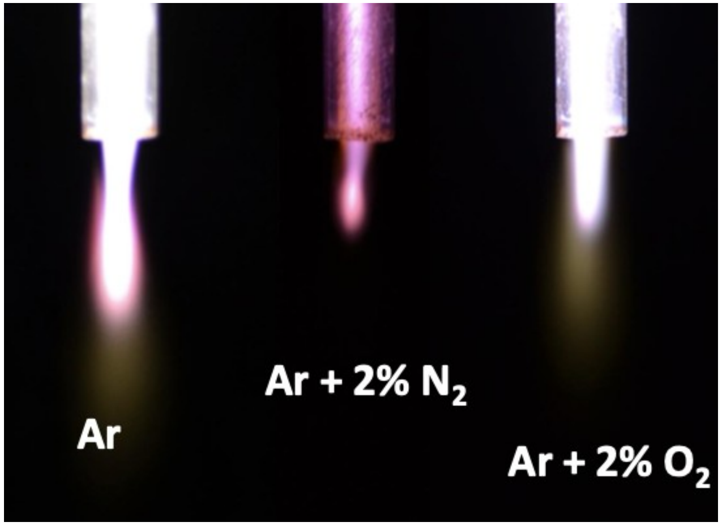
Plasma Physics 2

Lesson 05: High frequency discharges



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Lecture series contents

1. Townsend breakdown theory, Paschen‘s law
2. Glow discharge
3. Electric arc at low and high pressures
4. Magnetized low-pressure plasmas and their role in material deposition methods.
5. **Brief introduction to high-frequency discharges**
6. Streamer breakdown theory, corona discharge, spark discharge
7. Barrier discharges
8. Leader discharge mechanism, ionization and discharges in planetary atmospherres
9. Discharges in liquids, complex and quantum plasmas
10. Thermonuclear fusion, Lawson criterion, magnetic confinement systems, plasma heating and intertial confinement fusion.

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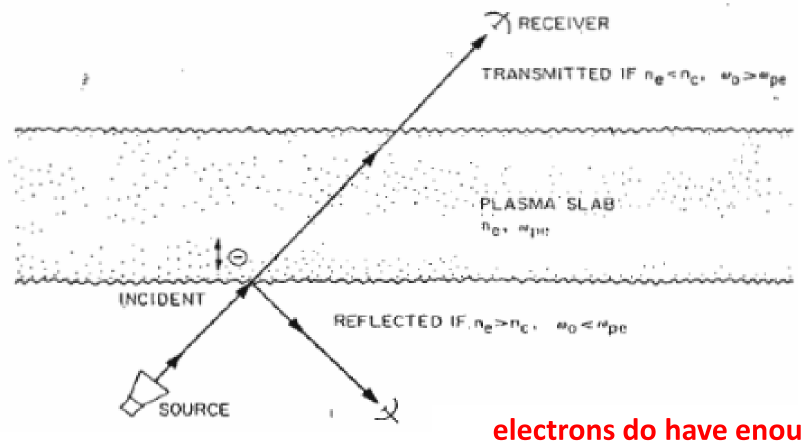
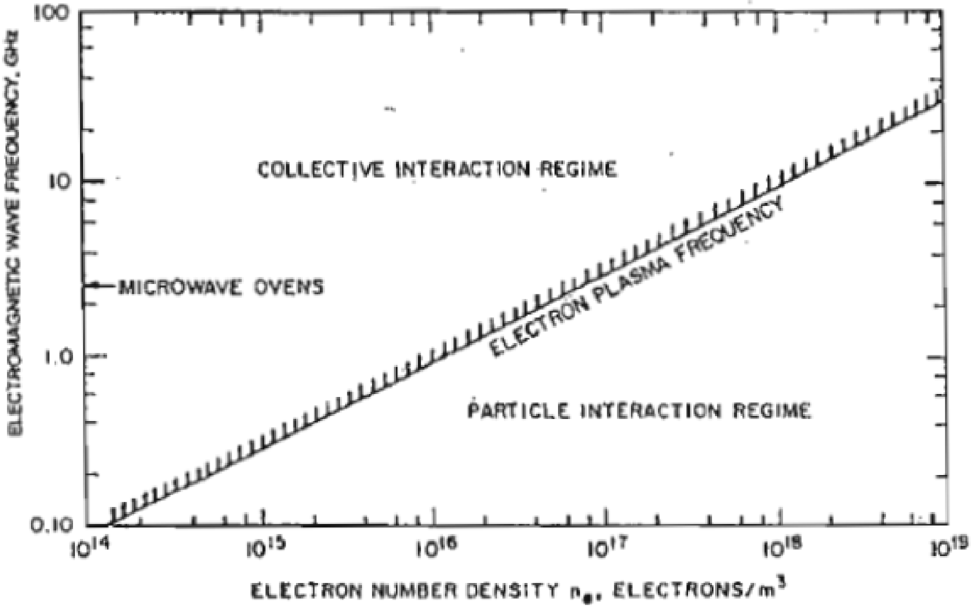
High frequency discharges

- enable plasma discharge even for non-conductive electrodes
- electron plasma frequency

$$\omega_{pe} = \left(\frac{ne^2}{m\varepsilon_0}\right)^{1/2} \qquad \text{(rad/s)}$$

- numerically $n_e \approx 10^{10}$ cm^{-3} je f=0,9 GHz





electrons do have enough time to react to the external electric field!

- varieties:
  - MHz = RF plasma, ohřev plazmy posuvným proudem
    - capacitively coupled plasma – collisionall and collisionless heating, can run at very low pressures
    - inductively coupled plasma – heating on the plasma surface or in plasma volume
  - GHz = microwave discharges, surface wave heating or volume heating

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High frequency discharges

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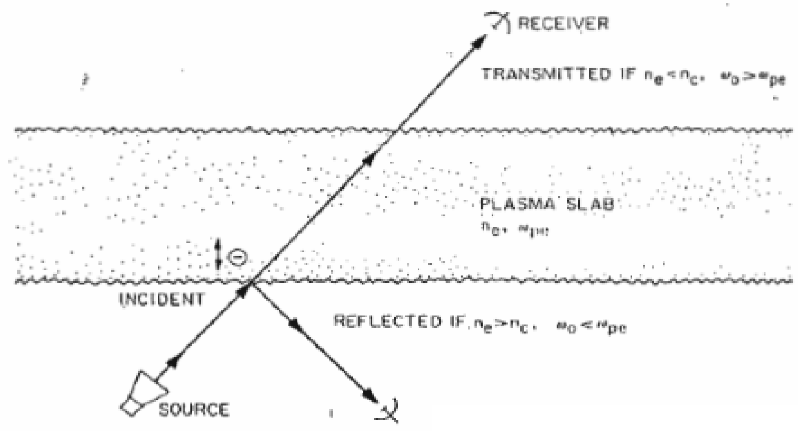
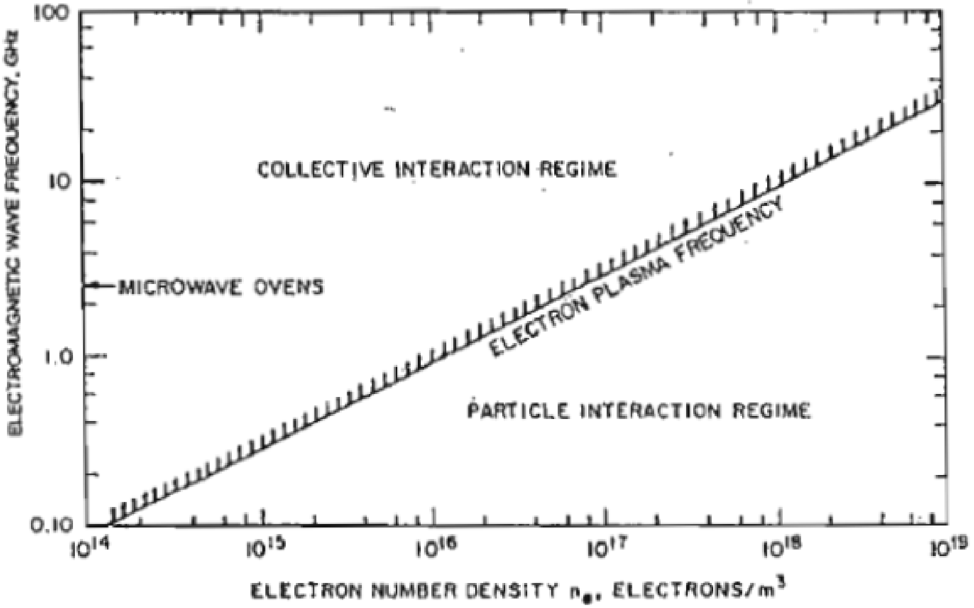




