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Plasma Physics 2

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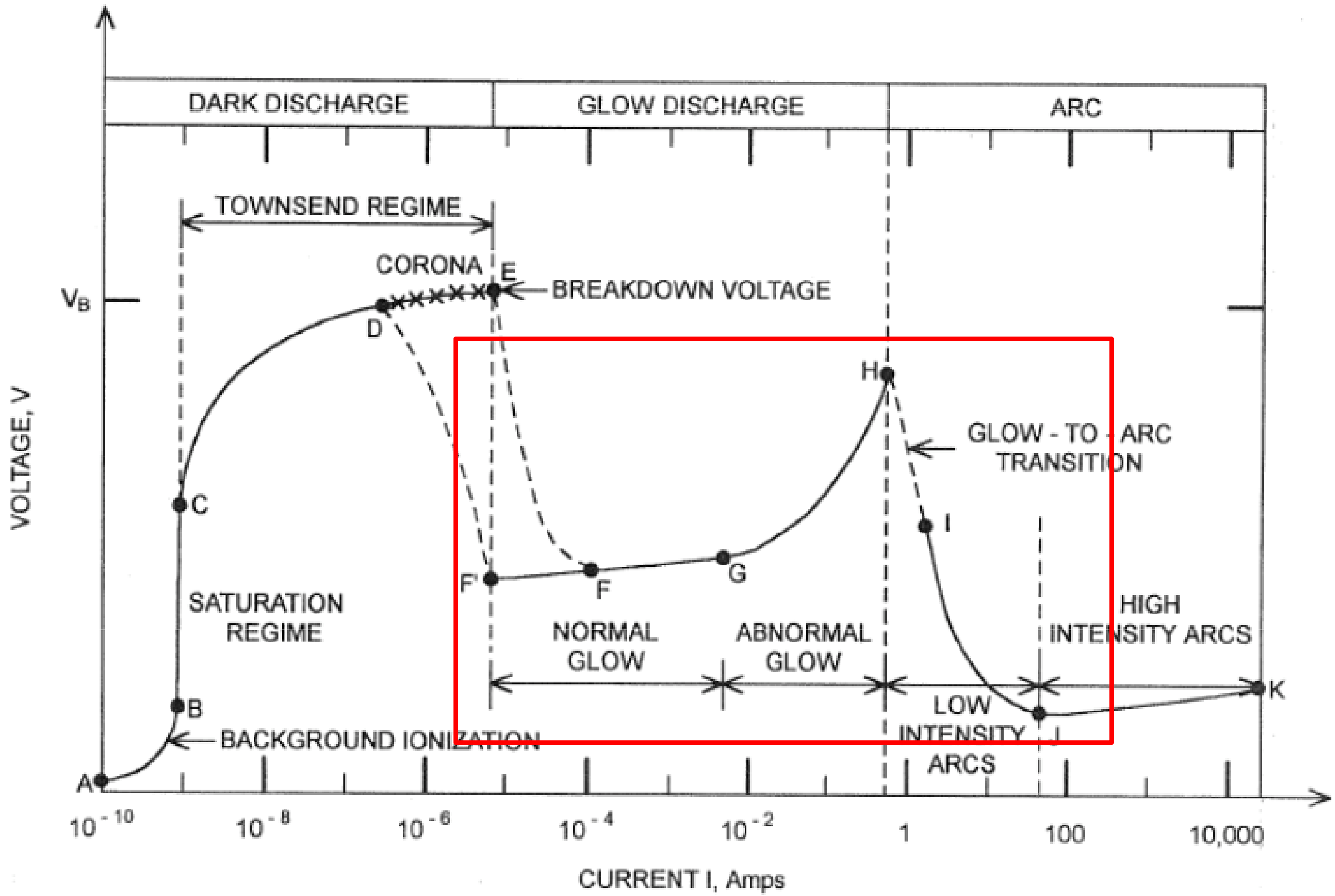
Lecture series contents

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.

Discharges – what this Lesson covers?



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Contents of this lesson

– The diffusivity tensor – why do we magnetize plasma?

– Estimating when the magnetic confinement makes sense – numerical assessment and intro to BOLSIG+

– Important applications of magnetized plasmas:
  – Magnetron sputtering PVD and its broad applications.
  – Vacuum arc PVD
  – ECR particle generators
  – Hall thrusters

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The diffusivity tensor – why do we magnetize plasma

