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.

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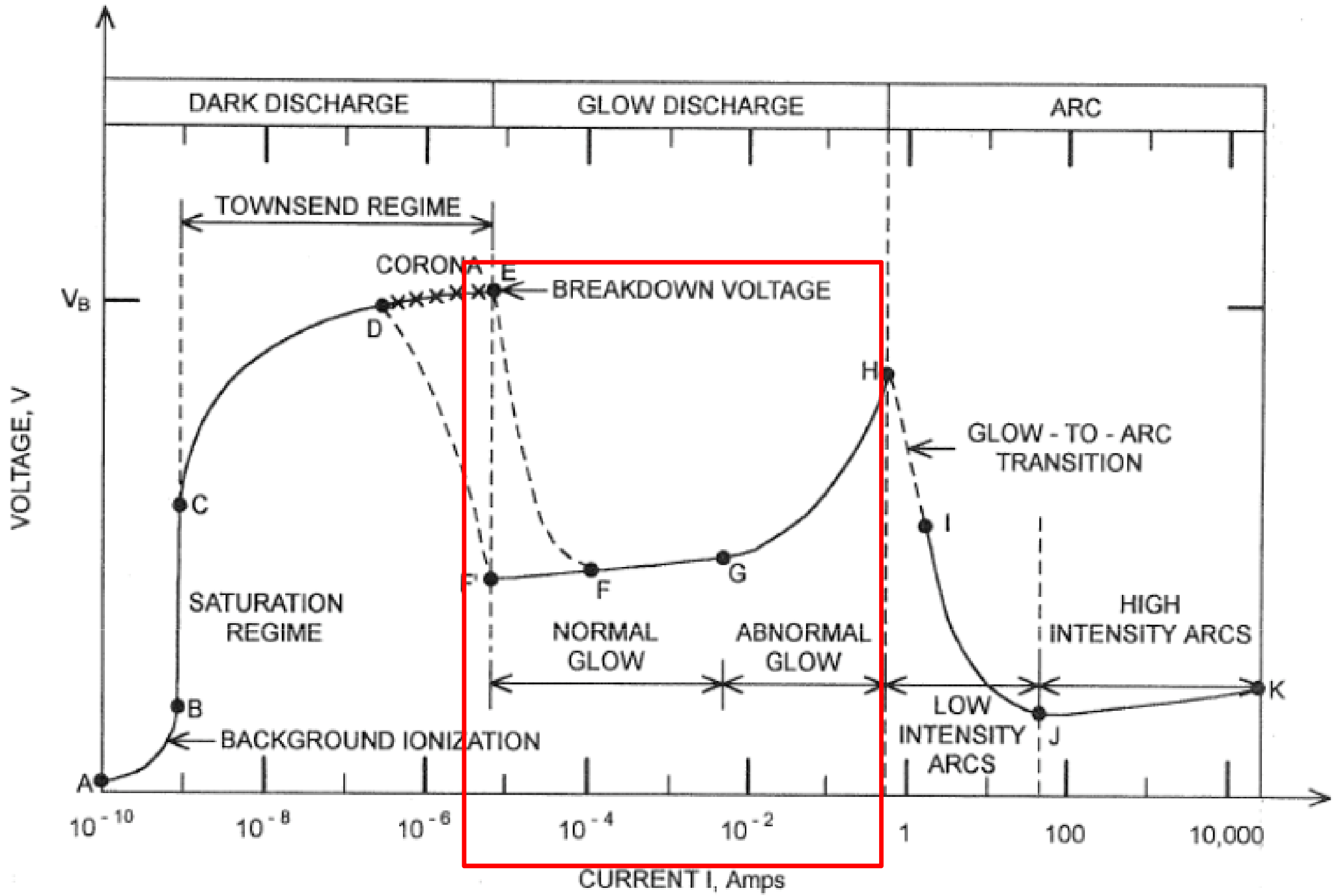
Discharges – what this Lesson covers?



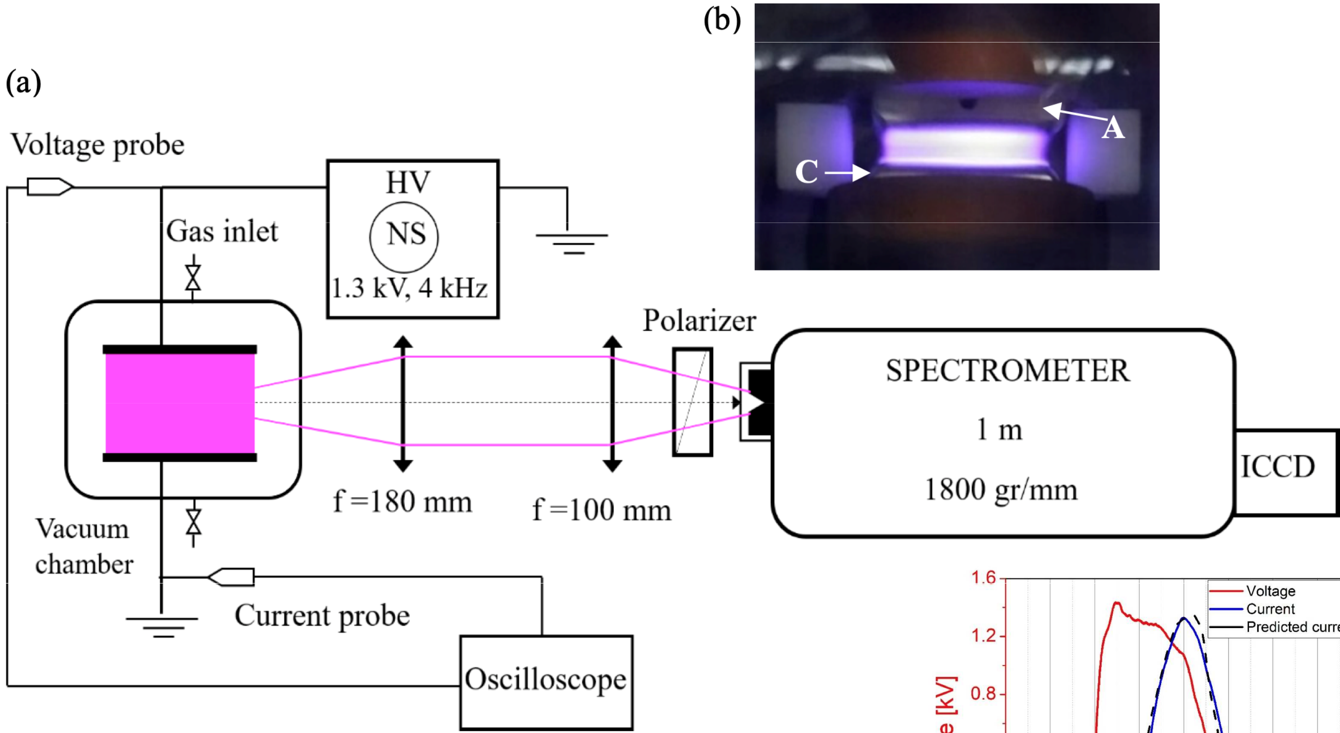
Contents of this lesson

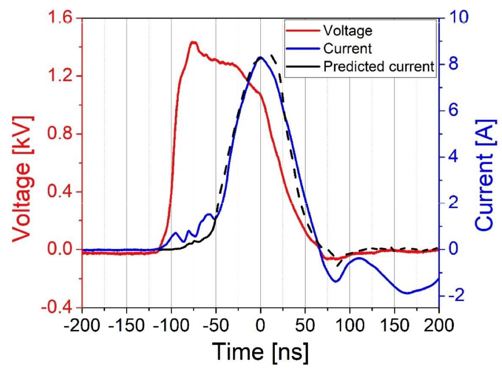
- Transition between Townsend and Glow discharge modes – what we observe and what is the physics behind it.
- Typical glow discharge structure and how it changes with conditions.
- Glow discharge scaling laws
- Glow discharge applications

Observation of the transition between Townsend and Glow Dischage

Observation: Townsend > Glow transition

- The relevant phenomena take place at the time scale of single ns.
- Light or electrical signals **travel ca 30 cm in 1 ns** => very high demands on instrumentation and triggering.
- **ns-plasmas and processes are in focus of fundamental plasma reaseach in the past decade.**





[M. S. Simeni, Y. Zheng, E. V. Barnat, and P. J. Bruggeman, “Townsend to glow discharge transition for a nanosecond pulse plasma in helium: space charge formation and resulting electric field dynamics,” Plasma Sources Science and Technology, vol. 30, no. 5. IOP Publishing, p. 055004, May 01, 2021. doi: 10.1088/1361-6595/abf320]

