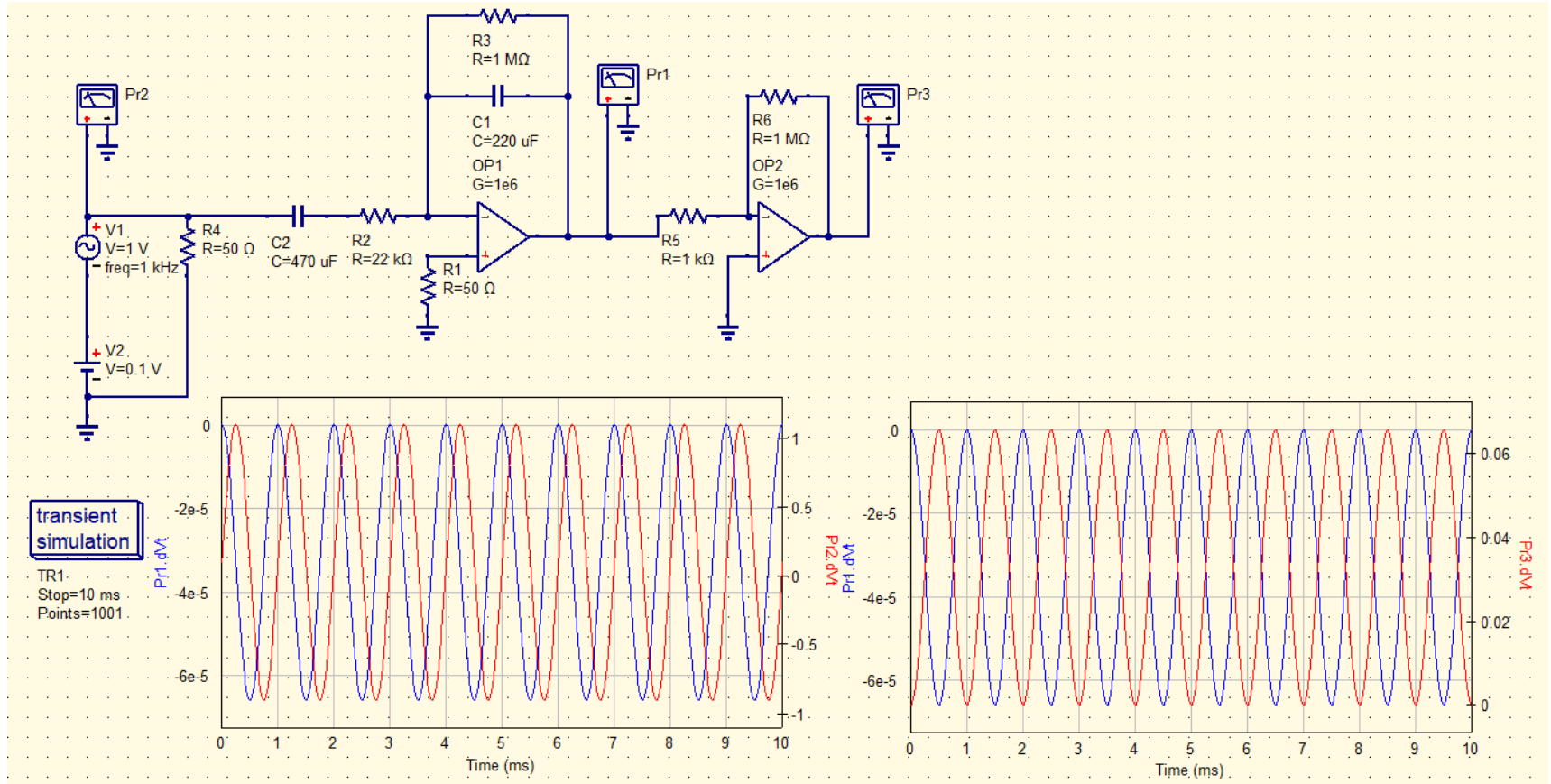
$$\int d\vec{A} \nabla \times \vec{E} = \oint \vec{E} d\vec{l} = V = - \int d\vec{A} \frac{\partial}{\partial t} \vec{B}$$

$$V \sim -A \frac{\partial B}{\partial t} \quad B = - \int \frac{V}{A} dt \sim -\frac{1}{A} \int V dt$$

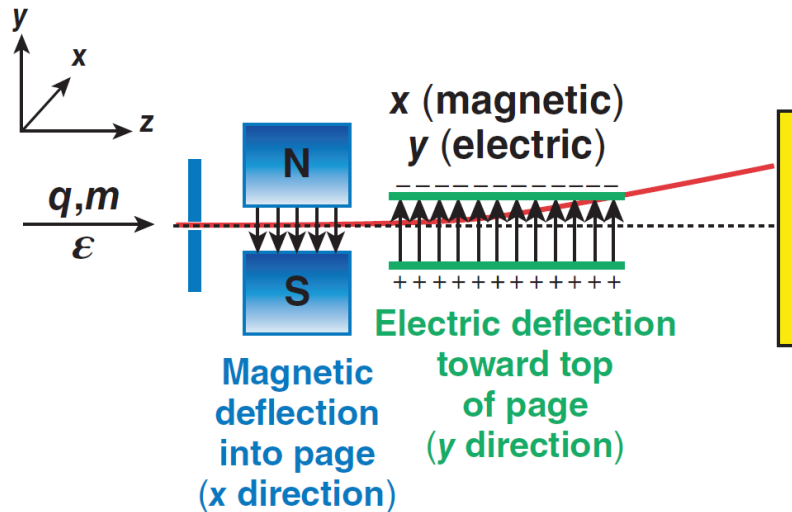


Courtesy by 林耕宇.

The signal from the B-dot probe is integrated and amplified



A Thomson parabola uses parallel electric and magnetic fields to deflect particles onto parabolic curves that resolve q/m



- Deflection caused by magnetic field $\sim q/p$
- Deflection caused by electric field $\sim q/KE$
- Ion traces form parabolic curves on detector plane

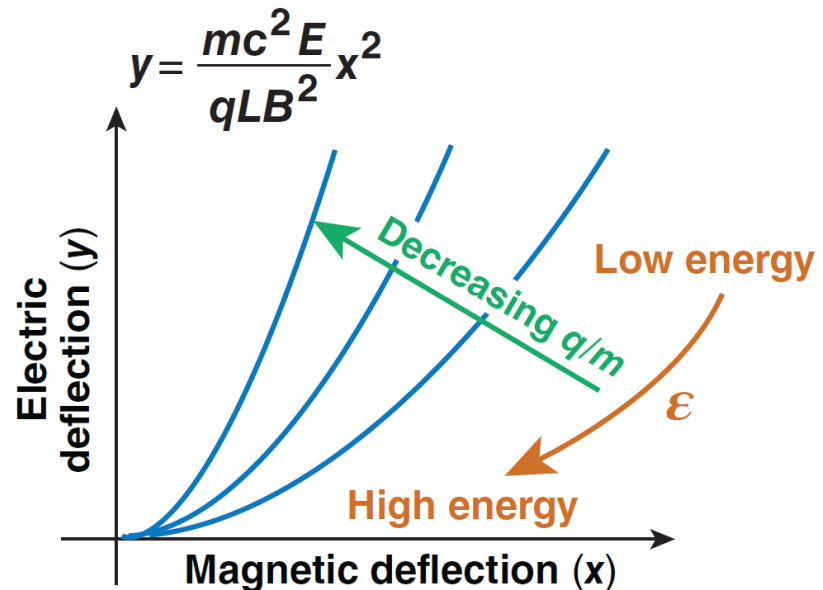
$$\tan \Delta\theta_x = \Delta\theta_x = \frac{qBL}{c\sqrt{2m\epsilon}}$$

$$y \text{ deflection} \quad \epsilon = \frac{q^2 B^2 L^2}{c^2 2m \Delta\theta_x^2}$$

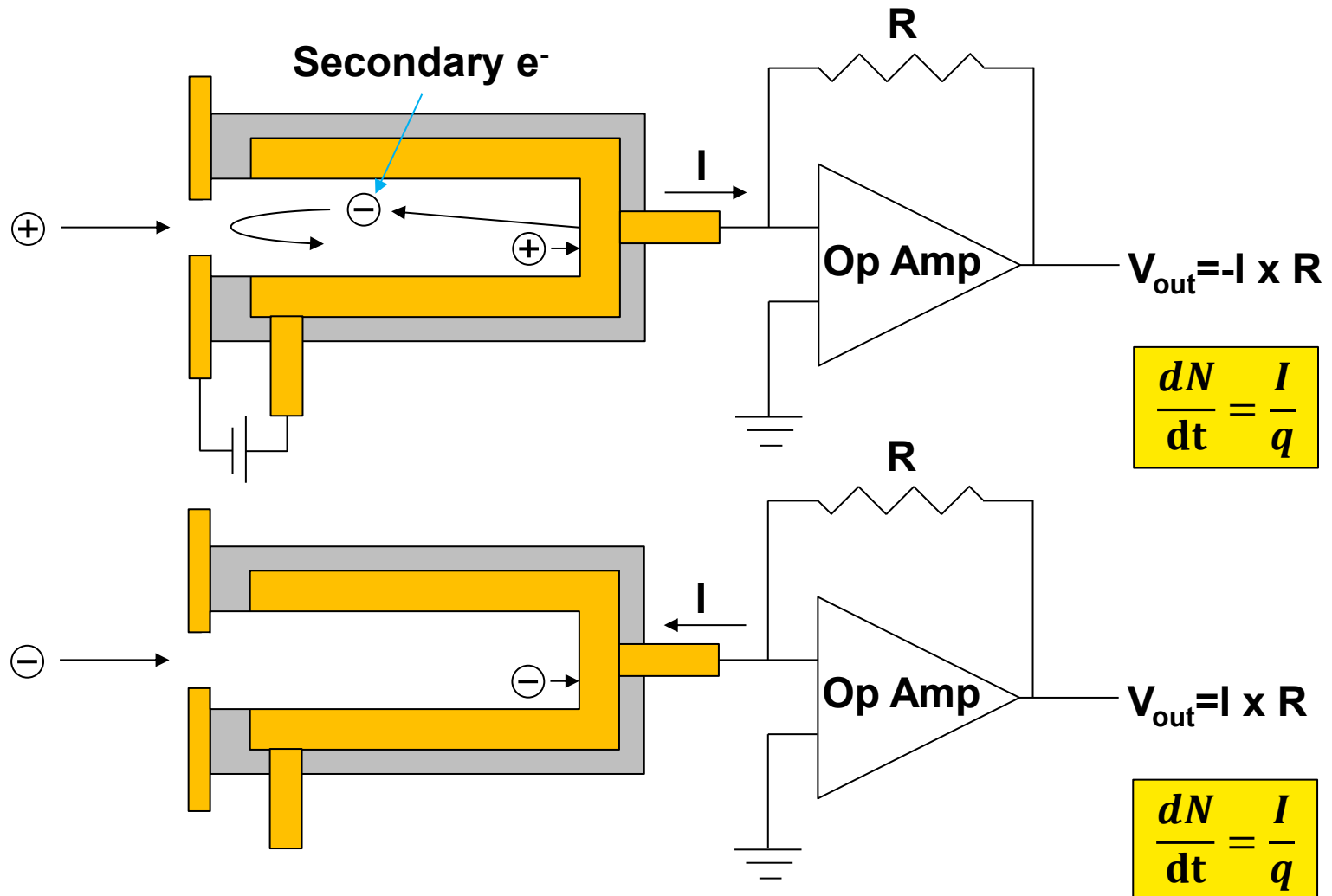
$$F_{\perp} = qE$$

$$\Delta m V_y = qE\tau = \frac{qEL}{v}$$

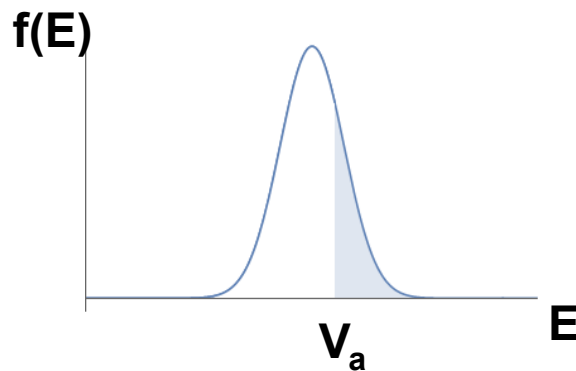
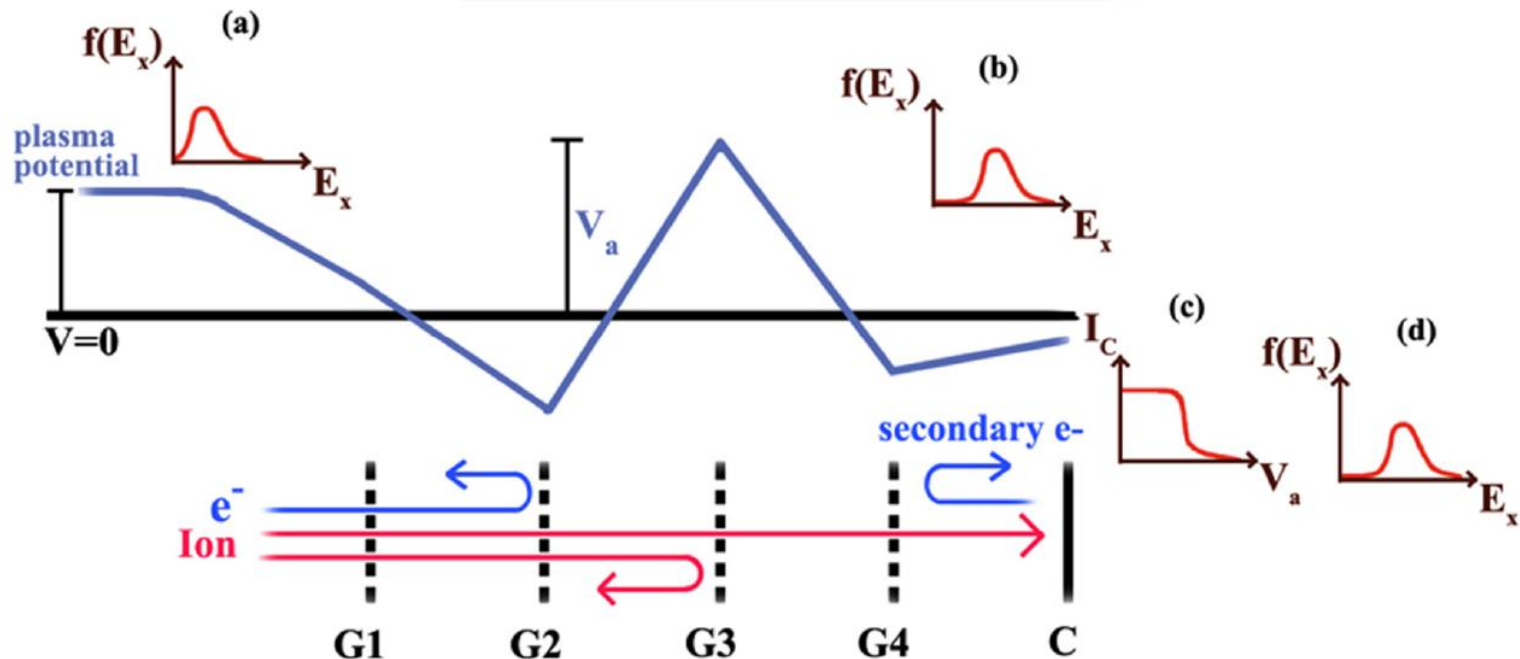
$$\tan \theta_y \sim \theta_y = \frac{\Delta m V_y}{mV} = \frac{qEL}{2\epsilon}$$



A faraday cup measures the flux of charge particles



Retarding potential analyzer measures the energy / velocity distribution function



The photon energy spectrum provides valuable information

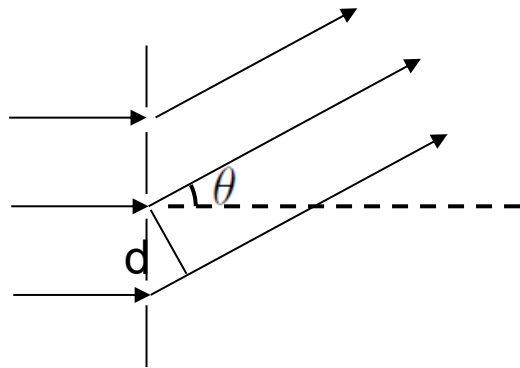


- **Plasma conditions can be determined from the photon spectrum**
 - visible light: absorption and laser-plasma interactions
 - x rays: electron temperature, density, plasma flow, material mixing
- **There are three basic tools for determining the spectrum detected**
 - filtering
 - grating spectrometer
 - Bragg spectrometer

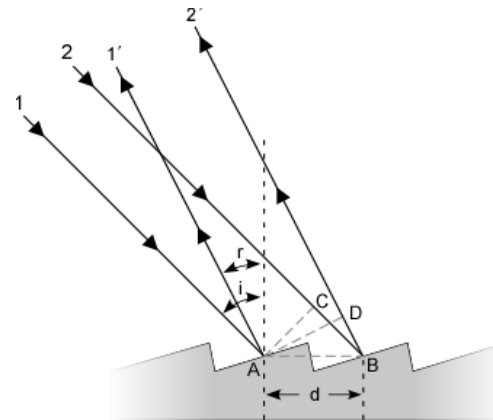
Spectrum can be obtained using grating



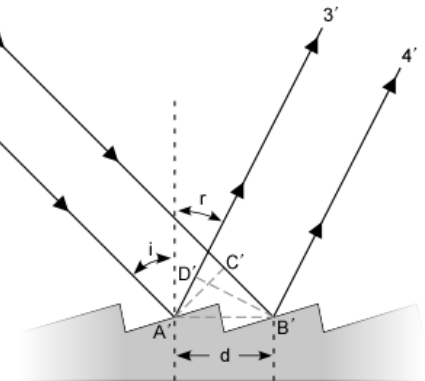
- Grating is used to disperse the light



$$d \sin \theta = m\lambda$$

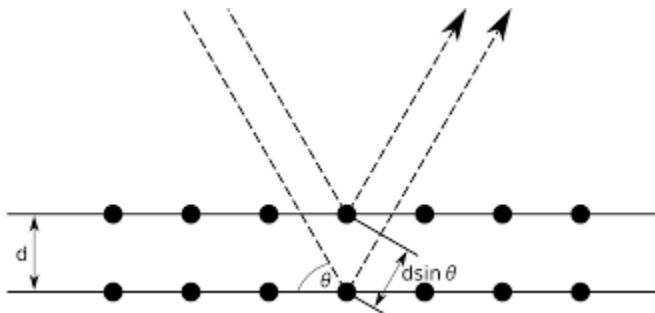


$$n\lambda = d(\sin(i) + \sin(r))$$



$$n\lambda = d(\sin(i) - \sin(r))$$

- Bragg condition in the crystal is used for X-ray.

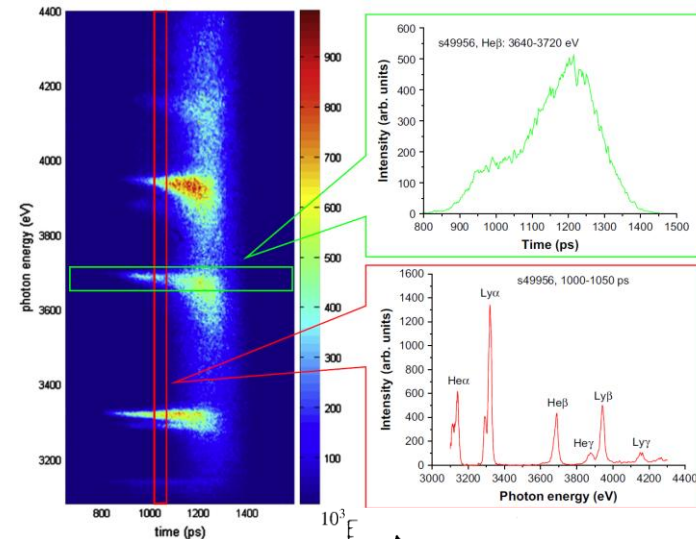
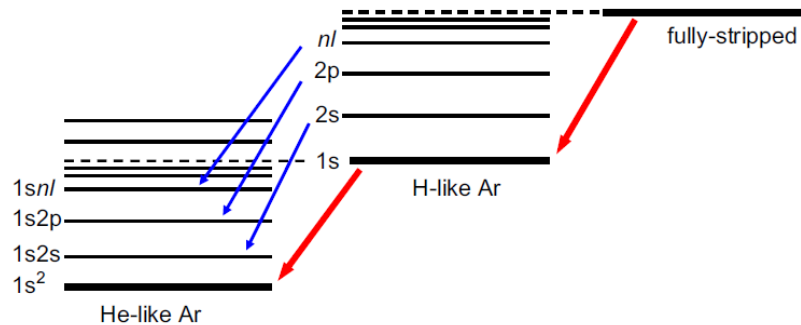


$$2d \sin \theta = m\lambda$$

Temperature and density can be obtained from the emission

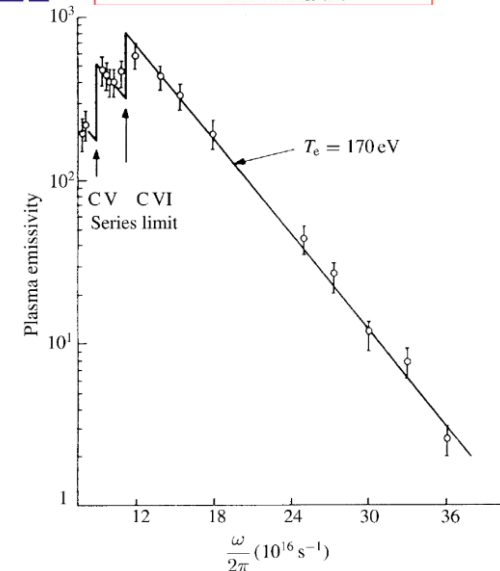


Line emission



Bremsstrahlung emission

$$\eta_{\nu} = \frac{16\pi}{3\sqrt{6\pi}} \frac{e^6}{m_e^2 c^3} \frac{Z_i^2 n_e}{\sqrt{k_B T_e / m_e A m_p}} \exp\left(-\frac{h\nu}{k_B T_e}\right)$$



Information of x-ray transmission or reflectivity over a surface can be obtained from the Center for X-Ray Optics



- http://henke.lbl.gov/optical_constants/



X-Ray Database

- Nanomagnetism
- X-Ray Microscopy
- EUV Lithography
- EUV Mask Imaging
- Reflectometry
- Zoneplate Lenses
- Coherent Optics
- Nanofabrication
- Optical Coatings
- Engineering
- Education
- Publications
- Contact



The Center for X-Ray Optics is a multi-disciplined research group within Lawrence Berkeley National Laboratory's (LBNL)

X-Ray Interactions With Matter

Introduction

Access the [atomic scattering factor](#) files.
Look up [x-ray properties of the elements](#).
The [index of refraction](#) for a compound material.
The x-ray [attenuation length](#) of a solid.

X-ray transmission

- Of a [solid](#).
- Of a [gas](#).

X-ray reflectivity

- Of a [thick mirror](#).
- Of a [single layer](#).
- Of a [bilayer](#).
- Of a [multilayer](#).

The diffraction efficiency of a [transmission grating](#).

Related calculations:

- Synchrotron [bend magnet radiation](#).