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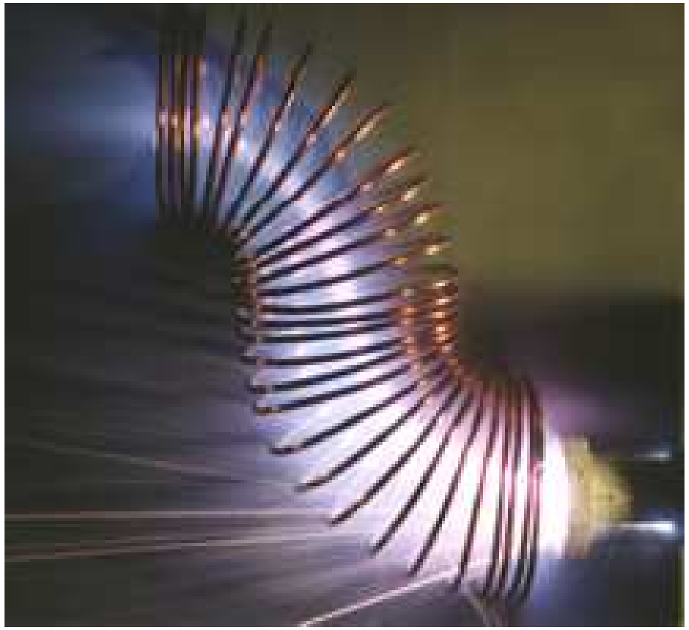
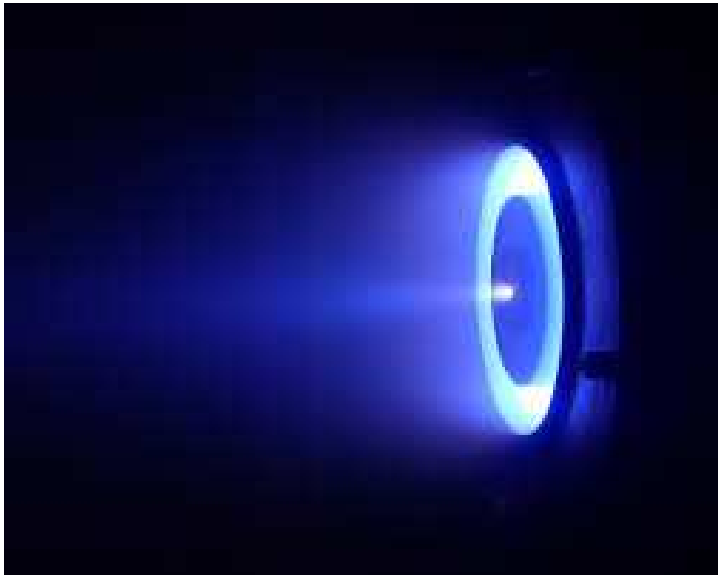
Why do we magnetize plasma?

– To control its spatial distribution or to provide ExB acceleration…

Filtered vacuum arc



Hall thruster for satellites



Magnetron sputtering plasma
(likely a wafer processing setup)

Why do we magnetize plasma?

- In the non-magnetized case, electron and ion diffusive flux is described as

$$\Gamma_{\mathrm{e}} = -D_{\mathrm{e}} \nabla n_{\mathrm{e}} - \mu_{\mathrm{e}} n_e \mathbf{E} \text{ and } \Gamma_{\mathrm{i}} = -D_{\mathrm{i}} \nabla n_{\mathrm{i}} + \mu_{\mathrm{i}} n_i \mathbf{E}$$

- Due to higher electron mobility, $D_{\mathrm{e}} \gg D_{\mathrm{i}}$ and $\mu_{\mathrm{e}} \gg \mu_{\mathrm{i}}$
- By assuming local balance $\Gamma_{\mathrm{e}} = \Gamma_i$ and quasineutrality $n_{\mathrm{e}} = n_{\mathrm{i}} = n$, we can derive an expression for the overall diffusivity of the plasma, the so-called Ambipolar diffusion coefficient

$$D_{\mathrm{amb}} = \frac{D_{\mathrm{e}}\mu_{\mathrm{i}} + D_{\mathrm{I}}\mu_{\mathrm{e}}}{\mu_{\mathrm{i}} + \mu_{\mathrm{e}}} \text{ when } \Gamma_{\mathrm{e}} = \Gamma_{\mathrm{i}} = \Gamma \ = -D_{\mathrm{amb}} \nabla \mathrm{n}$$

- This describes the motion of the plasma as a quasineutral fluid and it is valid in the plasma bulk, not in the plasma sheath. Practical if the sheaths are thin and the bulk is large.
- **Where do we get the value of the Diffusion coefficients?**

AO’s favourite reference for all the derivations mentioned here is the Liebermann book

Values of diffusion coefficients

- Diffusion coefficients of species can be expressed through their temperature and their collision frequency

$$D_e = \frac{k_{\mathrm{B}} T_{\mathrm{e}}}{m_{\mathrm{e}} \nu_{\mathrm{e}}} \text{ and } D_e = \frac{k_{\mathrm{i}} T_{\mathrm{i}}}{m_{\mathrm{i}} \nu_{\mathrm{i}}} \ldots \text{ also } D = \mu k_B T$$

- The tricky part about this is finding the values of ν_{e} and ν_{i}.
- In a laboratory plasma, you can usually assume that ions collide only elastically with the background gas, so ν_{i} depends only on the elastic collision cross-section for ions $\sigma_{\mathrm{i}} \approx 10^{-18}\ \mathrm{m}^{-2}$
- Electrons in the laboratory plasma undergo many more types of collisions, so **obtaining ν_{e} is non-trivial and often requires a numerical procedure**.