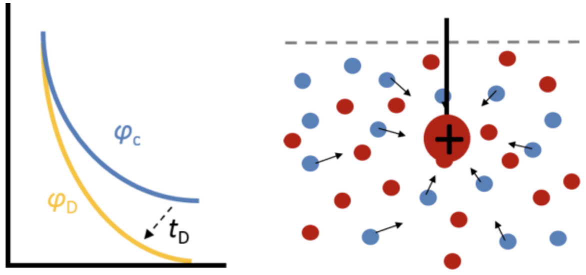


Fig. 4: Response time to form a Debye sheath

$$t_D \simeq \frac{\lambda_D}{v_{te}} = \left(\frac{\varepsilon_0 k_B T_e}{e^2 n_e} \cdot \frac{m}{k_B T_e}\right)^{1/2} = \omega_p^{-1}$$

$$L >> \lambda_D$$

$$N_D := \frac{4\pi}{3} n \lambda_D^3 >> 1$$

$$n_e = \sum n_i$$

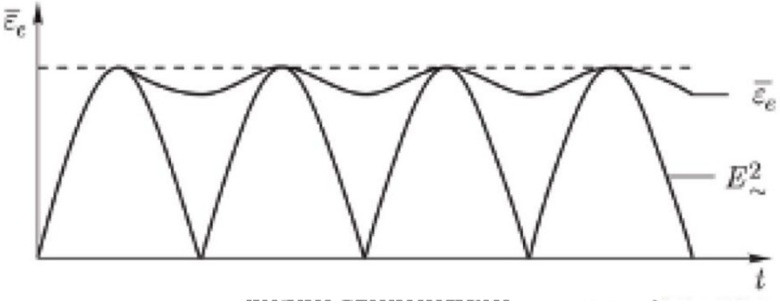
$$\nu_{en} < \nu_{pl} \quad (\text{kde } \nu_{pl} = \omega_{pl}/2\pi)$$

HIGH FREQUENCY BREAKDOWN

[redacted]

High frequency breakdown

- At about 100 kHz, the time that the electron needs to transfer between the electrodes starts to be comparable with the period of the external electric field. **The electron avalanche does not reach the electrode and it reverses direction!**
- electron heating in the external field is given as: $P = jE = \frac{e^2E^2}{m} \cdot \frac{n_e \nu_{en}}{\nu_{en}^2 + \omega^2}$



Mean electron energy

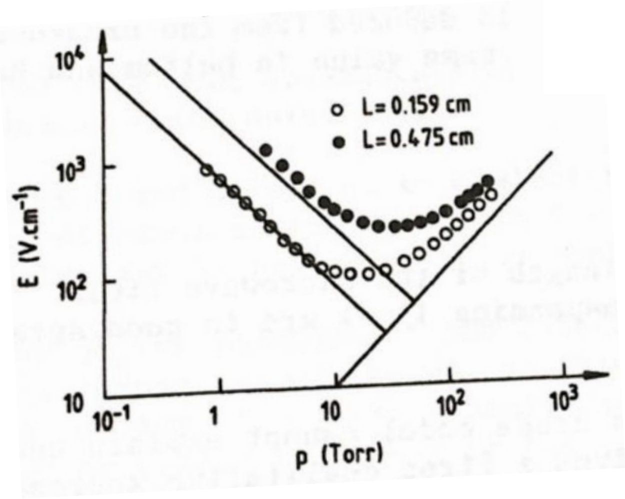
External electric field

Low frequencies

- The optimum power is reached when:

$$\left(\frac{dP}{d\nu_{en}} = 0\right)$$

$$\omega = \nu_{en}$$



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High frequency breakdown

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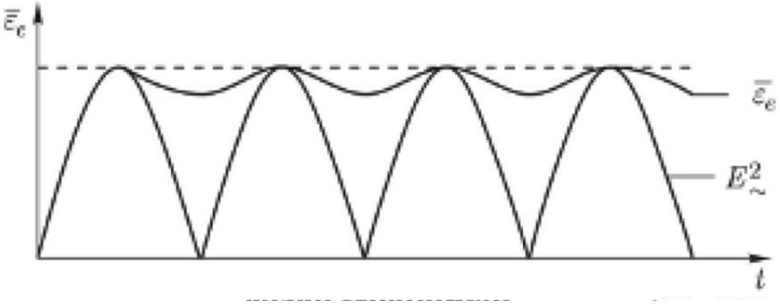

Mean electron energy

External electric field

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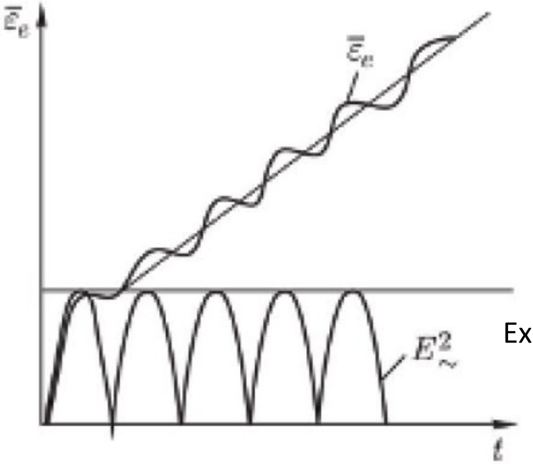
Mean electron energy (prior to multiplication)



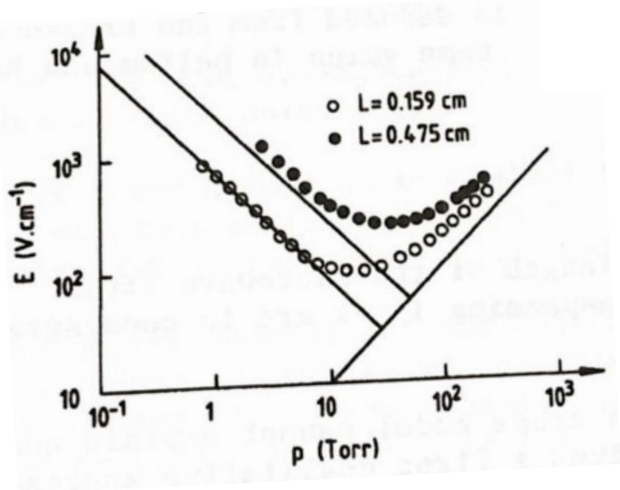
External E field

High frequency

- The optimum power

$$\left(\frac{dP}{dv_{en}} = 0\right)$$

$$\omega = v_{en}$$



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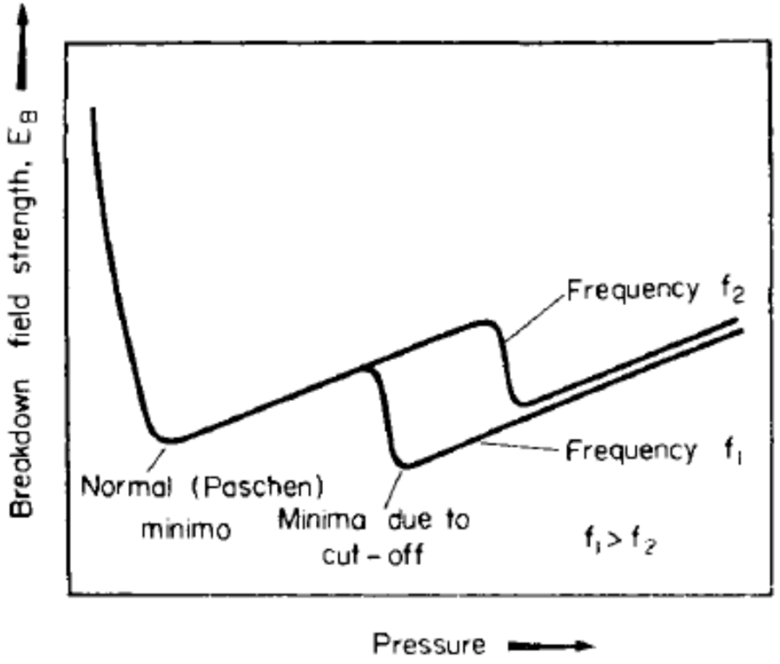
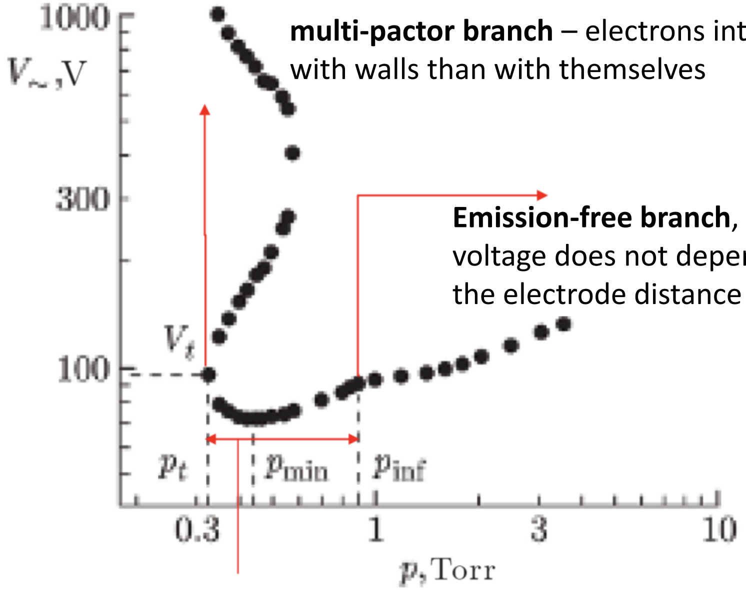
High Frequency breakdown