Observation: Townsend > Glow transition

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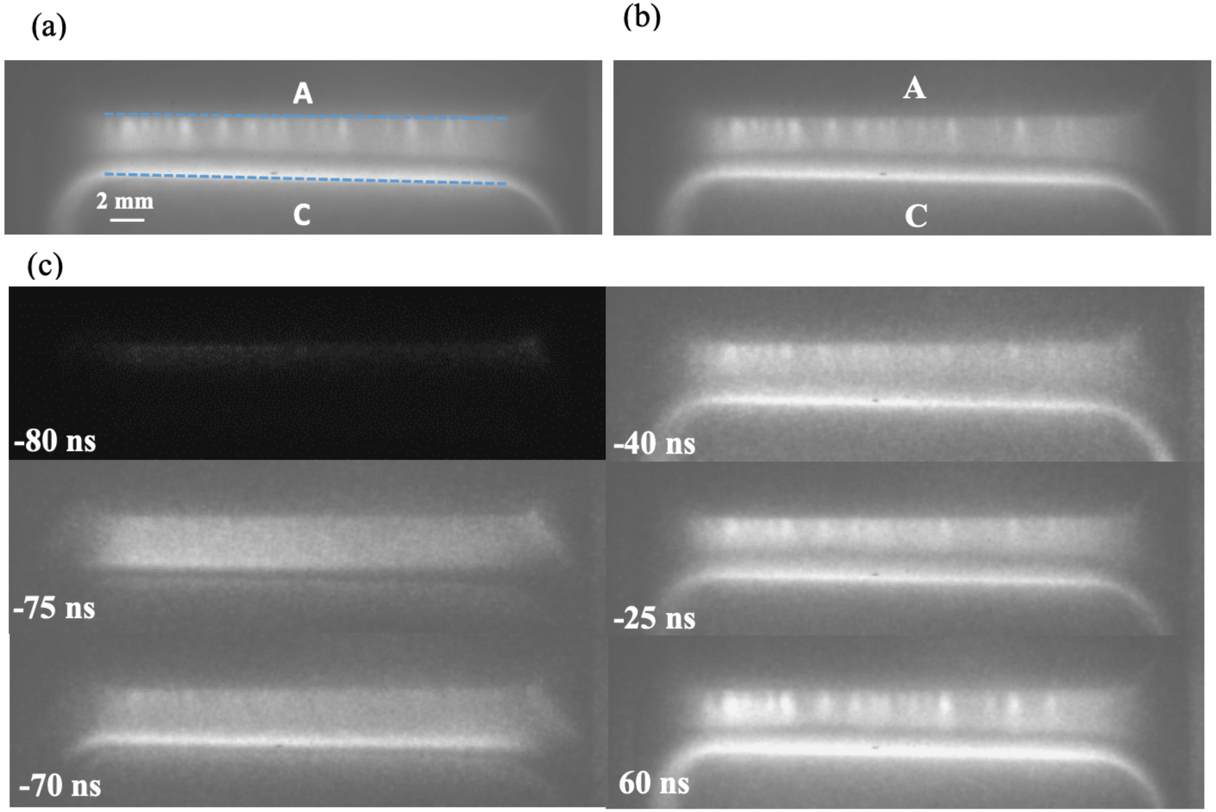


Figure 3. Broadband ICCD images of the parallel plate helium discharge. (a) Single-shot, 1µs gate. (b) 50-shots averaged, 1µs gate. (c) Time-resolved images with camera gate of 5 ns. Each image is an accumulation of 20 discharge pulses. The time delays relative to the moment when the peak of the current waveform occurs are shown in the images. The dash lines indicate the location of the electrodes surfaces.

[Reference see previous slide]

Mechanics behind the transition

Townsend > Glow transition mechanics

- The Poisson equation is at the center of this

$$\Delta V = -\frac{\rho}{\varepsilon_0} = -q_\mathrm{e}\frac{n_\mathrm{i} - n_\mathrm{e}}{\varepsilon_0}$$

- In Townsend regime, we claimed that r.h.s. is negligible

Q: What is the solution for potential in that case?

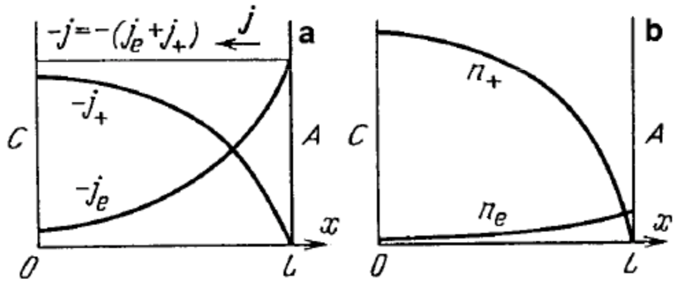
A: Linear function between V_{cathode} and V_{anode}

Q: What are the typical plasma densities in a Townsend discharge?

Townsend > Glow transition mechanics

- The Poisson equation is at the center of this

$$\Delta V = -\frac{\rho}{\varepsilon_0} = -q_\mathrm{e}\frac{n_\mathrm{i} - n_\mathrm{e}}{\varepsilon_0}$$



If we assume a plasma length of $d = 0.05\ \mathrm{m}$, plasma voltage $500\ \mathrm{V}$ and assume $n_\mathrm{i} \gg n_\mathrm{e}$ as the extreme case scenario, we can get an order of magnitude estimate as

$$\Delta V = \nabla \cdot \mathrm{E} \approx \frac{dE}{dx} \approx -q_\mathrm{e}\frac{n_\mathrm{i}}{\varepsilon_0}$$

and since we are really just concerned about the absolute values here

$$\left|\frac{dE}{dx}\right| \approx \left|q_\mathrm{e}\frac{n_\mathrm{i}}{\varepsilon_0}\right|$$

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Townsend > Glow transition mechanics

– Now let's try to substitute into our extremely simplistic Poisson equation

$$\left|\frac{dE}{dx}\right| \approx \left|q_\mathrm{e}\frac{n_\mathrm{i}}{\varepsilon_0}\right|$$

The meaningful absolute values are:

- If there is ideal vacuum, the field would be $E = 10\ 000\ \mathrm{V/m}$ (500 V over 5 cm, see previous slide)
- We want the r.h.s. to have a negligible impact on the electric field so we can say that we do not want the E field to change by more than $100\,\frac{\mathrm{V}}{\mathrm{m}}$ over some small distance $\mathrm{d}x = 0.001\ \mathrm{m}$.
- Solving for n_i, we get $n_{\mathrm{i,max}} = \frac{100}{0.001} \cdot \frac{8.85 \cdot 10^{-12}}{1.602 \cdot 10^{-19}} \approx \mathbf{5.5 \cdot 10^{12}\ m^{-3}}$

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Townsend > Glow transition mechanics

– When the charge density starts to increase and perturbs the E field, various mechanisms start to occur.

1. Most importantly, the electric field produced by the ions starts to pull in electrons => Plasma bulk becomes quasi-neutral and it starts to hold that $n_{\mathrm{i}} \approx n_e$.
2. Secondly, the electric field is no longer dictated by the vacuum Poisson equation – there is now a charge density distribution which can be non-uniform in space and that can create various, non-monotonic, contributions to $\frac{dE}{dx}$.

Generally, predicting the discharge structure is beyond anything we could/should compute analytically.