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Magnetized diffusion

- In the magnetic field, we usually assume that **ions are not affected by it**. The logic behind it is the large gyroradius (cyclotron radius) of ions, $r_g = \frac{mv_\perp}{|q|B}$ which is usually larger than the plasma itself.
- However, for electrons, the gyroradius is small => Their motion gets affected.
- Macroscopically, we derive the **electron diffusivity tensor** from the **linearlized Langevin equation**, arriving at

$$\Gamma_\mathrm{e} = -D_\mathrm{e} \cdot \nabla n_\mathrm{e}$$

$$D_e = \begin{pmatrix} D_\perp & D_\mathrm{H} & 1 \\ -D_\mathrm{H} & D_\perp & 1 \\ 1 & 1 & D_\parallel \end{pmatrix}$$

$$D_\perp = \frac{\nu_\mathrm{e}^2}{\nu_\mathrm{e}^2 + \omega_\mathrm{ce}^2} D_\mathrm{e}$$

Diffusion perpendicular to the magnetic field, always lower than D_e

$$D_H = \frac{\nu_\mathrm{e}\omega_\mathrm{ce}}{\nu_\mathrm{e}^2 + \omega_\mathrm{ce}^2} D_\mathrm{e}$$

Hall diffusion (e.g. gradient in X causes diffusion in Y direction)

$$D_\parallel = D_\mathrm{e}$$

Diffusion parallel to B => same as non-magnetized D_e

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Magnetized diffusion

- **Magnetic field hinders diffusion of electrons in the direction perpendicular to it** => electrons get more confined
- Due to the plasma space charge, ions get confined as well
- There is then something like „magnetized ambipolar diffusion“, but it cannot be expressed analytically.

$$\Gamma_\mathrm{e} = -D_\mathrm{e} \cdot \nabla n_\mathrm{e}$$

$$D_e = \begin{pmatrix} D_\perp & D_\mathrm{H} & 1 \\ -D_\mathrm{H} & D_\perp & 1 \\ 1 & 1 & D_\parallel \end{pmatrix}$$

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Diffusion parallel to B => same as non-magnetized D_e

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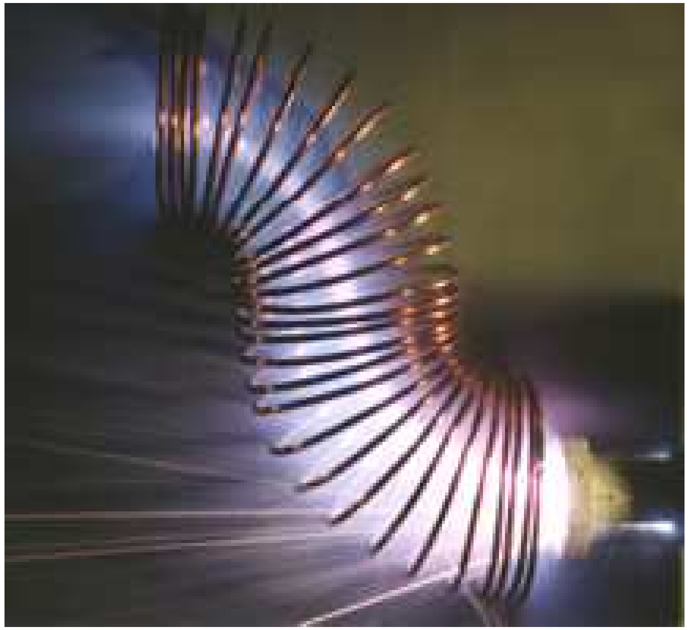
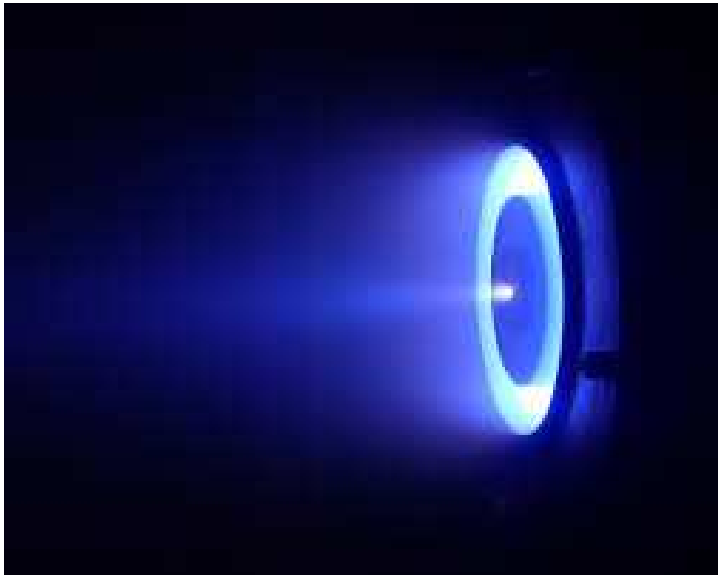
Why do we magnetize plasma?