J. Phys. D: Appl. Phys. **31** (1998) 3349–3357.



multi-pactor branch – electrons interact more with walls than with themselves

Emission-free branch, breakdown voltage does not depend on the electrode distance

Drift-diffusion branch – secondary emission affects the breakdown voltage

- The Paschen curve for RF breakdown has two minima:
  1) **Classical DC-like**: Electron attains some „ideal“ energy when traversing between electrodes
  2) **Resonance capture of electrons:** electrons bounce off a plasma sheath that is approaching them.

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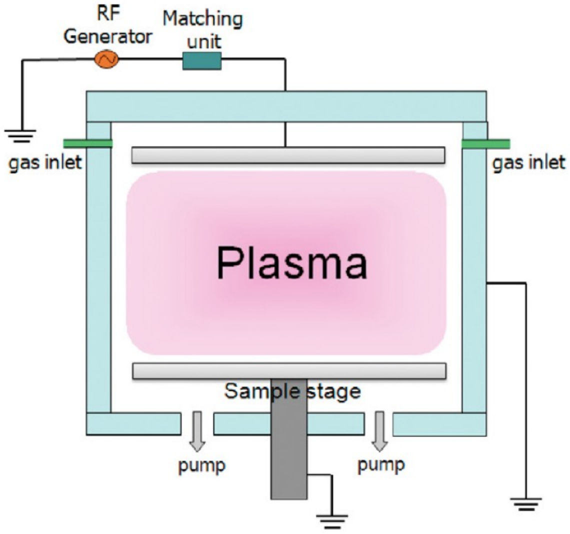
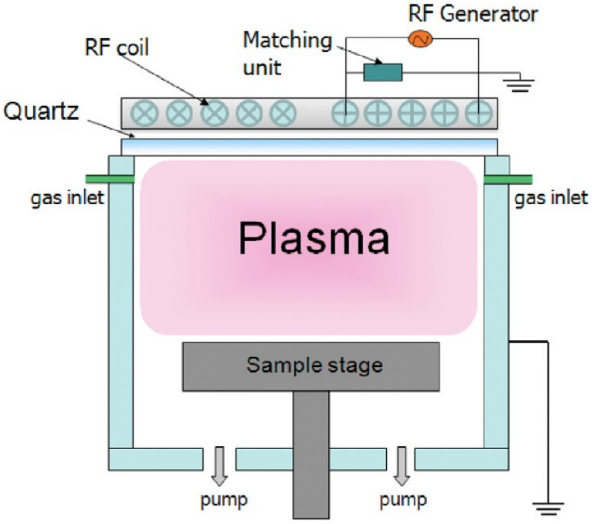
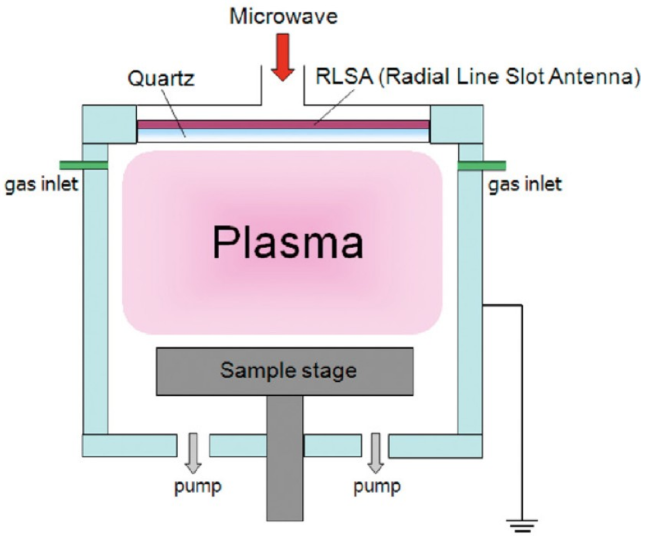
CCP vs ICP vs MW plasma



(a) Capacitively coupled plasma



(b) Inductively coupled plasma



(c) Microwave plasma

CAPACITIVELY COUPLED PLASMA ANATOMY

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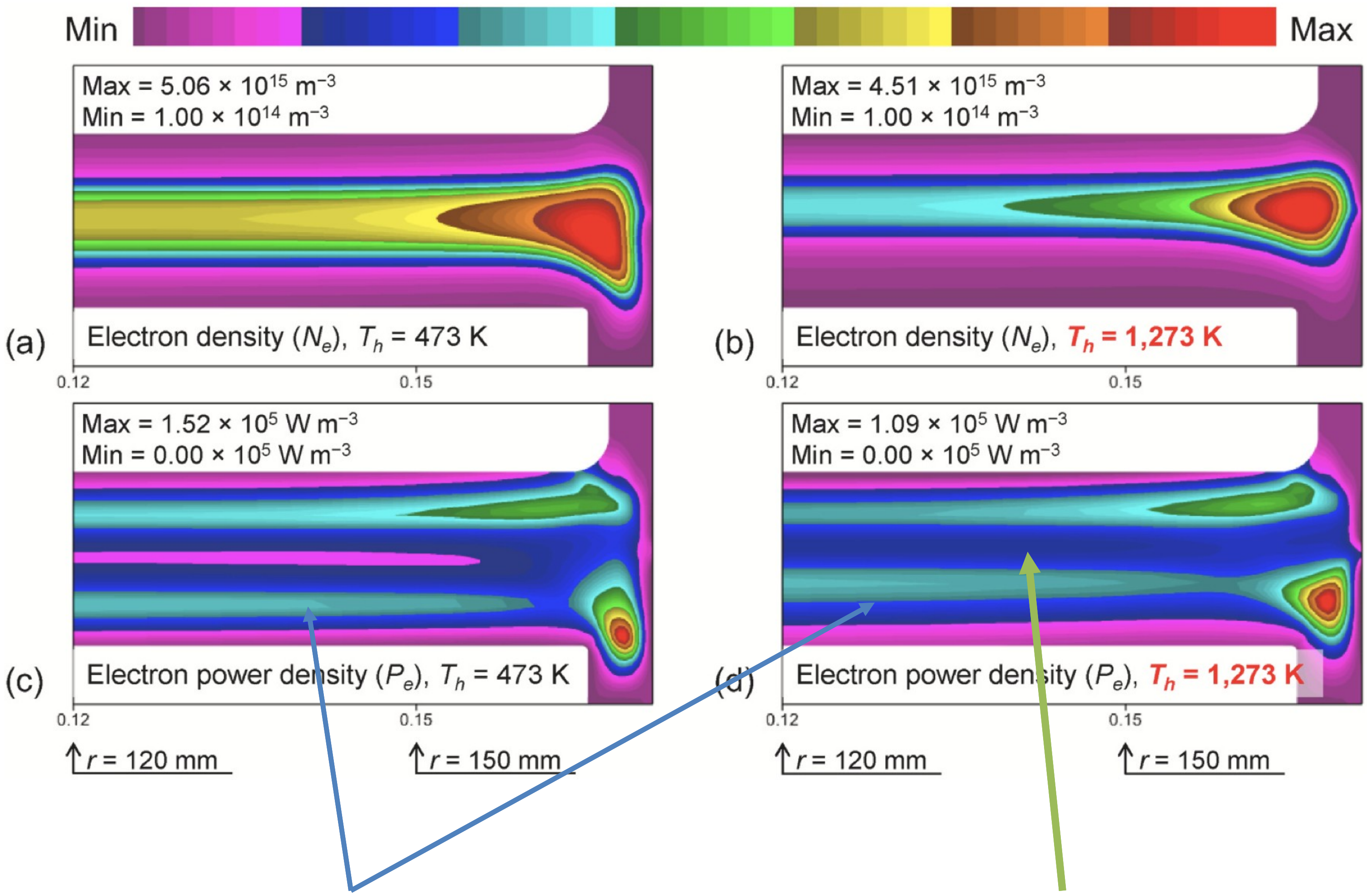
CCP plasma anatomy

