I-V-Characteristics and the Transition from Glow to Arc: **Defining glow and arc discharges without resorting to current and voltage**

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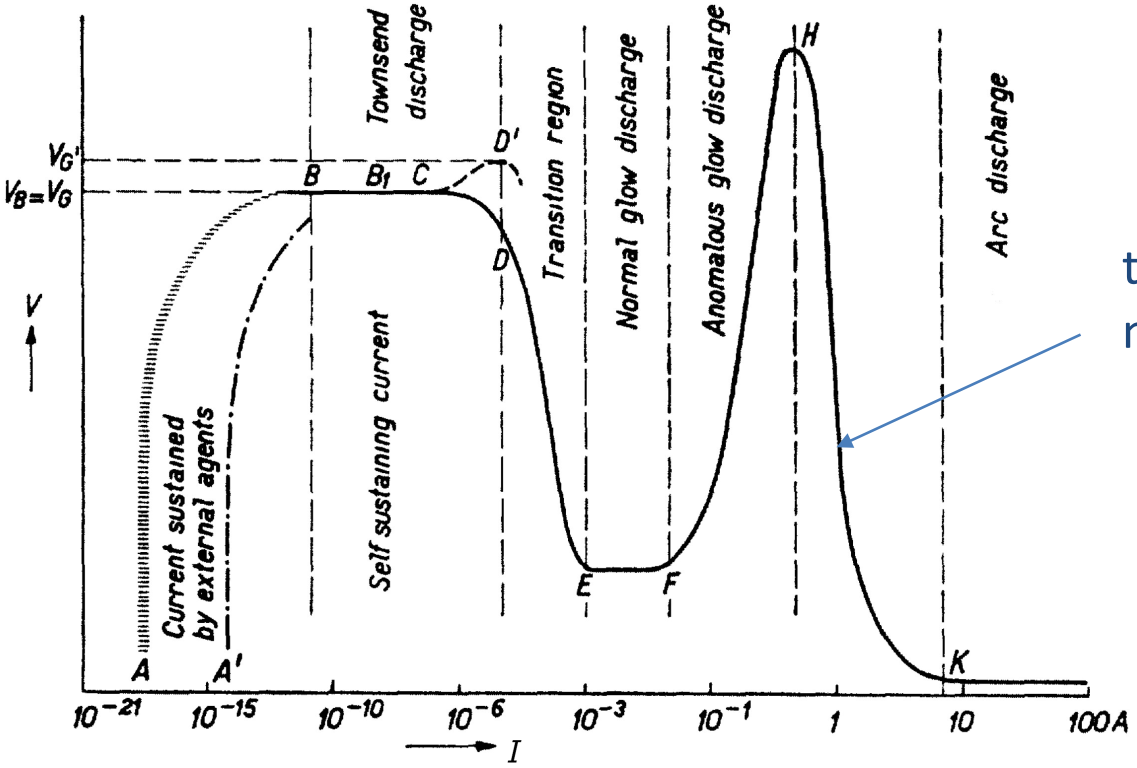
Classic source for *I-V* characteristics (1940, 1953)

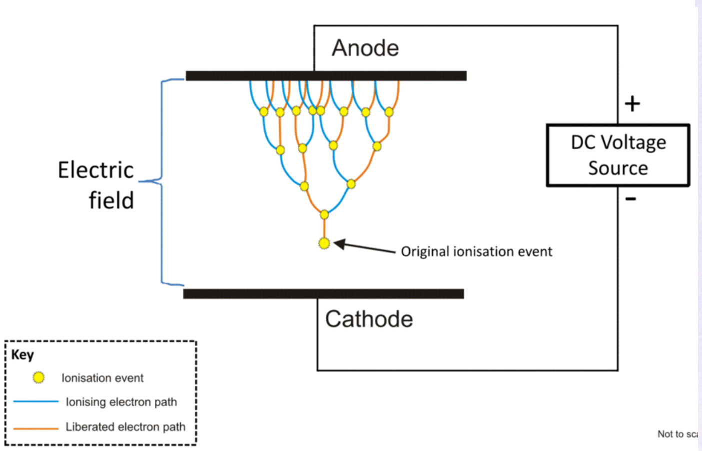


this smooth transition is not necessarily correct

M.J. Druyvesteyn, F.M. Penning, Rev. Mod. Phys., 12 (1940) 87-174.
copied by: J.M. Meek, J.D. Craggs, Electrical Breakdown of Gases, Clarendon Press, Oxford, 1953.