– Just by looking at these plasmas, we can sometimes guess the direction of B fields

Filtered vacuum arc



Hall thruster for satellites



Magnetron sputtering plasma
(likely a wafer processing setup)

Magnetized diffusion - quantifying

- **So let's ask a question – when is magnetic confinement helpful?**
  - To answer that question, we will compare the perpendicular and parallel terms

$$D_e = \begin{pmatrix} D_\perp & D_\mathrm{H} & 1 \\ -D_\mathrm{H} & D_\perp & 1 \\ 1 & 1 & D_\parallel \end{pmatrix}$$

$$D_\perp = \frac{\nu_\mathrm{e}^2}{\nu_\mathrm{e}^2 + \omega_\mathrm{ce}^2} D_\mathrm{e} \qquad D_\parallel = D_\mathrm{e}$$

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Magnetized diffusion - quantifying

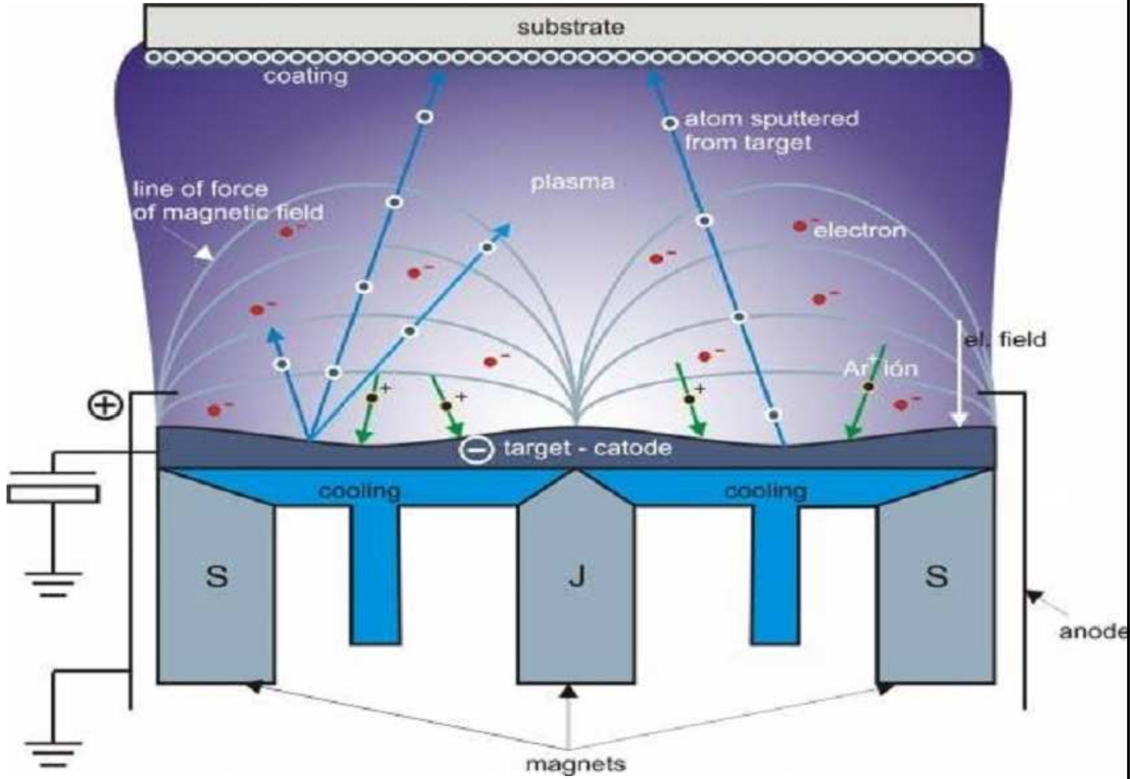
We learned a few things:

- With permanent magnets, we can only confine plasma at the low pressures
- At higher pressures or even atm. pressure, extremely high B field would be required for the confinement, attainable only by coils, ideally superconducting ☺
- At high pressures, the high collisionality breaks the confinement
- On a microscopic level, we can imagine that the gyrating electron **undergoes too many collisions during one gyration**.

Applications of magnetized plasma

Applications – magnetron sputtering

- Magnetron sputtering is a so called PVD (physical vapor deposition) technique for converting solids to gases at the low temperature.
- On the plasma physics level, it is a magnetized glow discharge.



