Plasma Physics 2

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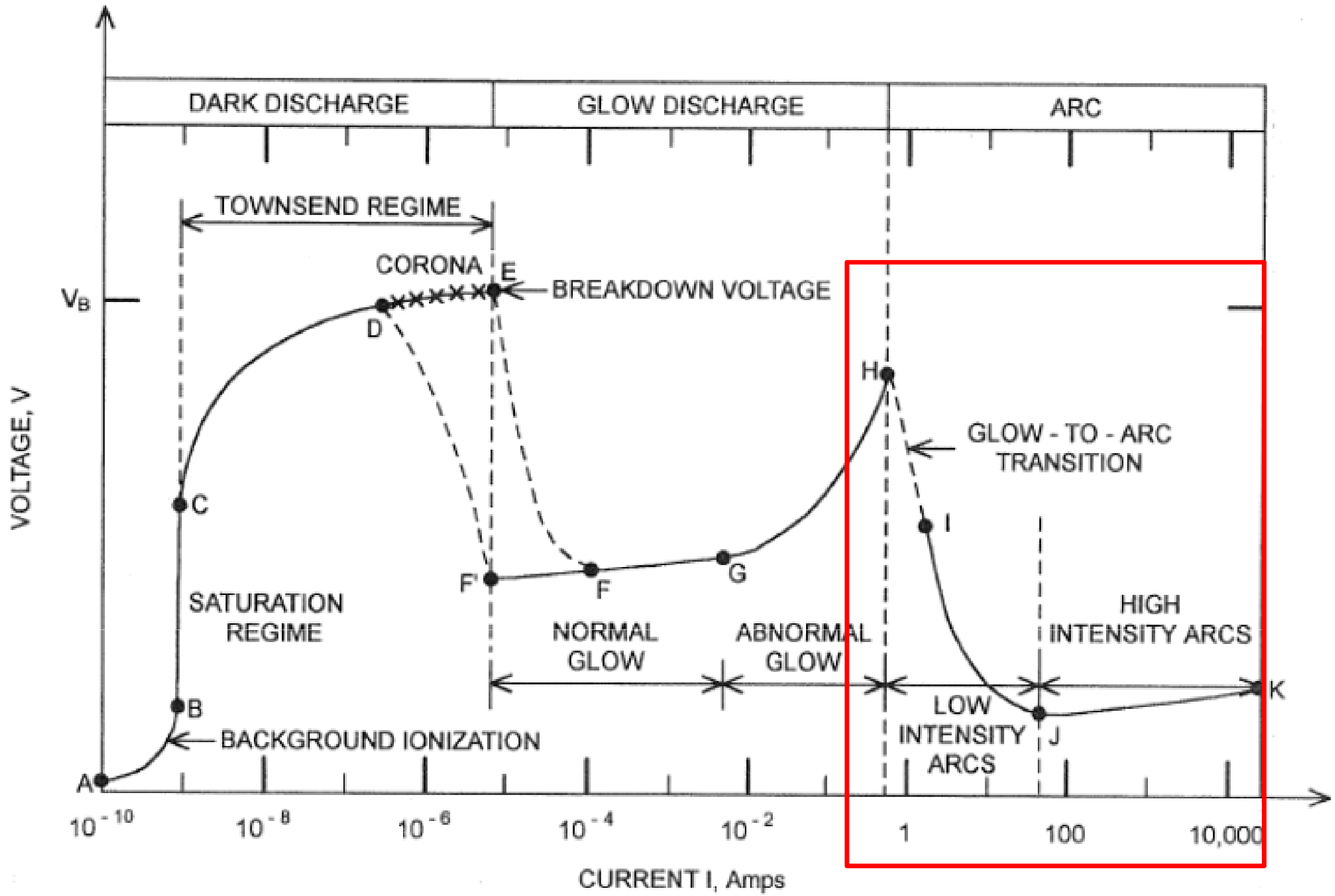
Lecture series contents

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

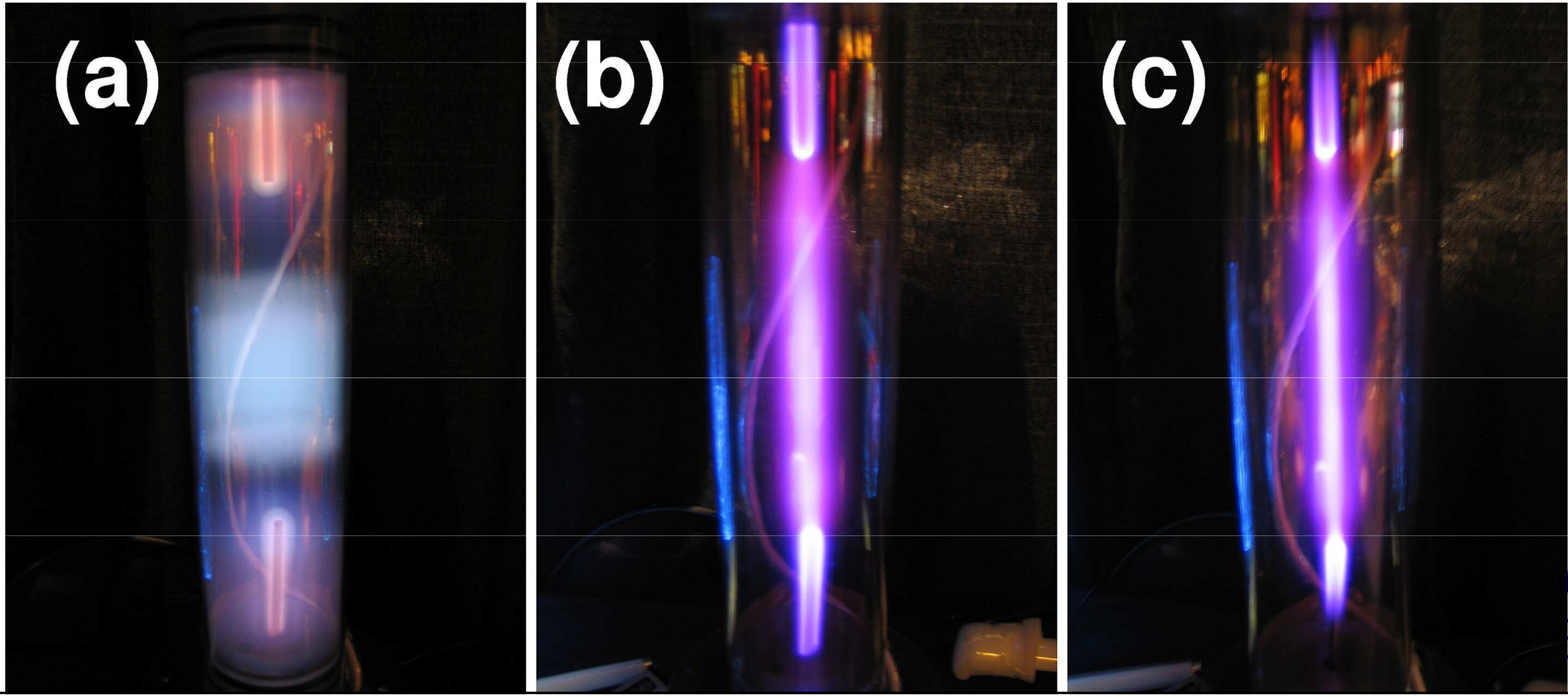
- Transition from glow to arc, mechanisms, fundamental properties of arcs.
- Physics of arc plasmas, analytical models for high power LTE arcs.
- A short but important note on vacuum arcs
- Applications of arc plasmas