Numerical models are used for accurate prediction + similarity laws are formulated as fast “rules of

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Glow discharge structure, typical conditions and similarity laws

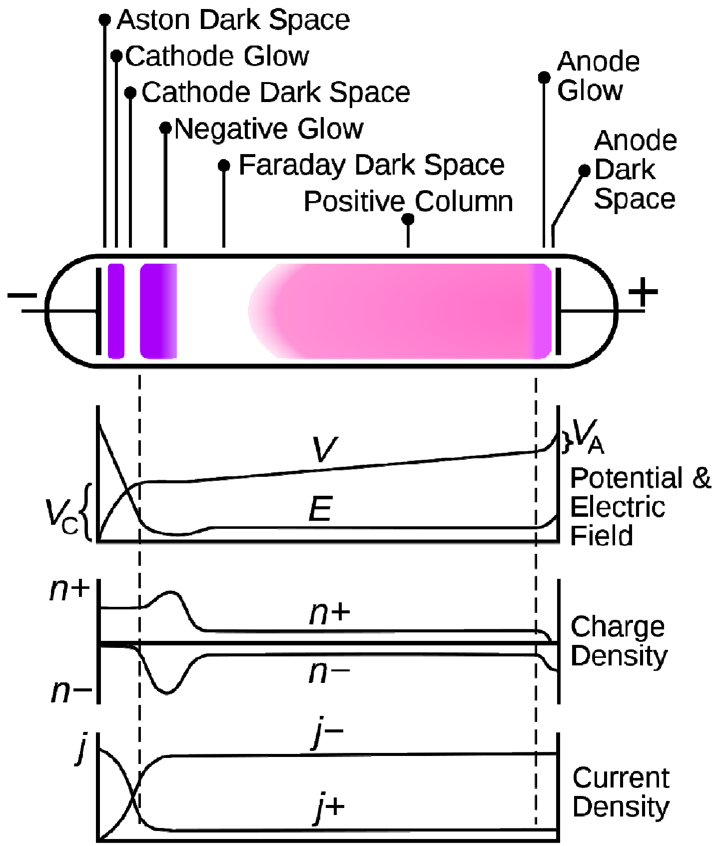
Townsend > Glow transition mechanics

The structures below have been observed.

Depending on the layout, many of them may not form.

- *d* is the thickness of the cathode voltage drop
- V_C is the cathode potential

- **Aston space** immediately close to the cathode, the electrons do not have enough energy to ionize or excite.
- **Cathode light** – accelerated electrons start to excite neutral species, which de-excite while emitting a photon.
- **Cathode dark space –** the mean energy exceeds a certain threshold, beyond which they can ionize. This leads to a decrease in the absolute count of excitations.
- **Negative glow** – Electrons have lost some energy due to ionizations, light emission may increase again.
- **Faraday dark space** – electrons have now passed the crazy sheath region and entered the region with a rather low energy, so the emission is reduced again.
- **Positive column** – always exists, this is the bulk plasma with small but consistent E field. Electrons are in equilibrium with the field and continuously excite.
- **Anode light** – slight acceleration of electrons by the anode voltage bump.



Townsend > Glow transition mechanics

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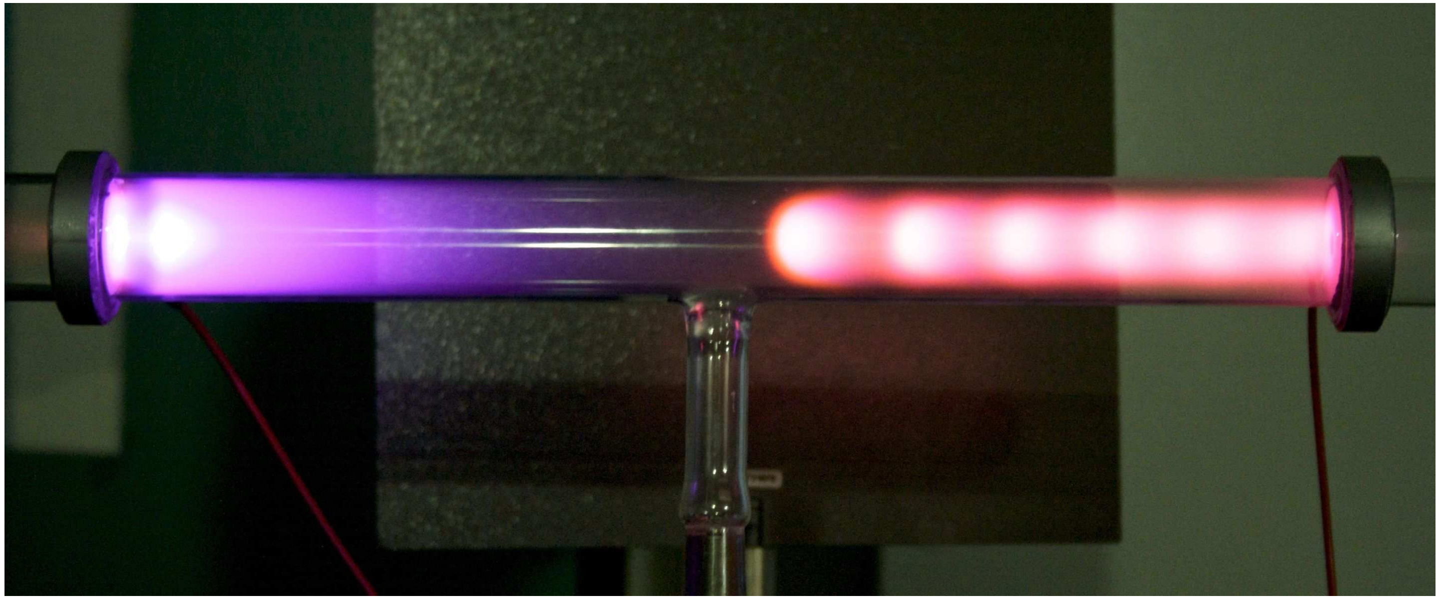

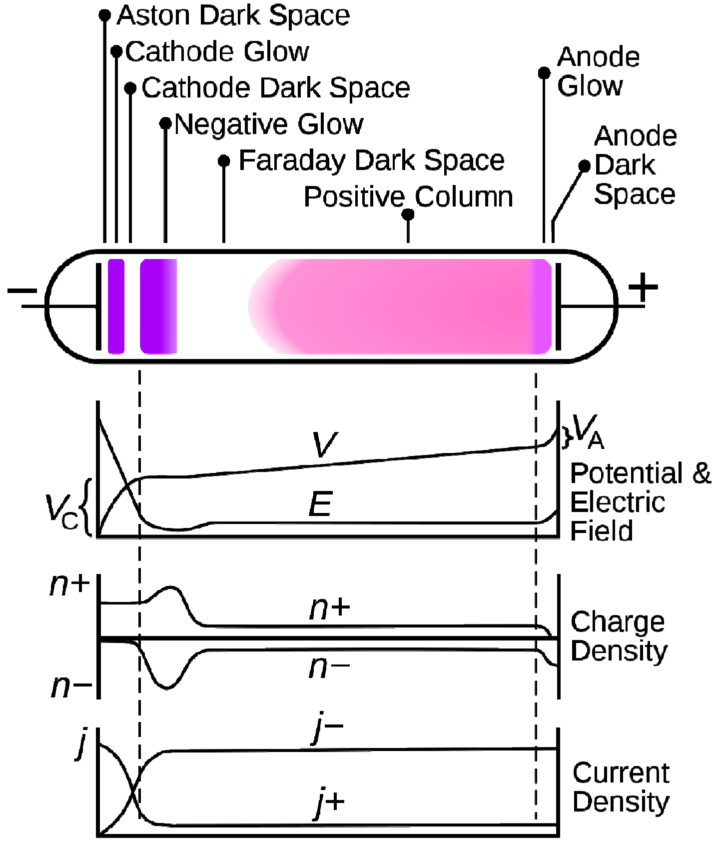

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Townsend > Glow transition mechanics

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[V. Gorokhovsky Modeling of DC Discharges in Argon at Low Pressures. COMSOL Conference 2012]

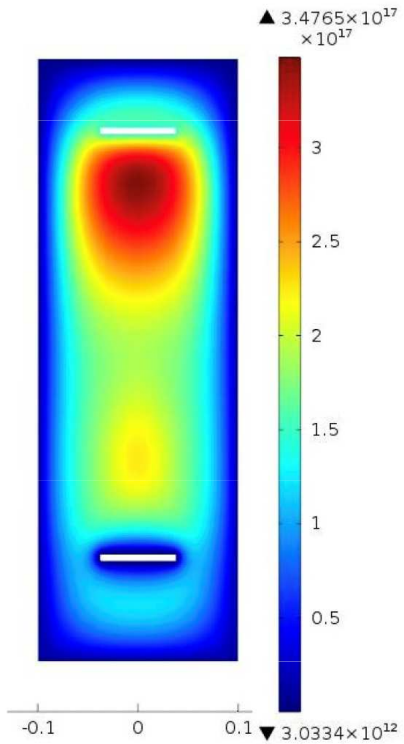


Figure 2. Plasma distribution in the floating metal discharge tube.