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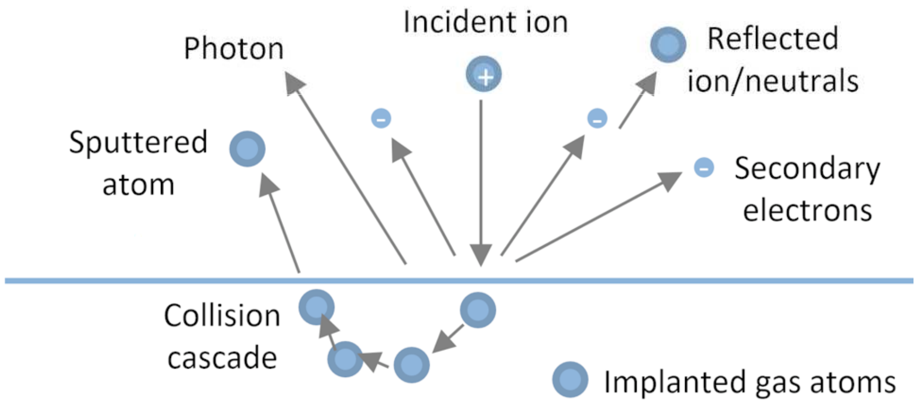
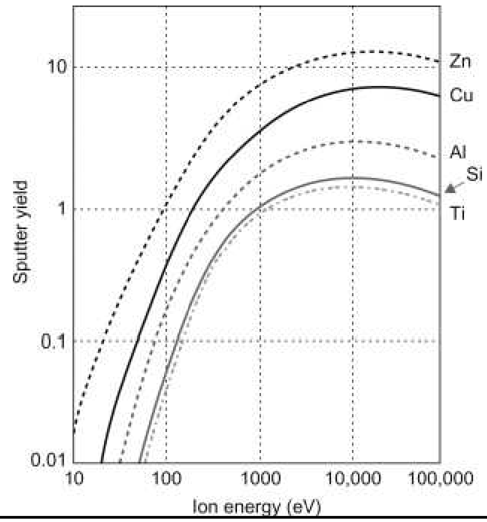
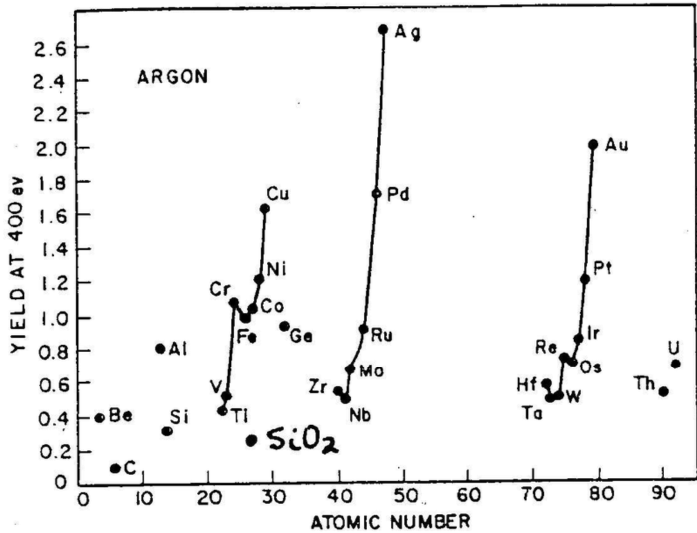
Applications – magnetron sputtering

- On the surface, the the so-called **collision cascade** can occur, whereby a neutral atom is knocked off the solid phase by an incoming ion at high kinetic energy https://www.youtube.com/watch?v=TyYBIj-A9tY
- This effect occurs if the ion energy is significantly above the suface binding energy (10-20 eV).
- The probability of this effect is called **the sputtering yield** and depends highly on material