Typical frequencies: 10 MHz – 100 MHz (13.56 MHz ”standard”)
Typical pressure: 1 Pa – 1000 Pa



Near-electrode electron heating (stochastic)

Bulk plasma heating (ohmic)

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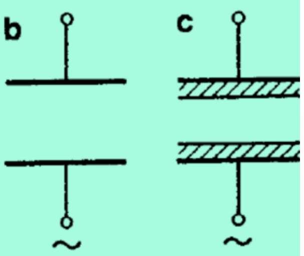
CCP plasma anatomy

- Simples case are two planar electrodes, covered with dielectric. Potential and density evolution during phase as follows:



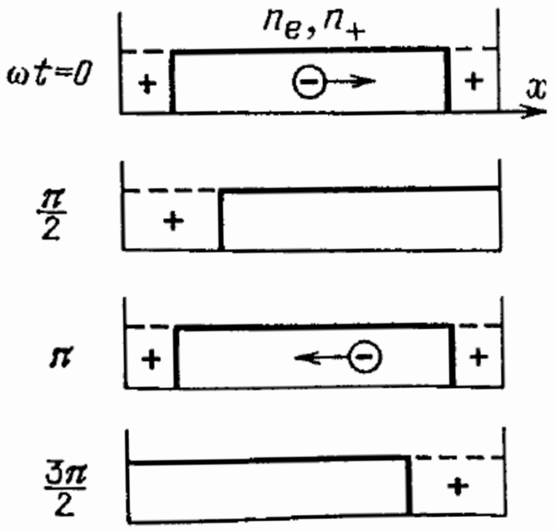


Fig. 13.1. Swings of the electron gas. The gas of ions is assumed to be fixed and uniform. Time is measured from the moment when electrons pass through the equilibrium position when moving to the right. Distributions $n_e(x)$ are shown for every quarter of the period

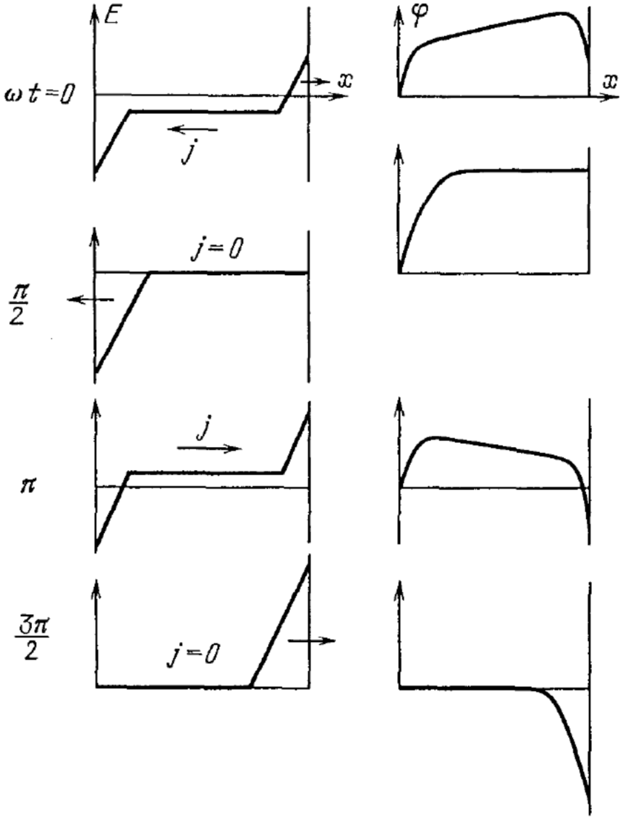


Fig. 13.2. Field and potential distributions in the gap corresponding to Fig. 13.1

[redacted]

CCP plasma – self bias voltage

- In CCP plasmas, we see emergence of the **so-called self-bias DC voltage.**
- empirically, we see: $\frac{V_1}{V_2} = \left(\frac{A_2}{A_1}\right)^q$ $\quad 1 \leq q \leq 2.5$ where A_1, A_2 are electrode surface areas
- An approximate derivation can be made as follows – we assume that the ion current on both electrodes has to be the same:

$$I_{i1} = I_{i2}$$

$$A_1 e n_{i1} \bar{v}_{i1} = A_2 e n_{i2} \bar{v}_{i2}$$

$$\bar{v}_i = \sqrt{\frac{2eV}{m_i}}$$

- And if we further assume that the ion densities in front of both electrodes are the same $n_{i1}=n_{i2}$ a $m_{i1}=m_{i2}$ we obtain

$$A_1 e n_i \sqrt{\frac{2eV_1}{m_i}} = A_2 e n_i \sqrt{\frac{2eV_2}{m_i}}$$

- And ultimately

$$\frac{A_1}{A_2} = \sqrt{\frac{V_2}{V_1}}$$

The smaller electrode has to have **higher negative voltage** to draw the same ion current => it acts as a cathode and it can be used e.g. for sputtering of material

This derivation is still extremely simplistic, will be done more properly in Plasma Physics 3

INDUCTIVELY COUPLED PLASMA ANATOMY

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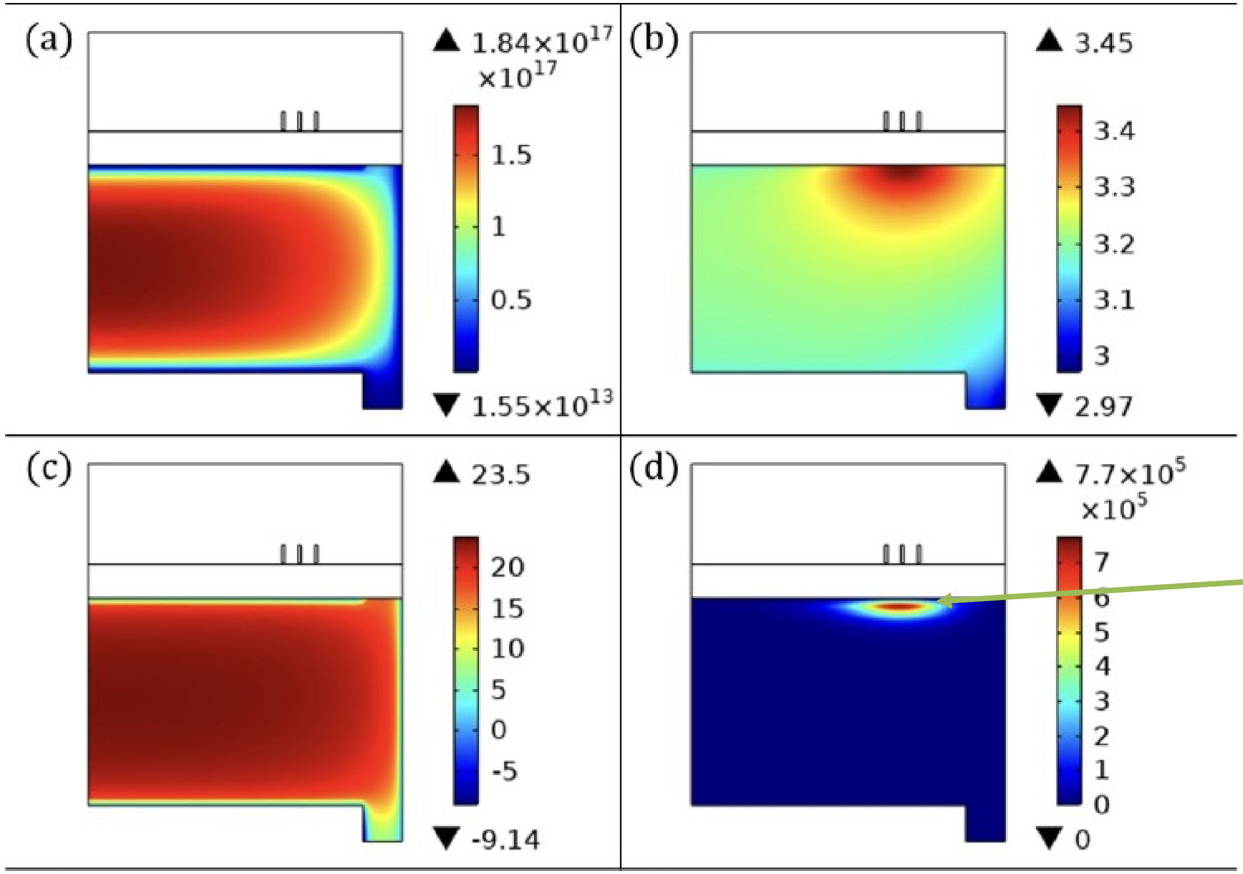
ICP plasma anatomy

Typical frequencies: 10 MHz – 100 MHz (13.56 MHz ”standard”)
Typical pressure: 1 Pa – 1000 Pa



Localized power deposition

Figure 4. Plasma properties computed for Druyvesteyn EEDF at 10 mTorr and gas flow rate of 100 sccm, and absorbed power of 570 W; (a) electron density (1/m^3), (b) electron temperature (eV), (c) plasma potential (V), and (d) power density (W/m^3).