Townsend → Corona → Streamer-Leader Discharge (Lightning)

- Townsend regime: dark discharge, low current density ($\lambda_D \approx L$), no plasma yet
- High electric field allows acceleration of charge carriers and further ionization events
- Corona discharge facilitated by field enhancement near sharp edges
- Streamers-Leader Discharge: conducting channels with high space charge at tip of channel



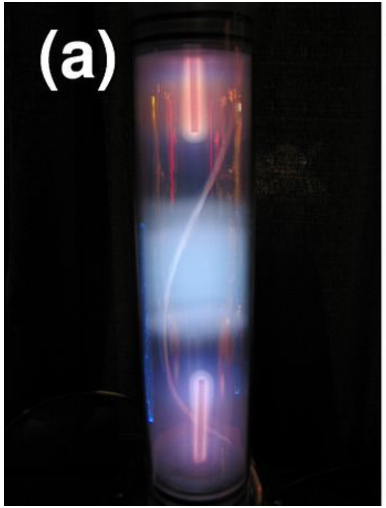
https://en.wikipedia.org/wiki/Electric_discharge_in_gases#/media/File:Electron_avalanche.gif

https://de.wikipedia.org/wiki/Elmsfeuer#/media/Datei:Elmo's_fire-2.jpg

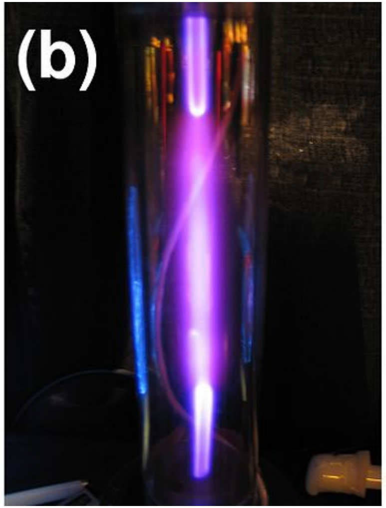
https://www.diyphotography.net/this-breathtaking-photo-shows-rare-st-elmos-fire-from-an-airplane-cockpit/

Glow discharge vs. Arc discharge

- **Glow**: low current, high voltage, electrons via secondary electron emission
- **Arc** discharge: high current, low voltage; 2 main modes:
  - hot cathode, thermionic emission → **thermionic arc**
  - cold cathode but hot spots, thermofield emission turns explosive → **cathodic arc**



glow



thermionic arc

cathodic arc

https://en.wikipedia.org/wiki/Electric_discharge_in_gases#/media/File:Glow2arc.jpg http://nanoarctech.com/equipments/cathodic-arc-pvd/

Classic source for *I-V* characteristics (1991)