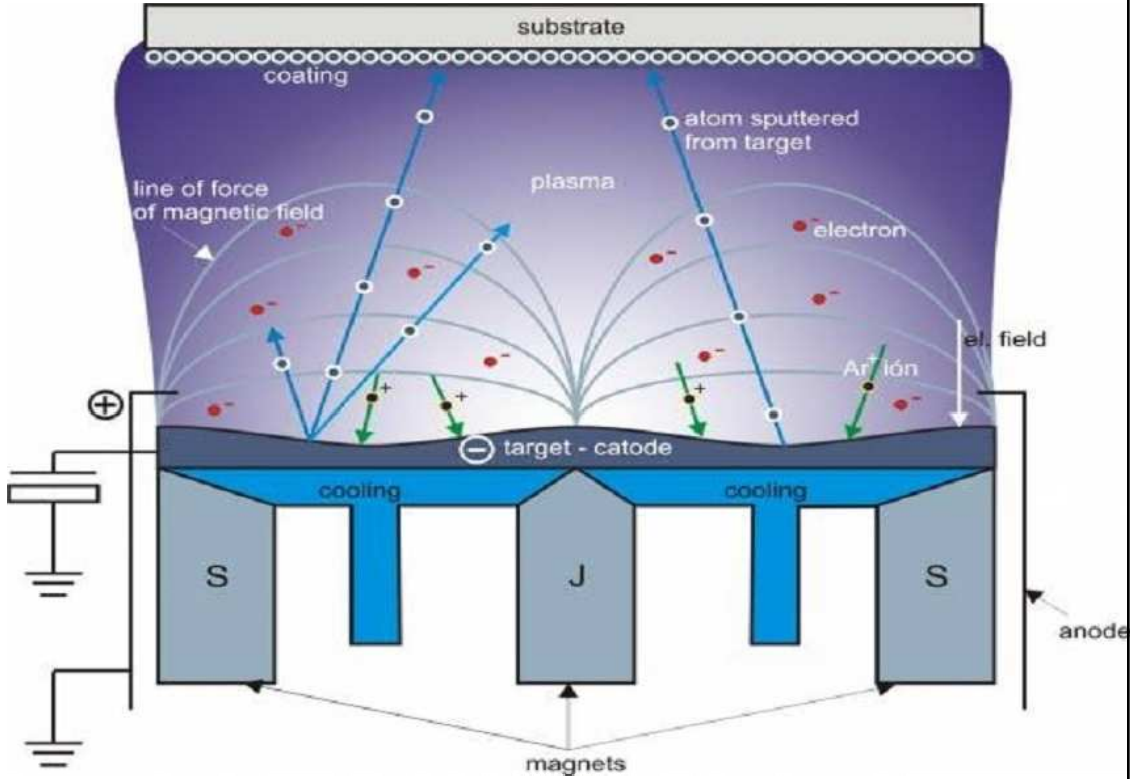






Applications – magnetron sputtering

- Why cannot we sputter without B field, e.g. by increasing the pressure?
- Our **primary objective** is depositing metal atoms onto the surface. The higher the pressure, the more they will scatter and the larger the material loss.
- We want to have plasma at **as low pressure as possible** but still **as dense as possible** => This is usually the argument for magnetizing plasmas ☺
- Magnetic field ensures that the plasma is dense where we want it – at the surface of the sacrificial cathode.



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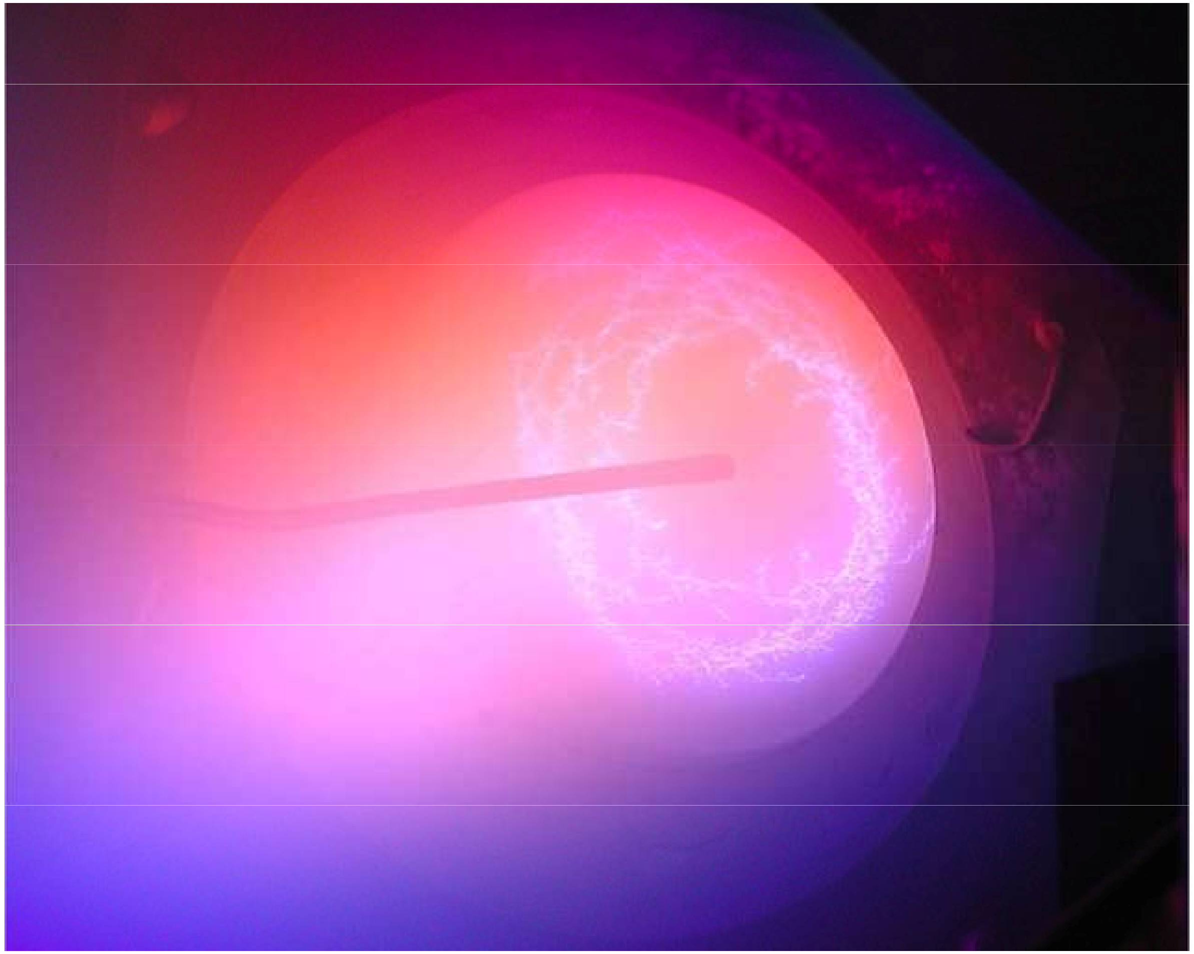
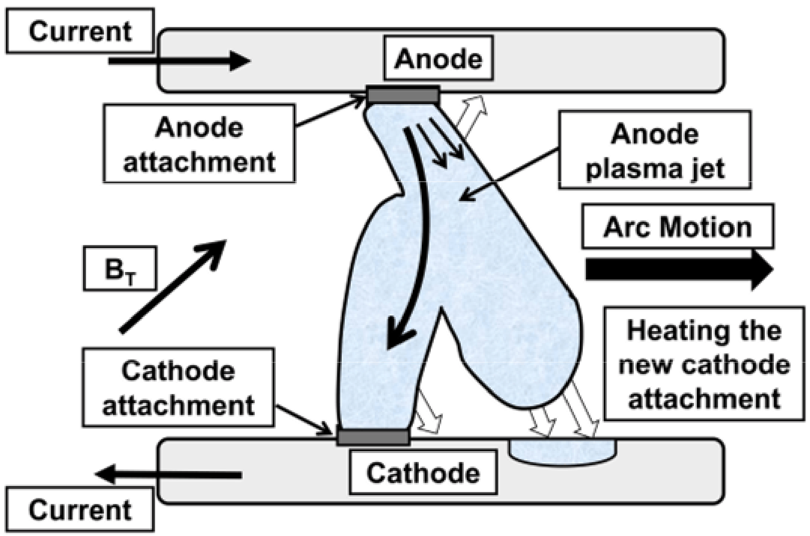
Applications – low pressure vacuum arc