Observation of the transition between Glow Dischage and Arc Discharge

Glow > Arc transition mechanics

Visuals first: https://www.youtube.com/watch?v=VAwnxlc0-6E

Pressure increase or power increase



Glow > Arc transition mechanics

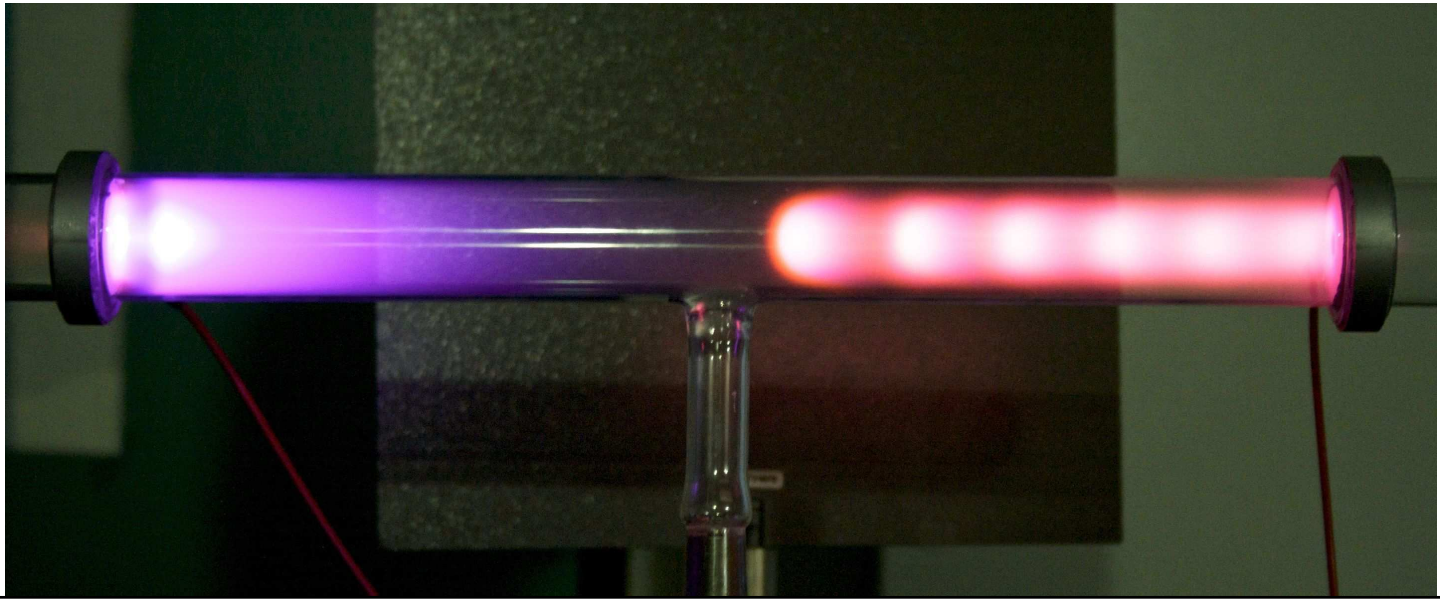
Q: What happens if you start increasing plasma power in glow discharge?

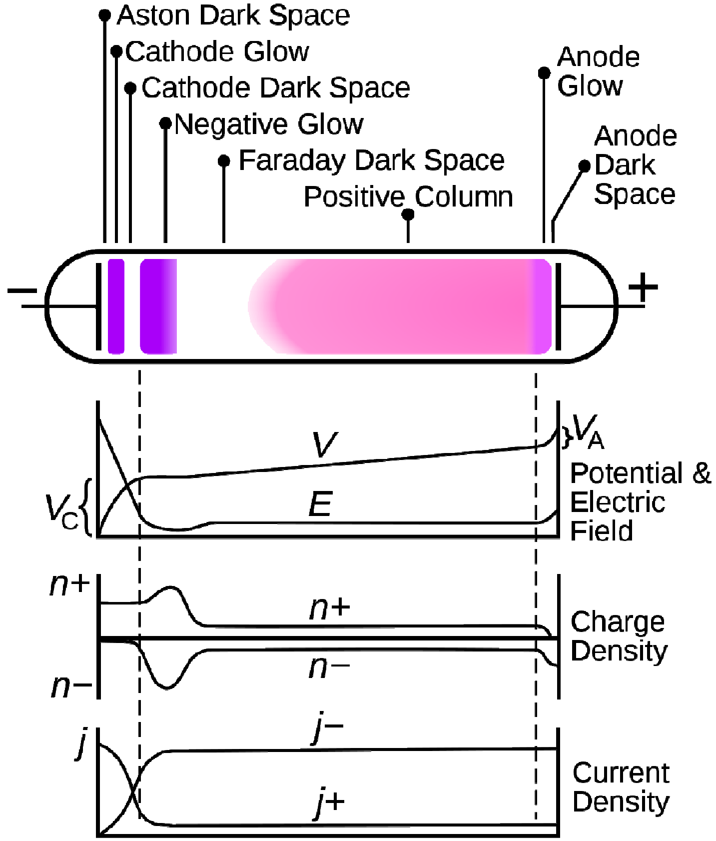
A1: Plasma gets generally more dense

A2: Cathode sheath gets thinner even though voltage keeps growing.

A3: Electric field in the cathode drop increases.

A4: More ions bombard the cathode surface.