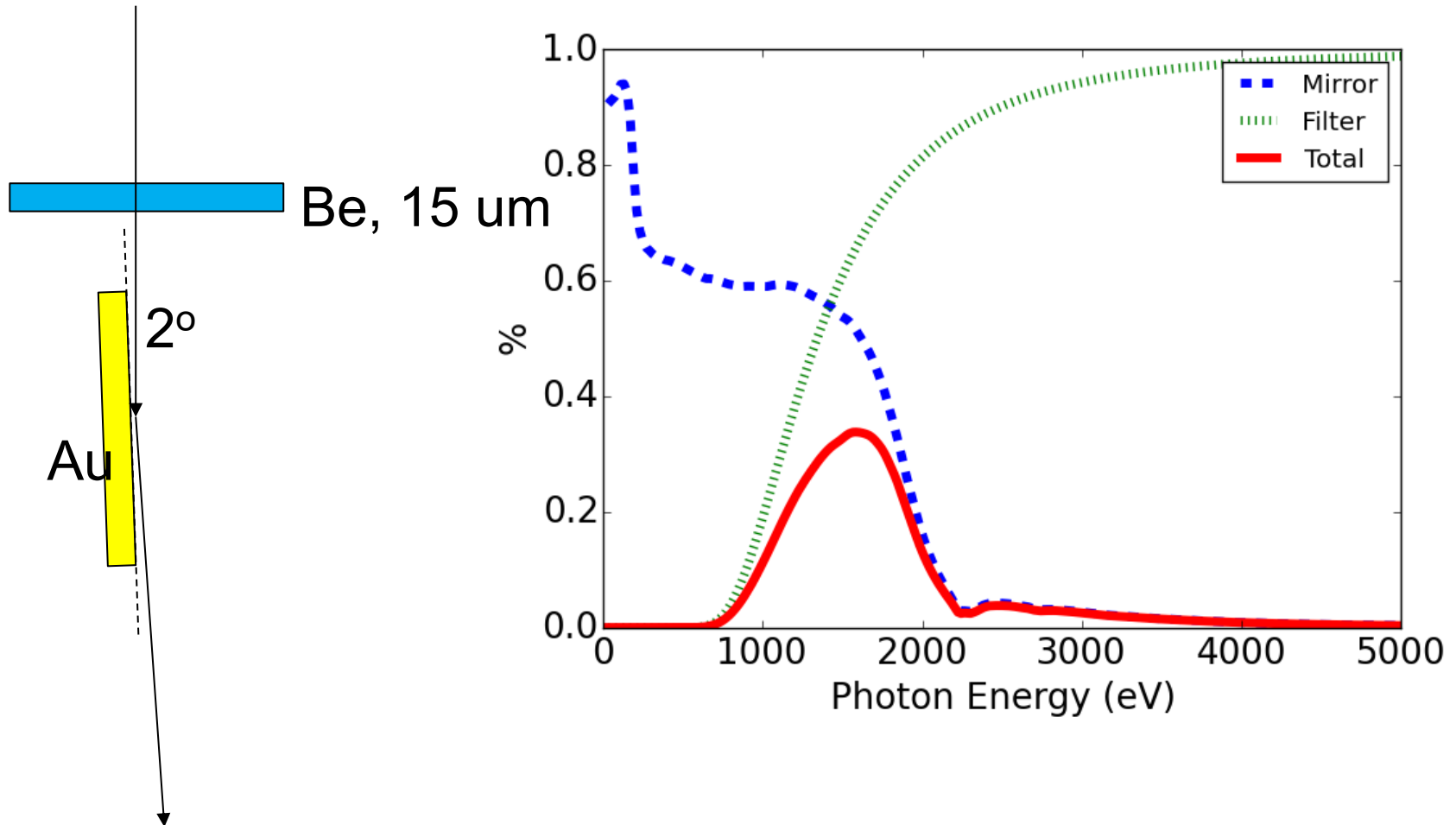
[Other x-ray web resources.](#)

[X-ray Data Booklet](#)

Reference

B.L. Henke, E.M. Gullikson, and J.C. Davis. *X-ray interactions: photoabsorption, scattering, transmission, and reflection at E=50-30000 eV, Z=1-92*, Atomic Data and Nuclear Data Tables Vol. **54** (no.2), 181-342 (July 1993).

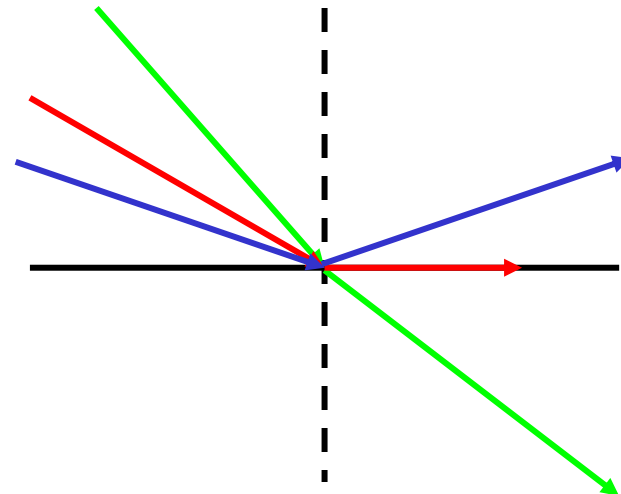
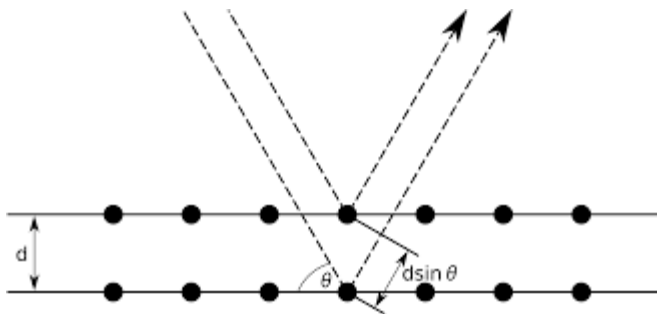
A band pass filter is obtained by combining a filter and a mirror



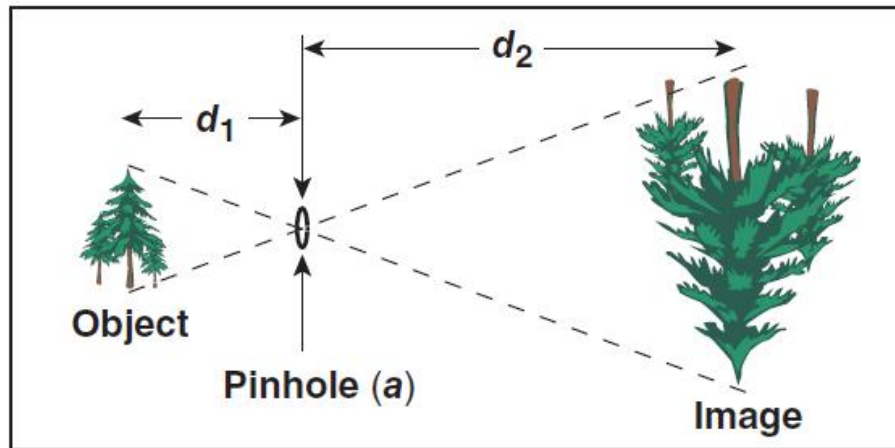
X rays can not be concentrated by lenses



- X-ray refractive indices are less than unity, $n \lesssim 1$
- For those with lower refractive indices, the absorption is also strong
- X-ray mirrors can be made through
 - Bragg reflection
 - External total reflection with a small grazing angle



The simplest imaging device is a pinhole camera



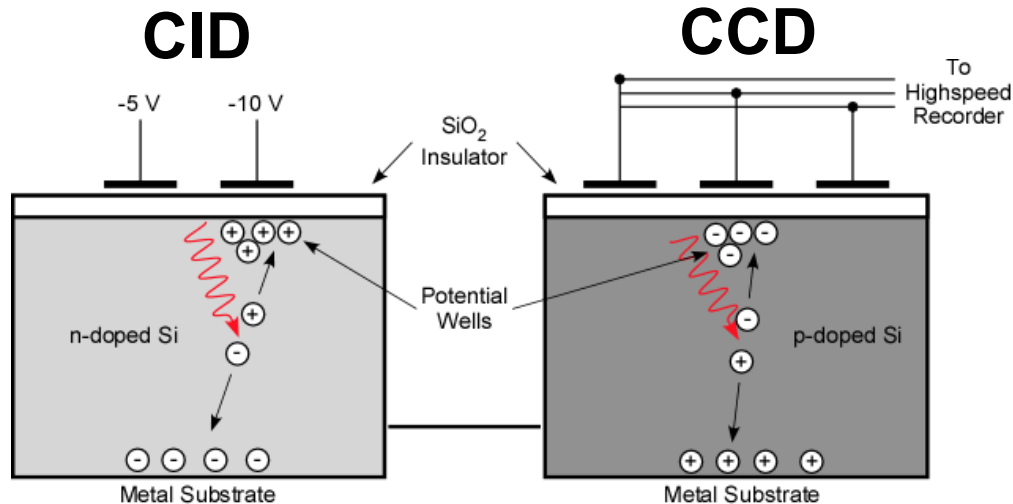
Kodak Brownie camera



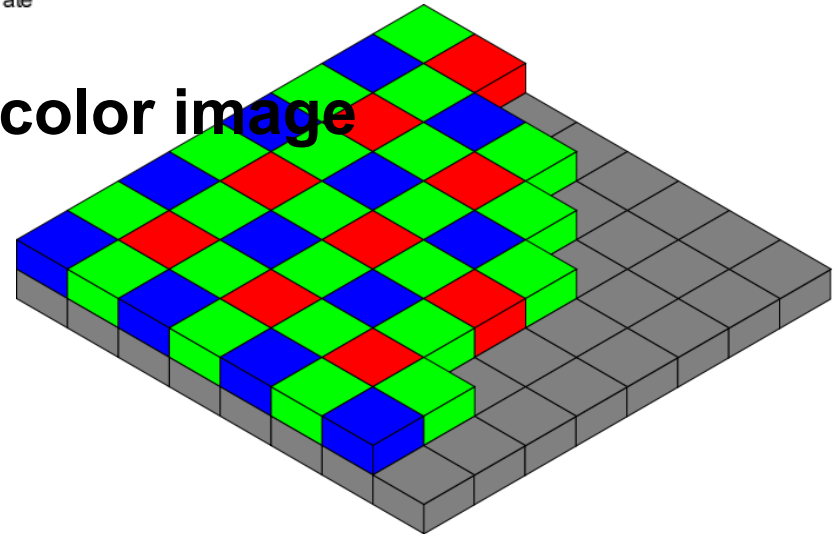
- Magnification = $\frac{d_2}{d_1}$
- Infinite depth of field (variable magnification)
- Pinhole diameter determines
 - resolution $\sim a$
 - light collection: $\Delta\Omega = \frac{\pi}{4} \frac{a^2}{d_1^2}$

Imaging optics (e.g., lenses) can be used for higher resolutions with larger solid angles.

2D images can be taken using charge injection device (CID) or charge coupled device (CCD)



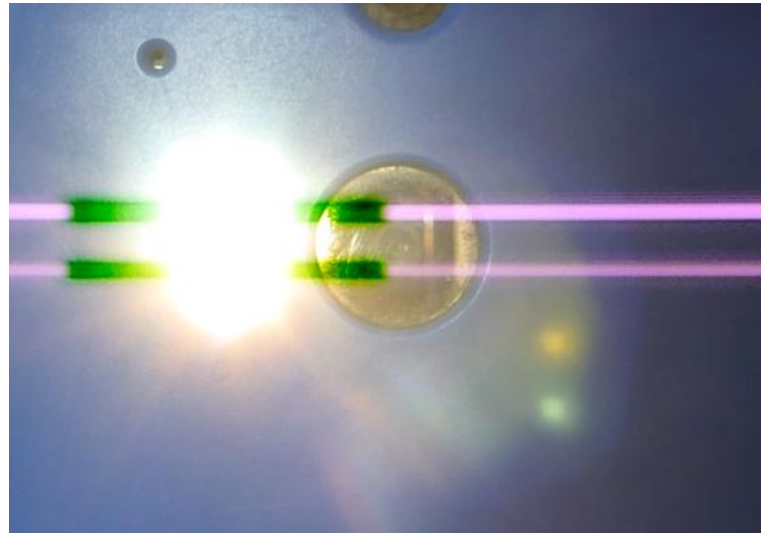
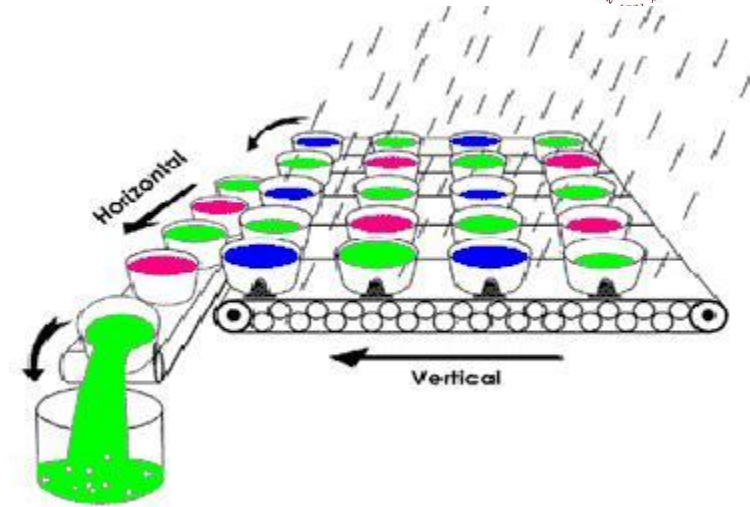
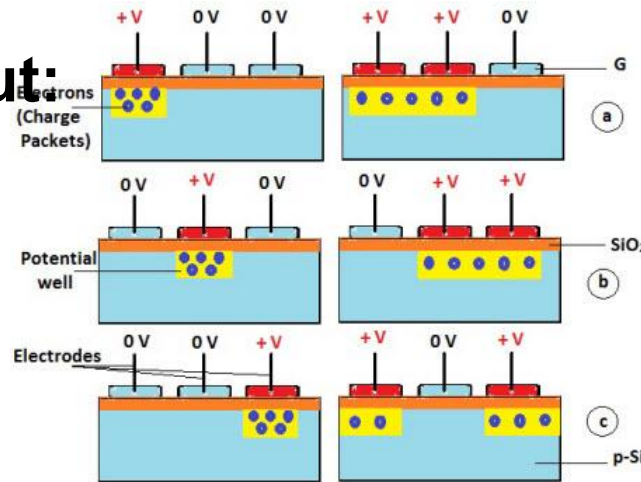
- Color mask is used for color image



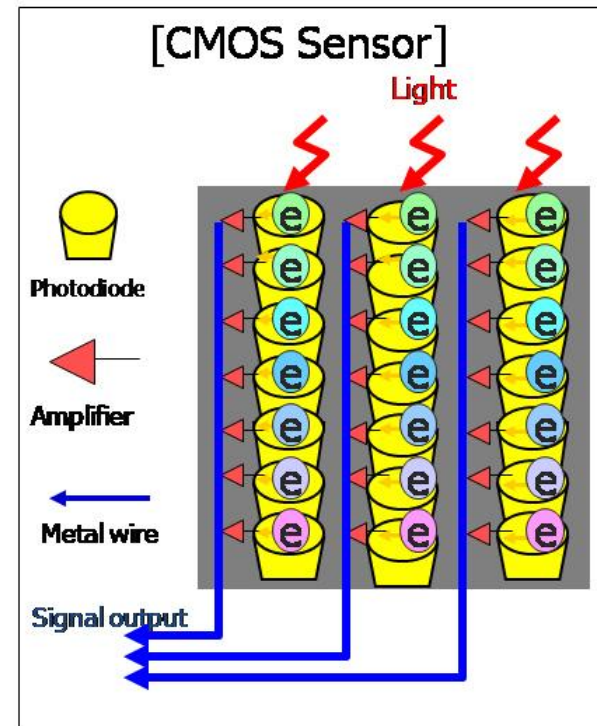
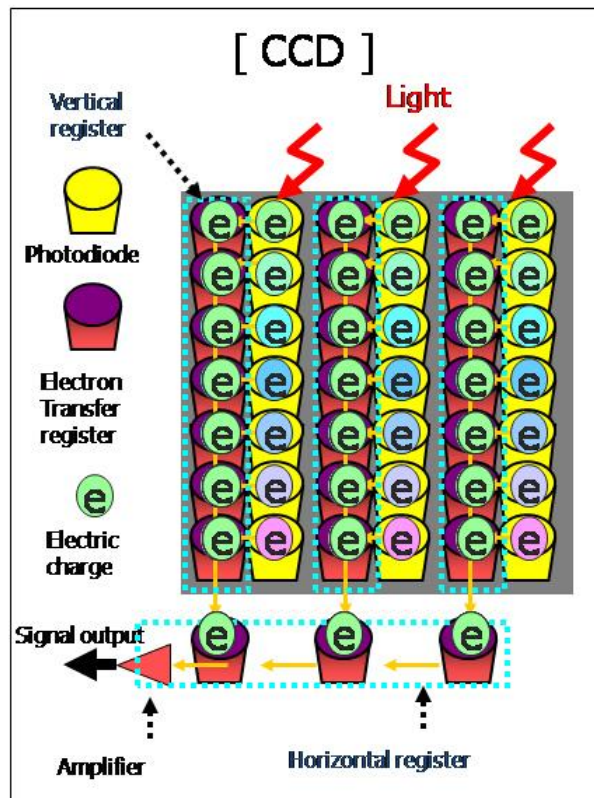
Charges are transferred along the array for readout in CCD



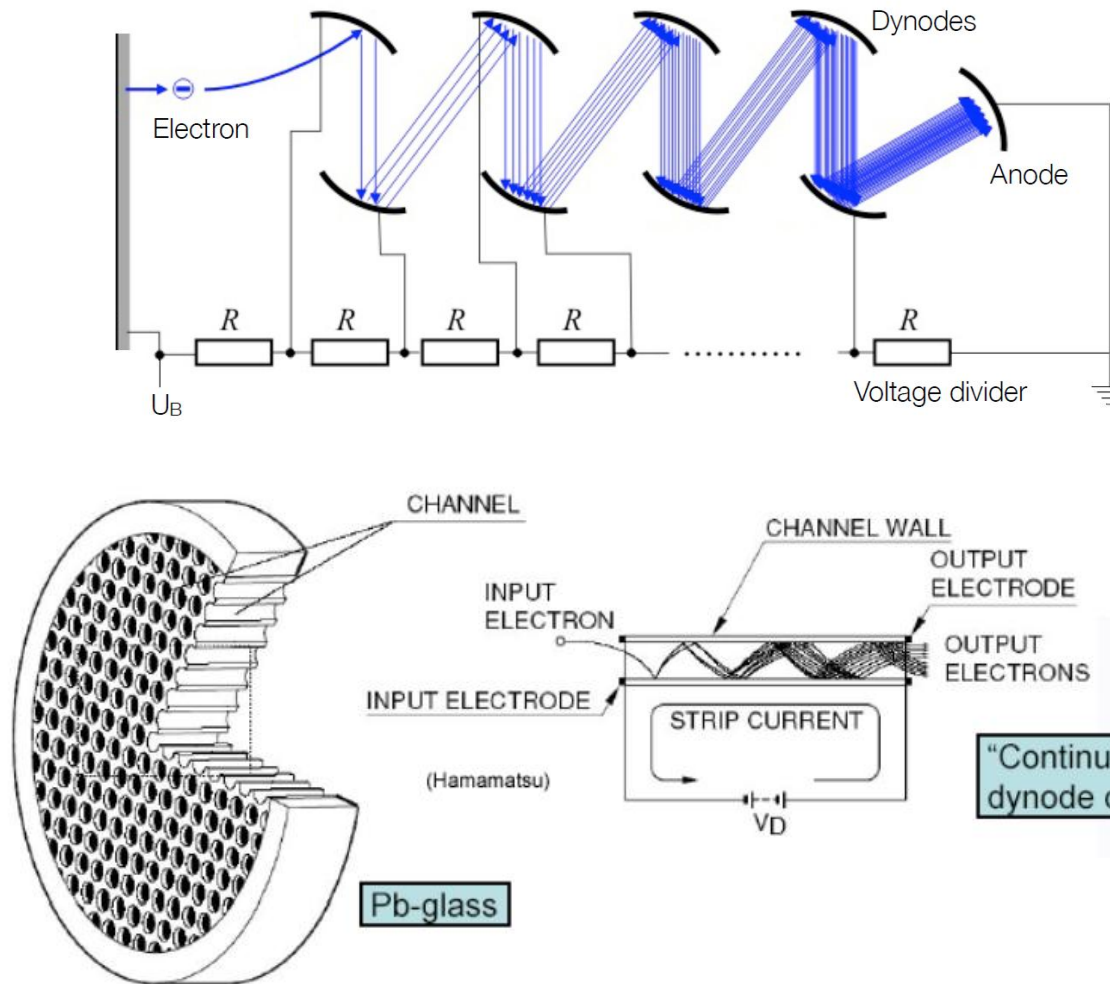
CCD readout:



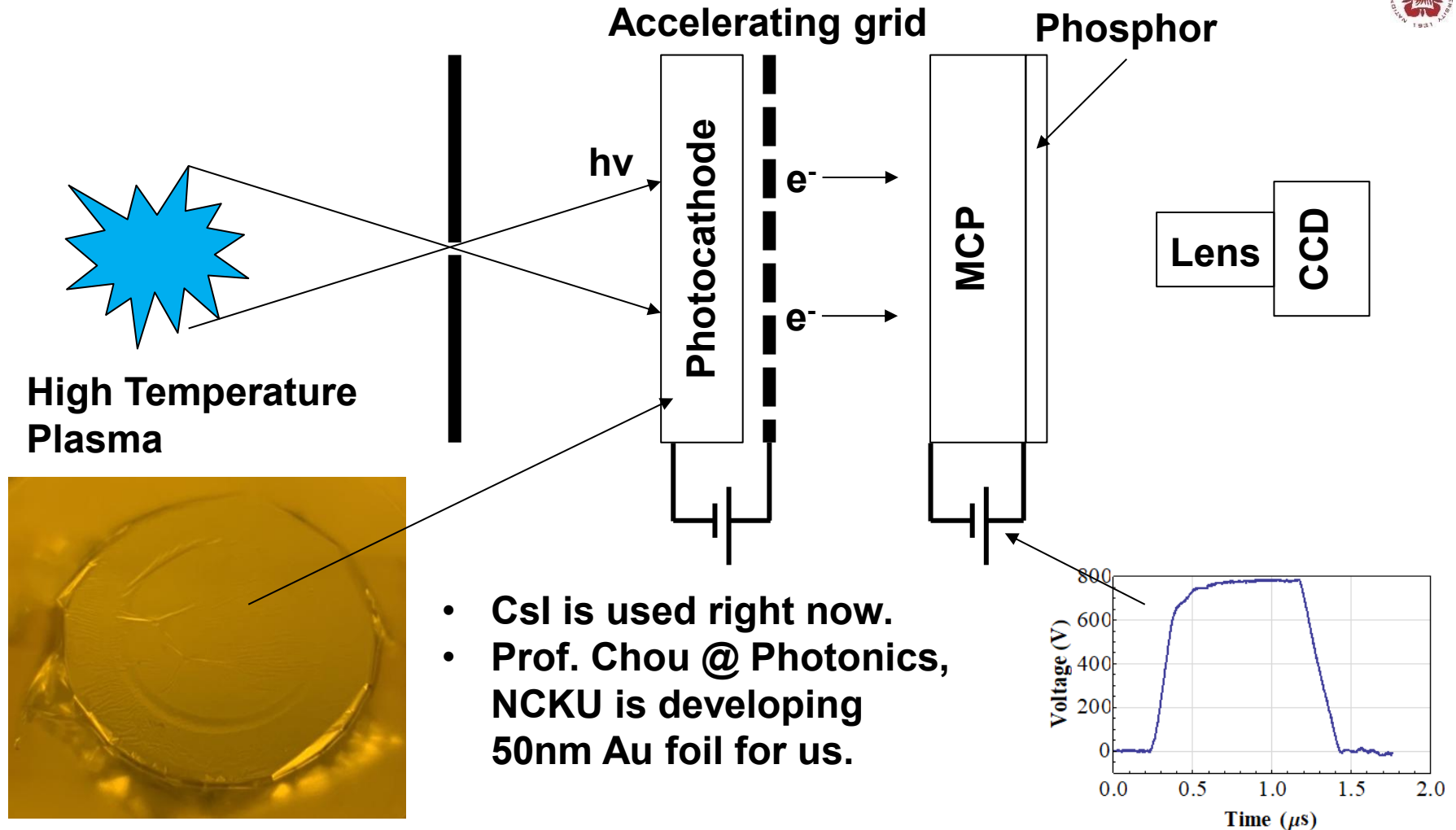
Signal is readout individually in CMOS sensor