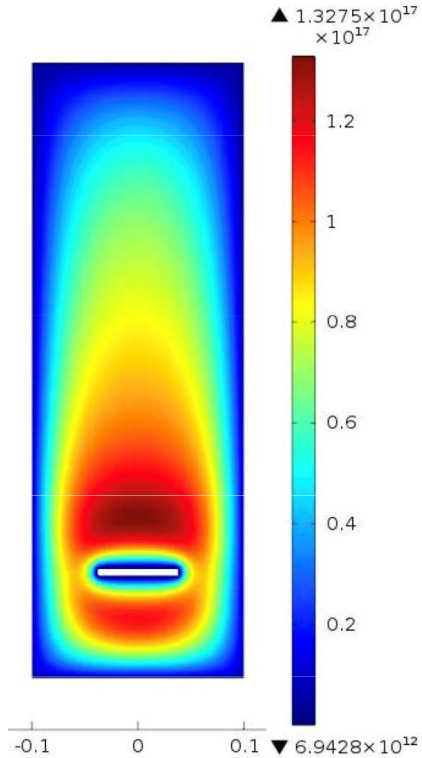
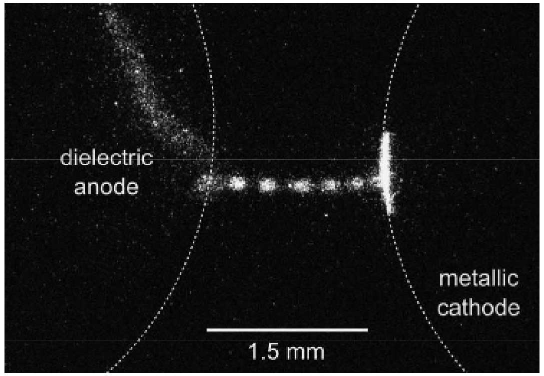
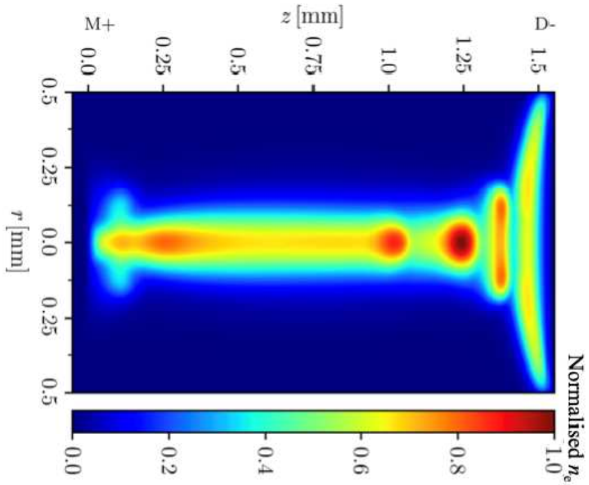


Figure 3. Plasma distribution in the metal discharge tube-anode.

[T. Hoder and team]





Pressure/geometry vs discharge strucure

- If we are decreasing the pressure at fixed other conditions OR increase voltage at fixed pressure: **The negative glow and Faraday space start to increase, positive column shortens, until it disappears completely.** https://www.youtube.com/shorts/nn8796OnTsk

- If we reduce the cathode-anode distance: **Positive glow again starts to shorten while the negative glow and Faraday space remain the same. Ultimately, there is a minimum distance at which the plasma will still operate.**

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Plasma properties in glow discharge

Theoretically, you can construct arbitrarily large glow discharges, but the typical reasonable conditions are as follows:

Quantity	Usual range	Comment
Gas pressure	0.1 – 1000 Pa *APGD up to 1 atm	No ignition for too low pressures, development of plasma instabilities for high pressures. APGD = atmpospheric-pressure glow discharge, requires tiny gaps and very high electrode precision.
Plasma density	$10^{15} – 10^{19}$ m^{-3}	At higher densities, conductivity is too high and plasma collapses into arc discharge.
Electron mean energy	1– 2.5 eV in positive column	In the positive column, electrons reach some type of equilibirum (especially at higher pressures). In the near-electron regions, the EEDF is highly non-Maxwellian
Gas temperature	300 – 500 K * up to 2000 K in hollow cathode configs	
Input power	10 W – 1 kW *up to 20 kW in hollow chathode configs	

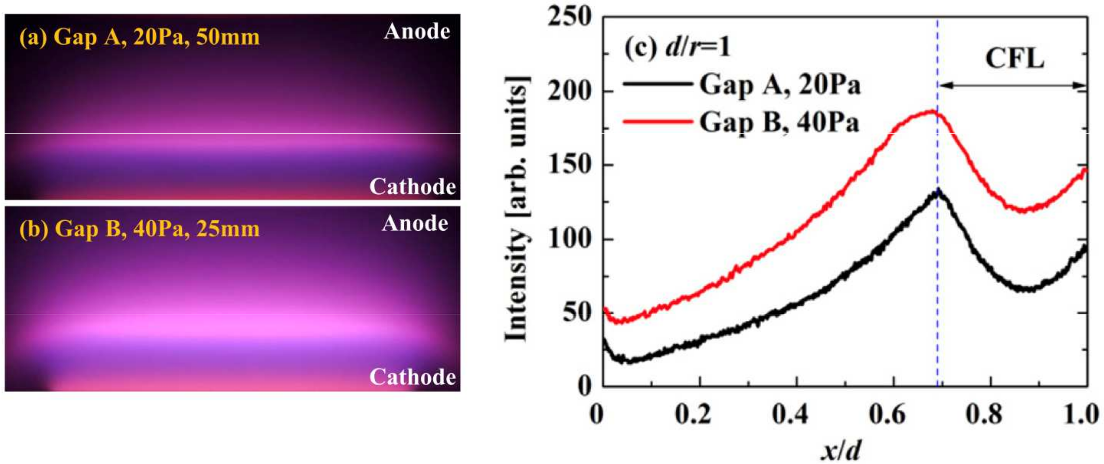
Similarity laws

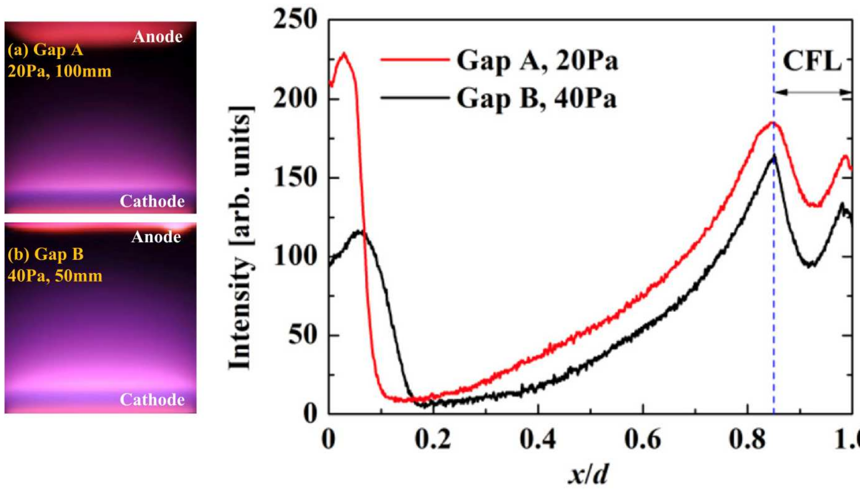
- There have been various attempts to identify similarity laws for glow discharges – essentially attempting to answer the question “at what two conditions do I get the same discharge structure?”

- **This is quite important for practical applications of plasmas** – in many cases, we want to make a small-scale prototype for testing and then upscale it. **But the plasma behaves in a highly non-linear manner!**

Similarity laws

- **Example 1:** Y Fu et al. Physics of Plasmas **24**, 083510 (2017); doi: 10.1063/1.4997425
  - The correlation metric is the discharge emission.
  - Demonstrates that in glow discharge, not only pd is important but also $\frac{d}{r}$ has to be the same to maintain the same emission.