[redacted]

ICP plasma anatomy

- Plasma is generated by **electromagnetic induction – The RF coil creates H field, which creates poloidal E field in the volume**
- This wireless transfer of energy makes it **possible to run the system at very high temperatures**, because the walls can be made of ceramics with high thermal resistivity.

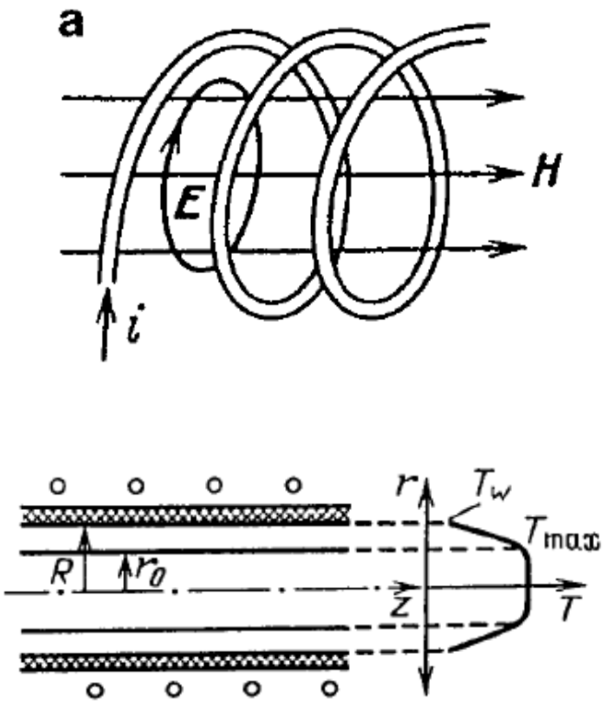


Fig. 11.1. Induction discharge in a tube of radius R placed inside a long solenoid; r_0 is the discharge radius. The radial temperature distribution is given on the *right*

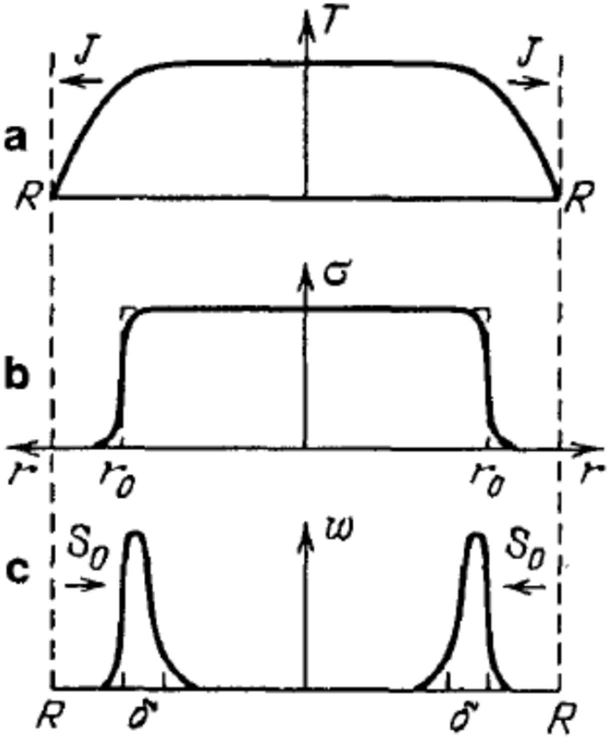


Fig. 11.2. Radial distributions of **(a)** temperature, **(b)** conductivity, and **(c)** Joule heat release in induction discharge. Dashed curves correspond to step function $\sigma(r)$ in the metallic cylinder model. *Arrows:* J, heat flux; S_0, electromagnetic energy flux; δ, skin layer thickness

MICROWAVE PLASMA ANATOMY

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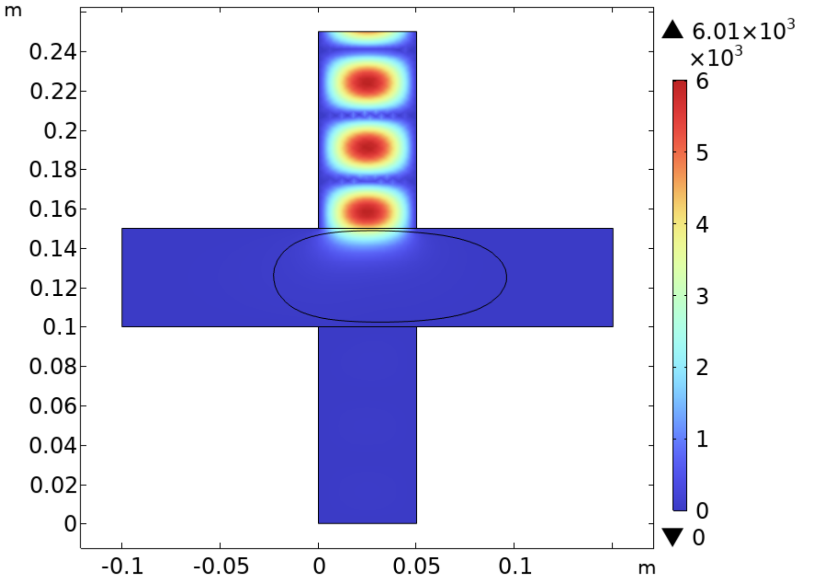
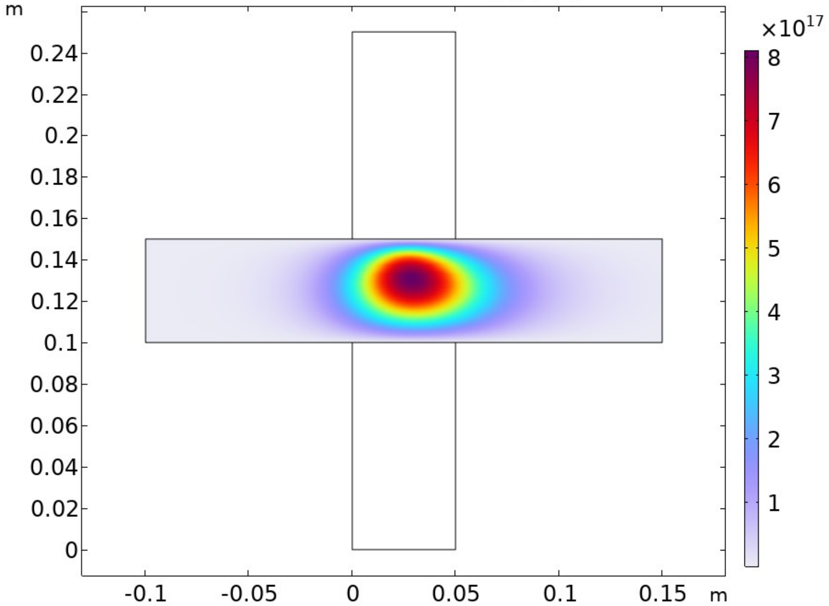
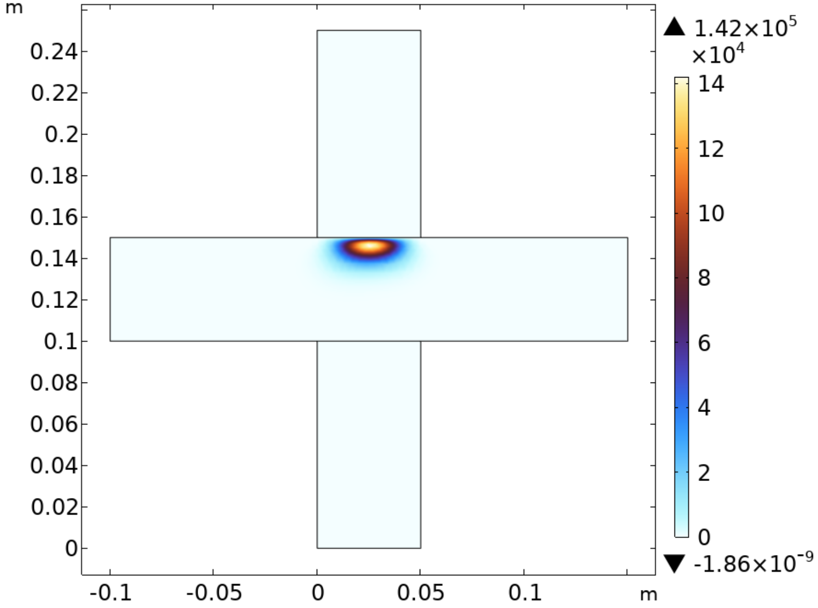
MW plasma anatomy