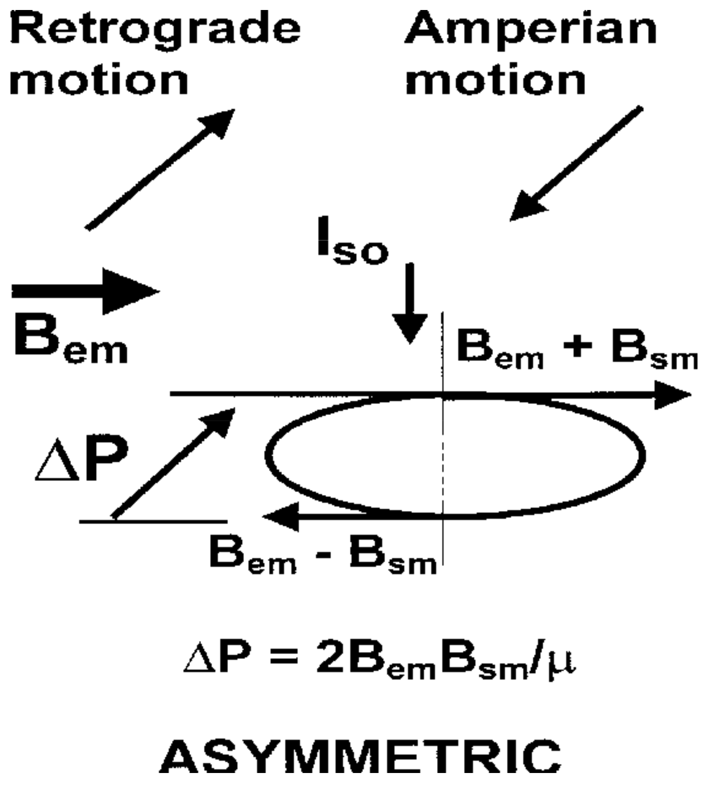
- In a vacuum arc PVD, almost an identical B field setup is used but for different reasons!
- Also, gas pressure in vacuum arcs is higher, about 1-3 Pa.
- The plasma is not a nice and stable glow discharge but a rather stochastic arc discharge. https://www.youtube.com/shorts/rx6uX3g1Ss8