The number of electrons can be increased through photomultipliers or microchannel plate (MCP)

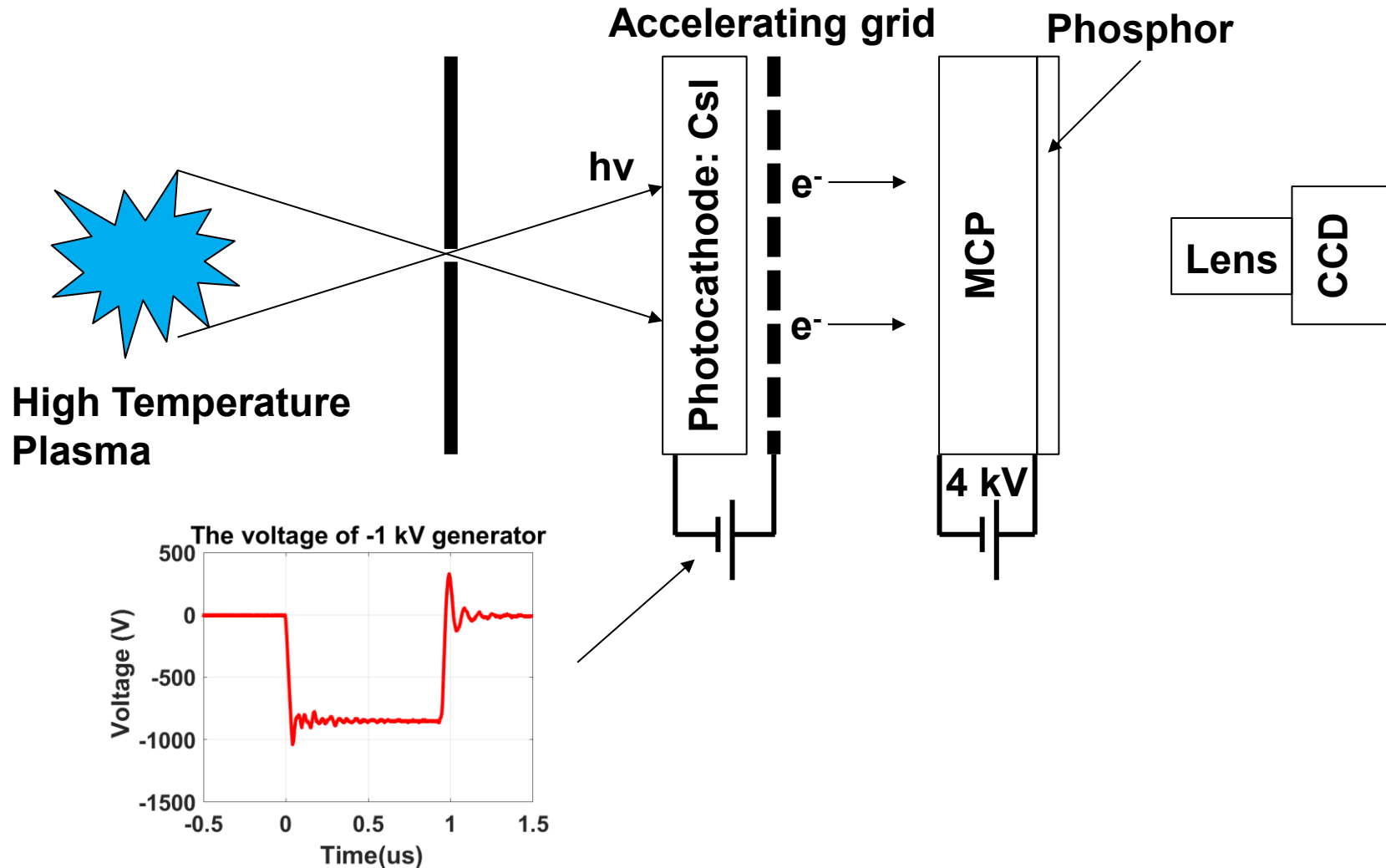


X-rays are imaged using photocathode, MCP, phosphor, and CCD



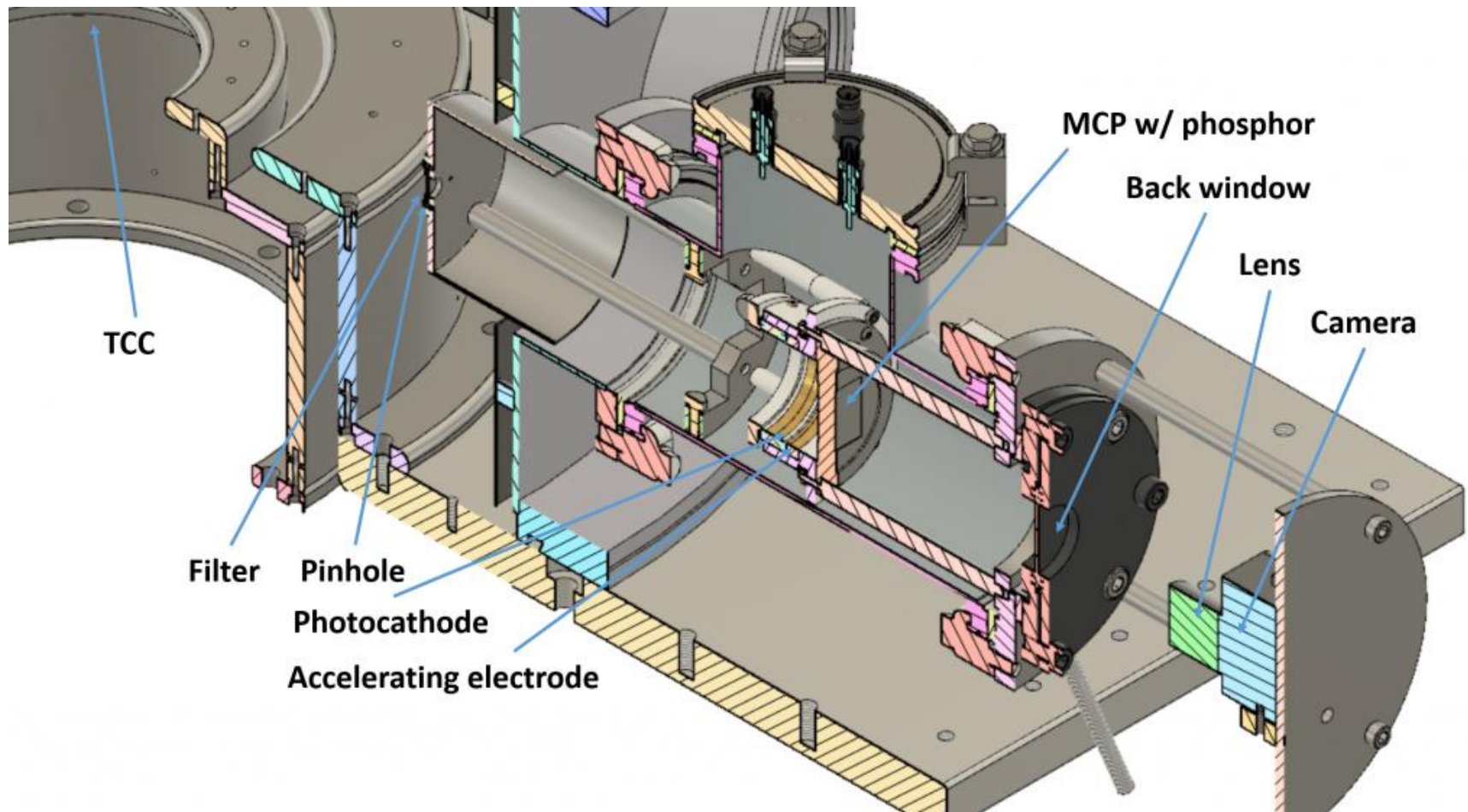
- Images can be gated using fast high voltage pulses.

A negative high-voltage pulse is used in our x-ray pinhole camera

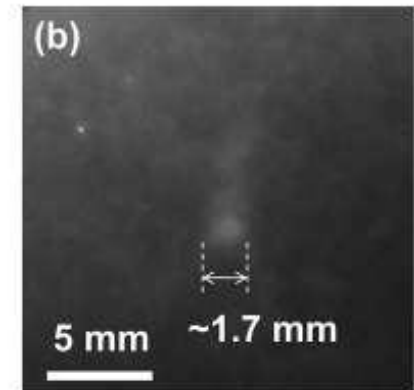
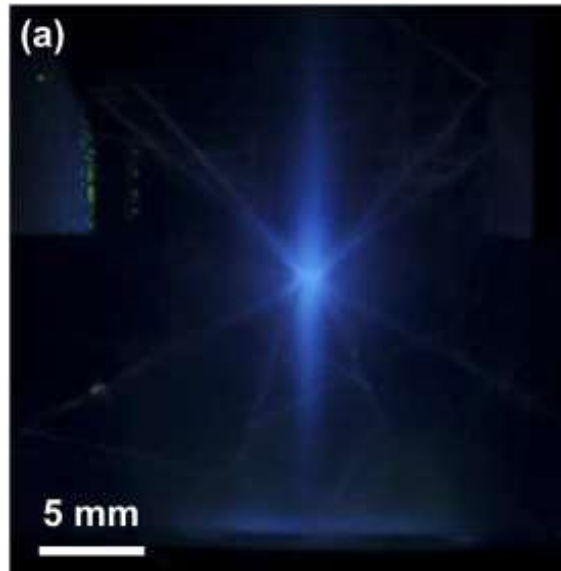
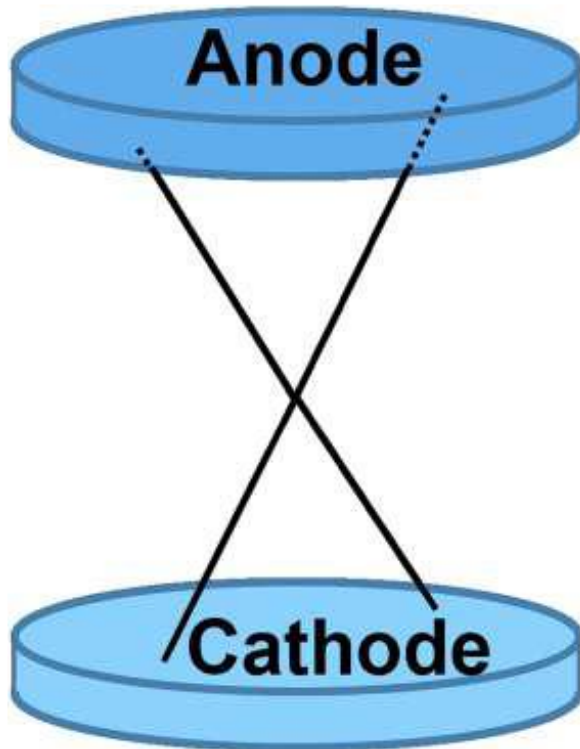


- The x-ray camera with a shutter opening time of ≤ 10 ns will be built.

A pinhole camera was designed and was built



Emission from an x pinch

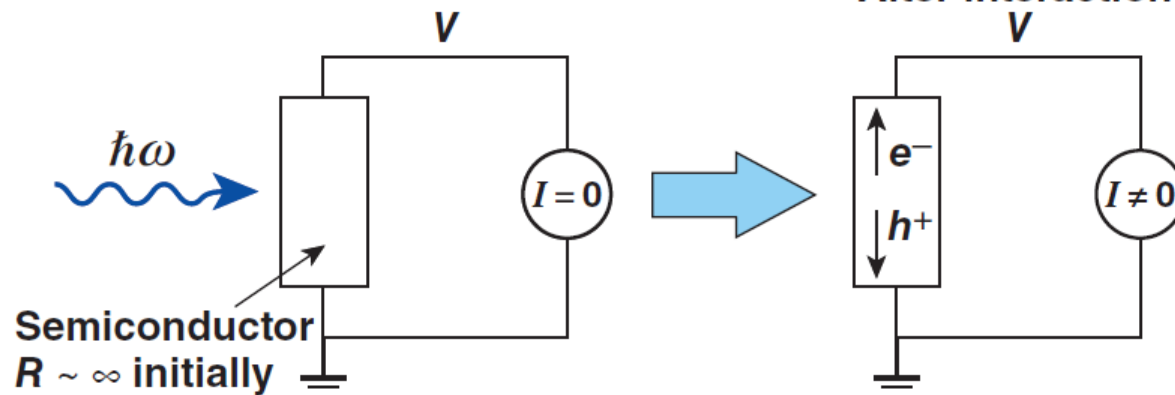


Electronic detectors provide rapid readout

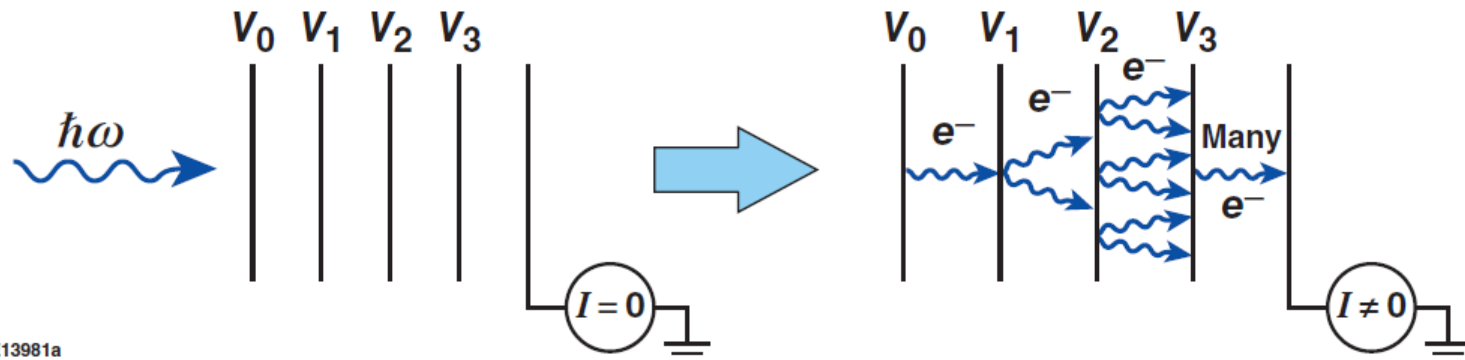


- Electronic detectors are typically semiconductors or ionization-based stacks (e.g., photomultipliers)

Semiconductor detectors



Ionization detectors

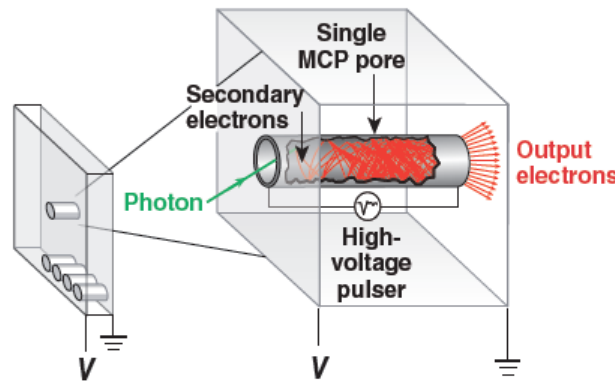


E13981a

A framing camera provides a series of time-gated 2-D images, similar to a movie camera



- The building block of a framing camera is a gated microchannel-plate (MCP) detector
- An MCP is a plate covered with small holes, each acts as a photomultiplier



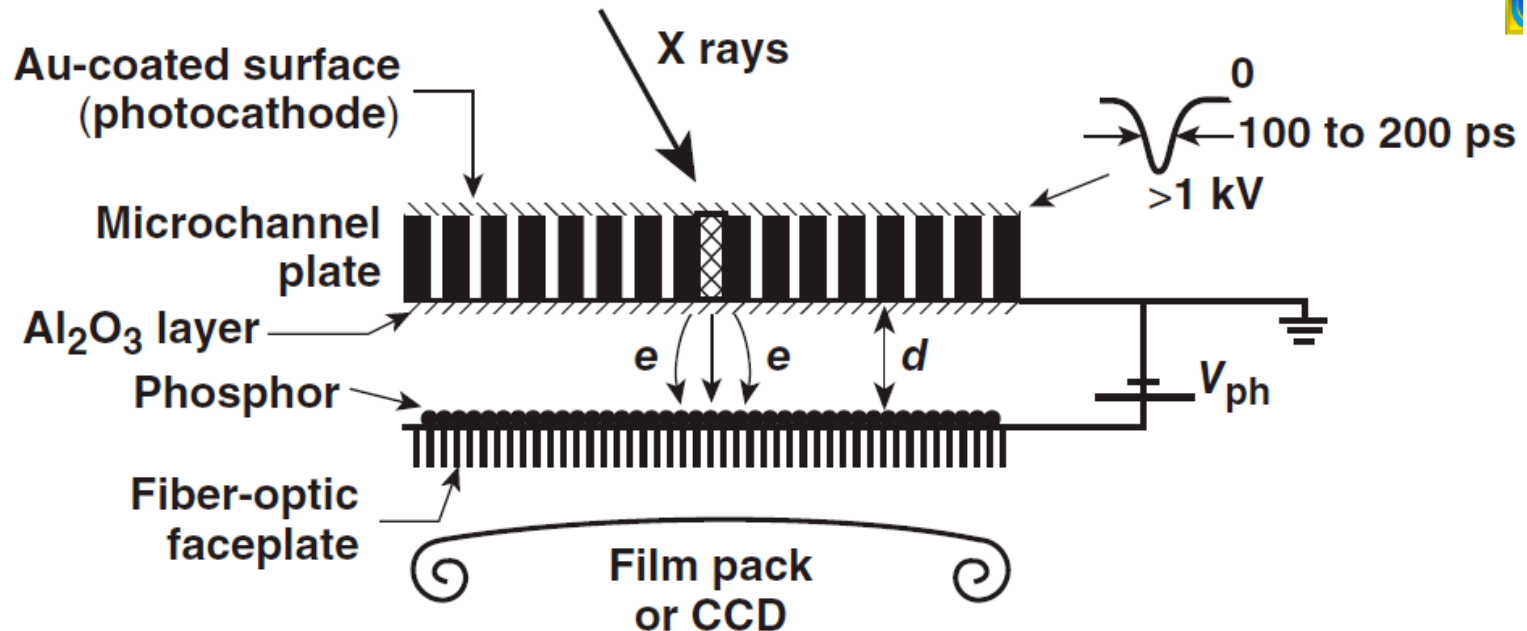
Multiple electrons are produced each time an electron or photon hits the wall

- A voltage pulse is sent down the plate, gating the detector



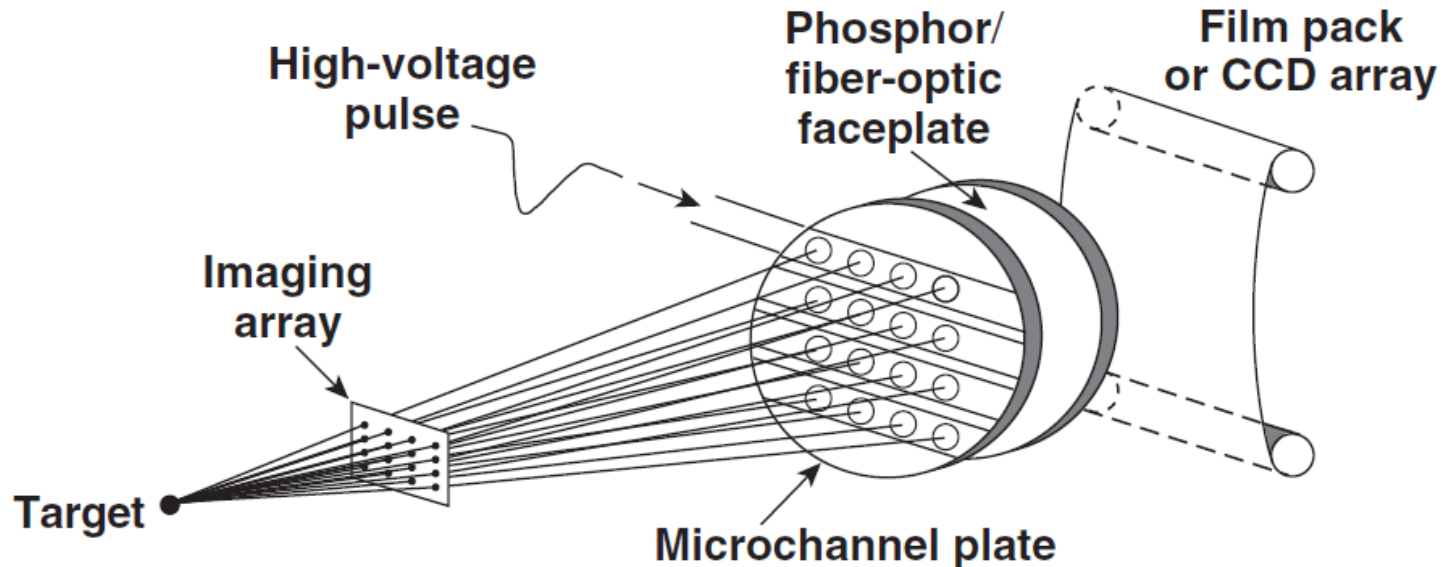
The detector is only on when the voltage pulse is present

A framing camera detector consists of a microchannel plate (MCP) in front of a phosphor screen