Typical frequencies:
100 MHz – 10 GHz MHz (2.45 GHz ”standard”)
Gas pressure:
100 Pa – 1 atm


Time=0.01 s Surface: Electric field norm (V/m) Contour: Electron density (1/m^3)


Time=0.01 s Surface: Electron density (1/m^3)


Time=0.01 s Surface: Resistive losses (W/m^3)

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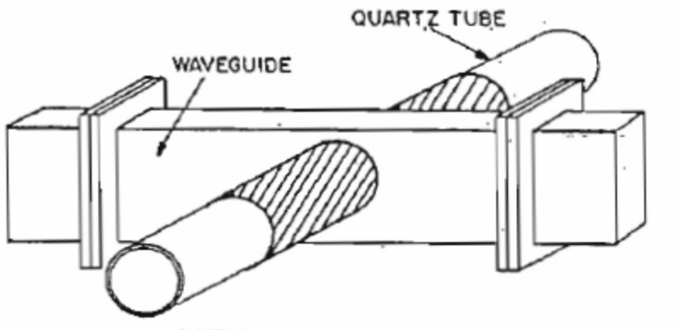
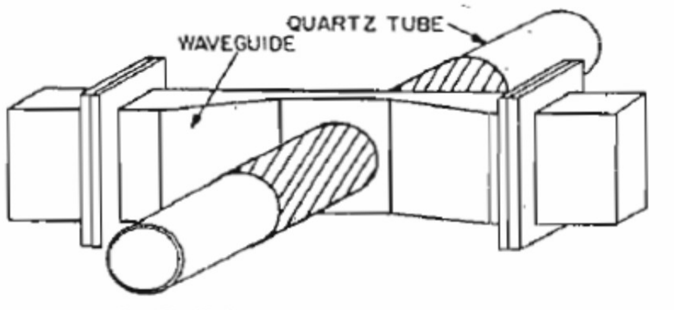
MW plasma anatomy

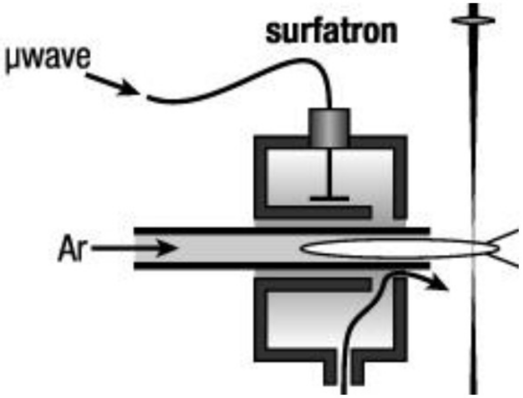
- There are various setups for MW plasma generation – surfatron, surfaguide, coaxial line, ….



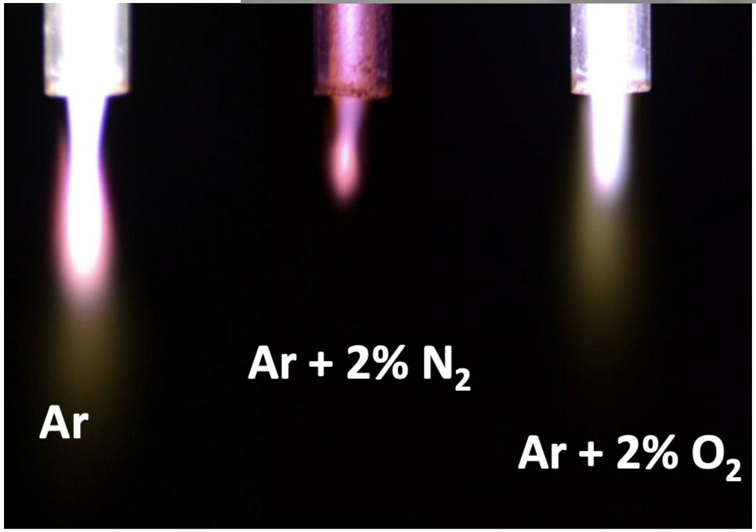
a) STANDARD PLASMA APPLICATOR



b) HIGH ELECTRIC FIELD APPLICATOR



Sairem, SURFATRON 80



L.Potočňáková, Dipl. práca

APPLICATIONS OF CCP, ICP, MW

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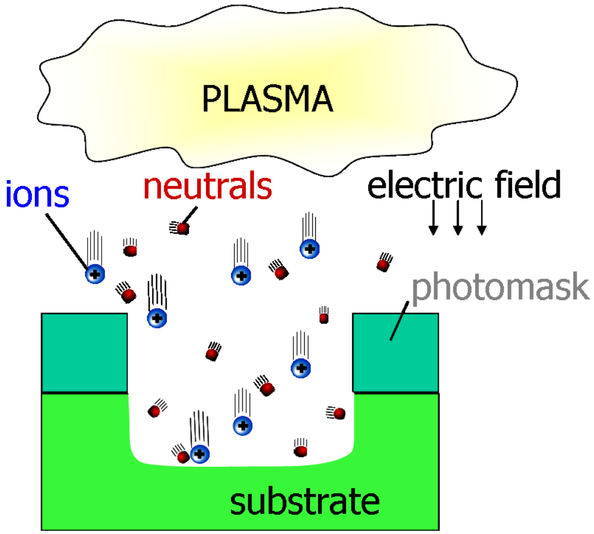
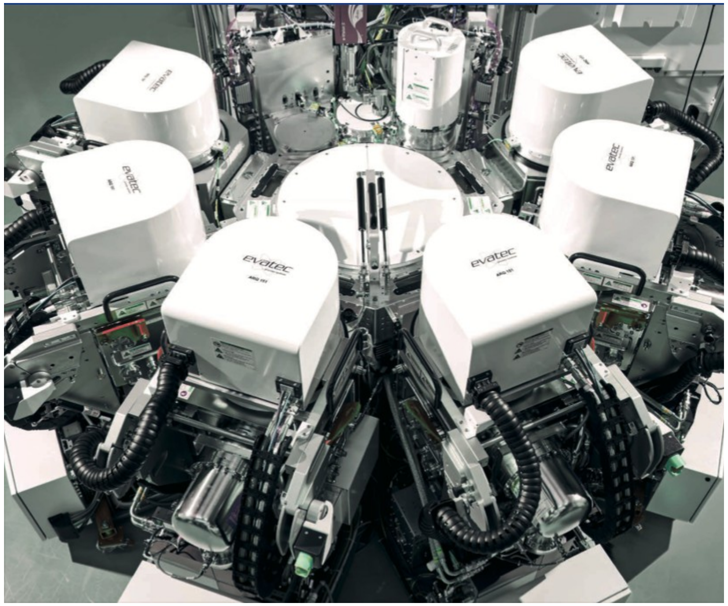
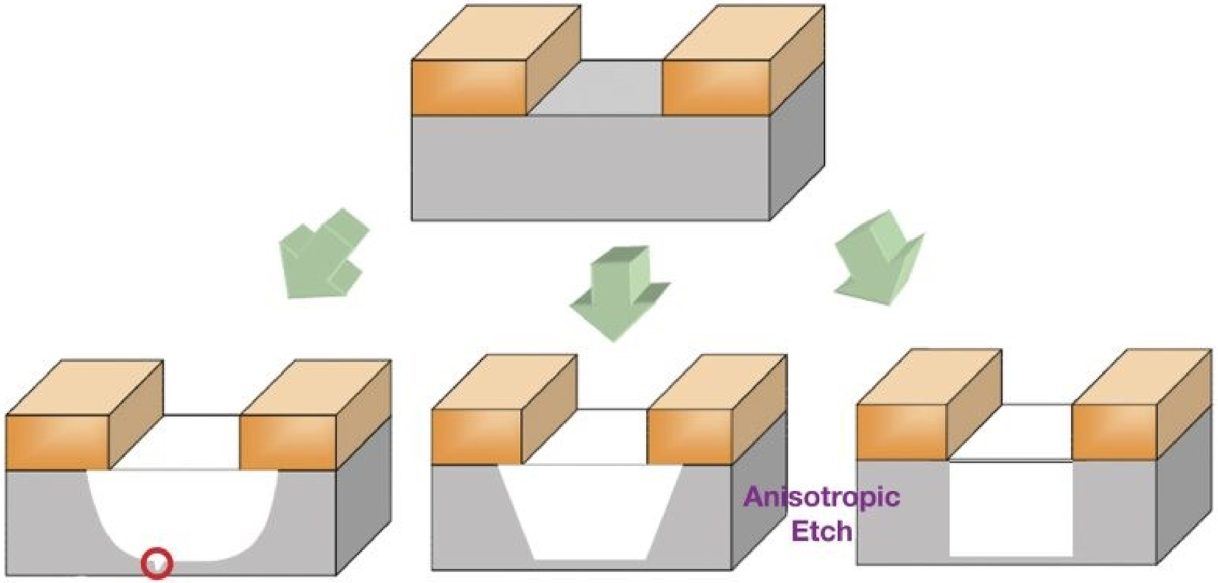
CCP and ICP applications – semiconductor etching