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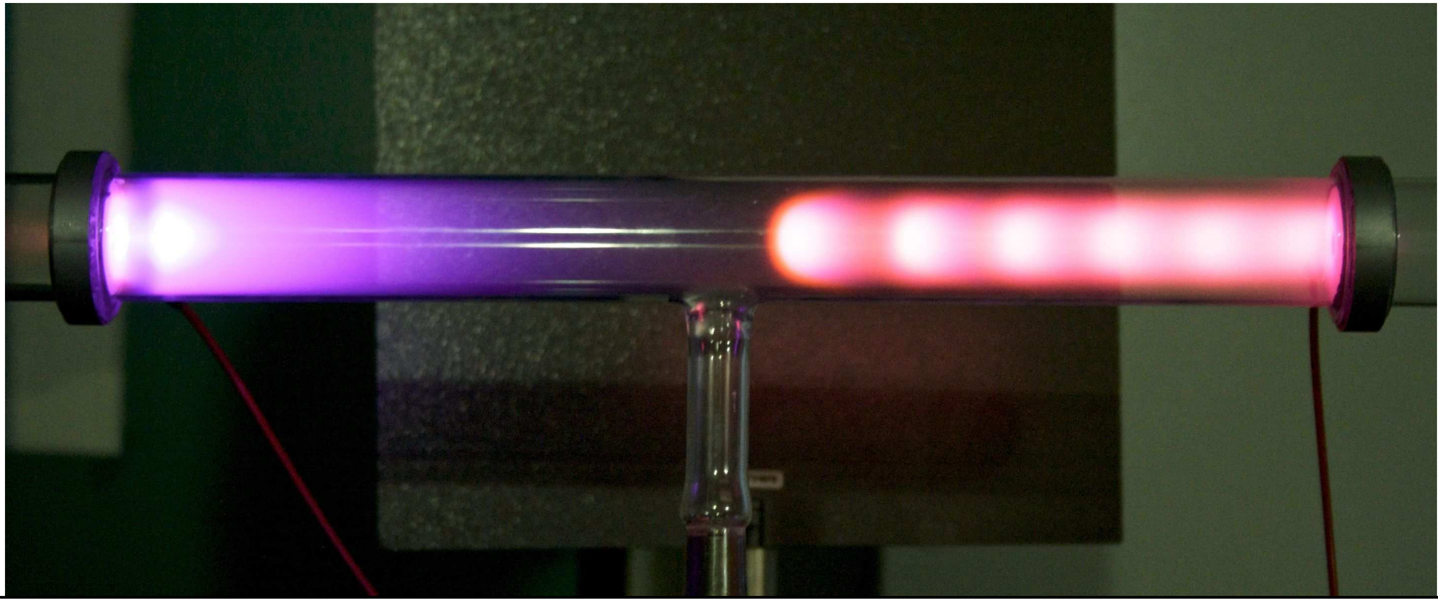
Glow > Arc transition mechanics

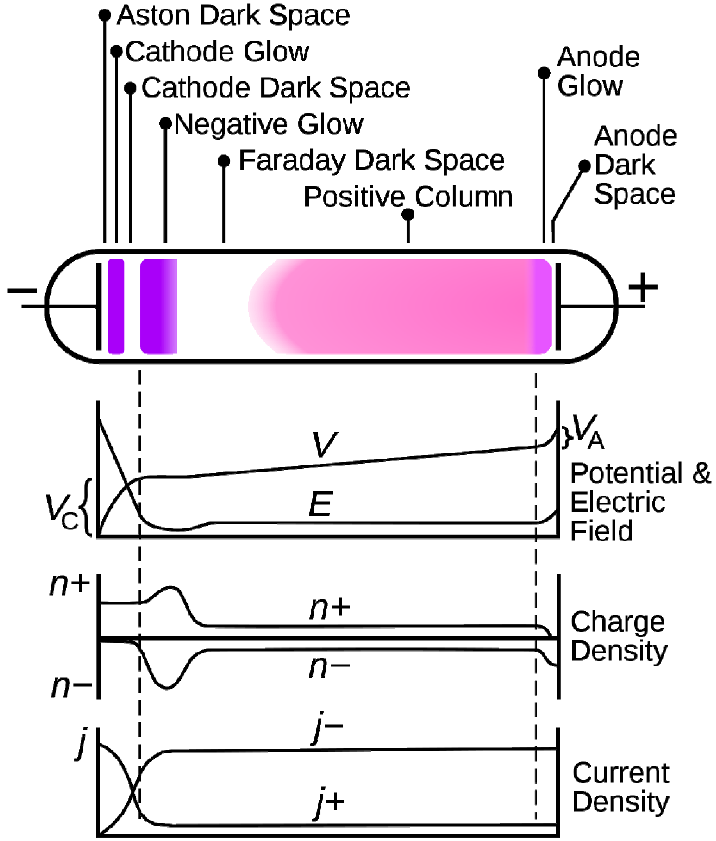
Q: When will this stop? What do you think happens to the cathode?

A1: It gets hot (more ions) => thermoemission of electrons

A2: It is subject to locally strong electric field => field emission

We get 2 new effects that further boost the plasma density!





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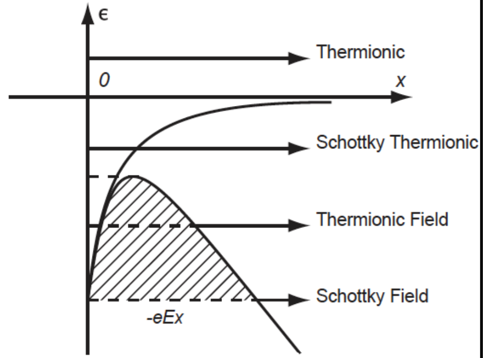
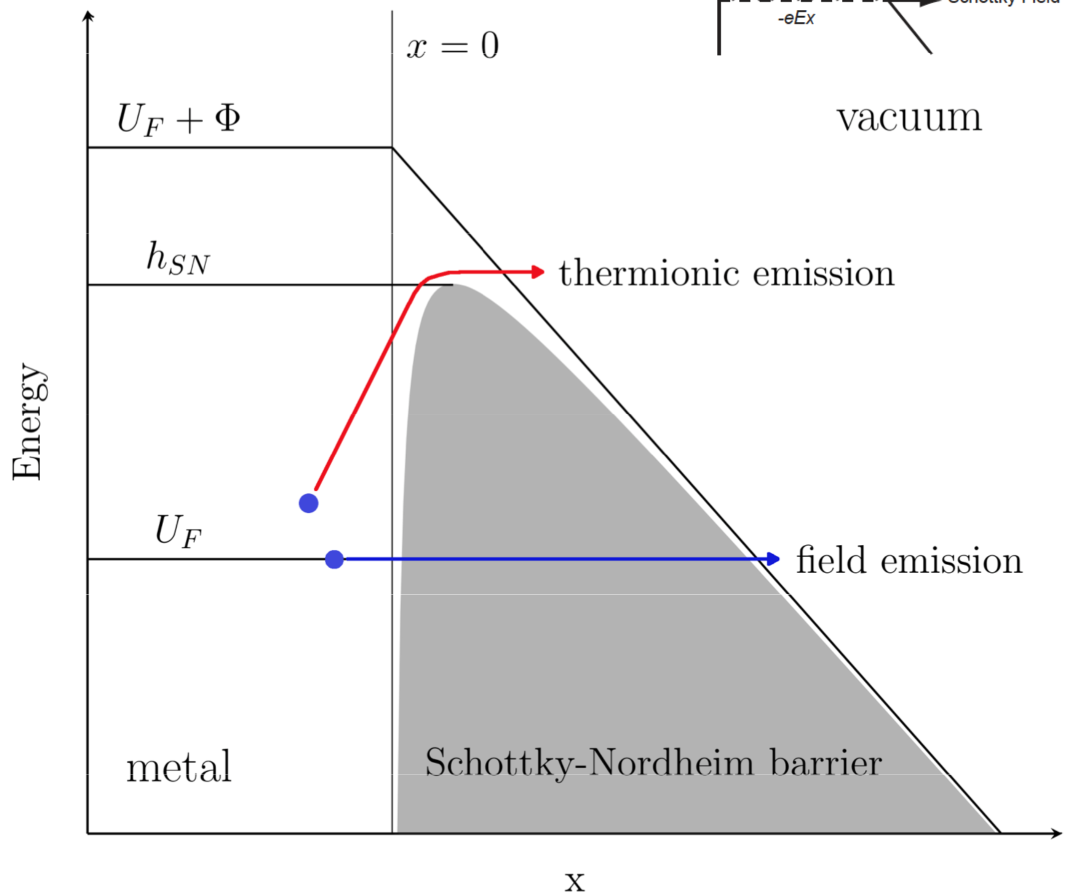
Glow > Arc transition mechanics



- First, let’s qualitatively assess this on the quantum mechanics level.
- Heating up the metal ensures that there are more and more electrons getting over the work function barrier.
- Electric field close to the metal surface further reduces the energy barrier for electrons to get out.