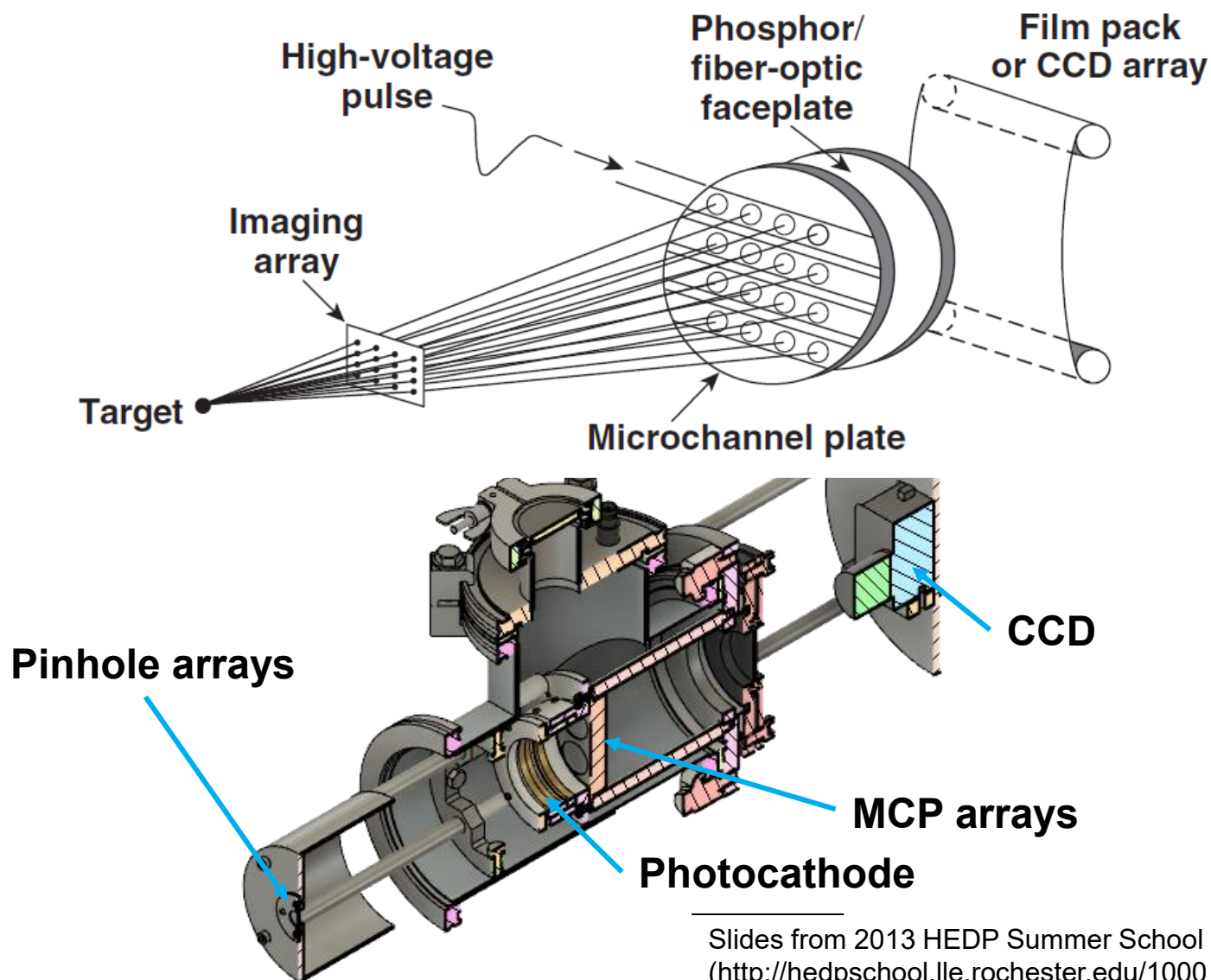
- Electrons are multiplied through MCP by voltage V_c
- Images are recorded on film behind phosphor
- Insulating Al_2O_3 layer allows for V_{ph} to be increased, thereby improving the spatial resolution of phosphor

Two-dimensional time-resolved images are recorded using x-ray framing cameras

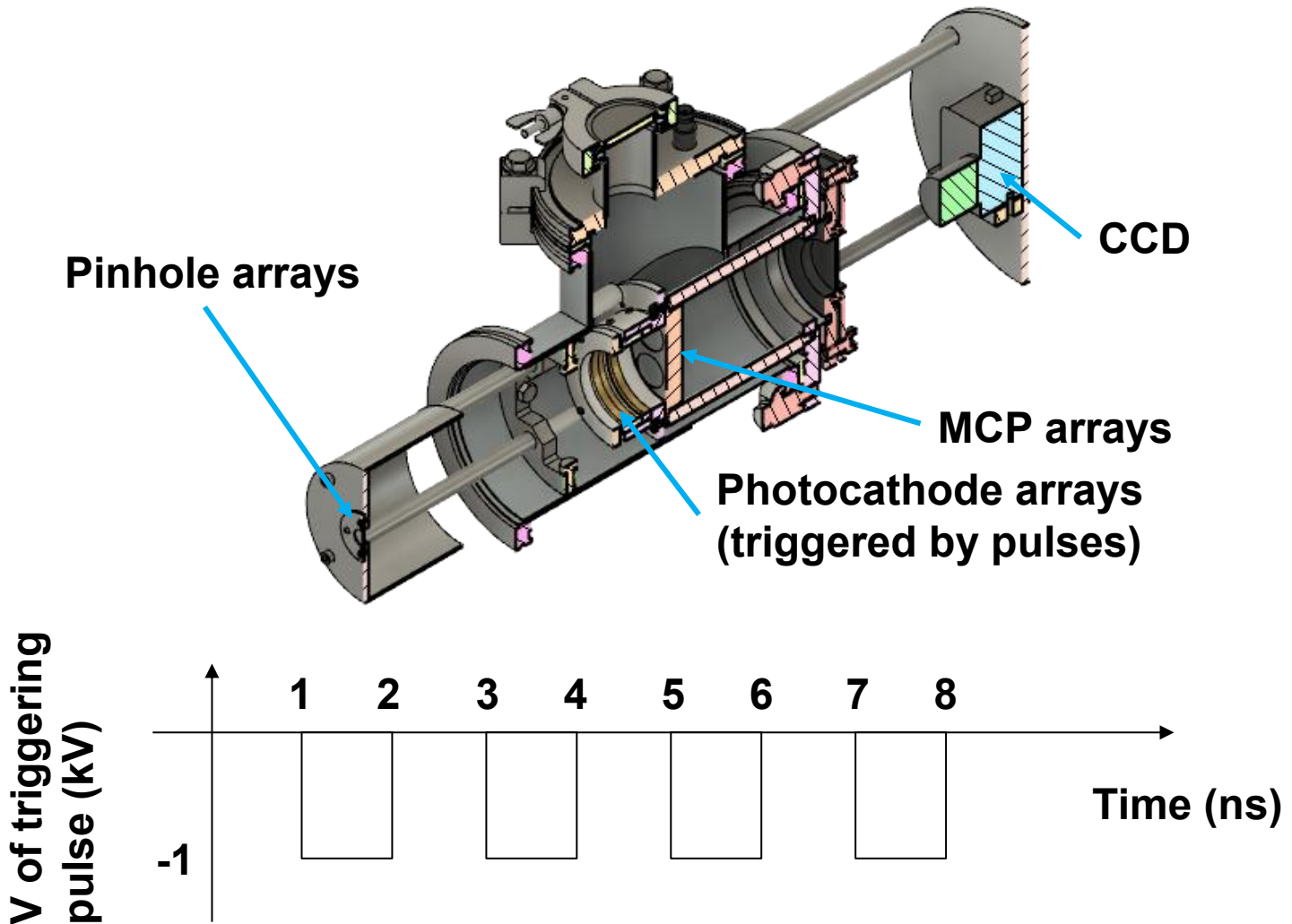


- Temporal resolution = 35 to 40 ps
- Imaging array: Pinholes: 10- to 12- μm resolution, 1 to 4 keV
- Space-resolved x-ray spectra can be obtained by using Bragg crystals and imaging slits

X-ray framing cameras for recording two-dimensional time-resolved images will be built by the end of 2021



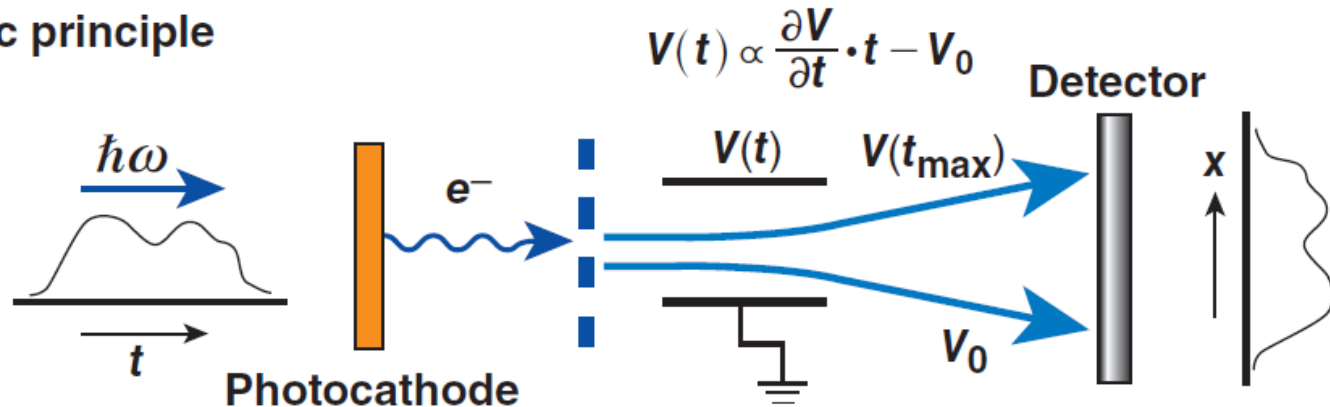
Each pinhole camera will be triggered separately



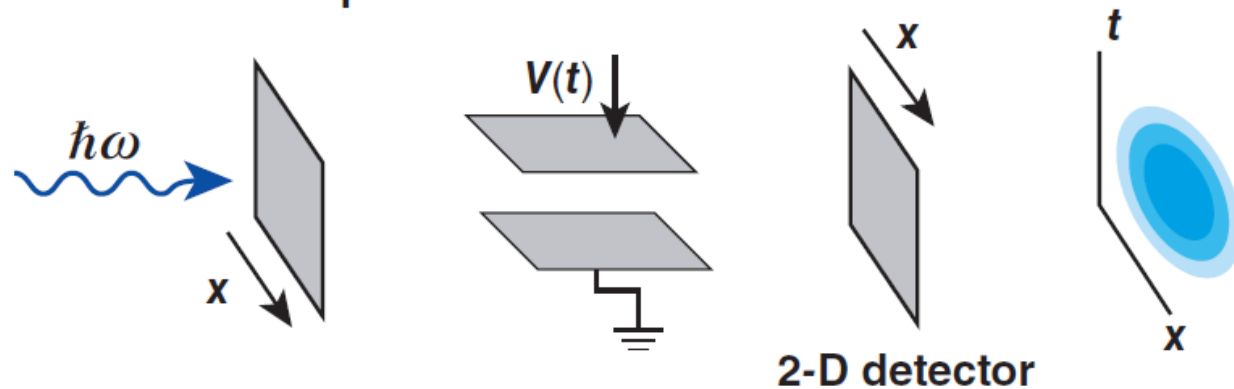
A streak camera provides temporal resolution of 1-D data



Basic principle



A streak camera can provide 2-D information

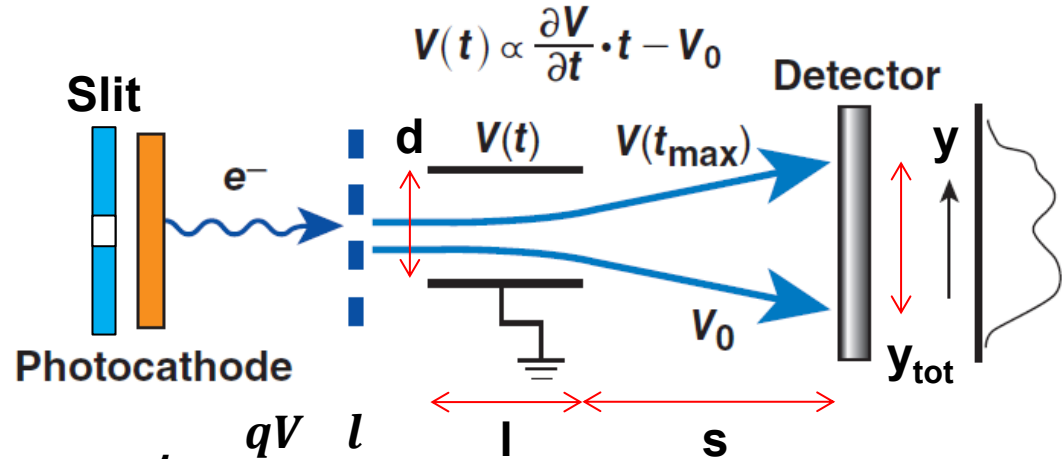


A temporal resolution higher than 15 ps is expected



Imaging system

- Visible light: regular lens
- X rays: pinhole



$$a = \frac{F}{m} = \frac{qE}{m} = \frac{qV}{md} \quad v_{\perp} = at = \frac{qV}{md} \frac{l}{v_{\parallel}}$$

$$y = s \tan \theta = s \frac{V_{\perp}}{V_{\parallel}} = \frac{1}{2E_k} \frac{l}{d} sqV = \frac{1}{2E_k} \frac{l}{d} sq(V_0 + V't)$$

- Let $d=10$ mm, $l=20$ mm, $s=50$ mm, $E_k=1$ keV, $V=-200 \sim 200$ V

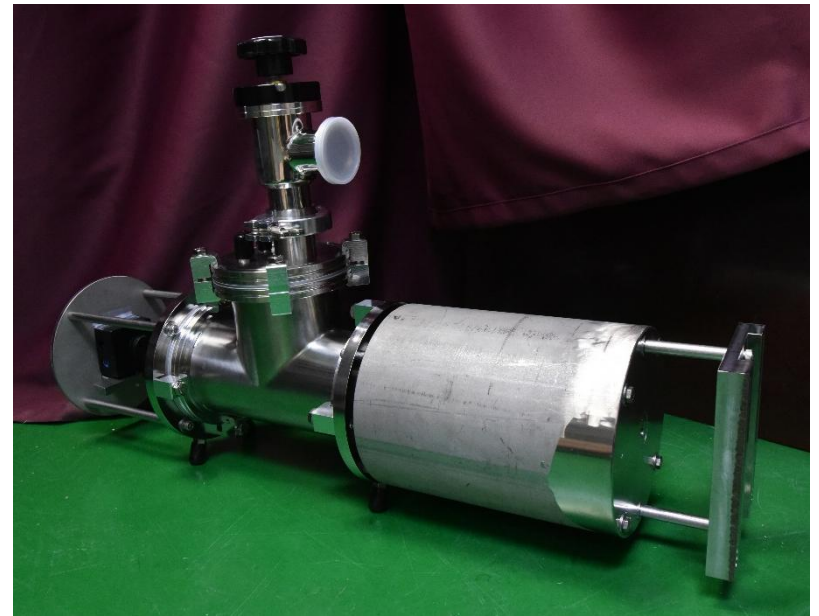
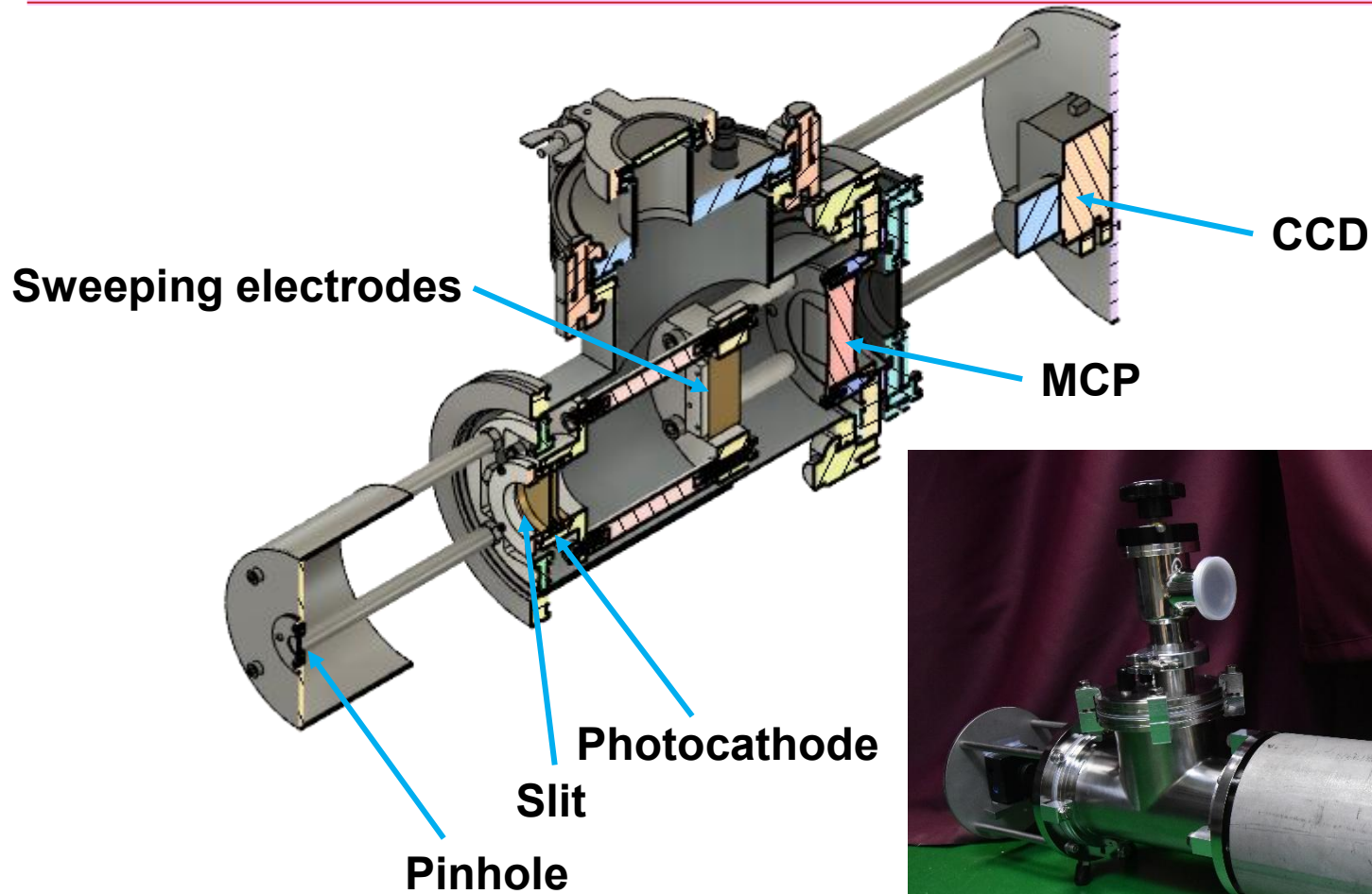
$$V' \equiv \frac{V_{\text{tot}}}{t_{\text{tot}}} = 0.06 \text{ kV/ns} \quad y_{\text{tot}} = 15 \text{ mm} \quad y_{\text{tot}} = 15 \text{ mm}$$

- Temporal resolution:

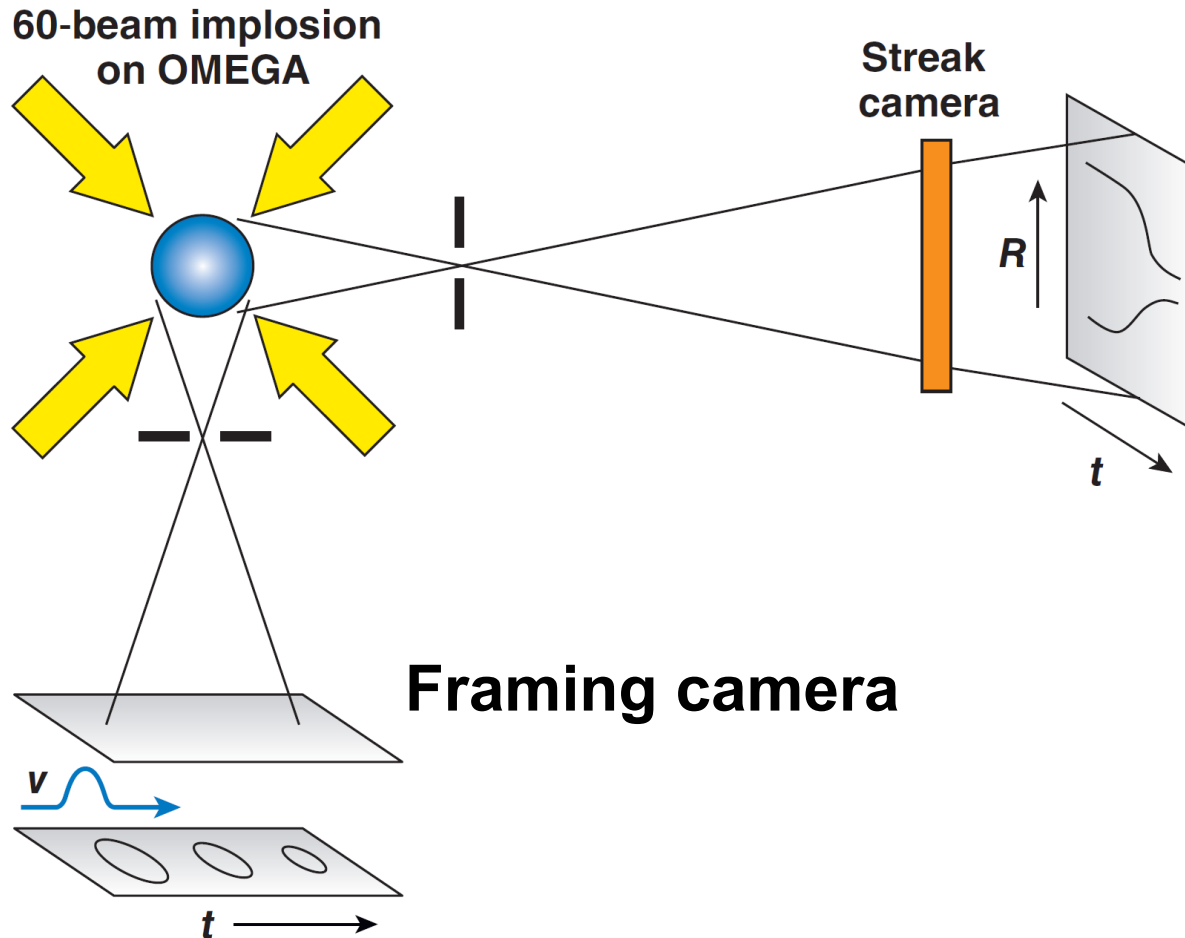
$$\delta t = \delta y \frac{2E_k d}{lsqV'} = 15 \text{ ps for } \delta y = 45 \mu\text{m}$$

- δt will be adjusted by changing E_k .