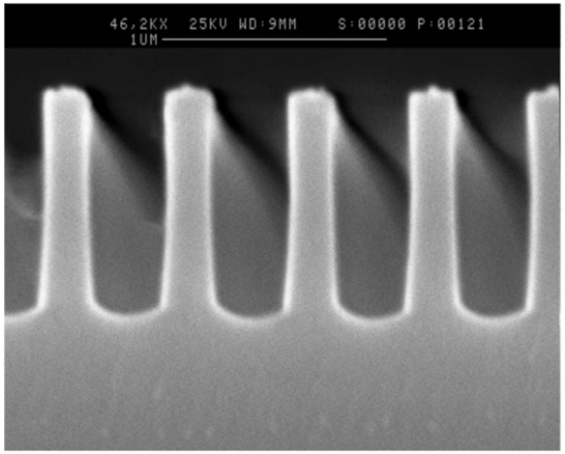




Isotropic Etch

Directional Etch

Vertical Etch



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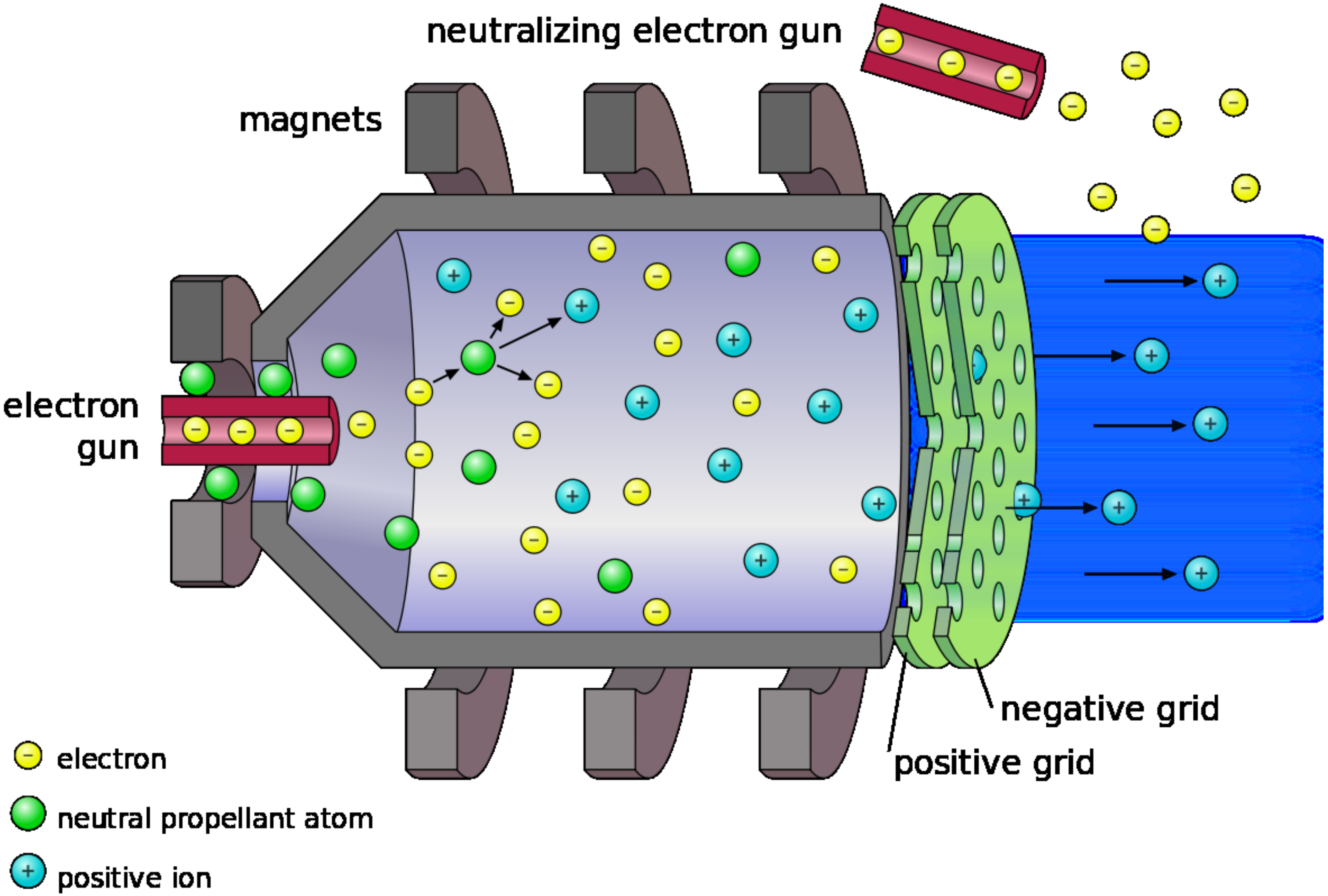
CCP application – gridded ion thruster



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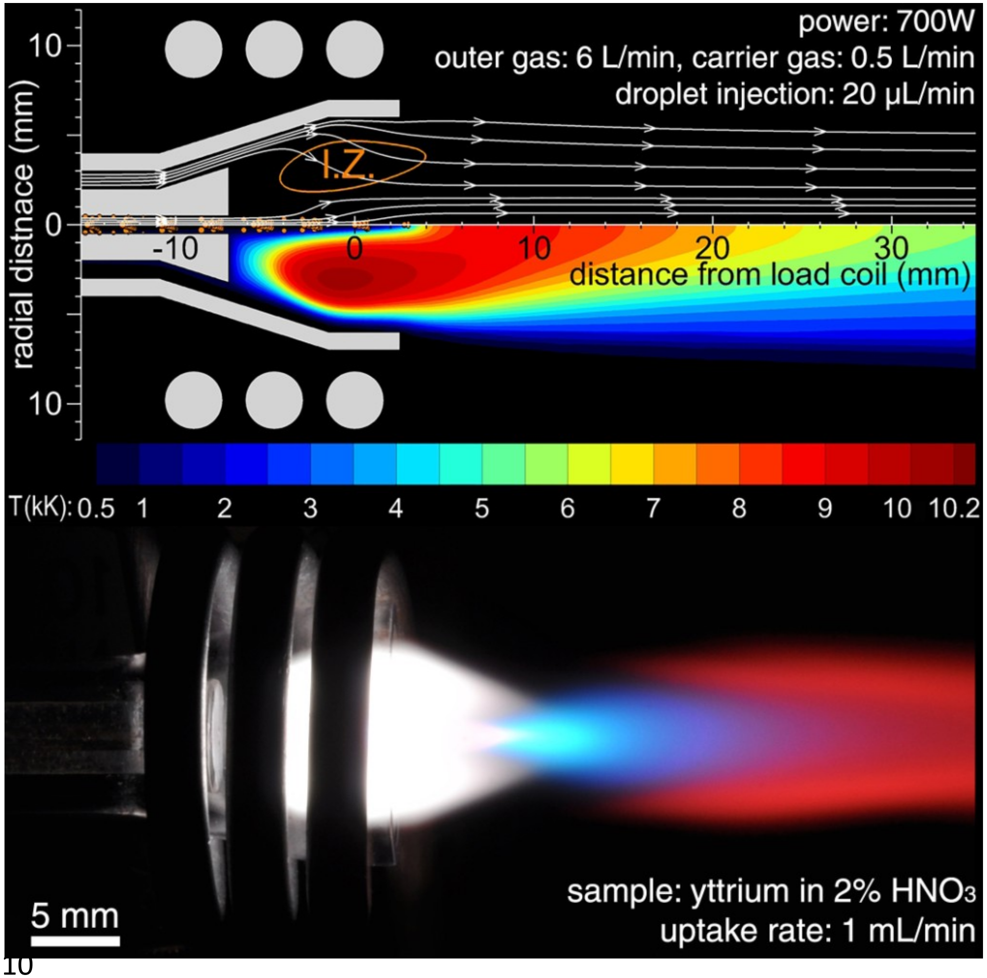
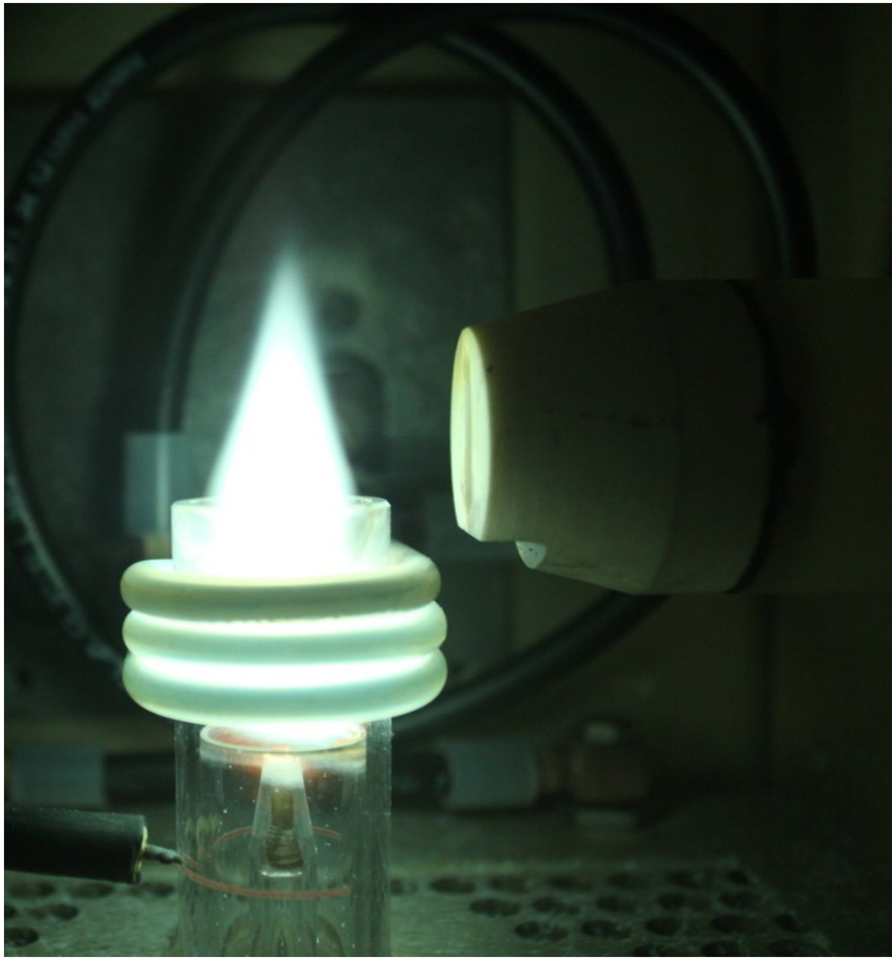
ICP application – DC torch analogue