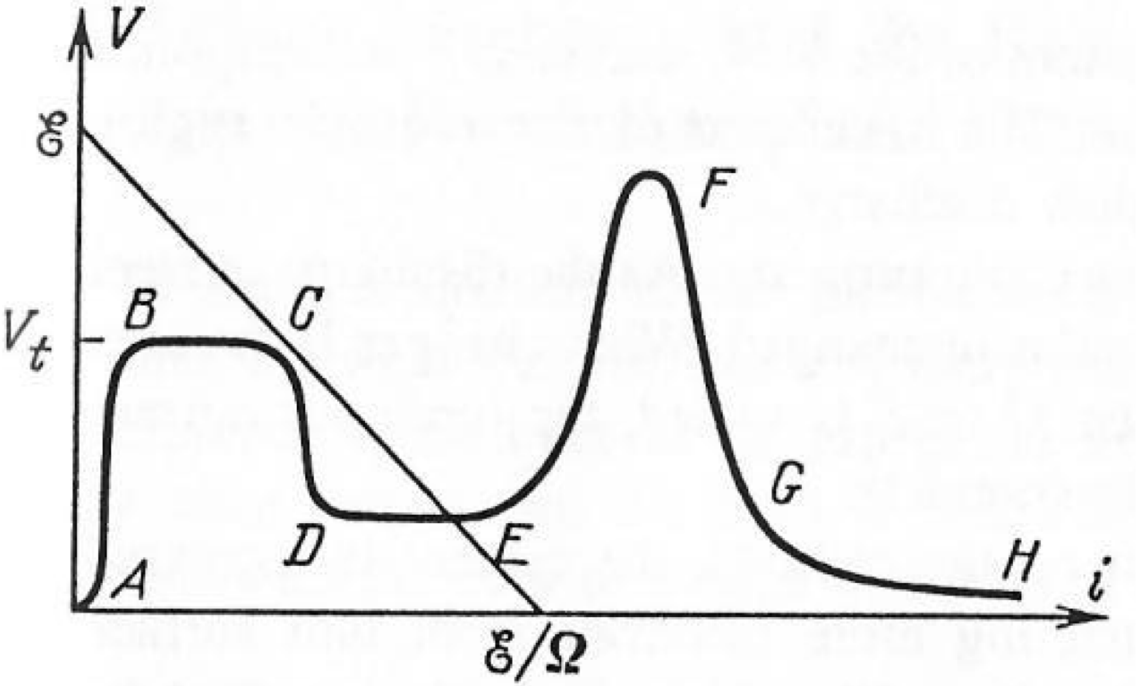
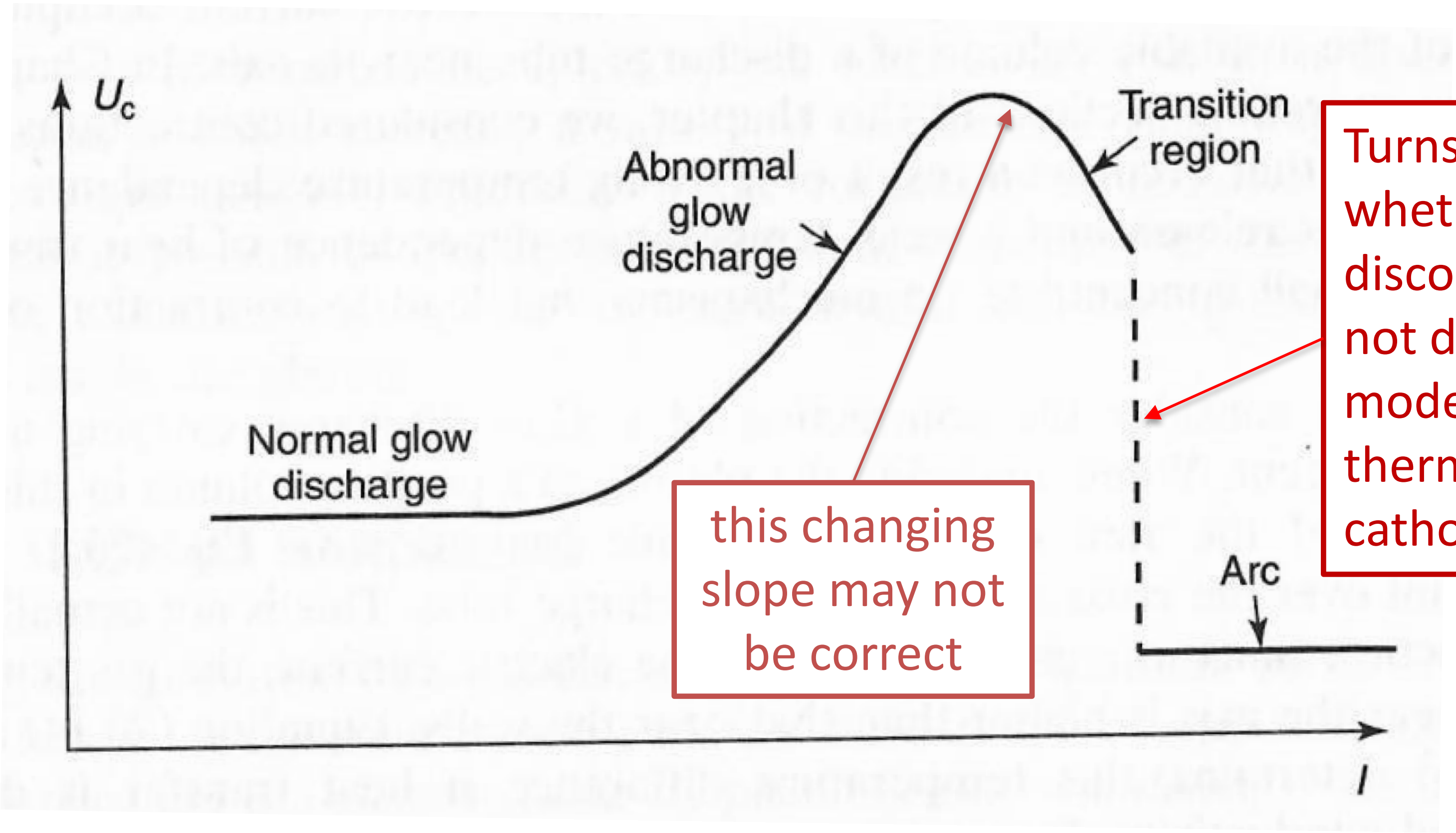


Fig. 8.4. $V - i$ characteristic of discharge between

Y.P. Raizer, Gas Discharge Physics, Springer, Berlin, 1991.

Classic source for *I-V* characteristics (2001)