Interesting Q: what is the plasma density in metals?

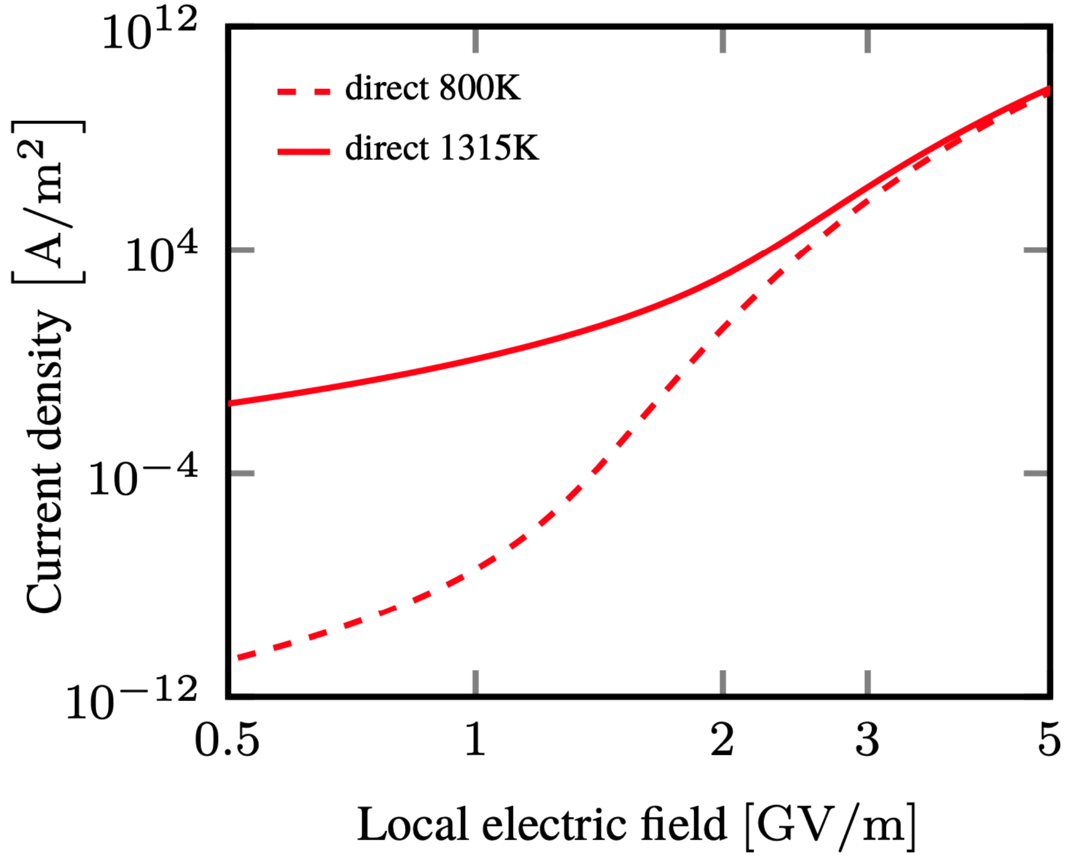
A: About 10^{29} m^{-3}, so there is enough electrons ☺.



Glow > Arc transition mechanics

- At high E fields, the field emission effect lowers the barrier to such extent, that electron emission becomes mostly insensitive to metal temperature.

- Current densities in an arc discharge actually can and do reach MA/m^2 (that is mega-Amperes)



Macroscopic treatment of electrode processes

- The aforementioned processes at the cathode are very important for sustaining an arc plasma.
- Thermionic emission is well described by so-called **Richardson's law**, which connects emitted current density with surface temperature and work function as:

$$J = A_{\mathrm{G}} T^2 \mathrm{e}^{\frac{-W}{kT}}$$

- Where A_G is a material-specific constant (tabulated) and W is the work-function of the material.
- Interestingly, the AG constant is only mildly sensitive to the material

$$A_{\mathrm{G}} = \lambda_{\mathrm{R}} A_0 \longleftarrow \lambda_{\mathrm{R}} \approx 0.3 - 0.8$$

$$A_0 = \frac{4\pi m k^2 q_e}{h^3} = 1.20173 \times 10^6 \,\mathrm{A\,m^{-2}\,K^{-2}}$$

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Macroscopic treatment of electrode processes

- The aforementioned processes at the cathode are very important for sustaining an arc plasma.
- To account for the fact that the electric field at the electrode facilitates easier emission (also known as **Schottky effect/Schottky emission**), the Richardson law can be modified as:

$$J(E,T,W) = A_{\mathrm{G}} T^2 e^{\frac{-(W-\Delta W)}{kT}}$$

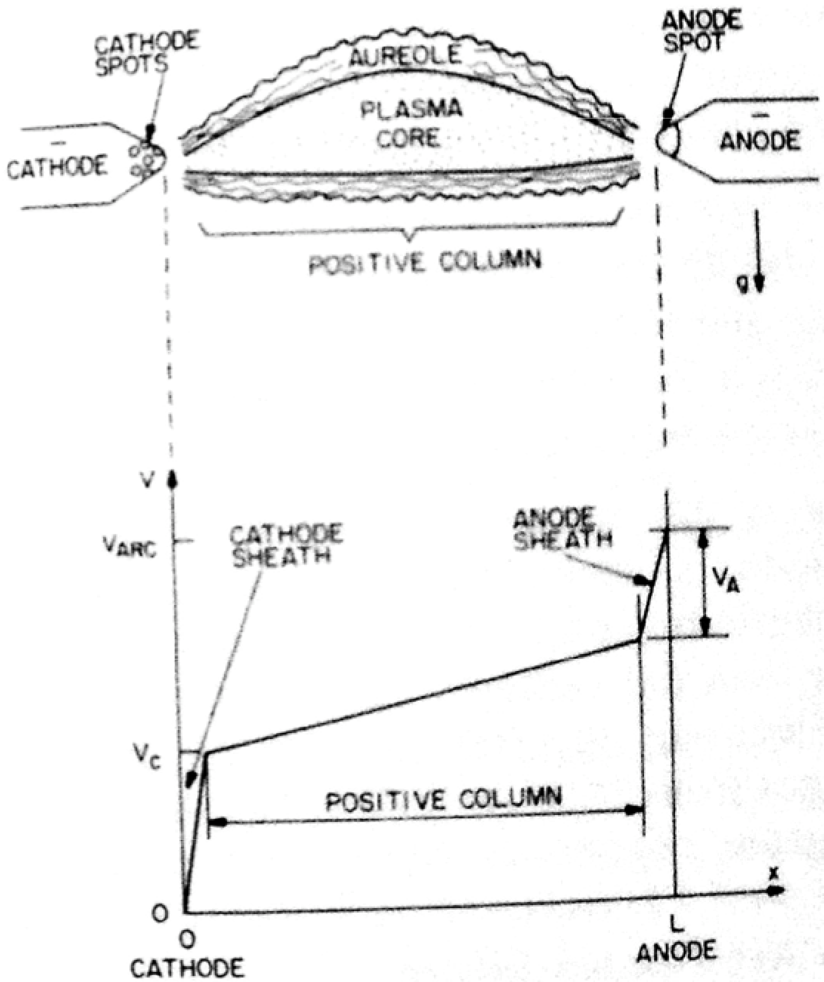
$$\Delta W = \sqrt{\frac{{q_e}^3 E}{4\pi\epsilon_0}},$$

Where we see that the electric field is effectively reducing the work function of the material, as expected from the QM perspective.