(c) I = 3mA, d/r = 2

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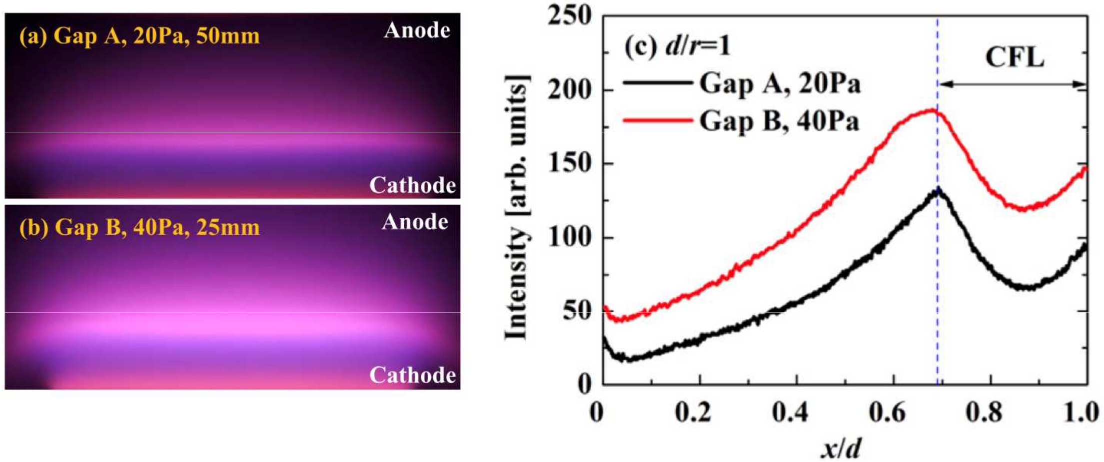

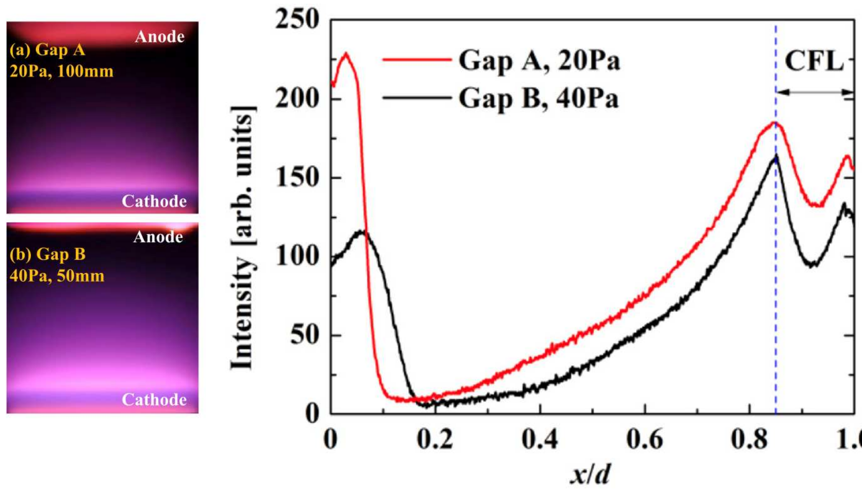

(c) I = 3mA, d/r = 2

Similarity laws

– **Example 2:** Deriving a similarity law for normal glow discharge

(1) As we have seen, most of the voltage drop occurs in the cathode region and indeed, in most glow discharge conditions, majority of energy is dissipated in the cathode fall.

(2) So let’s see if we can derive a useful expression for the current conducted through the cathode fall.

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Similarity laws

- **Example 2:** Deriving a similarity law for normal glow discharge

  For the current density at the cathode, it must hold that:

$$j = j_e + j_i = (1+\gamma)j_i = (1+\gamma)q_e n_i \mu_i E_c$$

  where we have used usual meaning of symbols and E_c is the electric field in the cathode drop.

  Next, we use a similar trick for solving the Poisson equation that we used in the Townsend discharge **because the cathode sheath is not quasineutral, electrons are effectively pushed away by the cathode potential**

$$\frac{dE}{dx} = \frac{q_e(n_i - n_e)}{\varepsilon_0} \approx \frac{q_e(n_i)}{\varepsilon_0}$$

  This yields $n_i \approx \frac{\varepsilon_0}{q_e}\frac{|E_c|}{d}$ and

$$j \approx (1+\gamma) \cdot \frac{\varepsilon_0 \mu_i V_c^2}{d^3}$$

  We can expand this expression by multiplying by $\frac{p^3}{p^3}$ yielding

$$\frac{j}{p^2} \approx (1+\gamma) \cdot \frac{\varepsilon_0 \mu_i p V_c^2}{p^3 d^3} = (1+\gamma) \cdot \frac{\varepsilon_0 \mu_i^{\mathrm{R}} V_c^2}{p^3 d^3}$$

Similarity laws

- **Example 2:** Deriving a similarity law for normal glow discharge

  And because the discharge has the natural tendency to attain minimum potential energy, it actually stabilizes in the minimum point (Stoletow point) of the Paschen curve, so that

$$\frac{j}{p^2} \approx (1+\gamma) \cdot \frac{\varepsilon_0 \mu_i^{\mathrm{R}} V_{c,\min}^2}{(pd)_{\min}^3}$$

And we see that we have only quantities which are constant for a given gas on the r.h.s. ($\mu_i^{\mathrm{R}} = \mu_i p$ is the reduced mobility, constant for a given gas at fixed temperature)

Interpretation:

1. When we are increasing the pressure, the current density through the discharge tends to grow accordingly.
2. If we increase the total current, the current density tends to remain the same, which means that the diameter of the glow discharge is increasing or shrinking depending on the total current/power.
3. For a given combination of gas and electrode, the cathode fall thickness and the voltage in the cathode drop are approx. constant.

Similarity laws

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3. **For a given combination of gas and electrode, the cathode fall thickness and the voltage in the cathode drop are approx. constant – you can find tables for various gasses that tell you with which parameters will the discharge stabilize.**

Table 8.3. Normal current density j_n/p^2 [μA/(cm^{2}Torr^2)] at room temperature

gas / cathode	air	Ar	H_2	He	Hg	N_2	O_2	Ne
Al	330	–	90	–	4	–	–	–
Au	570	–	110	–	–	–	–	–
Cu	240	–	64	–	15	–	–	–
Fe, Ni	–	160	72	2.2	8	400	–	6
Mg	–	20	–	3	–	–	–	5
Pt	–	150	90	5	–	380	550	18
glass[a]	40	–	80	–	–	–	–	–

Pc
Ní
vz
ef
na
pc

Table 8.1. Normal cathode fall V_n [V] [8.2, 4]

gas / cathode	air	Ar	He	H_2	Hg	Ne	N_2	O_2	CO	CO_2
Al	229	100	140	170	245	120	180	311	–	–
Ag	280	130	162	216	318	150	233	–	–	–
Au	285	130	165	247	–	158	233	–	–	–
Bi	272	136	137	140	–	–	210	–	–	–
C	–	–	–	240	475	–	–	–	526	–
Cu	370	130	177	214	447	220	208	–	484	460
Fe	269	165	150	250	298	150	215	290	–	–
Hg	–	–	142	–	340	–	226	–	–	–
K	180	64	59	94	–	68	170	–	484	460
Mg	224	119	125	153	–	94	188	310	–	–
Na	200	–	80	185	–	75	178	–	–	–
Ni	226	131	158	211	275	140	197	–	–	–
Pb	207	124	177	223	–	172	210	–	–	–
Pt	277	131	165	276	340	152	216	364	490	475
W	–	–	–	–	305	125	–	–	–	–
Zn	277	119	143	184	–	–	216	354	480	410
glass[a]	310	–	–	260	–	–	–	–	–	–

Table 8.2. Normal cathode layer thickness $(pd)_n$ [cm·Torr] at room temperature

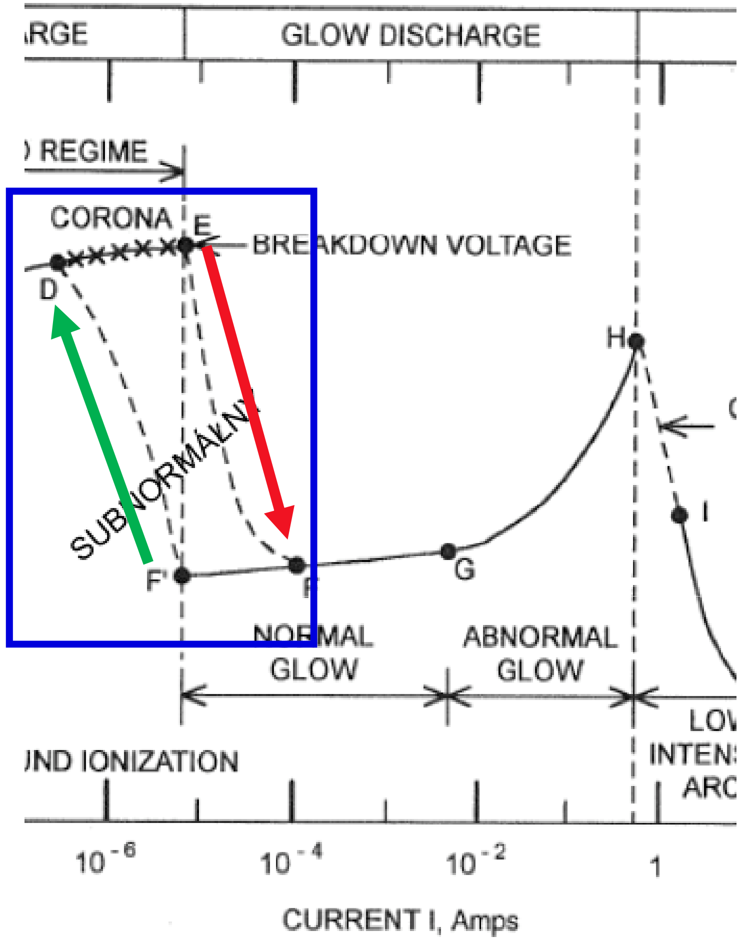
gas / cathode	air	Ar	H_2	He	Hg	N_2	Ne	O_2
Al	0.25	0.29	0.72	1.32	0.33	0.31	0.64	0.24
C	–	–	0.90	–	0.69	–	–	–
Cu	0.23	–	0.80	–	0.60	–	–	–
Fe	0.52	0.33	0.90	1.30	0.34	0.42	0.72	0.31
Mg	–	–	0.61	1.45	–	0.35	–	0.25
Hg	–	–	0.90	–	–	–	–	–
Ni	–	–	0.90	–	–	–	–	–
Pb	–	–	0.84	–	–	–	–	–
Pt	–	–	1.00	–	–	–	–	–
Zn	–	–	0.80	–	–	–	–	–
glass[a]	0.30	–	0.80	–	–	–	–	–