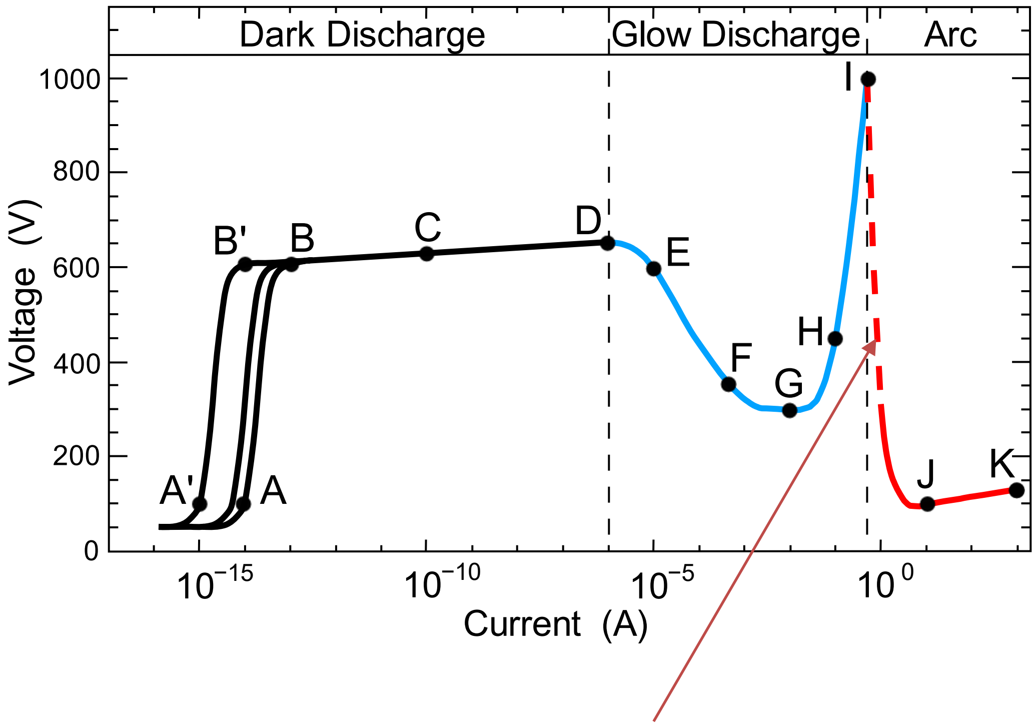


this changing slope may not be correct

Turns out: whether discontinuous or not depends mode of arc: thermionic or cathodic

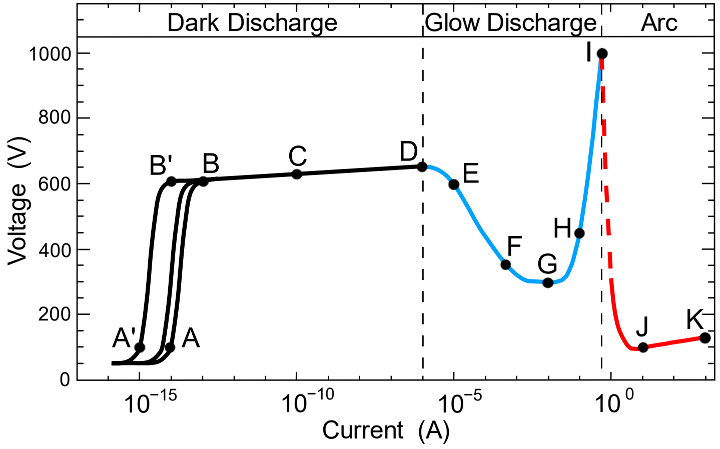
B.M. Smirnov, Physics of Ionized Gases, John Wiley & Sons, New York, 2001.

A look at Wikipedia: *V-I* characteristics (2023)

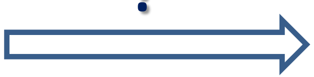


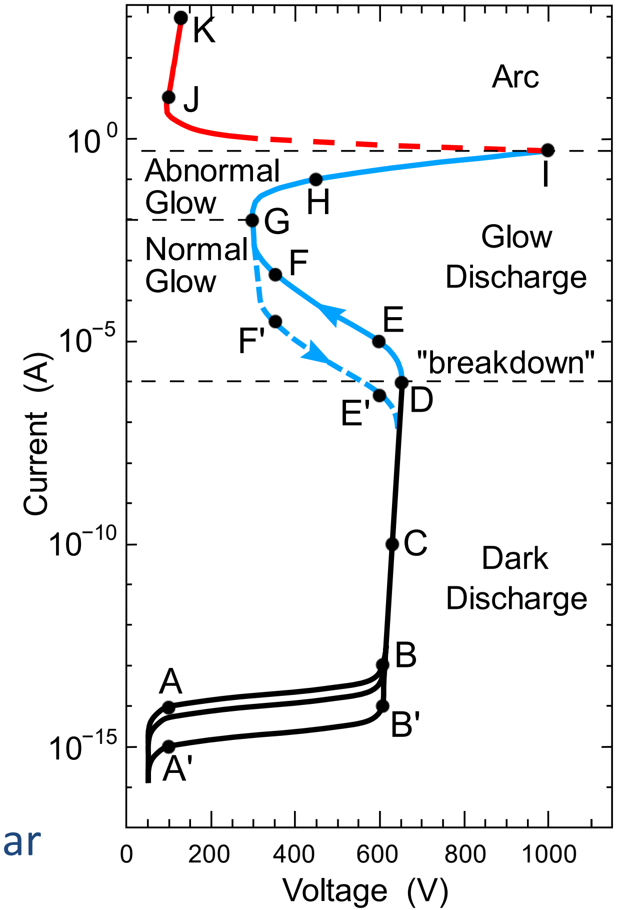
- looks like a function *V*(*I*), with an uncertain (?) transition when the arc starts
- As a student, I asked: ***Why is current on the "x" (independent) axis, not voltage?***

Why I-V and not *V-I* ?



?