Structure and properties of an arc plasma, z-pinch effect

Structure and parameters of an arc

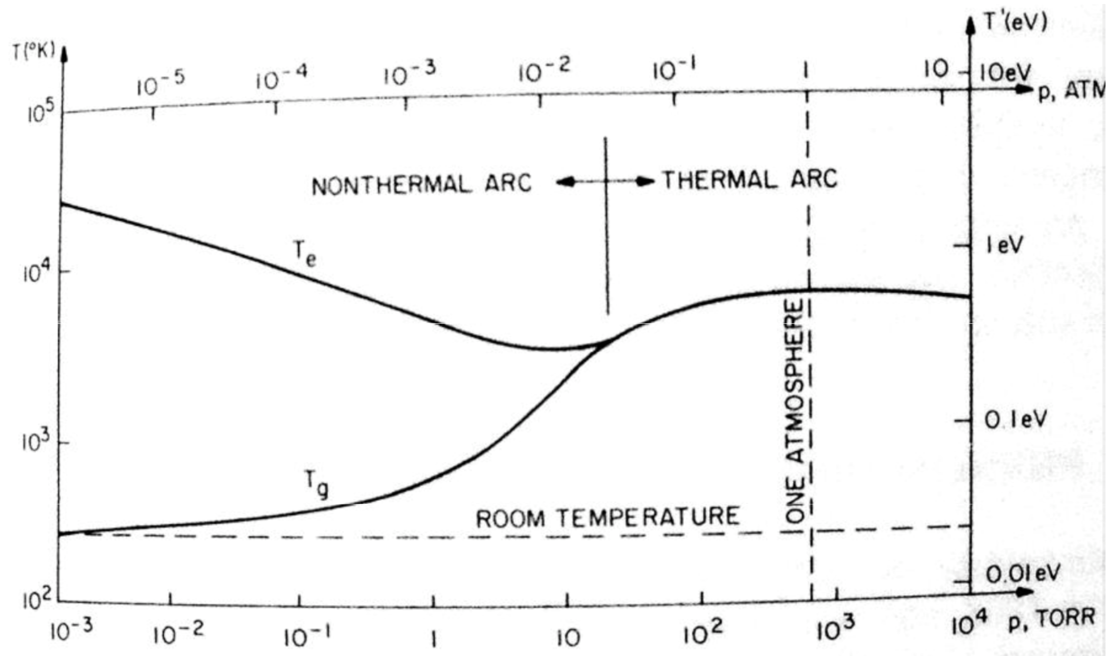
- An arc plasma is mostly the positive column
- Anode and cathode falls are typically highly constricted to the surface (10s of micrometers – milimeter)
- At the electrode, an arc imprint can be either constricted to spot(s) or diffuse
- Voltage drop in the cathode sheath is very small – 10-50 V



Structure and parameters of an arc

- There are generally two types of arc plasmas – equilibrium and non-equilibrium
- The type depends on current but also on the pressure
- Thermal arcs have been operated up to 1 MW of plasma power.

Plasma parameter	Non-thermal arc	Thermal arc
Equilibrium state	Kinetic	LTE
Electron density, n_e (electrons/m^3)	$10^{20} < n_e < 10^{21}$	$10^{22} < n_e < 10^{25}$
Gas pressure, p (Pa)	$0.1 < p < 10^5$	$10^4 < p < 10^7$
Electron temperature, T_e', (eV)	$0.2 < T_e' < 2.0$	$1.0 < T_e' < 10$
Gas temperature, T_g' (eV)	$0.025 < T_g' < 0.5$	$T_g' = T_e'$
Arc current, I (A)	$1 < I < 50$	$50 < I < 10^4$
E/p (V/m-Torr)	High	Low
IE (kW/cm)	$IE < 1.0$	$IE > 1.0$
Typical cathode emission	Thermonic	Field
Luminous intensity	Bright	Dazzling
Transparency	Transparent	Opaque
Ionization fraction	Indeterminate	Saha equation
Radiation output	Indeterminate	LTE



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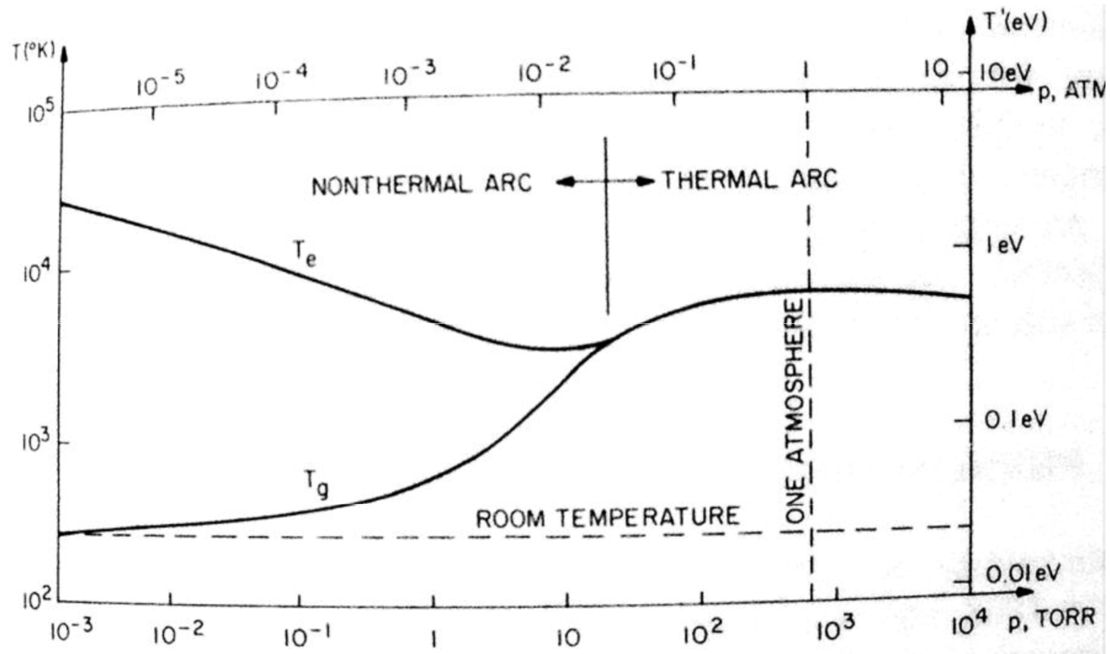