A streak camera with temporal resolution of 15 ps has been developed



Shell trajectories can be measured using framing camera or streak camera

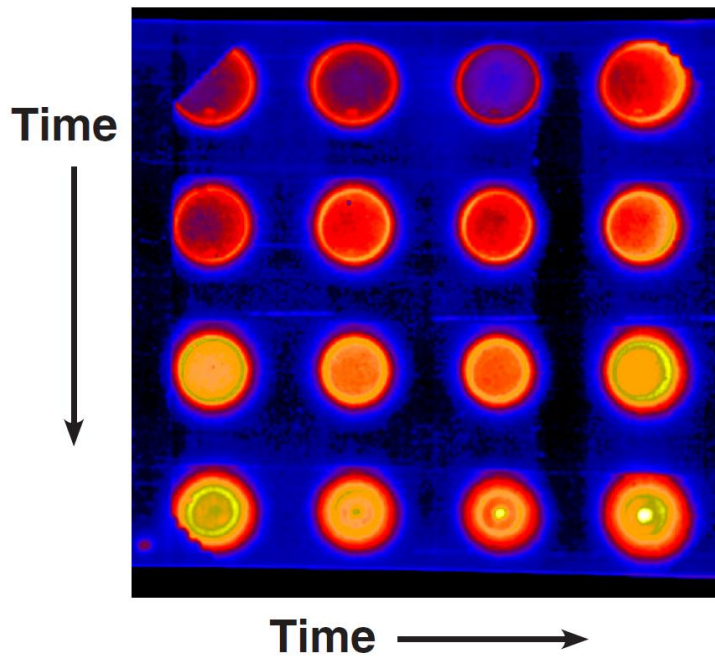


Comparison of images from framing camera versus streak camera



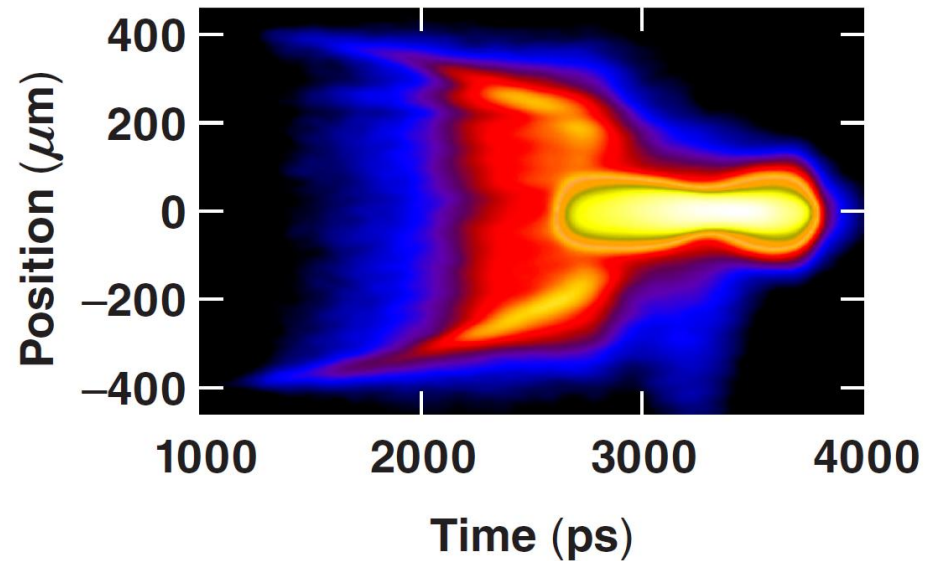
Framing-camera image
6× magnification

Shot 13377

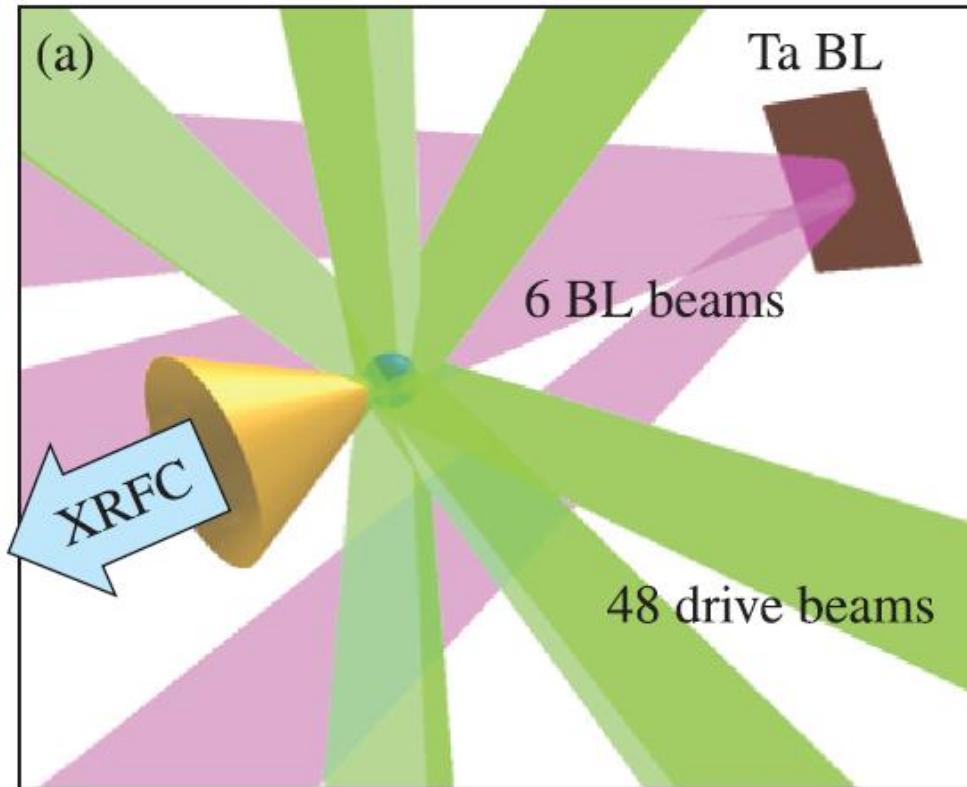


Streak-camera image

Shot 13377



The optical density can be measured using the absorption of a backlighter

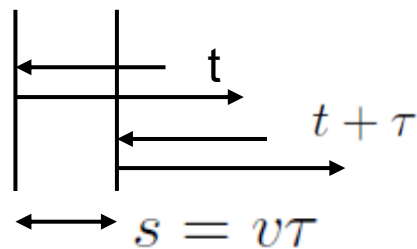
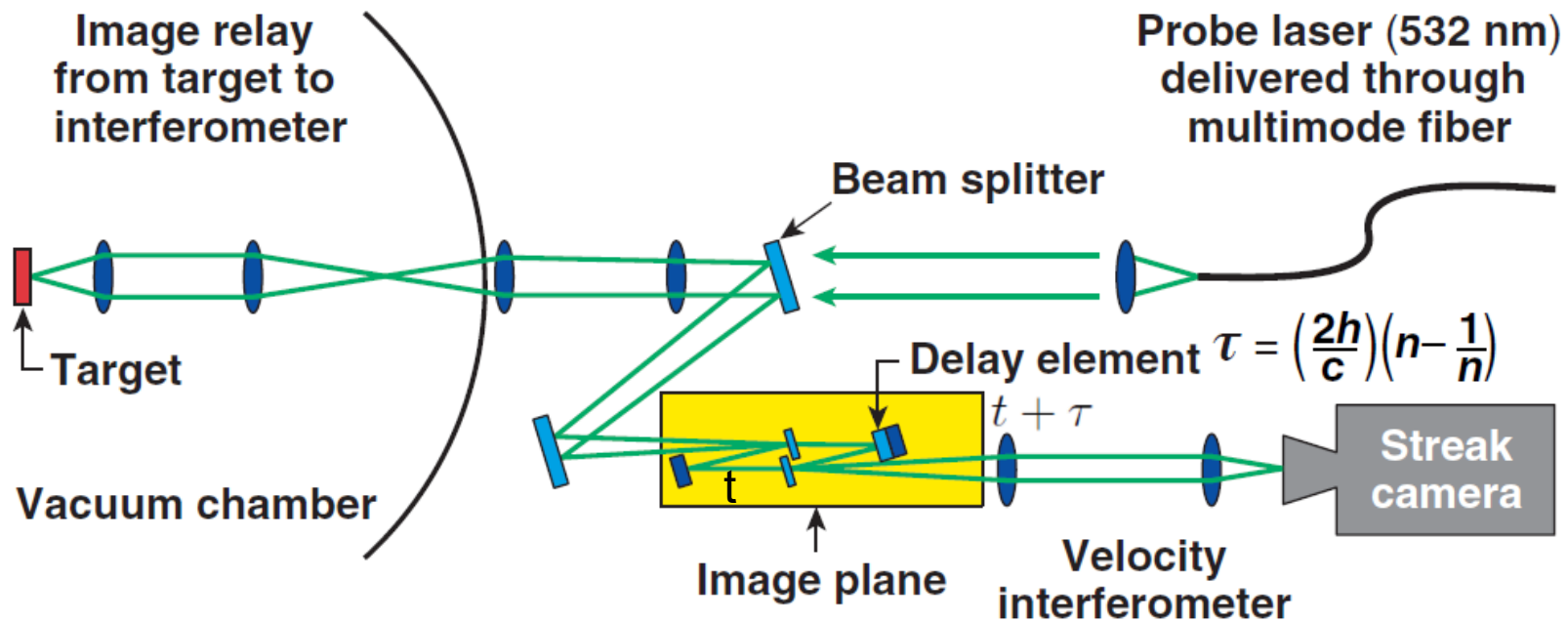


$$I = \int I(\varepsilon) \exp(-\mu(\varepsilon) \rho \delta) d\varepsilon$$

$$I = I_{BL} \exp(-\bar{\mu} \rho \delta)$$

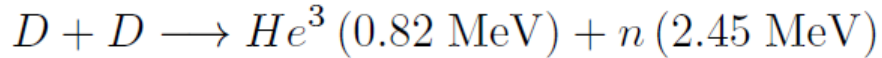
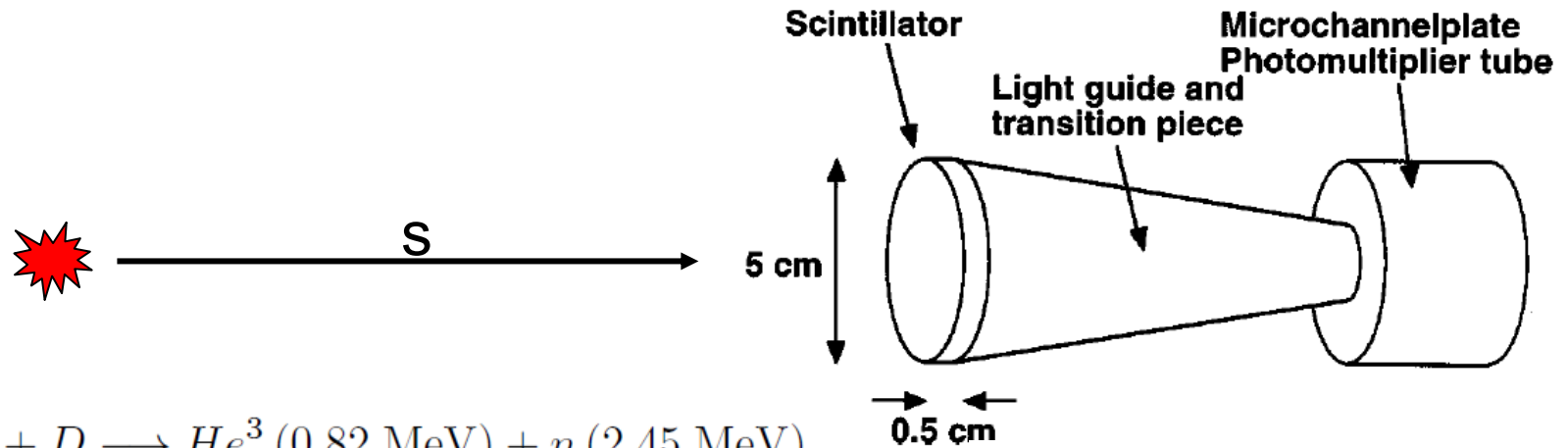
$$\ln I = \ln I_{BL} - \mu \rho r$$

Shock velocities are measured using time-resolved Velocity Interferometer System for Any Reflector (VISAR)



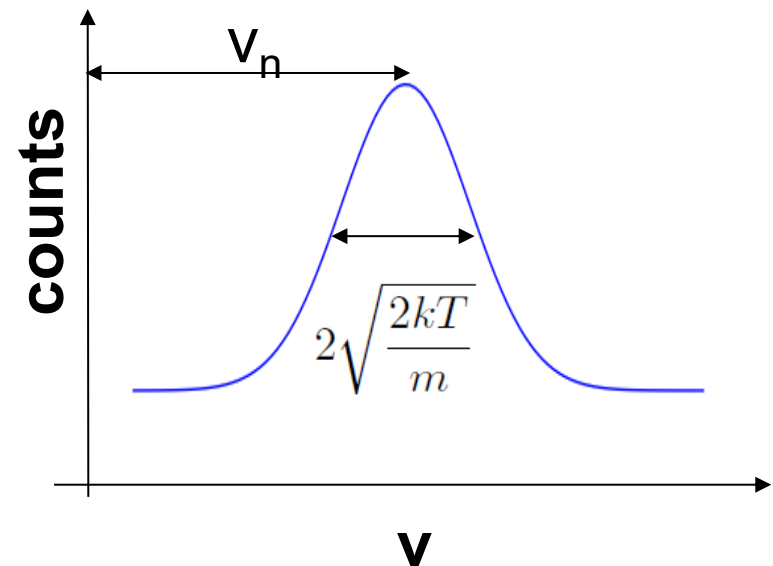
$$\Delta\phi = \frac{v\tau}{\lambda} \propto v$$

Neutron average temperature is obtained using Neutron Time of Flight (NToF)



$$s = vt \quad v = \frac{s}{t}$$

$$f(v) = \sqrt{\left(\frac{m}{2\pi kT}\right)} \exp\left(-\frac{mv^2}{2kT}\right)$$



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

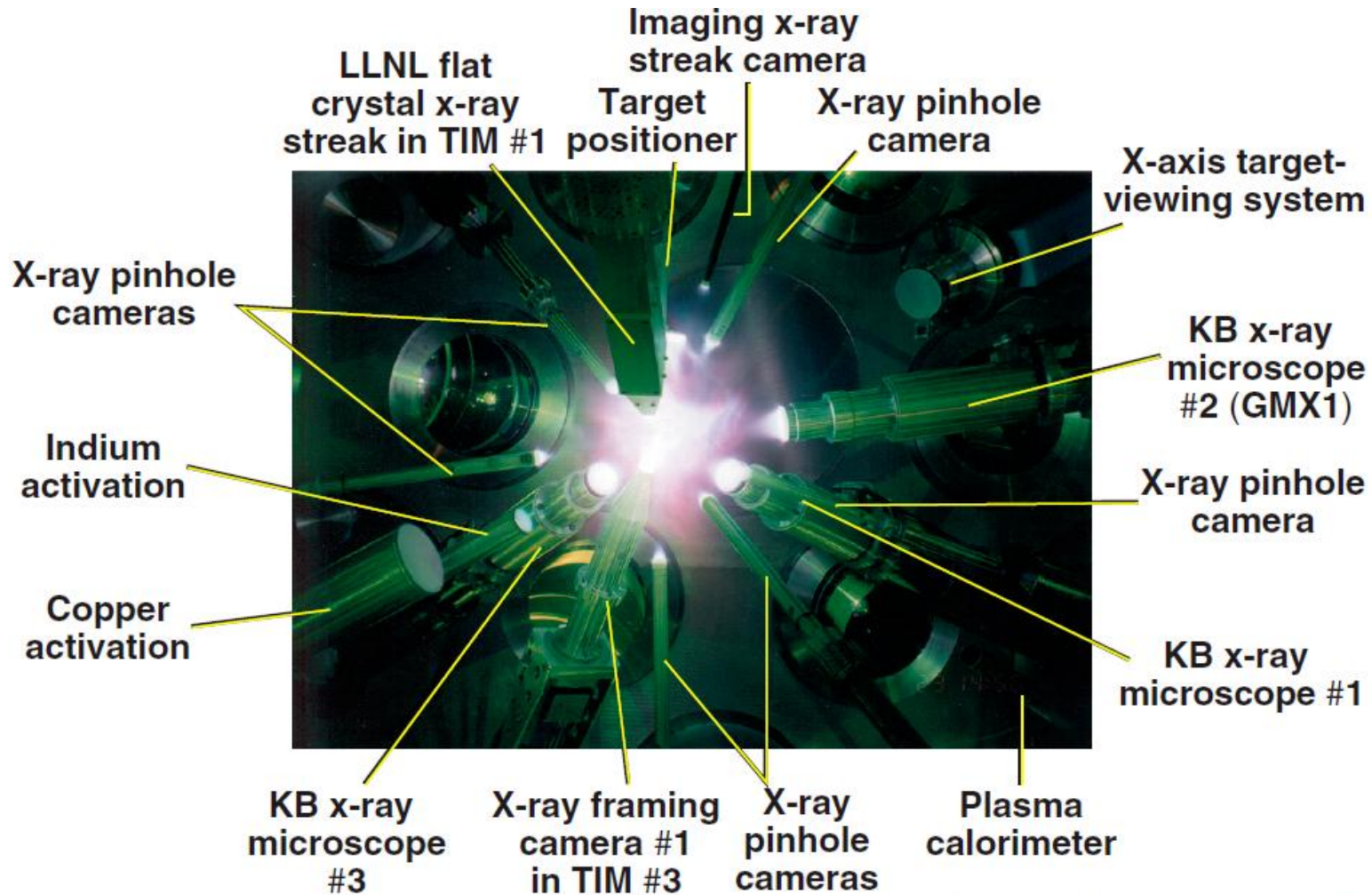
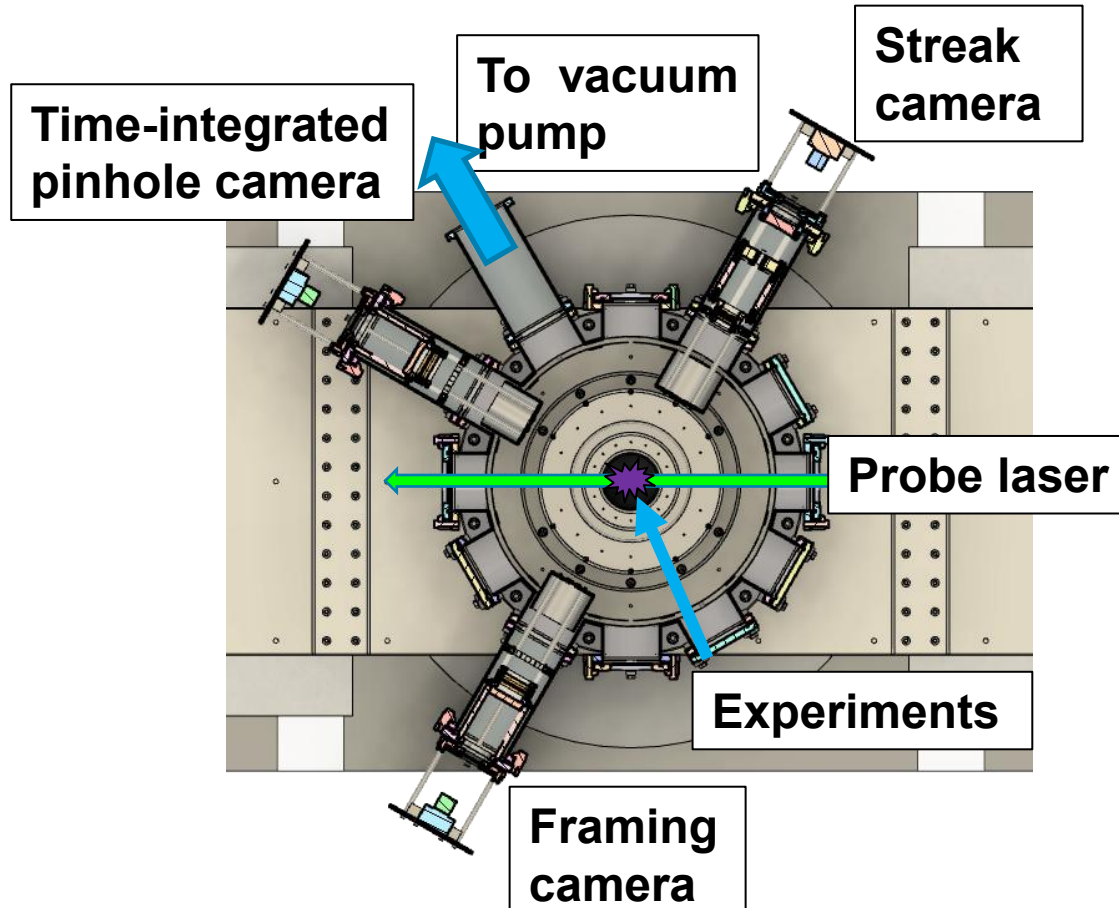


Photo taken from port H11B

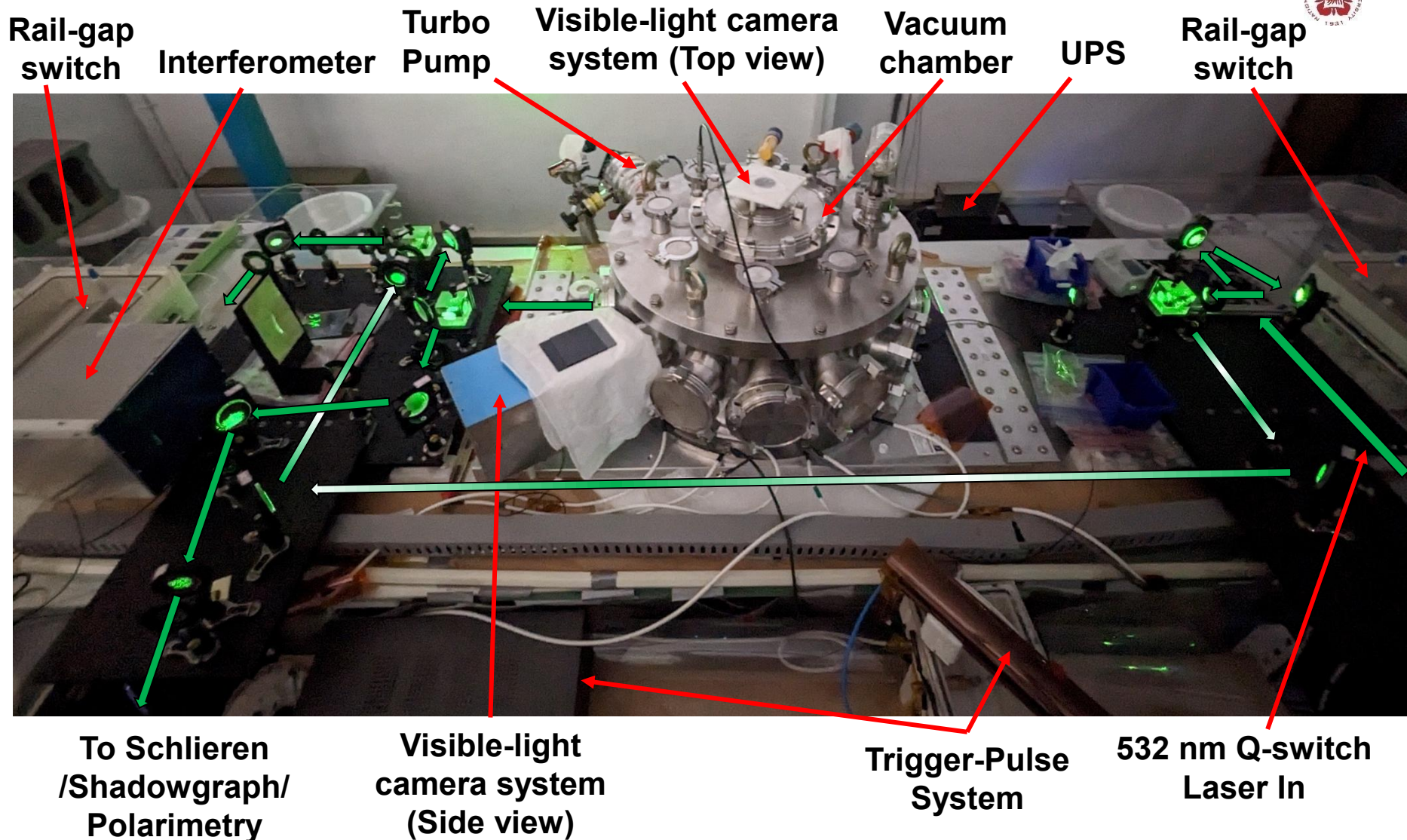
A suit of diagnostics in the range of (soft) x-ray are being built



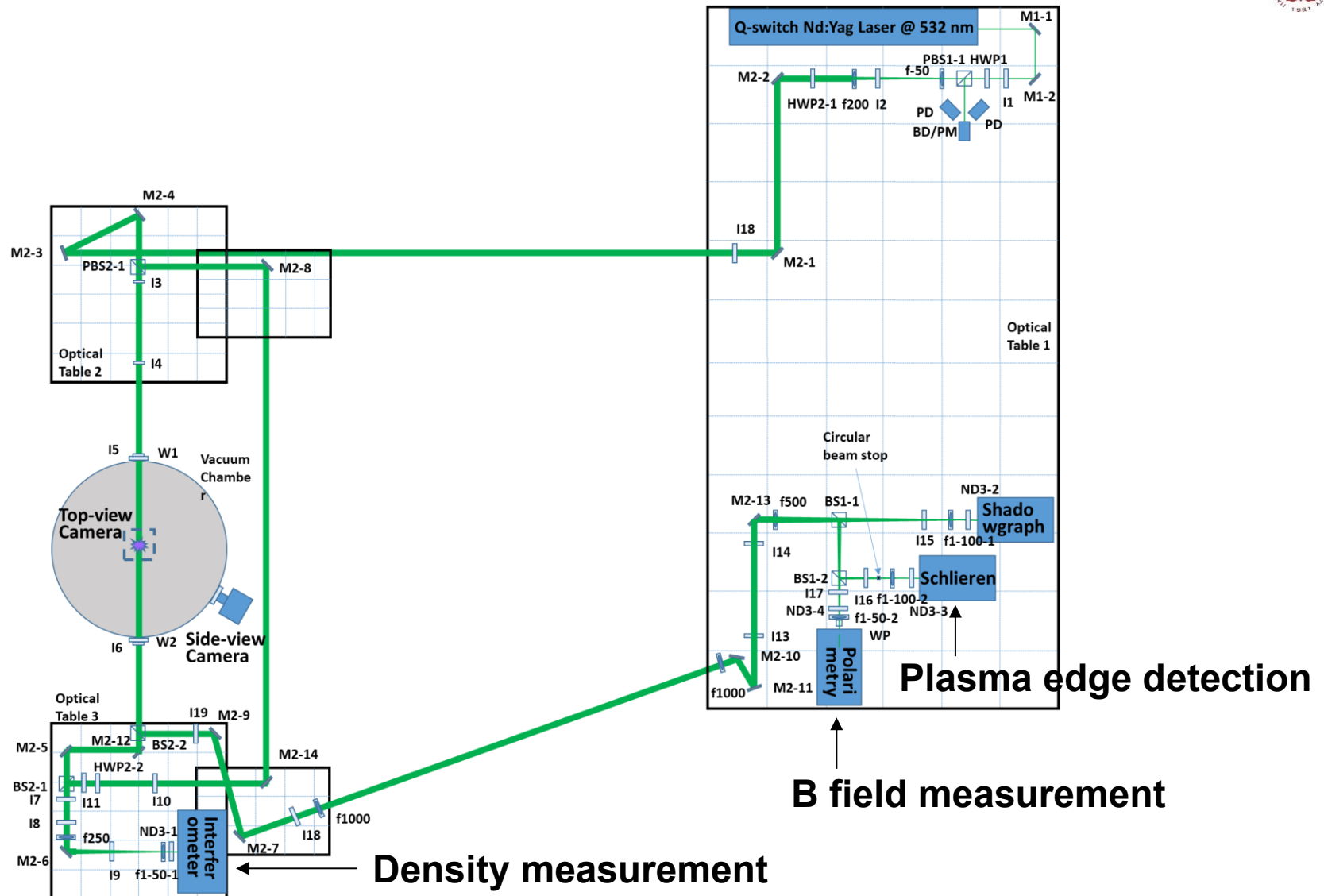
- CsI are used as the photocathode for all x-ray imaging system.
- Au photocathode may be used in the future.