Subnormal / normal / abnormal glow discharge

- **Subnormal glow discharge** = space-charge is already significant, so this is not a Townsend discharge.
- But losses of electron-ion pairs are dominant and the diameter of the discharge is small, so the subnormal glow requires a rather high voltage to be established.
- There is hysteresis behavior – this is caused by ISEE:

  Current increase branch: plasma diameter is small, contribution of ISEE negligible. Voltage has to be high.

  Current decrease branch: ISEE is significant and the secondary electrons are increasing $j_{cathode}$ and voltage remains low even if current is decreased.

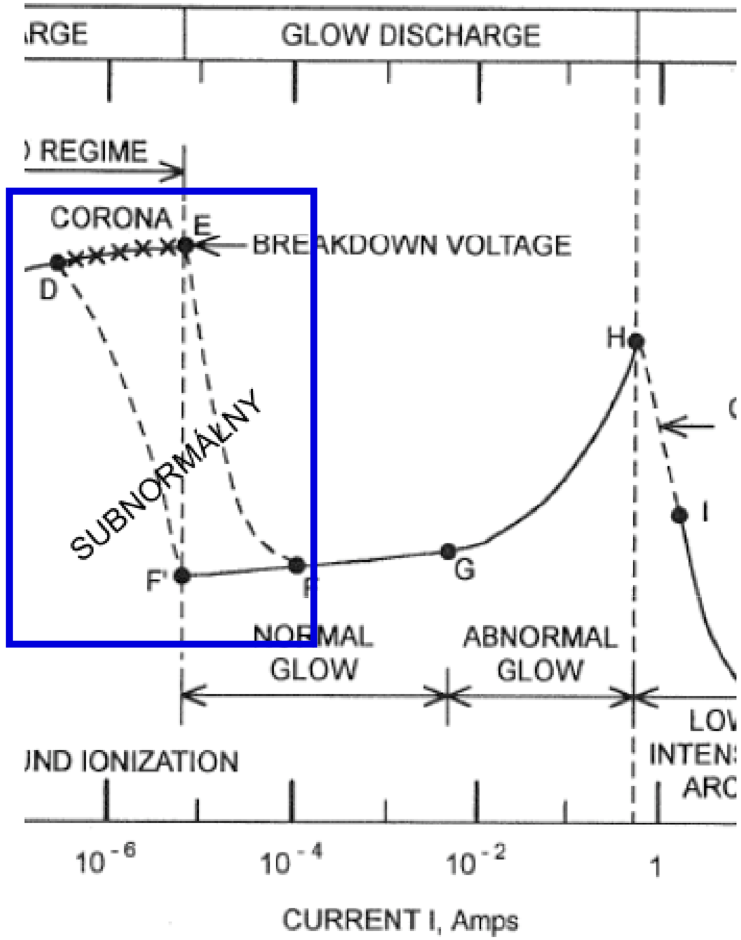


Subnormal / normal / abnormal glow discharge

- **Normal glow discharge** = as discussed above, follows the scaling law

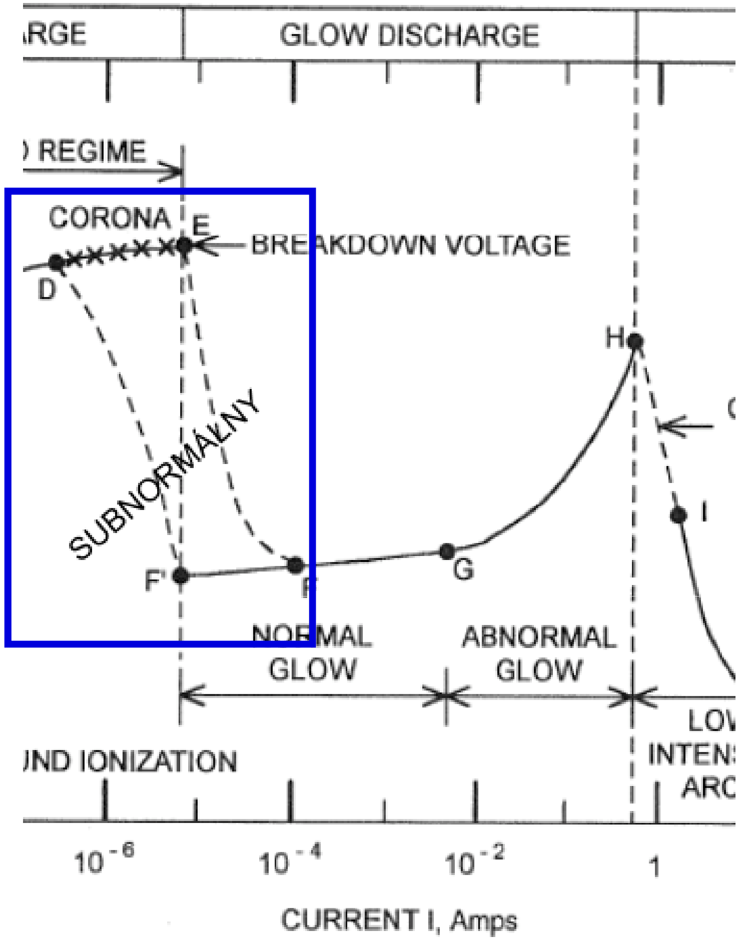
$$\frac{j}{p^2} \approx (1+\gamma) \cdot \frac{\varepsilon_0 \mu_i^{\mathrm{R}} V_{c,\min}^2}{(pd)_{\min}^3}$$

When we increase current, voltage stays nearly the same. This is because the cross-section of the discharge is increasing, the discharge is filling the electrode surface.



Subnormal / normal / abnormal glow discharge

- **Abnormal glow discharge** = when the discharge has filled the entire electrode surface, the scaling law stops to work.
- **Simply put, the plasma starts to behave like a resistor – to force more current through it, you need a higher voltage.**
- In reality, it is a slightly non-linear resistor, conductivity changes due to the change in voltage and current.