Applications – low pressure vacuum arc

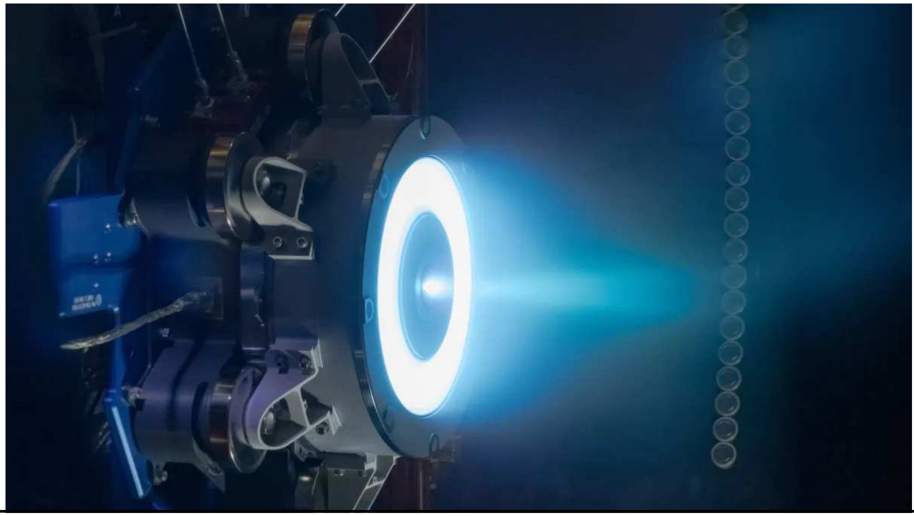
- Without the B field, the cathode spot of the arc jumps around randomly around the target.
- With the magnetic field, the motion of the spot is still stochastic but happens within some trajectory given by the B field.
- **The behavior is peculiar, the arc sometimes moves in the direction $j\times B$, but sometimes in $-j\times B$**

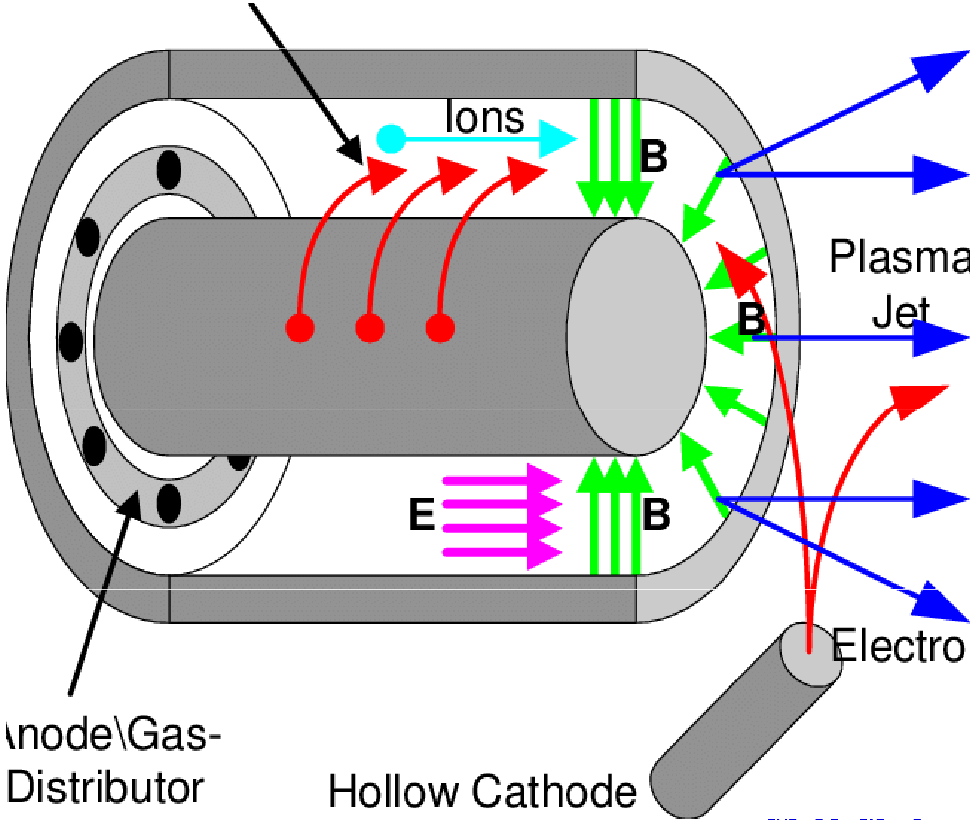




Application – Hall thrusters

- One of the most established methods of satellite electric propulsion.
- Plasma is accelerated through ExB drift and the extracted plasma is **quasineutral**





Take aways

- Why use magnetic field in a plasma?
- How to quantify when magnetizing the plasma is going to have some effect?
- Applications of magnetized plasma discharges and difference between the magnetic field role in arc PVD and sputter PVD