- Pinhole camera:
 - Magnification: 1x
 - Exposure time: 1 μ s
- Streak camera:
 - Magnification: 1x
 - Temporal resolution: 15 ps
- Framing camera:
 - Magnification: 0.3x
 - Temporal resolution: $\sim$ ns using 4 individual MCPs
- Laser probing:
 - For interferometer, schlieren, shadowgraphy, Thomson scattering.
 - Temporal resolution: $\sim$ 300 ps using stimulated brillouin scattering (SBS) pulse compression in water

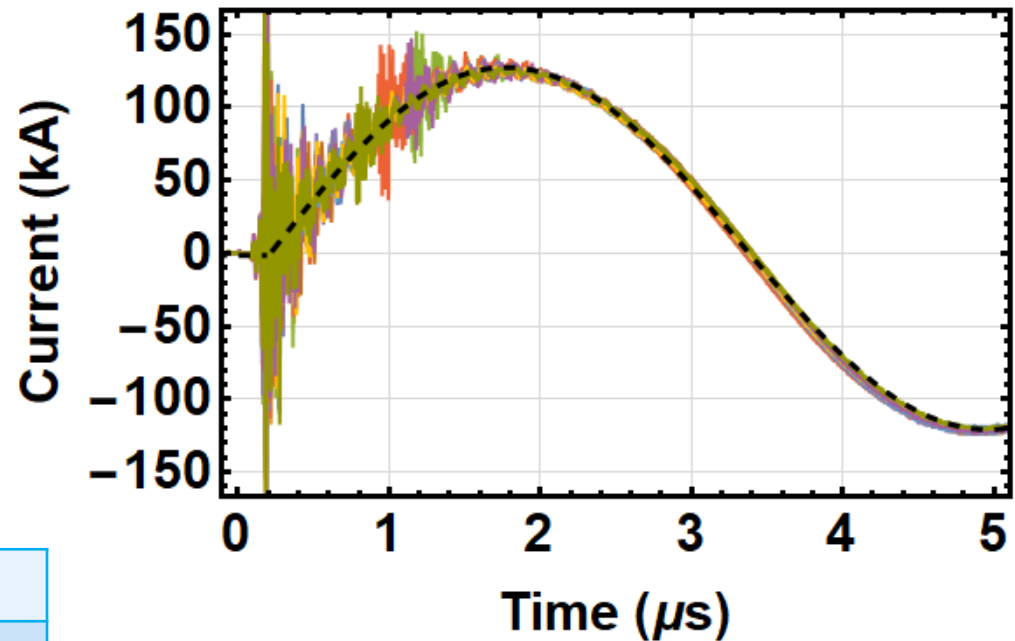
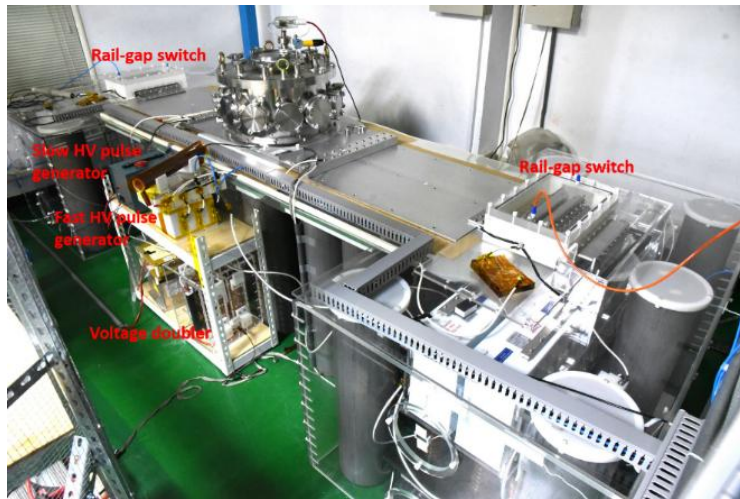
The pulsed-power system with diagnostic system



Time-resolved imaging system with temporal resolution in the order of nanoseconds was implemented



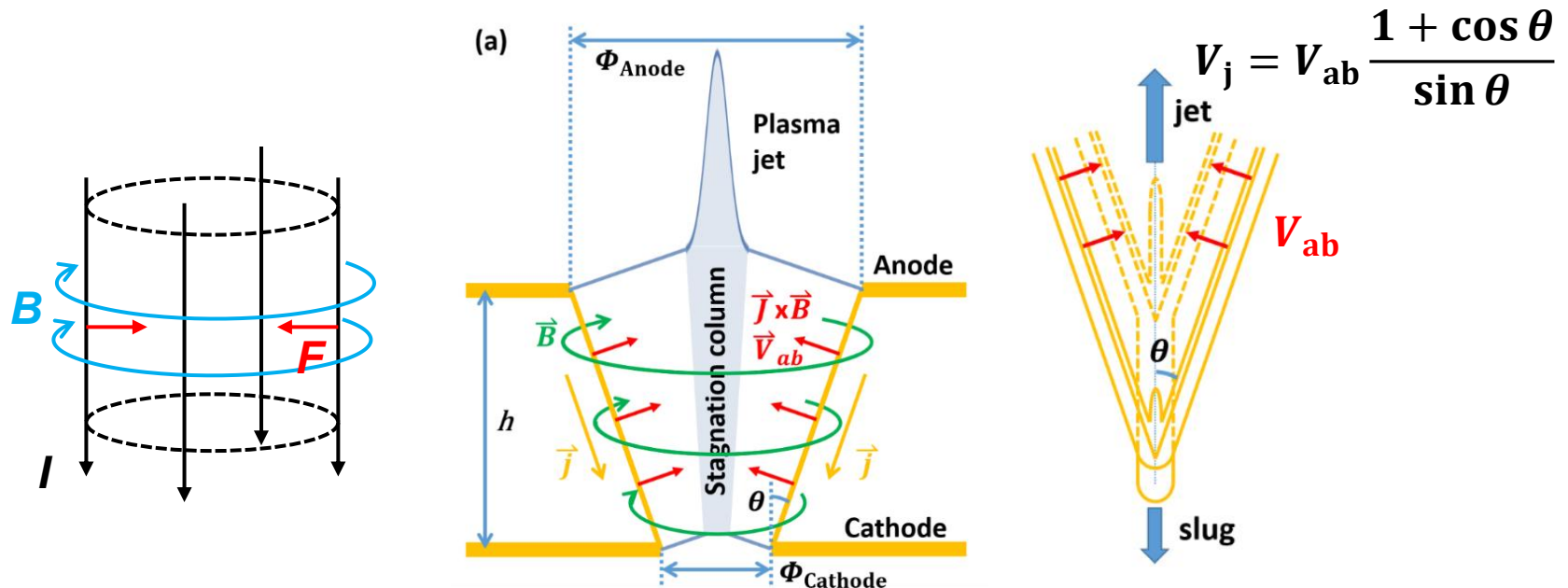
A peak current of ~ 135 kA with a rise time of ~ 1.6 μ s is provided by the pulsed-power system



Capacitance (μ F)	5
V_{charge} (kV)	20
Energy (kJ)	1
Inductance (nH)	204 ± 4
Rise time (quarter period, ns)	1592 ± 3
I_{peak} (kA)	135 ± 1

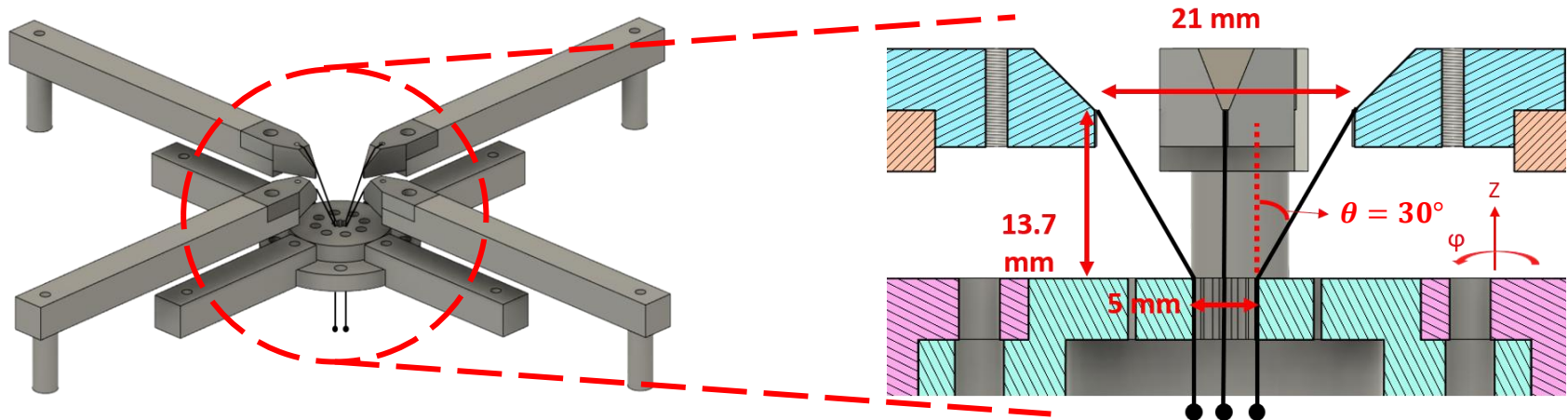
- EUV generation using discharged-produced plasma:
 - PP-PP-002 Chenghan Du
 - PP-PP-003 Jia-Kai Liu

A plasma jet can be generated by a conical-wire array due to the nonuniform z-pinch effect

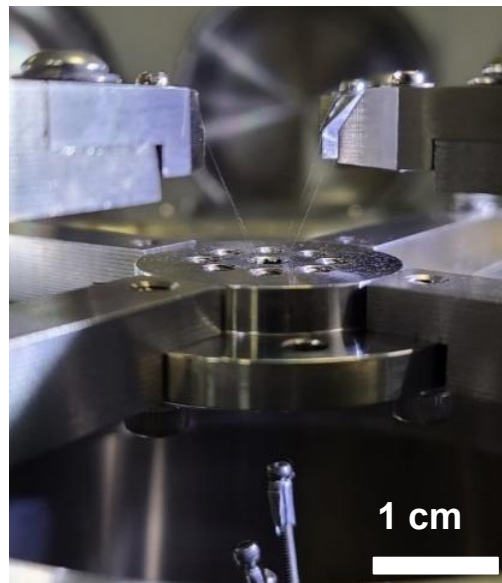
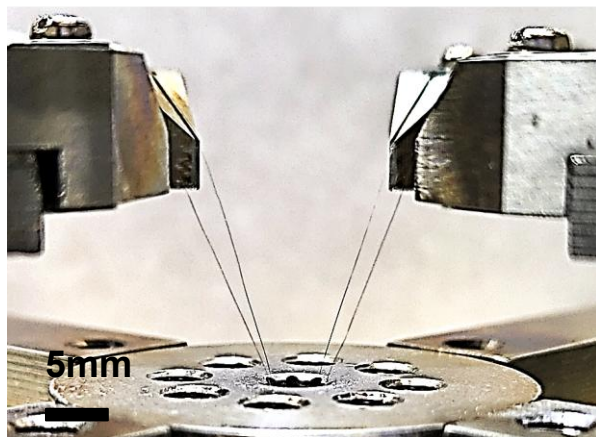


1. Wire ablation : corona plasma is generated by wire ablations.
2. Precursor : corona plasma is pushed by the $\vec{J} \times \vec{B}$ force and accumulated on the axis forming a precursor.
3. Plasma jet is formed by the nonuniform z-pinch effect due to the radius difference between the top and the bottom of the array.

Our conical-wire array consists of 4 tungsten wires with an inclination angle of 30° with respect to the axis



- Conical-wire array

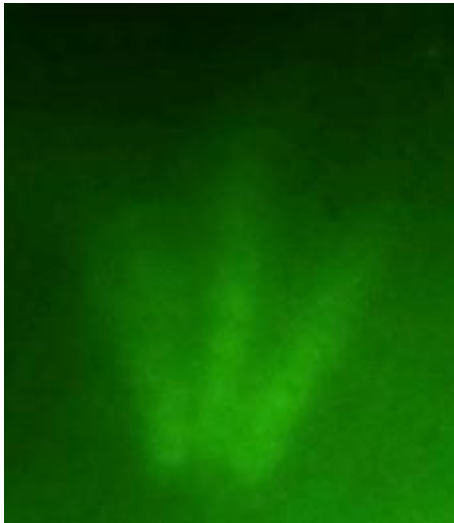


- Material : Tungsten.
- Number of wires : 4.
- Diameter : $20\ \mu\text{m}$.

Self-emission of the plasma jet in the UV to soft x-ray regions was captured by the pinhole camera



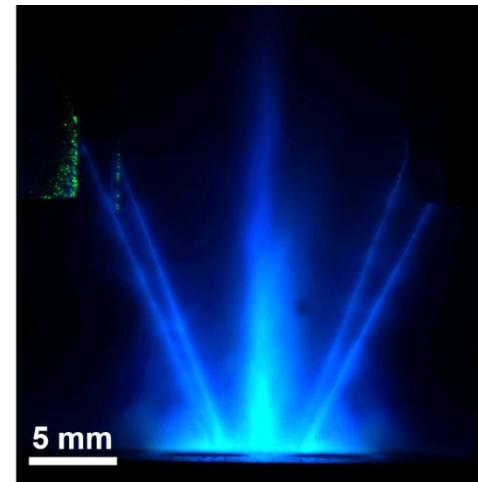
- Image in UV/soft x ray



(Brightness is increased by 40 %.)

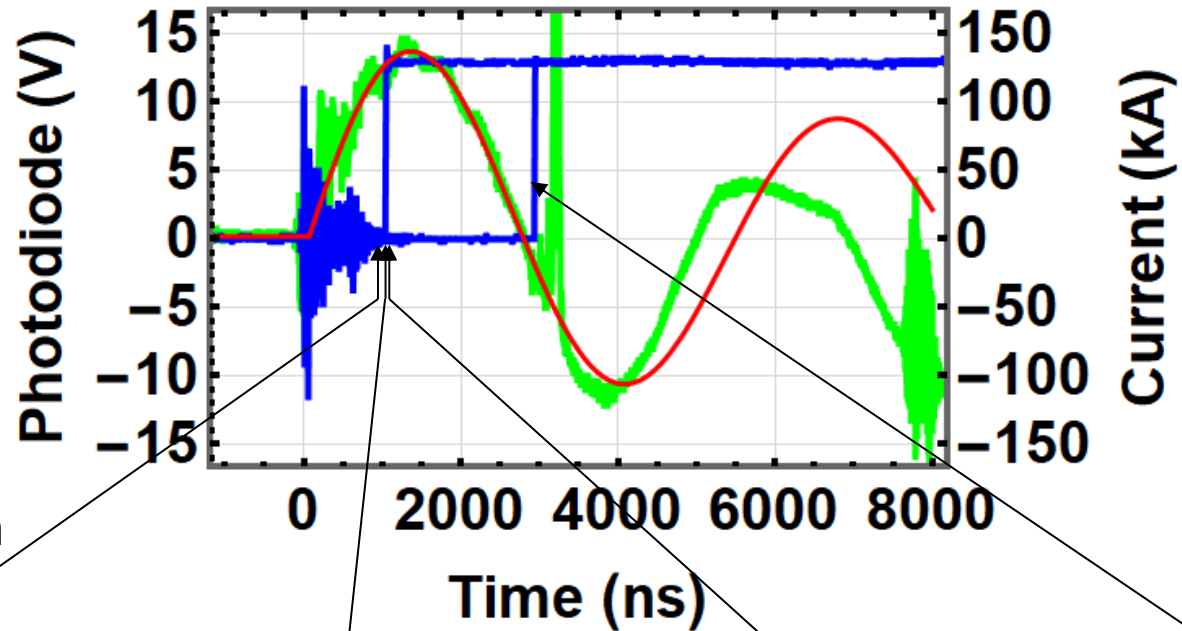
- Pinhole diameter: 0.5 mm, i.e., spatial resolution: 1 mm.

- Image in visible light

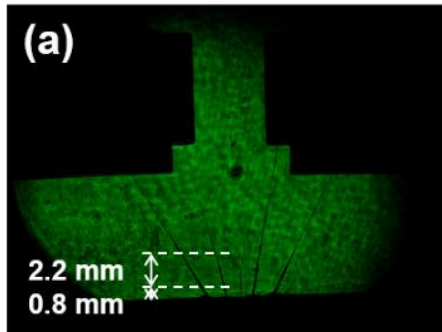


(Enhanced by scaling the intensity range linearly from 0 – 64 to 0 – 255.)

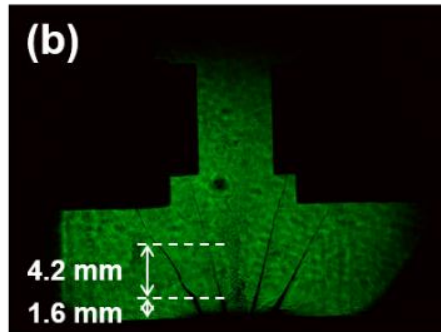
Plasma jet propagation was observed using laser diagnostics



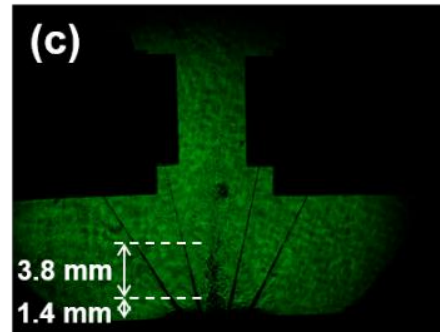
- Shadowgraph images:



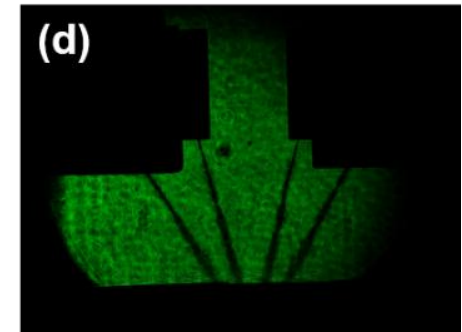
930 $\pm$ 20 ns



975 $\pm$ 2 ns



985 $\pm$ 3 ns

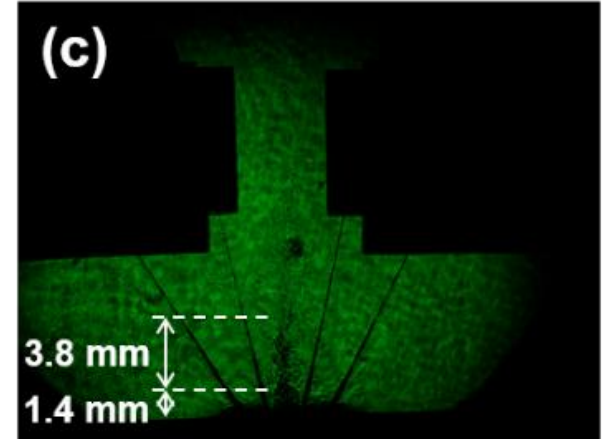
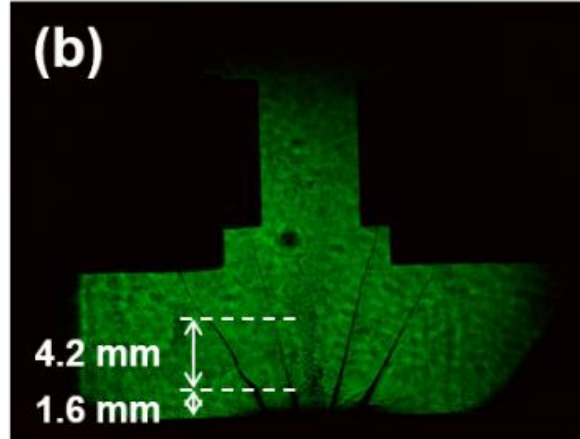
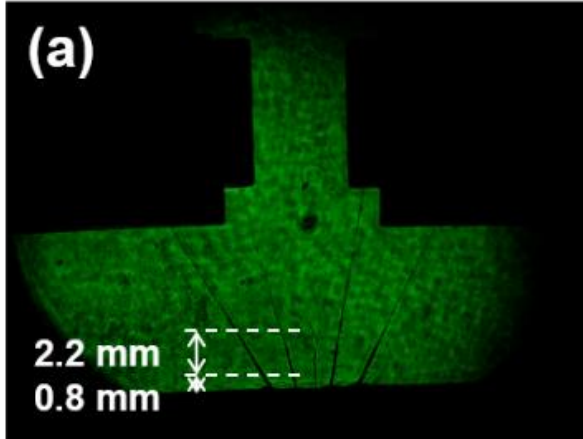


2945 $\pm$ 2 ns

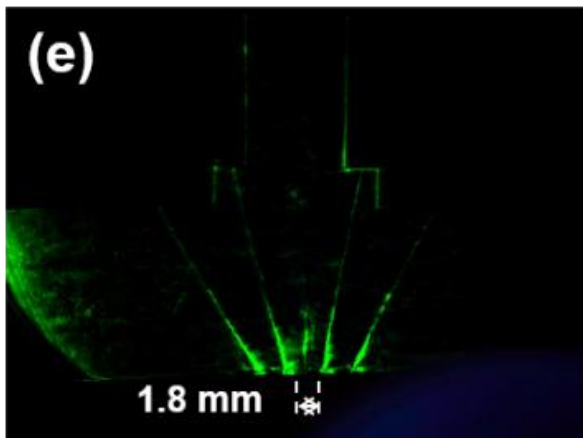
Length of the plasma jet at different time was obtained by the Schlieren images at different times