- At atm. pressure and high power levels, so-called ICP torches can generate fully ionized plasmas. Support similar power ranges (5 kW – 1 MW)
- Advantage over DC torches: no contact with metal





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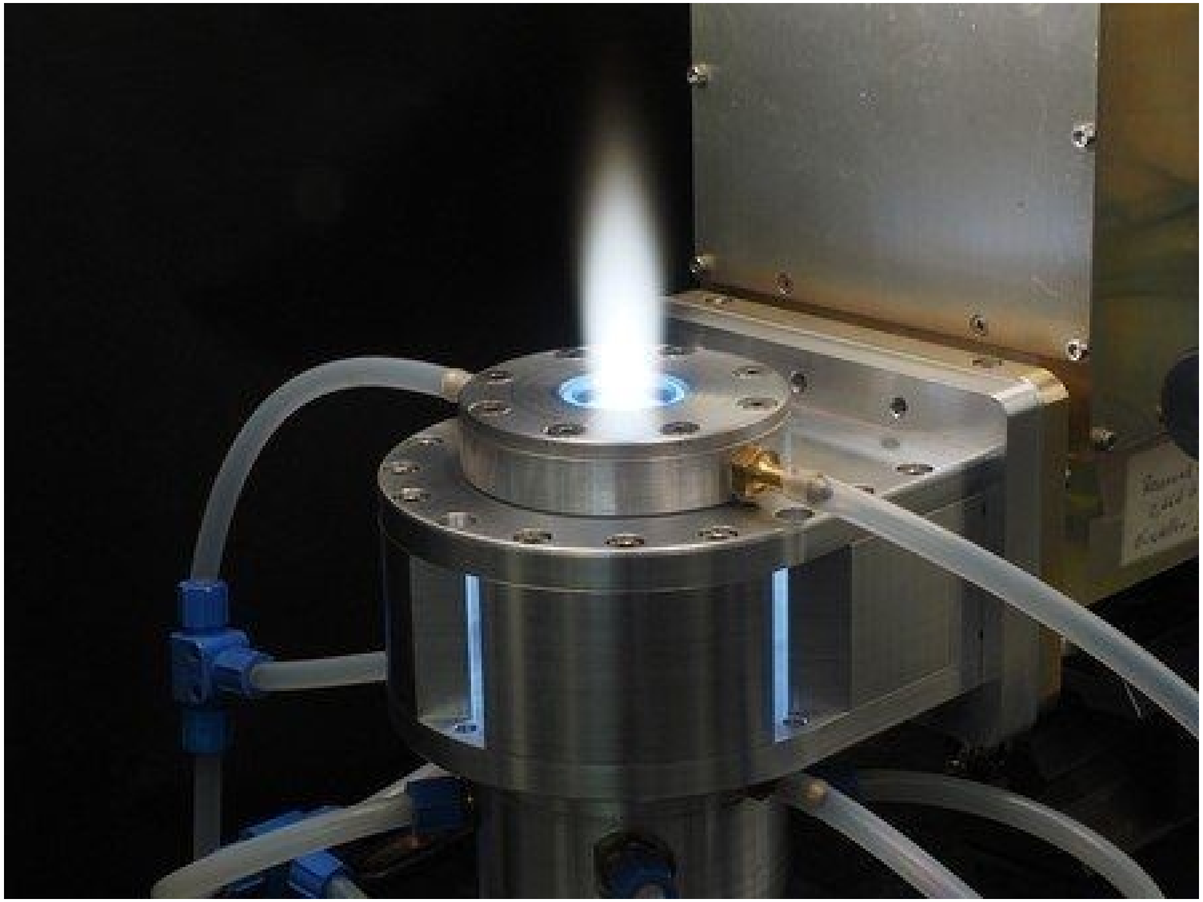
MW application – DC torch analogue

- MW plasma is also being used as an analogue to DC torches
- As opposed to DC or ICP torches, MW plasma typically operates at lower powers (tens of kW)
- Microwave plasma can also be non-LTE (plasma does not have to be so conductive to enable MW absorption) => lower plasma densities achievable



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MW application – Plasmaline for solar cells

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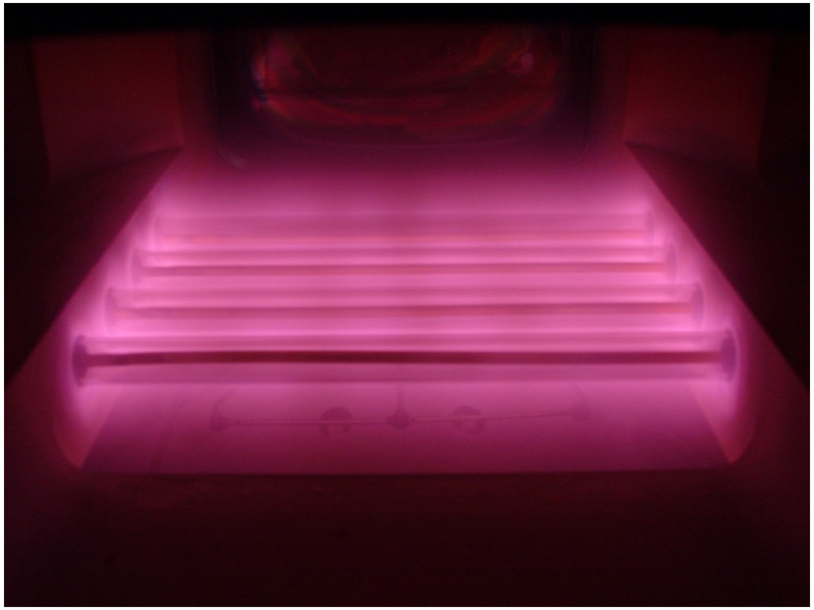

Takeaways

- High frequency breakdown
- Different layouts for wave-driven discharges
- CCP, ICP, MW – different power absorption mechanisms
- Applications