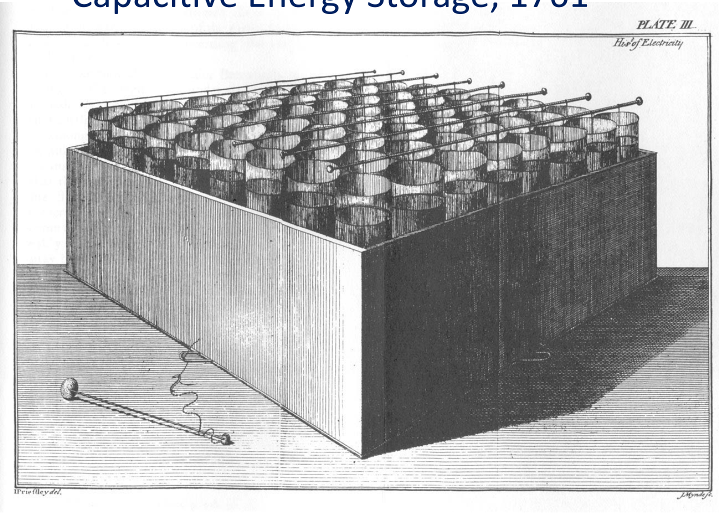
- *the V-I* presentation can be appropriate in light of switching supplies
- *I*(*V*) is clearly not a function → discharge modes appear

https://commons.wikimedia.org/wiki/File:Glow_discharge_current-voltage_curve_vertical.svg

Set current vs. voltage is determined by circuit incl. power supplies

- determine today how the plasma is responding, i.e. its characteristics
- arc suppression should not be determined by current threshold alone but by plasma impedance

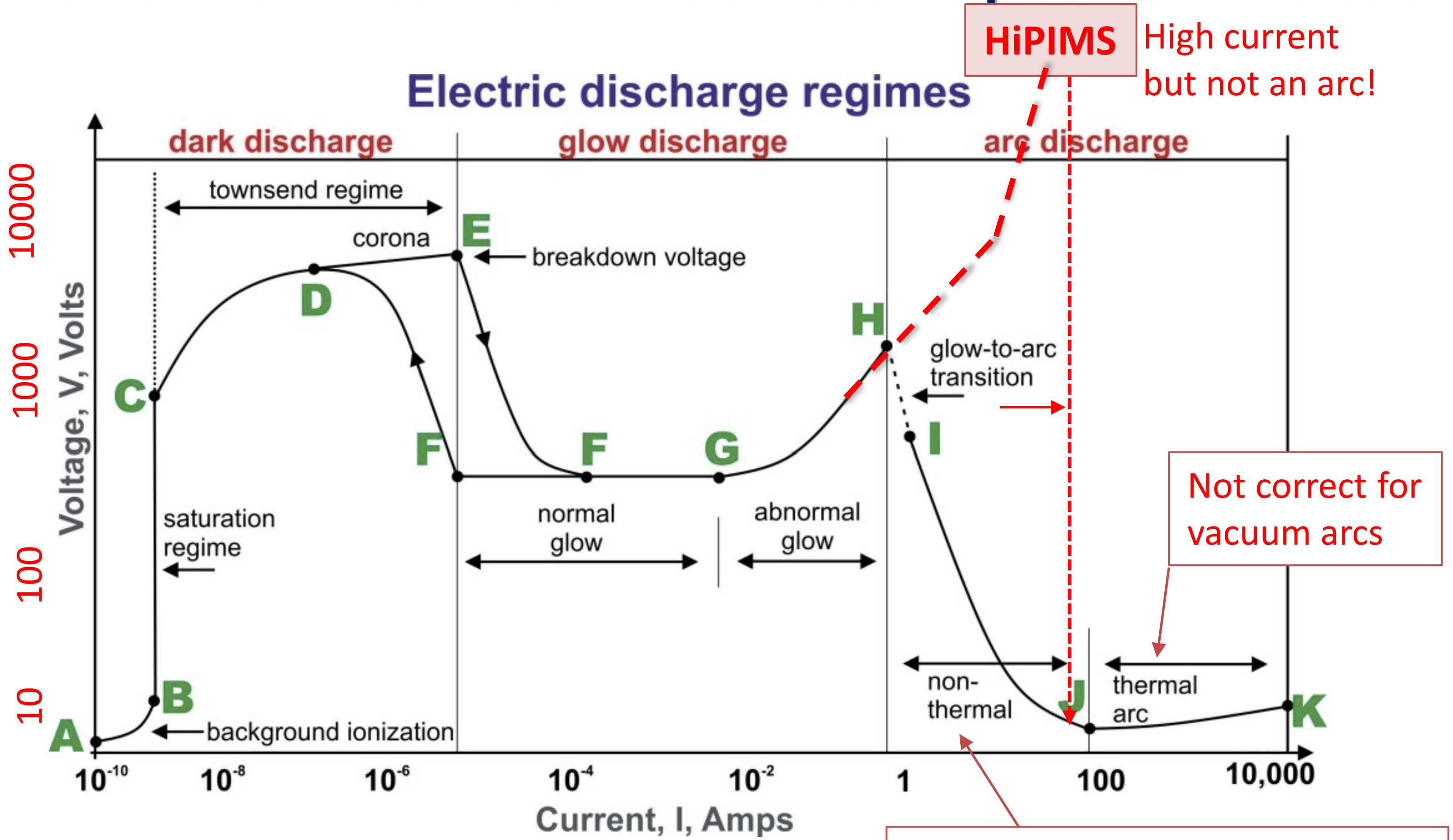
Capacitive Energy Storage, 1761



Modern "switching" power supplies

A. Anders, IEEE Trans. Plasma Sci. **31** (2003) 1052

A look at other resources: *V-I* characteristics in "plasma-universe.com"