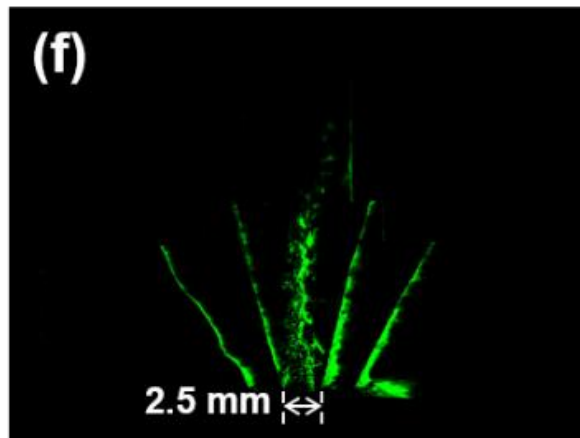
- Shadowgraph images:



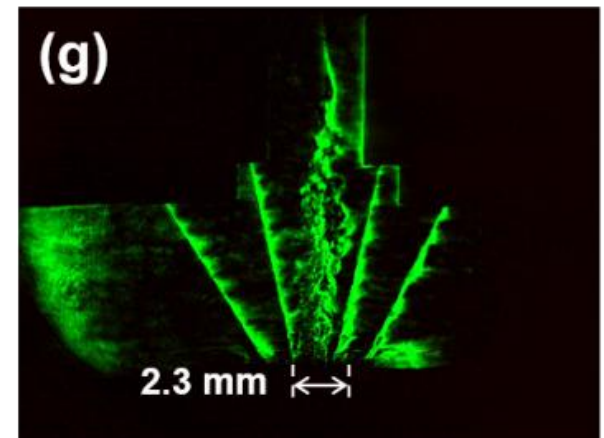
- Schlieren images:



930 ± 20 ns

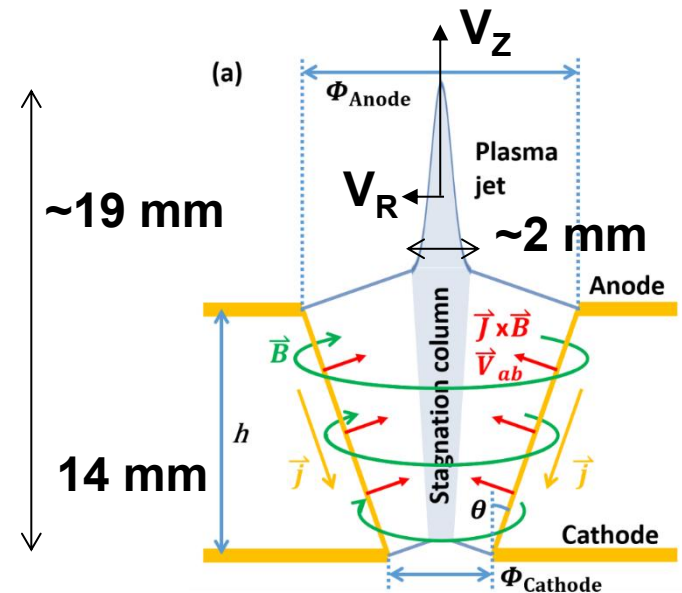
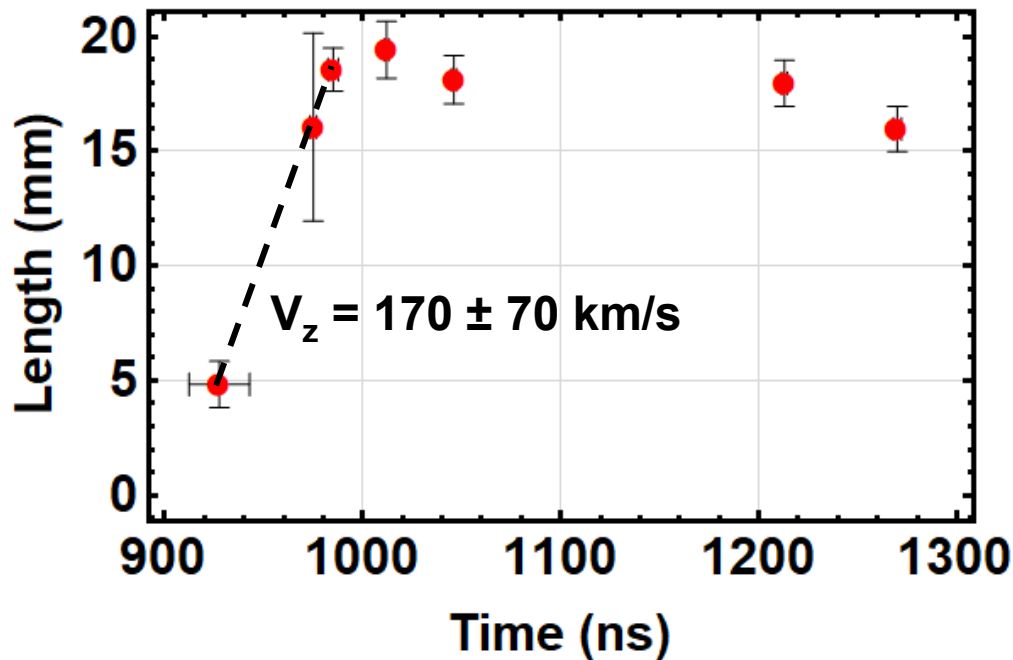


975 ± 2 ns



985 ± 3 ns

The measured plasma jet speed is 170 ± 70 km/s with the corresponding Mach number greater than 5



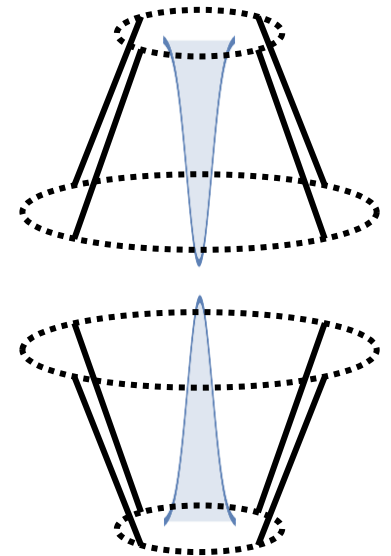
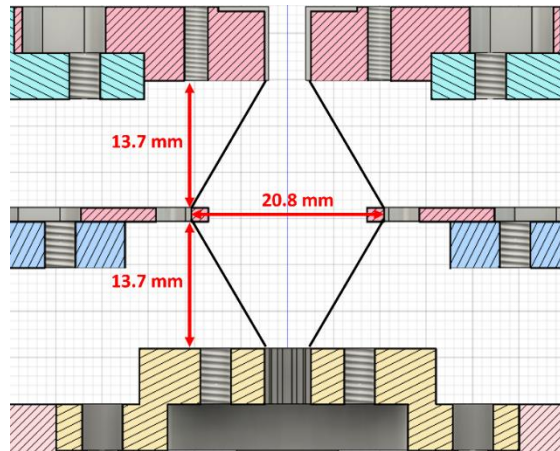
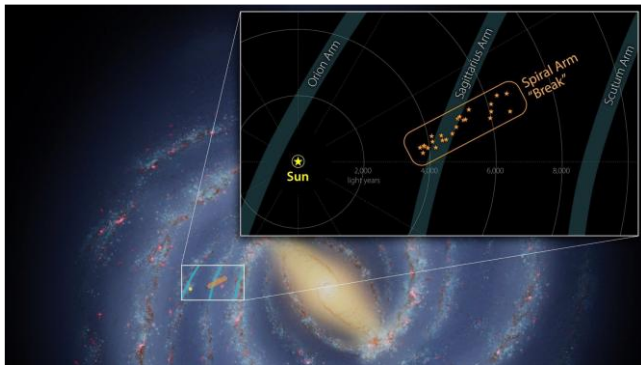
$$M = \frac{V_z}{V_R} \geq \frac{Z}{r} \approx \frac{(19 - 14) \text{ mm}}{\frac{2 \text{ mm}}{2}} = 5$$

$$V_{ab} = V_j \frac{\sin \theta}{1 + \cos \theta} = 50 \pm 20 \text{ km/s}$$

Plasma disk can be formed when two head-on plasma jets collide with each other



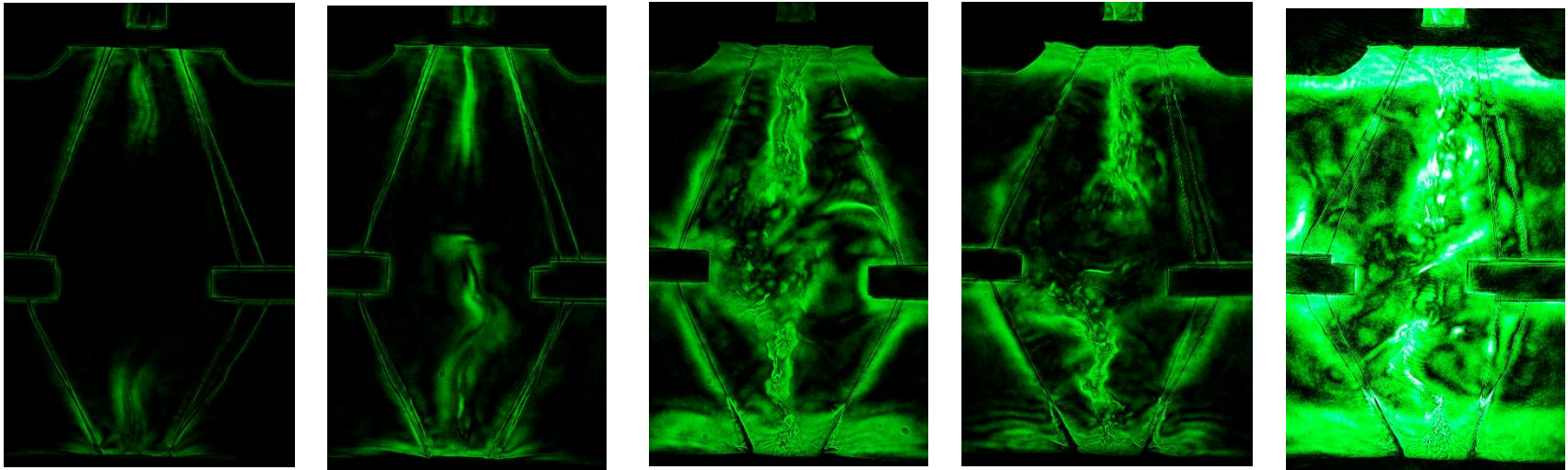
- Astronomers Find a 'Break' in One of the Milky Way's Spiral Arms.



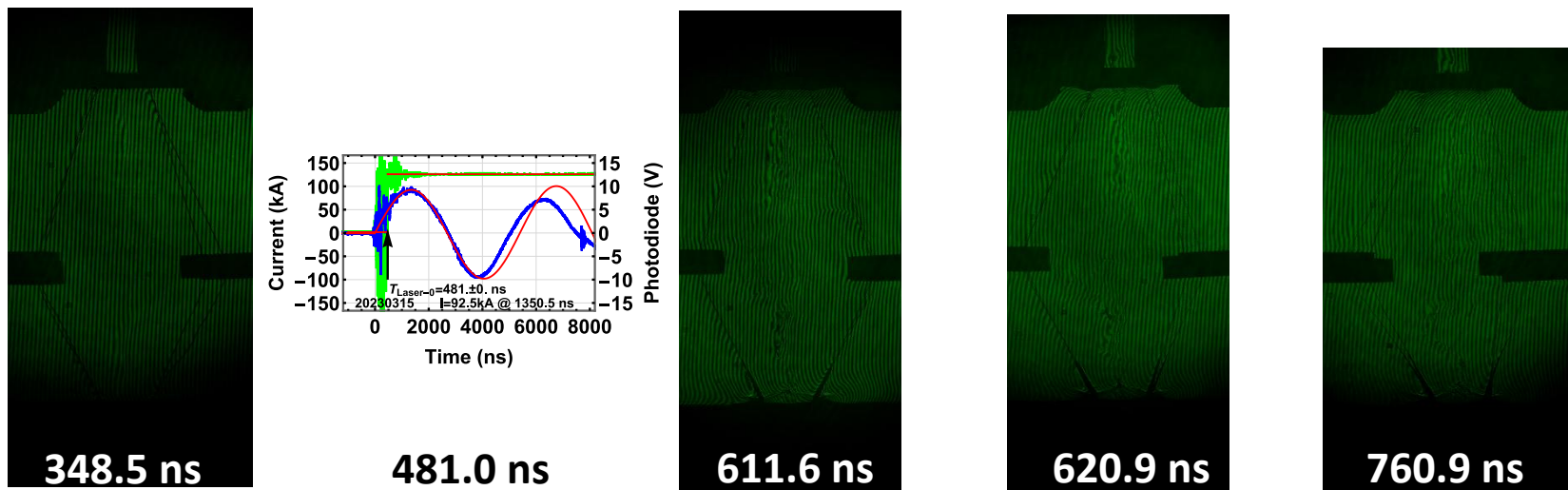
Plasma disk can be formed when two head-on plasma jets collide with each other



- Schlieren



- Interferometer

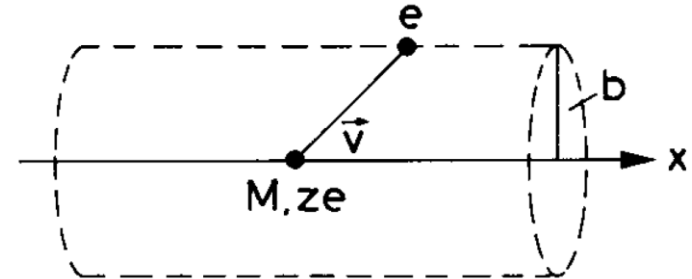


Energetic charged particles losses most of its energy right before it stops



Momentum transfer:

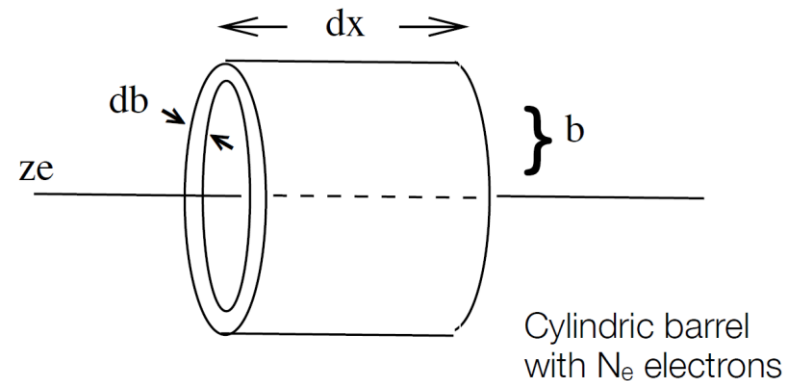
$$\Delta p_{\perp} = \int F_{\perp} dt = \int F_{\perp} \frac{dt}{dx} dx = \int F_{\perp} \frac{dx}{v}$$



$$= \int_{-\infty}^{\infty} \frac{ze^2}{(x^2 + b^2)} \cdot \frac{b}{\sqrt{x^2 + b^2}} \cdot \frac{1}{v} dx = \frac{ze^2 b}{v} \left[\frac{x}{b^2 \sqrt{x^2 + b^2}} \right]_{-\infty}^{\infty} = \frac{2ze^2}{bv}$$

$\Delta p_{\parallel}$: averages to zero

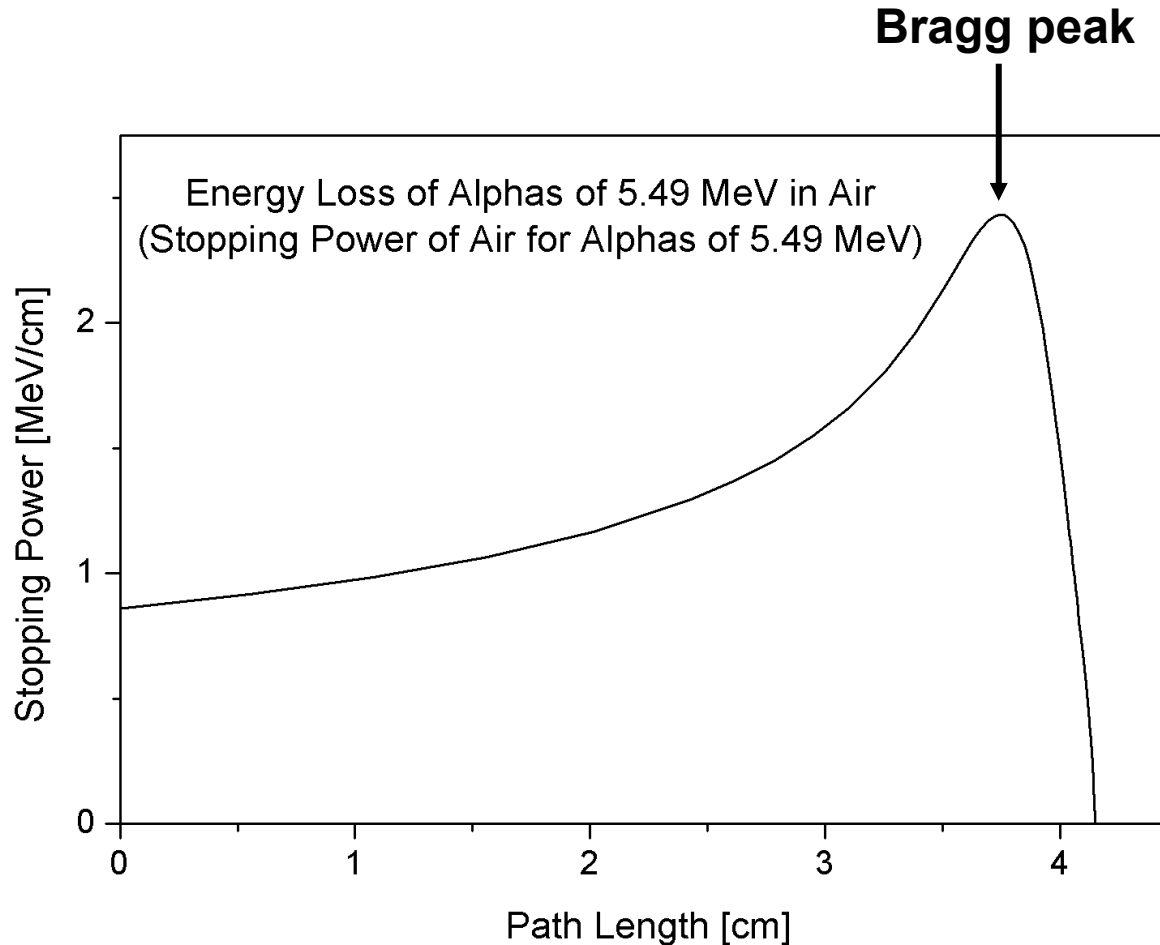
$$\Delta E(b) = \frac{\Delta p^2}{2m_e} \quad N_e = n \cdot (2\pi b) \cdot db dx$$



$$-dE(b) = \frac{\Delta p^2}{2m_e} \cdot 2\pi n b db dx$$

$$-\frac{dE}{dx} = \frac{4\pi n z^2 e^4}{m_e v^2} \cdot \int_{b_{\min}}^{b_{\max}} \frac{db}{b} = \frac{4\pi n z^2 e^4}{m_e v^2} \ln \frac{b_{\max}}{b_{\min}}$$

A particle loses most of its energy right before it stops



There are two suggested website for getting the information of proton stopping power in different materials



<http://www.nist.gov/pml/data/star/>

<http://www.srim.org/>

NIST [NIST Time](#) [NIST Home](#) [About NIST](#) [Contact Us](#) [A-Z Site Index](#)

Physical Measurement Laboratory

[About PML](#) [Publications](#) [Topic/Subject Areas](#) [Products/Services](#) [News/Multimedia](#) [Programs/Projects](#) [Facilities](#)

NIST Home > PML > Physical Reference Data > Stopping-Power & Range Tables: e-, p+, Helium Ions

NISTIR 4999 | [Version History](#) | [Disclaimer](#)

Stopping-Power and Range Tables for Electrons, Protons, and Helium Ions

M.J. Berger, J.S. Coursey, M.A. Zucker and J. Chang
(NIST, Physical Measurement Laboratory)



Abstract:
The databases ESTAR, PSTAR, and ASTAR calculate stopping-power and range tables for electrons, protons, or helium ions, according to methods described in ICRU Reports 37 and 49. Stopping-power and range tables can be calculated for electrons in any user-specified material and for protons and helium ions in 74 materials.

Contents:

1. Introduction
2. ESTAR: Stopping Powers and Ranges for Electrons
3. PSTAR and ASTAR: for Protons and Helium Ions (alpha particles)

[References](#)

[Appendix: Significance of Calculated Quantities](#)

Access the Data:

1. Electrons
2. Protons

請選擇語言 [SHARE](#) [f](#) [t](#) [e](#) [m](#)

由「Google 翻譯」技術提供



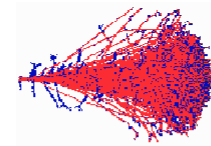
© Creations/2010 Shutterstock.com

Access the Data

[Electrons](#) | [Protons](#) | [Helium Ions](#)

NIST Standard Reference Database 124
Rate our products and services.
Online: October 1998 - **Last update:** August 2005

Contact
Stanley Seltzer



NEW! SRIM Textbook NEW!

Software	Science
SRIM / TRIM Introduction	Historical Review
Download SRIM-2013	Details of SRIM-2013
SRIM Install Problems	Experimental Data Plots
SRIM Tutorials	Stopping of Ions in Matter
Download TRIM Manual Part-1, Part-2	Stopping in Compounds
Scientific Citations of Experimental Data	High Energy Stopping

The thickness of a filter can be decided from the range data from NIST website



COPPER

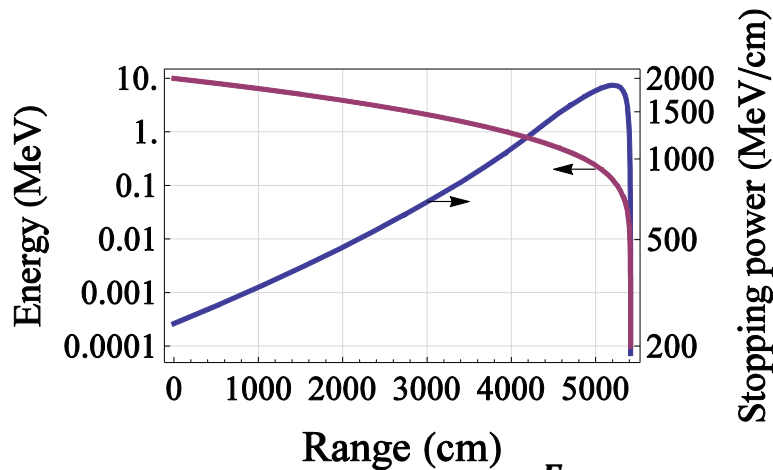
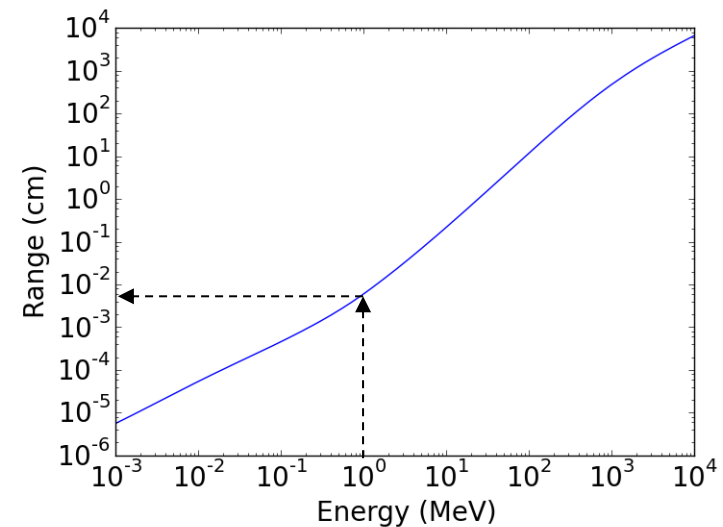
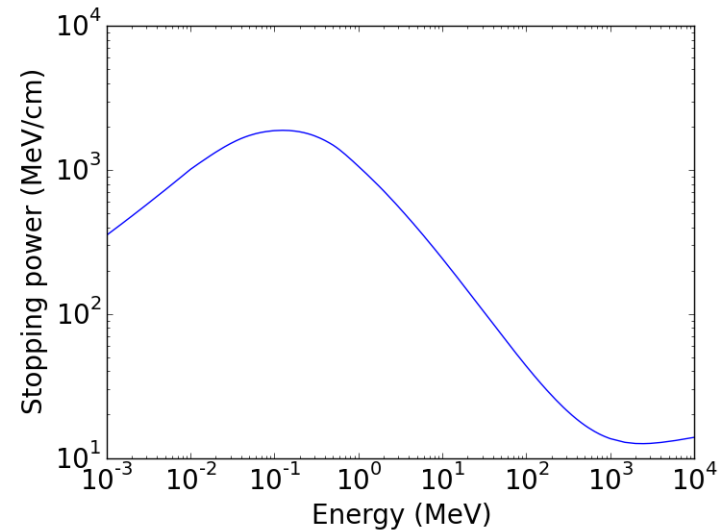
To download data in spreadsheet (array) form, choose a delimiter and use the checkboxes in the table heading. After downloading, save the output by using your browser's Save As feature.