Pinch effect in arc plasmas

- The high currents in arc plasmas generate substantial magnetic fields
- These fields lead to further constriction of the discharge channel
  – Benett's z-pinch

$B = (0, B_\theta, 0)$

$J = (0, 0, J_z) \qquad r \leqslant a$

$J = 0 \qquad r > a$

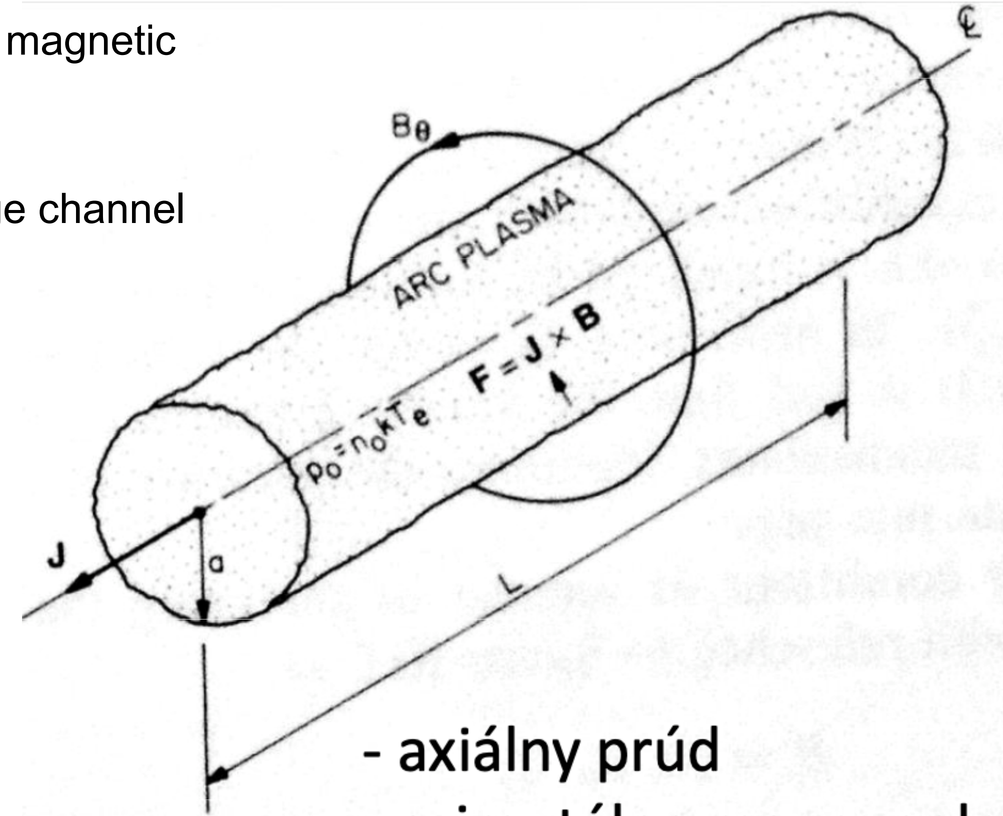
balance of forces:

$\nabla p = J \times B \quad \Rightarrow \quad -J_z B_\theta = \frac{dp}{dr}$

$\nabla \times B = \mu_0 J \quad \Rightarrow \quad \frac{1}{r}\frac{d}{dr}(r B_\theta) = \mu_0 J_z$

$$B_\theta = \begin{cases} \frac{1}{2}\mu_0 J_z r & r \leqslant a \\ \frac{1}{2}\mu_0 J_z (a^2/r) & r \geqslant a \end{cases}$$

$$p(r) = \frac{1}{4}\mu_0 J_z^2 (a^2 - r^2) \qquad r \leqslant a$$



- axiálny prúd
- azimutálne magn. pole

Apparent pressure which constricts the arc channel is proportional to the quare root of the current density

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Arc plasma as a conductive fluid, Saha equation, Ellenbaas-Heller equation

Arc as a conductive fluid

- In the 20th century, various applications for high-power arcs have appeared (t.b.d. later)
- Coincidentally, it turns out that high power arc plasma is much easier to model than e.g. glow discharge plasmas due to several simplifying factors:
  1. The sheath is thin (micrometers)
  2. Voltage drop in sheath is small (10 V) => kinetic effects simpler
  3. Gas and electron temperatures are equal (local Thermodynamic equilibrium)
  4. Ionization degree is high and electron energy distribution function is Maxwellian

This allows us to compute some plasma properties analytically, which is much more difficult for the glow discharge and other non-LTE discharges.

Saha ionization equation

– Describes ionization degree for an LTE plasma
– Connects the density of the (i+1)-th ionization state ions with i-th state ions => we can calculate ionization degree only based on the local temperature.

$$\frac{n_{i+1}n_e}{n_i} = \frac{2}{\lambda^3}\frac{g_{i+1}}{g_i}\exp\left[-\frac{(\epsilon_{i+1}-\epsilon_i)}{k_BT}\right]$$

n_i is the density of atoms in the *i*-th state of ionization, that is with *i* electrons removed.

g_i is the degeneracy of states for the *i*-ions

ϵ_i is the energy required to remove *i* electrons from a neutral atom, creating an *i*-level ion.

n_e is the electron density

λ is the thermal de Broglie wavelength of an electron

$$\lambda \stackrel{\text{def}}{=} \sqrt{\frac{h^2}{2\pi m_e k_B T}}$$

m_e is the mass of an electron

T is the temperature of the gas

h is Planck's constant

Ellenbaas-Heller Equation

- Simplest possible model for describing an arc plasma
  - Assumes that the energy is absorbed only through Joule heating and lost through heat conduction

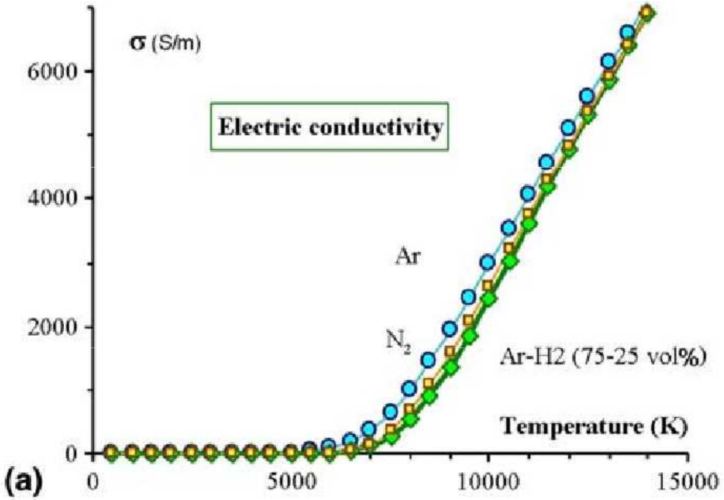
$$\sigma E^2 = -\nabla \cdot (k \nabla T)$$

  - We have to consider that thermodynamic properties of highly ionized gas are non-trivial!