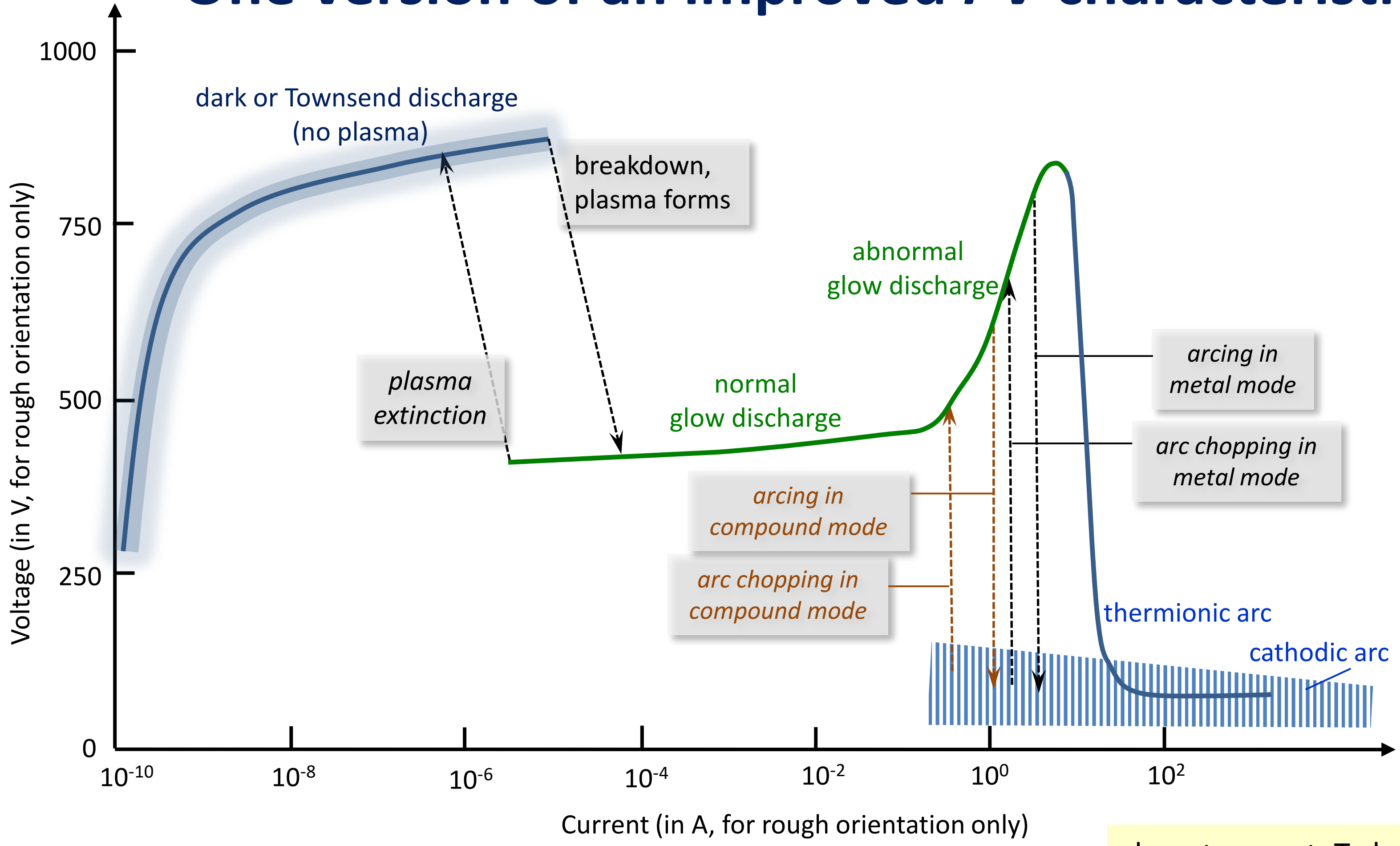


Not correct for vacuum arcs

Not correct for higher pressures!

https://www.plasma-universe.com/electric-glow-discharge/#cite_note-2

One version of an improved *I-V* characteristic



do not use yet: To be published (2023)

Individual versus Collective Electron Emission

- Individual: "γ-processes"
  - Photoemission
  - Secondary electron emission by primary ion emission