Delimiter:

- ☒ space
- ☐ (vertical bar)
- ☐ tab (some browsers may use spaces instead)
- ☐ newline

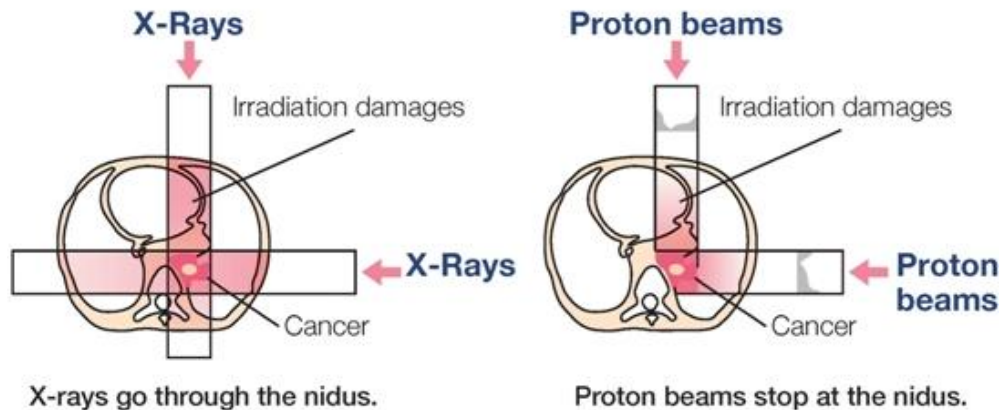
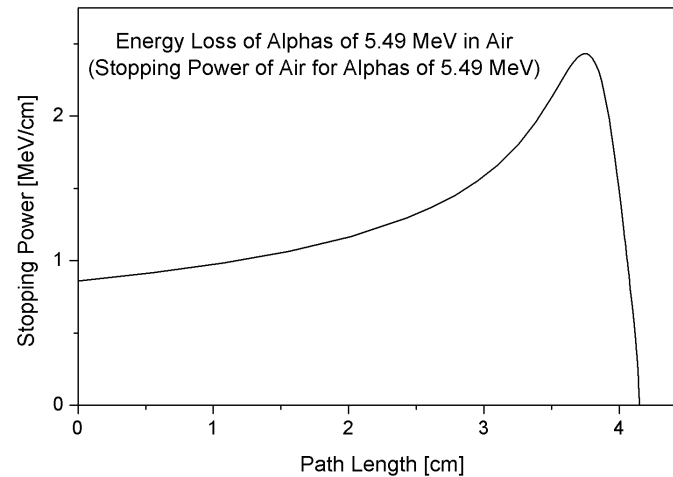
Download data [Reset]

(required) Kinetic Energy (MeV)	Stopping Power (MeV cm ² /g)			Range		
	Electronic	Nuclear	Total	CSDA (g/cm ²)	Projected (g/cm ²)	Detour Factor Projected / CSDA
1.000E-03	3.490E+01	4.408E+00	3.931E+01	4.116E-05	5.620E-06	0.1365
1.500E-03	4.274E+01	4.231E+00	4.697E+01	5.267E-05	8.301E-06	0.1576
2.000E-03	4.935E+01	4.049E+00	5.340E+01	6.263E-05	1.101E-05	0.1759
2.500E-03	5.518E+01	3.876E+00	5.906E+01	7.152E-05	1.374E-05	0.1921
3.000E-03	6.045E+01	3.718E+00	6.416E+01	7.964E-05	1.647E-05	0.2068
4.000E-03	6.980E+01	3.440E+00	7.324E+01	9.419E-05	2.194E-05	0.2329
5.000E-03	7.804E+01	3.207E+00	8.124E+01	1.071E-04	2.739E-05	0.2556
6.000E-03	8.548E+01	3.010E+00	8.849E+01	1.189E-04	3.280E-05	0.2758
7.000E-03	9.233E+01	2.840E+00	9.517E+01	1.298E-04	3.817E-05	0.2940
8.000E-03	9.871E+01	2.692E+00	1.014E+02	1.400E-04	4.347E-05	0.3106
9.000E-03	1.047E+02	2.561E+00	1.073E+02	1.496E-04	4.872E-05	0.3258
1.000E-02	1.104E+02	2.445E+00	1.128E+02	1.587E-04	5.391E-05	0.3398



$$\frac{dE}{dx} = f(E) \Rightarrow x = \int_{E_i}^{E_f} \frac{dE}{f(E)}$$

Proton therapy takes the advantage of using Bragg peak



Saha equation gives the relative proportions of atoms of a certain species that are in two different states of ionization in thermal equilibrium



$$\frac{n_{r+1}n_e}{n_r} = \frac{G_{r+1}g_e}{G_r} \frac{(2\pi m_e KT)^{3/2}}{h^3} \exp\left(-\frac{\chi_r}{KT}\right)$$

- n_{r+1} , n_r : Density of atoms in ionization state $r+1$, r (m^{-3})
- n_e : Density of electrons (m^{-3})
- G_{r+1} , G_r : Partition function of ionization state $r+1$, r
- $g_e=2$: Statistical weight of the electron
- m_e : Mass of the electron
- χ_r : Ionization potential of ground level of state r to reach to the ground level of state $r+1$
- T : Temperature
- h : Planck's constant
- K : Boltzmann constant

Some backgrounds of quantum mechanics



- Planck blackbody function:

$$u(\nu, T) = \frac{8\pi h \nu^3}{c^3} \frac{1}{e^{h\nu/KT} - 1} \text{ (W/m}^3 \text{ Hz)}$$

- Boltzmann formula:

- g_i, g_j : statistical weight

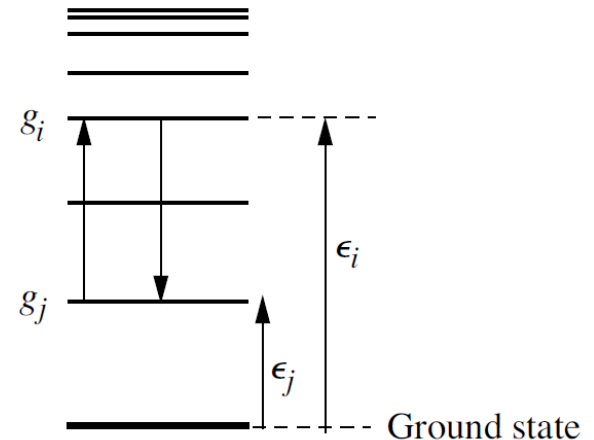
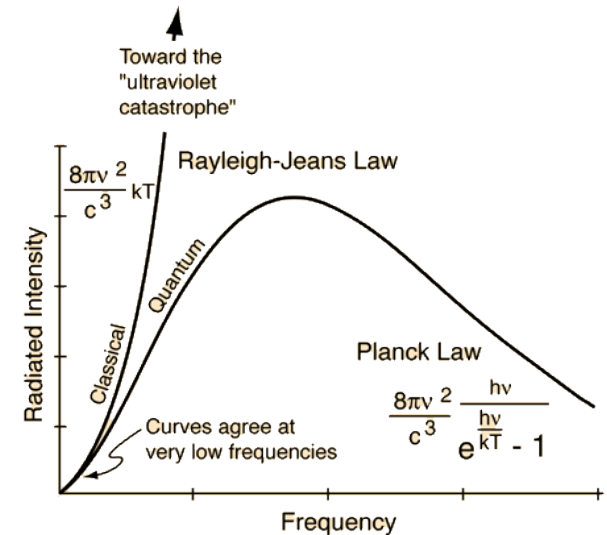
$$\frac{n_i}{n_j} = \frac{g_i e^{-\epsilon_i/KT}}{g_j e^{-\epsilon_j/KT}} = \frac{g_i}{g_j} e^{-h\nu_{ij}/KT} \quad \frac{g_i}{g_j} = \frac{2J_i + 1}{2J_j + 1}$$

(J: angular momenta quantum number)

- Number in the i^{th} state to the total atom:

$$\frac{n_i}{n} = \frac{n_i}{\sum n_j} \equiv \frac{g_i e^{-\epsilon_i/KT}}{G} \quad G \equiv \sum g_j e^{-\epsilon_j/KT}$$

G: partition function of statistical weight for the atom, taking into account all its excited states.



Einstein coefficient



- **Probability of electron energy transition:**

- **Excitation ($\uparrow$):** $P_{ji} = B_{ji}u(\nu, T)$

- **De-excitation ($\downarrow$):** $P_{ij} = A_{ij} + B_{ij}u(\nu, T)$

- **In thermal equilibrium:**

$$n_i(A_{ij} + B_{ij}u) = n_j B_{ji}u$$

$$\frac{g_i}{g_j} e^{-x} (A_{ij} + B_{ij}u) = B_{ji}u$$

$$u = a(e^x - 1)^{-1}$$

$$a \left(e^x B_{ji} - \frac{g_i}{g_j} B_{ij} \right) = (e^x - 1) \frac{g_i}{g_j} A_{ij}$$

$$x \equiv \frac{h\nu}{KT}$$

$$a \equiv \frac{8\pi h\nu^3}{c^3}$$

- **The Einstein coefficients are independent of T or ν .**

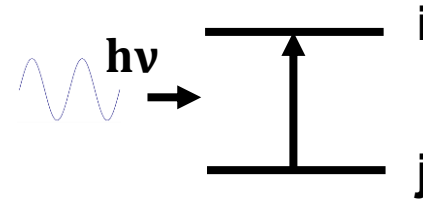
$$x \rightarrow 0, e^x \rightarrow 1$$

$$x \rightarrow \infty, e^x \rightarrow \infty$$

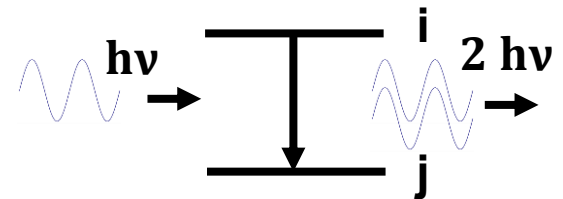
$$\frac{B_{ij}}{B_{ji}} = \frac{g_j}{g_i}$$

$$a B_{ji} = \frac{g_i}{g_j} A_{ij} \quad \frac{A_{ij}}{B_{ij}} = \frac{8\pi h\nu^3}{c^3}$$

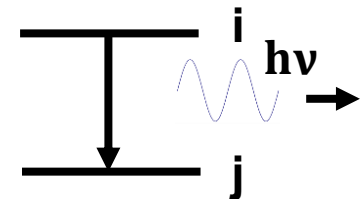
- **Photoexcitation:**



- **Induced radiation:**



- **Spontaneous radiation:**



Saha equation is derived using the transition between different ionization states



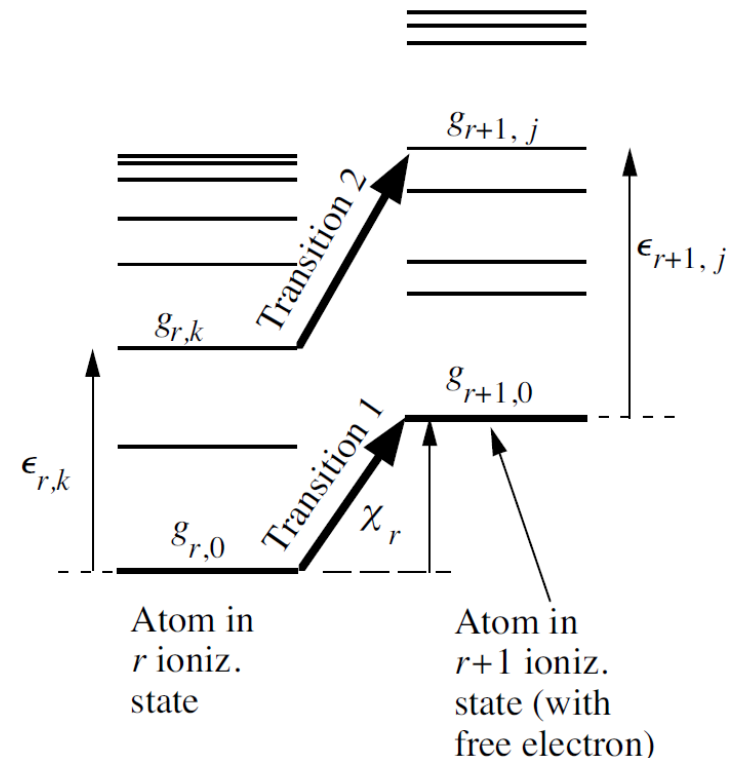
- Required photon energy for transition (1) from the ground state of r ionization state to the ground state of $r+1$ ionization state:

$$h\nu = \chi_r + \frac{p^2}{2m}$$

Energy of the free electron

- Required photon energy for transition (2) from the energy level k of r ionization state to the energy level j of $r+1$ ionization state:

$$h\nu = \chi_r + \epsilon_{r+1,j} - \epsilon_{r,k} + \frac{p^2}{2m}$$



Saha equation is derived using the transition between different ionization states



- Photoionization:

$$R_{\text{pi}} = n_{r,k} u(\nu) B_{r,k \rightarrow r+1,j}$$

- Induced radiation:

$$R_{\text{ir}} = n_{r+1,j} n_{e,p}(p) u(\nu) B_{r+1,j \rightarrow r,k}$$

- Spontaneous emission:

$$R_{\text{sr}} = n_{r+1,j} n_{e,p}(p) A_{r+1,j \rightarrow r,k}$$

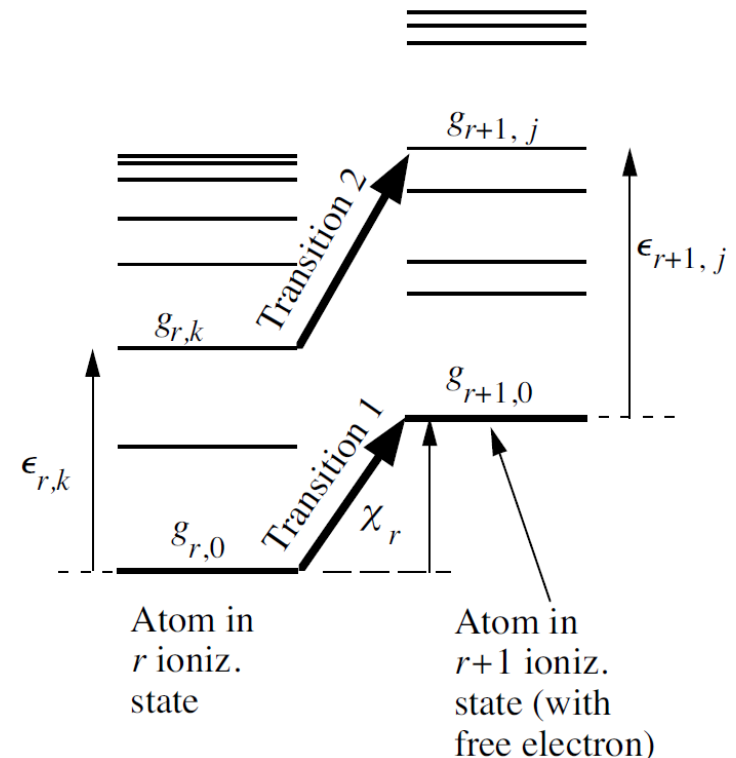
- In thermal equilibrium:

$$n_{r+1,j} n_{e,p} A_{r+1,j \rightarrow r,k} + n_{r+1,j} n_{e,p} u B_{r+1,j \rightarrow r,k} = n_{r,k} u B_{r,k \rightarrow r+1,j}$$

- Einstein coefficients:

$$\frac{B_{r,k \rightarrow r+1,j}}{B_{r+1,j \rightarrow r,k}} = \frac{g_{r+1,j}}{g_{r,k}} \frac{g_e 4\pi p^2}{h^3}$$

$$\frac{A_{r+1,j \rightarrow r,k}}{B_{r+1,j \rightarrow r,k}} = \frac{8\pi h \nu^3}{c^3}$$



Saha equation - continued



$$n_{r+1,j}n_{e,p}A_{r+1,j \rightarrow r,k} + n_{r+1,j}n_{e,p}uB_{r+1,j \rightarrow r,k} = n_{r,k}uB_{r,k \rightarrow r+1,j}$$

$$n_{r+1,j}n_{e,p} \frac{A_{r+1,j \rightarrow r,k}}{B_{r+1,j \rightarrow r,k}} + n_{r+1,j}n_{e,p}u = n_{r,k}u \frac{B_{r,k \rightarrow r+1,j}}{B_{r+1,j \rightarrow r,k}}$$

$$\frac{n_{r+1,j}n_{e,p}}{n_{r,k}} = \left(\frac{A_{r+1,j \rightarrow r,k}}{uB_{r+1,j \rightarrow r,k}} + 1 \right)^{-1} \frac{B_{r,k \rightarrow r+1,j}}{B_{r+1,j \rightarrow r,k}}$$

$$\frac{B_{r,k \rightarrow r+1,j}}{B_{r+1,j \rightarrow r,k}} = \frac{g_{r+1,j}}{g_{r,k}} \frac{g_e 4\pi p^2}{h^3}$$

$$n_{e,p}(p) = \frac{n_e 4\pi p^2}{(2\pi mKT)^{3/2}} \exp\left(-\frac{p^2}{2mKT}\right)$$

$$\frac{A_{r+1,j \rightarrow r,k}}{B_{r+1,j \rightarrow r,k}} = \frac{8\pi h\nu^3}{c^3}$$

$$\frac{n_{r+1,j}n_e}{n_{r,k}} = \frac{(2\pi mKT)^{3/2}}{4\pi p^2} \exp\left(\frac{p^2}{2mKT}\right) \left[\frac{c^3}{8\pi h\nu^3} (e^{h\nu/KT} - 1) \frac{8\pi h\nu^3}{c^3} + 1 \right]^{-1} \frac{g_{r+1,j}}{g_{r,k}} \frac{g_e 4\pi p^2}{h^3}$$

$$\frac{n_{r+1,j}n_e}{n_{r,k}} = \frac{(2\pi mKT)^{3/2}}{h^3} \frac{g_{r+1,j}g_e}{g_{r,k}} \exp\left[\frac{1}{KT} \left(\frac{p^2}{2m} - h\nu\right)\right]$$

Saha equation - continued



$$\frac{n_{r+1,j}n_e}{n_{r,k}} = \frac{(2\pi m_e K T)^{3/2}}{h^3} \frac{g_{r+1,j}g_e}{g_{r,k}} \exp \left[\frac{1}{K T} \left(\frac{p^2}{2m} - h\nu \right) \right]$$

$$\frac{n_{r+1,j}n_e}{n_{r,k}} = \frac{(2\pi m_e K T)^{3/2}}{h^3} \frac{g_{r+1,j}g_e}{g_{r,k}} \exp \left[\frac{1}{K T} \left(\frac{p^2}{2m} - \chi_r - \epsilon_{r+1,j} + \epsilon_{r,k} - \frac{p^2}{2m} \right) \right]$$

$$\frac{n_{r+1,j}n_e}{n_{r,k}} = \frac{(2\pi m_e K T)^{3/2}}{h^3} \frac{g_{r+1,j} \exp \left(-\frac{\epsilon_{r+1,j}}{K T} \right) g_e}{g_{r,k} \exp \left(-\frac{\epsilon_{r,k}}{K T} \right)} \exp \left(-\frac{\chi_r}{K T} \right)$$

$$\frac{n_{r,k}}{n_r} = \frac{g_{r,k} e^{-\epsilon_{r,k}/K T}}{G_r}$$

$$G_r = \sum g_{r,k} e^{-\epsilon_{r,k}/K T}$$

$$\frac{n_{r+1,j}}{n_{r+1}} = \frac{g_{r+1,j} e^{-\epsilon_{r+1,j}/K T}}{G_{r+1}}$$

$$G_{r+1} = \sum g_{r+1,j} e^{-\epsilon_{r+1,j}/K T}$$

$$\frac{n_{r+1}n_e}{n_r} = \frac{G_{r+1}g_e}{G_r} \frac{(2\pi m_e K T)^{3/2}}{h^3} \exp \left(-\frac{\chi_r}{K T} \right)$$

Saha equation – example: hydrogen plasma of the sun



- Photosphere of the sun – hydrogen atoms in an optically thick gas in thermal equilibrium at temperature $T=6400$ K.

- Neutral hydrogen (r state / ground state)

$$G_r = \sum g_{r,k} = g_{r,0} + g_{r,1} \exp\left(-\frac{\epsilon_{r,1}}{KT}\right) + \dots = 2 + 8 \exp\left(-\frac{10.2\text{eV}}{0.56\text{eV}}\right) + \dots \\ = 2 + 9.8 \times 10^{-8} + \dots \approx 2$$

- Ionized state (r+1 state)

$$G_{r+1} = \sum g_{r+1,j} = g_{r+1,0} + g_{r+1,1} \exp\left(-\frac{\epsilon_{r+1,1}}{KT}\right) + \dots \approx 1$$

- Other information: $g_e = 2$ $\chi_r = 13.6\text{eV}$; $KT = 0.56\text{eV}$ $n_{r+1} = n_e$

$$\frac{n_{r+1}^2}{n_r} = 2.41 \times 10^{21} \frac{1 \times 2}{2} (6400)^{3/2} \exp\left(-\frac{13.6}{0.56}\right) = 3.5 \times 10^{16} m^{-3}$$

It is mostly neutral in the photosphere of the sun



- Assuming 50 % ionization:

$$n_{r+1} = n_r = 3.5 \times 10^{16} m^{-3} \quad n = n_{r+1} + n_r = 7 \times 10^{16} m^{-3}$$

- At lower densities n at the same temperature, there should be fewer collisions leading to recombination and thus the plasma to be more than 50 % ionization.
- In the photosphere of the sun:

$$\rho \sim 3 \times 10^{-4} \text{ kg}/m^3 \rightarrow n = 2 \times 10^{23} m^{-3} \gg 7 \times 10^{16} m^{-3}$$

$\Rightarrow$ Less than 50 % ionization

- Use the total number density to estimate the ionization percentage:

$$n_{r+1} + n_r = 2 \times 10^{23}$$

$$\frac{n_{r+1}}{n_r} = 4 \times 10^{-4} @ 6400K$$