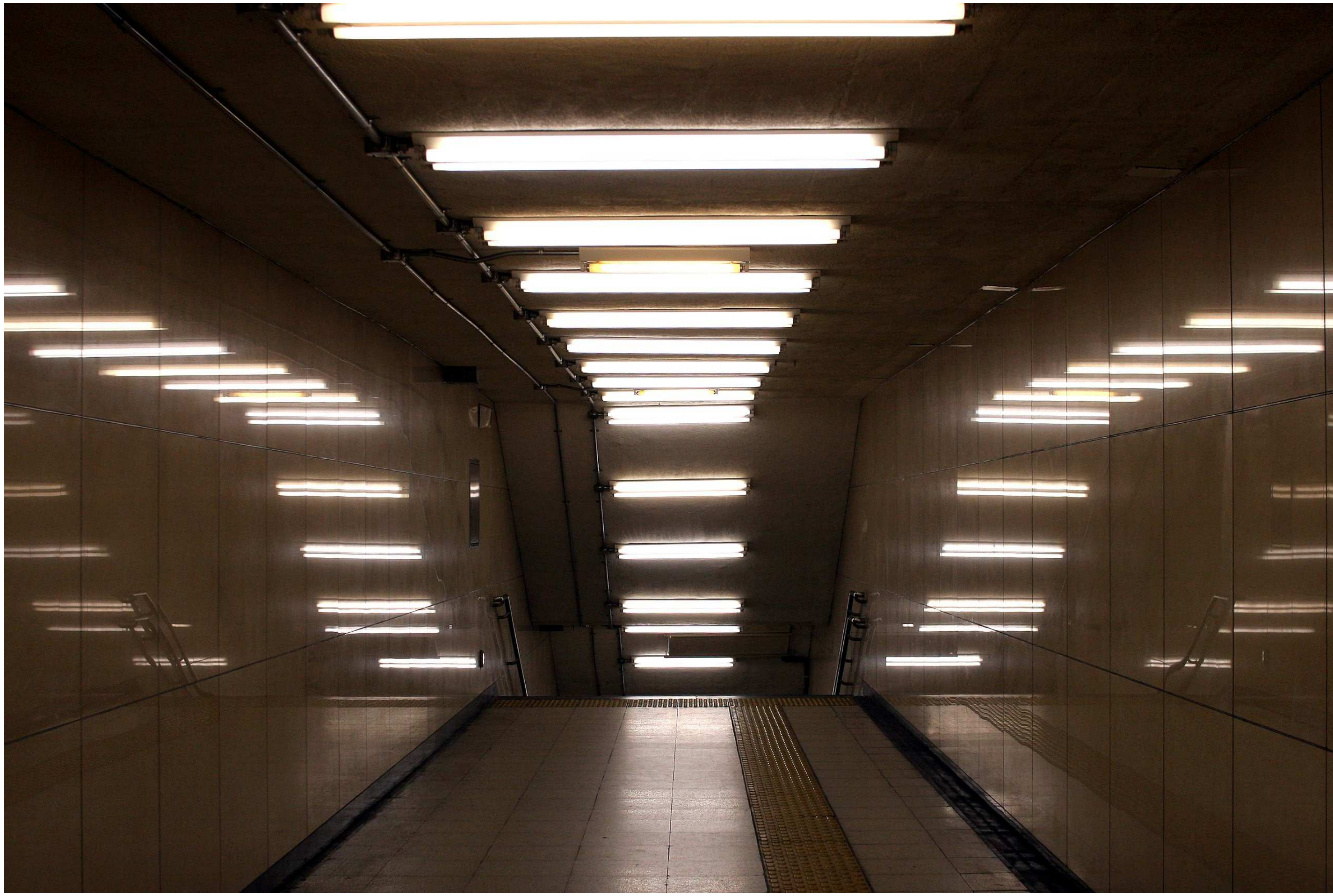


Applications of glow discharge

(today we cover only plain non-magnetized glow discharge in DC or slow AC < 1 kHz)

Application: Fluorescent lamps

- Nowadays an obsolete device, mostly surpassed by LEDs.
- Plasma ignited in mercury vapors producing UV
- UV causes fluorescence on a photofluorescent layer
- **Still the go-to method for producing large-scale UV e.g. for disinfection**



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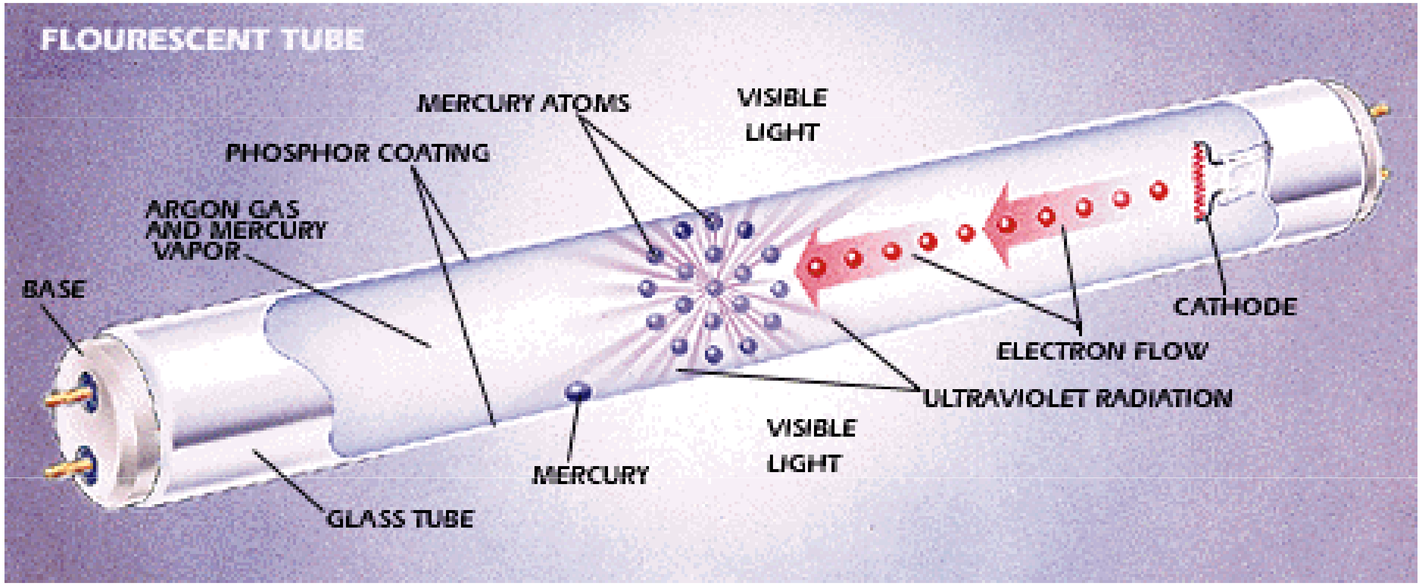
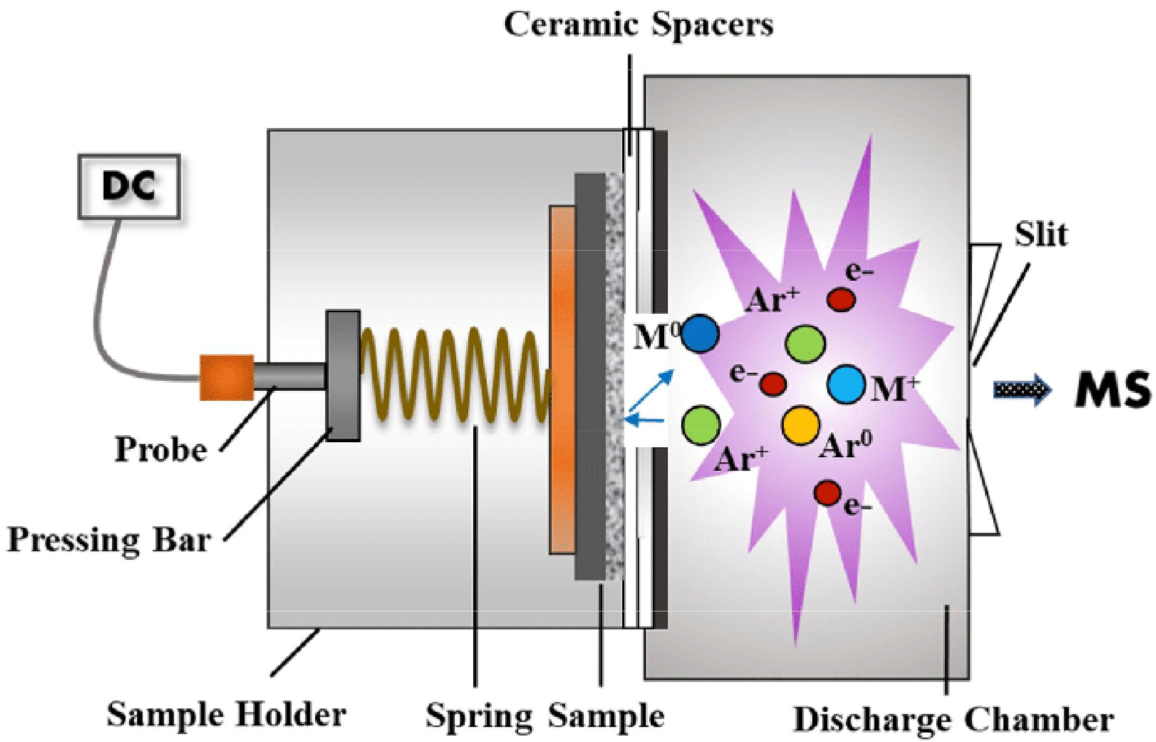


Application: GDMS

- **Glow discharge mass spectrometry** = glow discharge acts as a source of ionization of samples which cannot be ionized chemically or by photons

Q: Why are M atoms emitted from the surface?