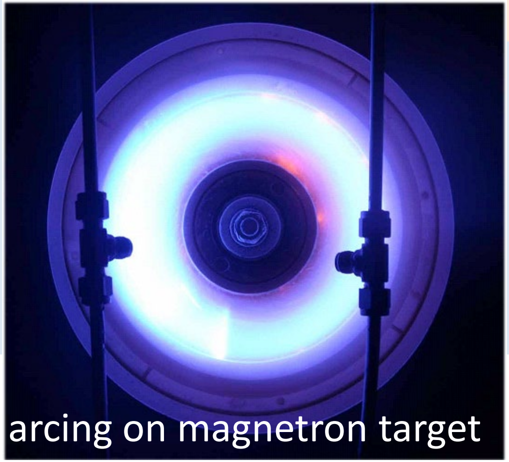
$$j_{SE} = Y_{SE}\, j_i$$

Proportional, linear

- Collective electron emission
  - Thermionic emission
  - Field emission
  - Thermo-field emission
  - Explosive emission

$$j_{TF}\left(T,\mathrm{E}\right) \approx k\left(AT^2 + B\mathrm{E}^{9/8}\right)\exp\left[-\left(\frac{T^2}{C}+\frac{\mathrm{E}^2}{D}\right)^{-1/2}\right]$$

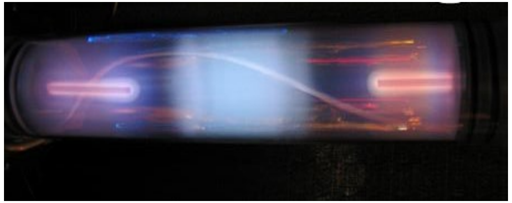
Highly nonlinear in *T, E*



arcing on magnetron target

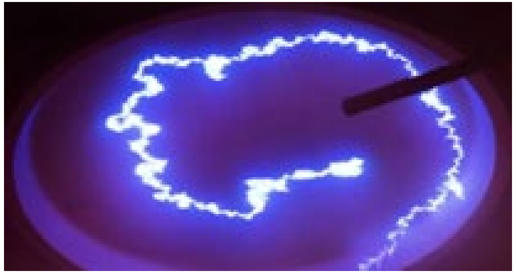
photo by B. Sproul

Glow versus arc discharge: definition #1



$$I < 0.1 \text{ A} \;\text{ and }\; V_{a-c} > 100 \text{ V, or } Z > 1 \text{ k}\Omega \quad \Rightarrow \quad \text{glow discharge}$$

$$I > 100 \text{ A} \;\text{ and }\; V_{a-c} < 100 \text{ V, or } Z < 1 \;\Omega \quad \Rightarrow \quad \text{arc discharge}$$

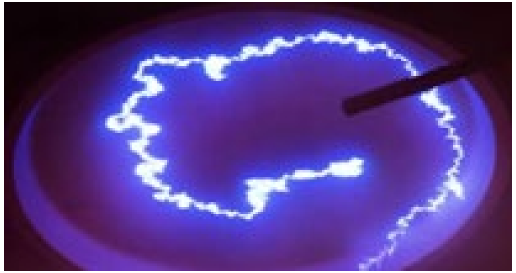


This is the classic definition , ok to use for low pressure discharge between electrodes (without magnetic field and fancy geometry conditions)

Glow versus arc discharge: definition #2

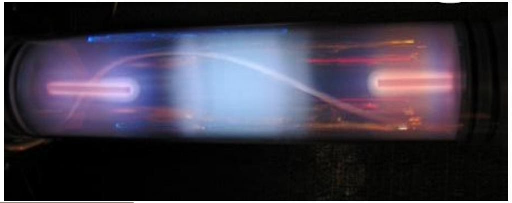
$$j_i + j_e < 10^4 \ \text{A/m}^2 \quad \text{and} \quad V_{a-c} > 100 \ \text{V} \quad \Rightarrow \quad \text{glow discharge}$$

$$j_i + j_e > 10^6 \ \text{A/m}^2 \quad \text{and} \quad V_{a-c} < 100 \ \text{V} \quad \Rightarrow \quad \text{arc discharge}$$

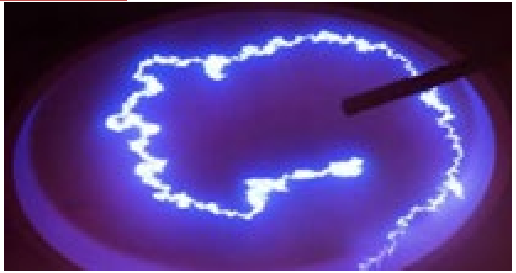


The physically relevant current DENSITY is used.