for a gas

$$\sigma \approx 0$$
$$k = a \cdot T + b$$

for a plasma



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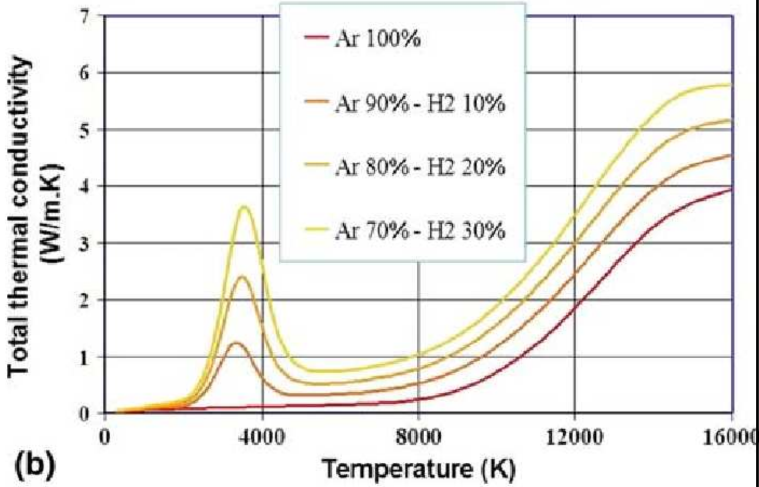
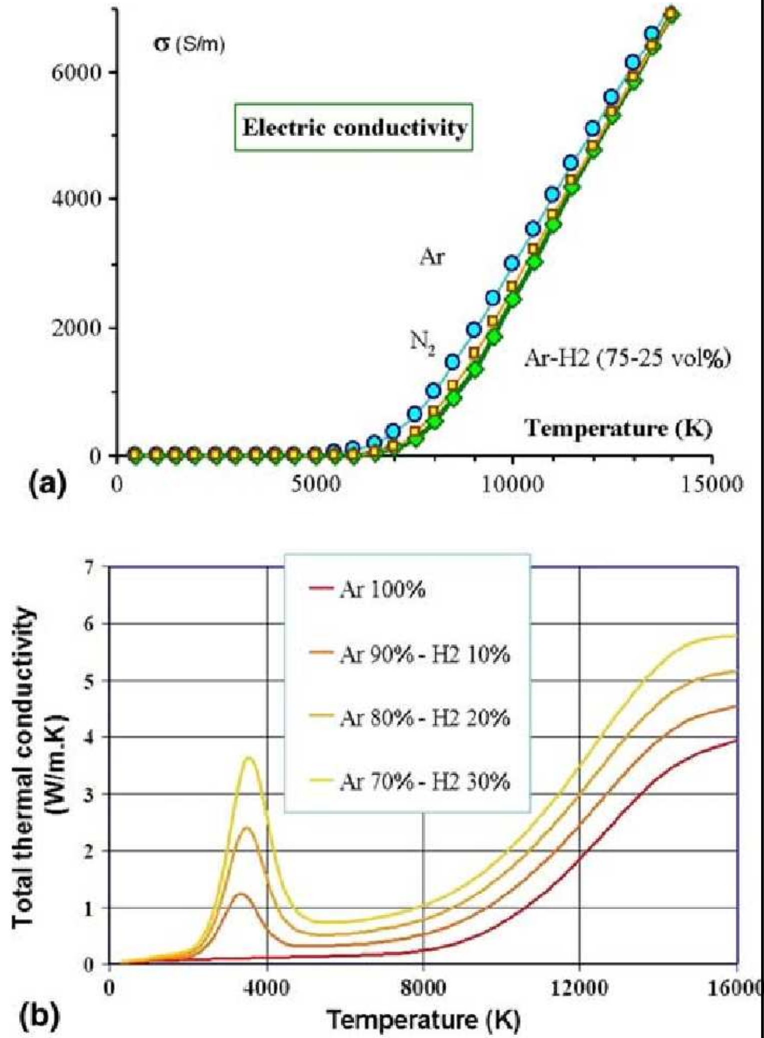


(b)

Plasma as a conductive fluid

- If the plasma is in LTE, it is actually easier to simulate and model than a milder non-LTE plasma.
- You do not have to worry about electron mobilities, ion mobilities.
- You do not have to worry about kinetic processes because they are already included in the thermodynamic properties‘ variations
- You do not have to solve the problematic Poisson equation because $n_e=n_i$.



Plasma as a conductive fluid

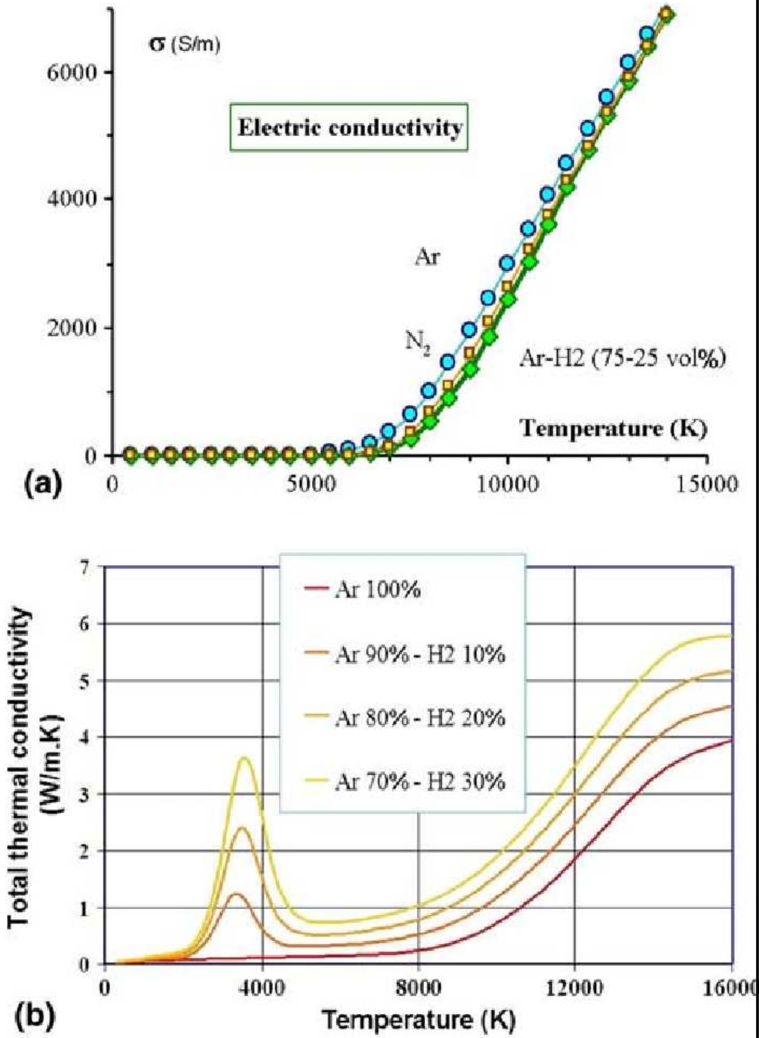
- A LTE arc plasma can be described by a set of equations with are much more linear and easier to solve

1. Navier-Stokes equations for the velocity vector **u**
2. Heat equation for the termperature T

$$\rho C_p\left(\frac{\partial T}{\partial t} + \mathbf{u}\cdot\nabla T\right) + \nabla\cdot(\mathbf{q}+\mathbf{q}_r) = Q = \sigma E^2$$