A: This is due to the effect of "sputtering" – low temperature removal of solid material by energetic ions (more on that next lecture)

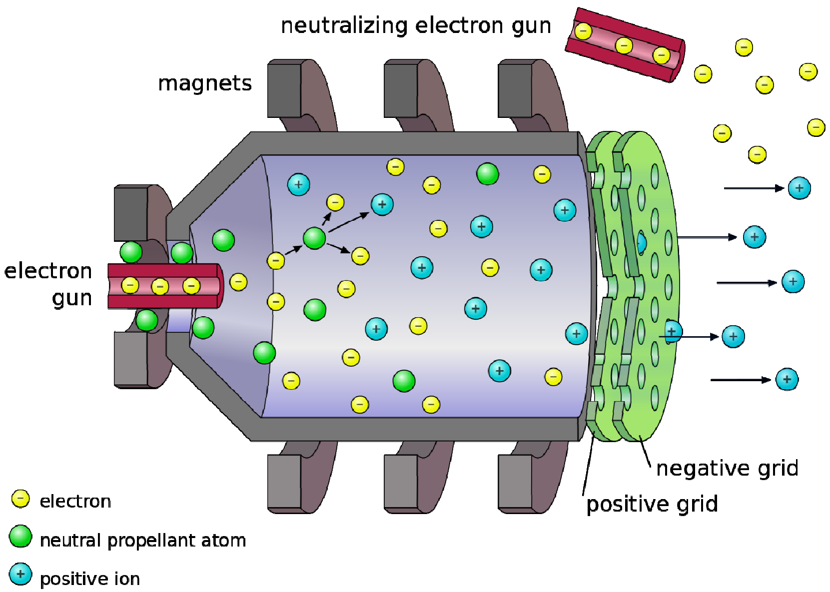


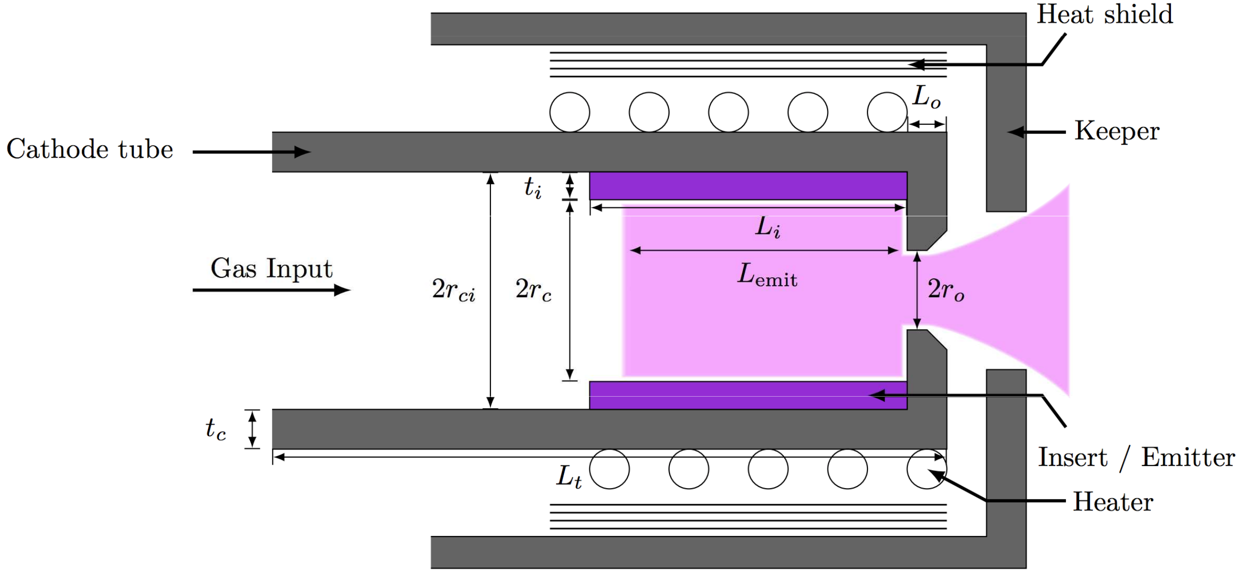
Application: Hollow cathode GD in satellite propulsion

– In a very special arrangement called the “hollow cathode”, glow discharge can generage **very dense but stable plasma at 10-100 A of current**.

Q: Why do you think a HC plasma can get much more dense than the typical glow discharge?

A: Due to secondary emission and thermoemission being confined in the volume – it is largely a geometrical effect.





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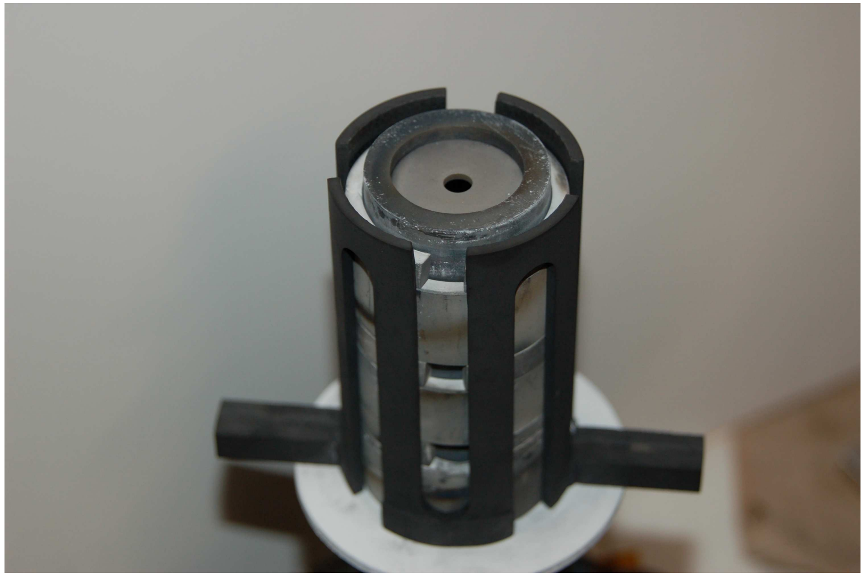

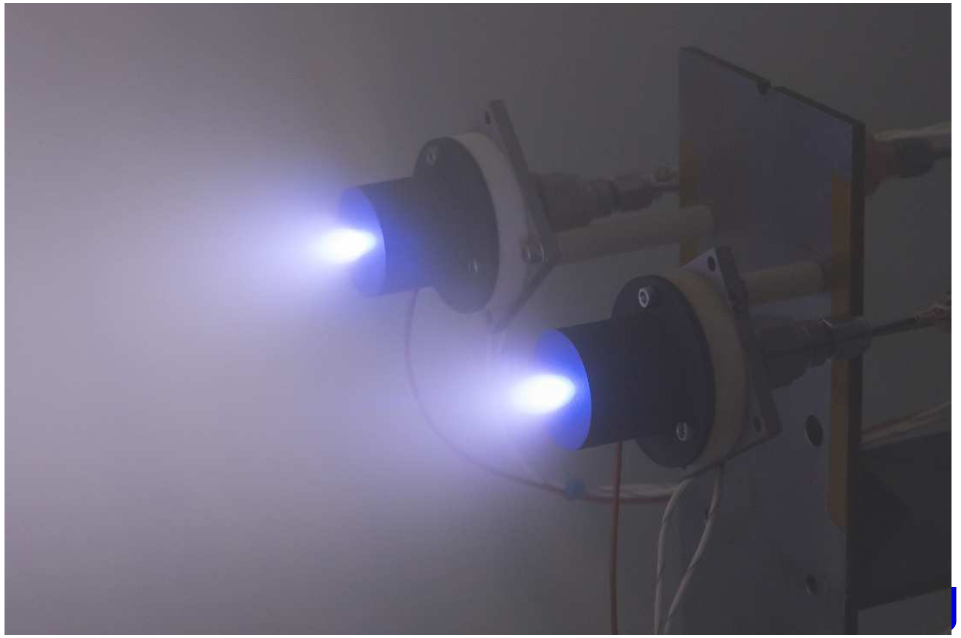

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Main take-aways

Take-aways from lesson 2

1. Mechanisms of Townsend to Glow transition
2. Similarity laws
3. Subnormal, normal and abnormal discharge
4. Application overview