Glow versus arc discharge: definition #3



$$\frac{j_{e,collective}}{j_{e,\gamma-proceeses}} = \begin{cases} <1 & \Rightarrow \text{glow discharge} \\ >1 & \Rightarrow \text{arc discharge} \end{cases}$$

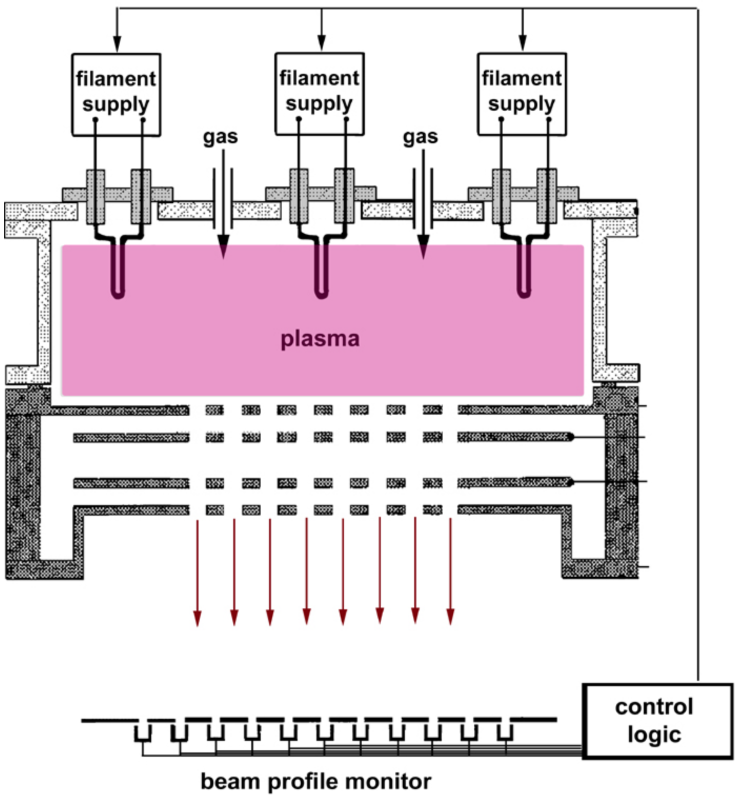


The physics of the emission process is used to define the discharge.

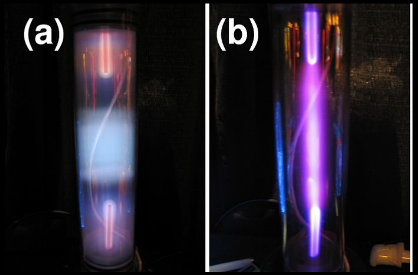
→ **No direct reference to current or voltage is needed or used.**

And what does this have to do with ion sources?

- Kaufman ion source: thermionic arc: preheat filament to avoid issues with glow-to-arc transition
- RF-ion sources avoid electrode effects altogether

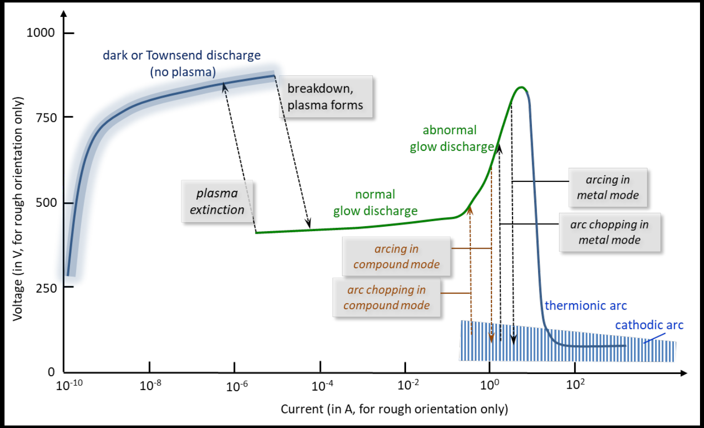


Example of Kaufman ion source from: M. Naito, et al., Rev. Sci. Instrum. 71 (2000) 1023.

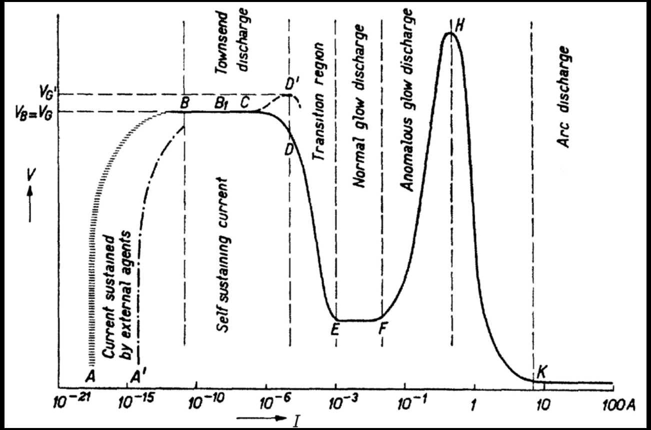


Summary

glows and arcs are long known



An improved current-voltage characteristic is proposed



Classic *I-V* characteristics are not generally valid → need to extended presentation and modified defintions

$$\frac{j_{e,collective}}{j_{e,\gamma-proceeses}} = \begin{cases} <1 & \Rightarrow \text{glow discharge} \\ >1 & \Rightarrow \text{arc discharge} \end{cases}$$

An alternative definition of glow and arc is proposed to avoid the difficulties with absolute current and voltage values.