3. Current continuity equation to obtain the current density and ohmic heating term for the heat equation.

$$\nabla\cdot(\sigma E) = 0$$



Practical configurations of arc plasmas

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Arc plasma layout: point2point

- Two electrodes opposing each other
- An electrode can be planar or point-like.
- Used in lighting applications and for fundamental studies

Arc plasma layout: gliding arc

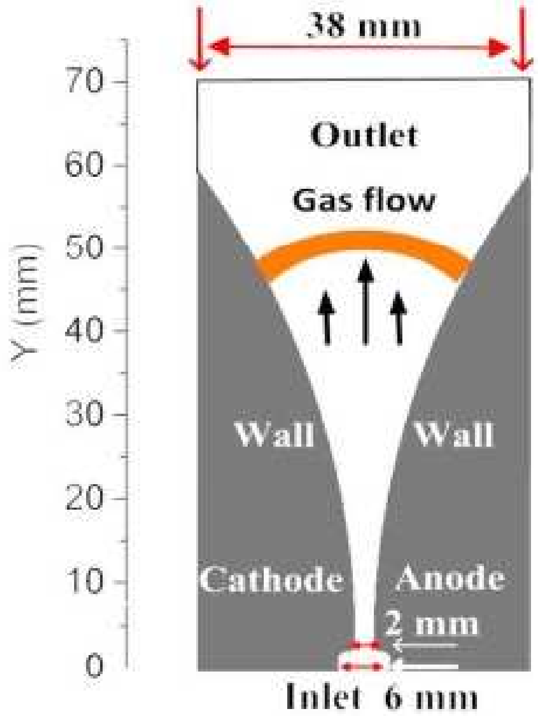
– Electrodes form a diverging “cone”

– Due to forced gas flow and/or gravity (plasma channel is heated), the arc is moving towards the diverging section of the electrodes, until it eventually extinguishes.

– https://www.youtube.com/watch?v=R1JL4gTRmQI (slow motion)

– https://www.youtube.com/watch?v=UHPqLGba4_k (real time)

(a)



(b)

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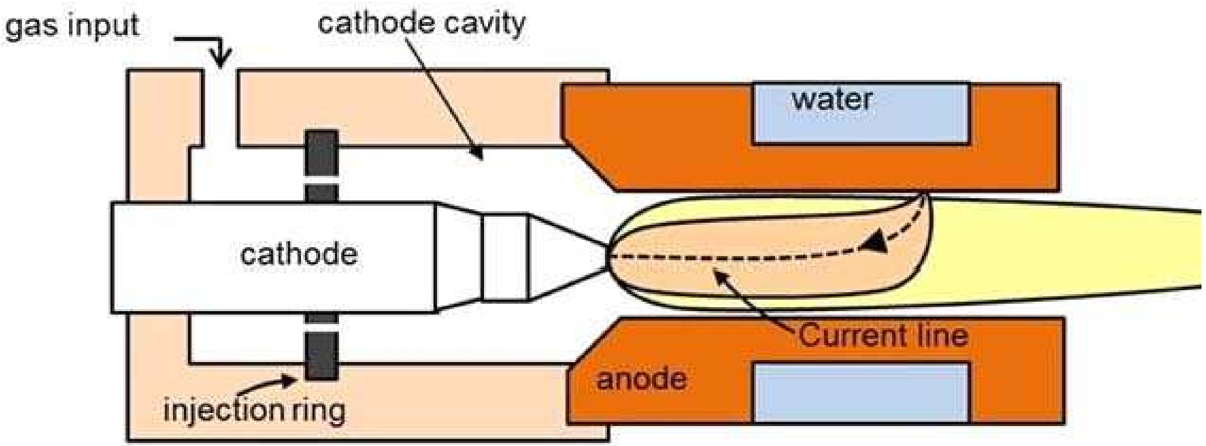
Arc plasma layout: DC torch

- In a DC torch, the cathode is point-like while the anode is coaxial.
- An „anode spot“ attaches to the anode and travels around it. **Q:** Why does the anode spot not stay in one position?
- The plasma is carried away by forced gas flow and forms a „torch“ which is used for various applications
- https://www.youtube.com/watch?v=GrmiCh5v83s
- https://www.youtube.com/watch?v=vA_mstwsPGc



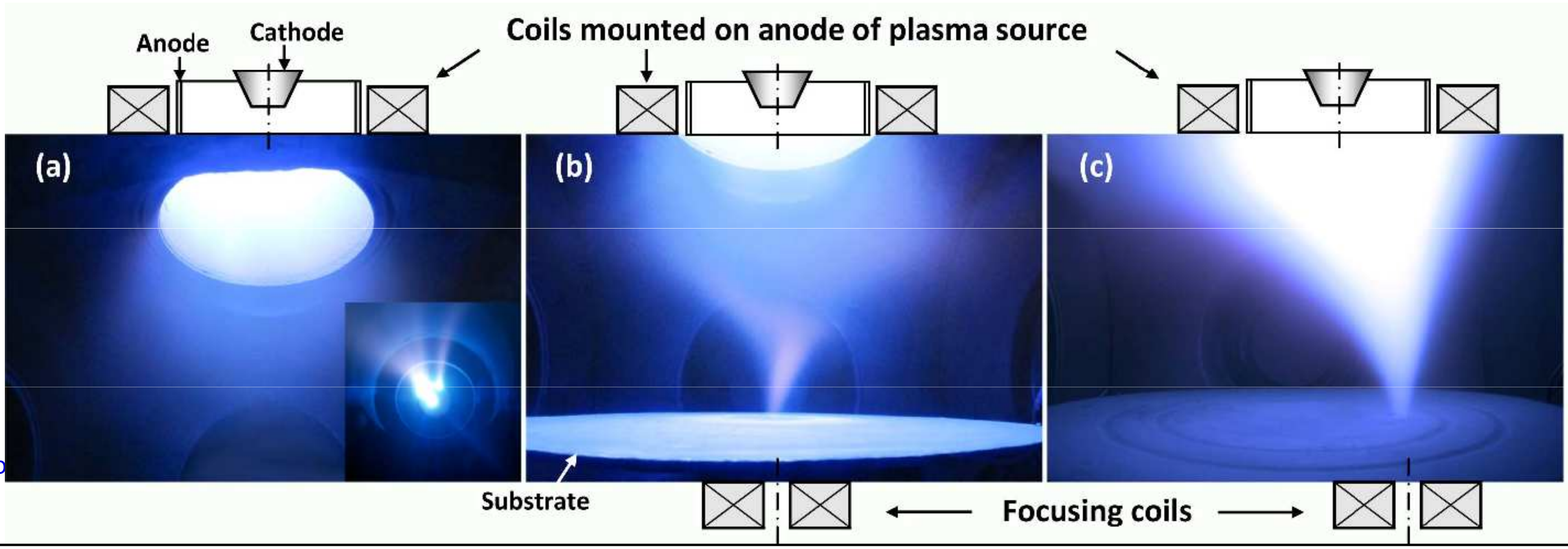
A short but important note on vacuum arcs

Vacuum arcs

– It turns out that arc plasma **does not need gas background to operate**.

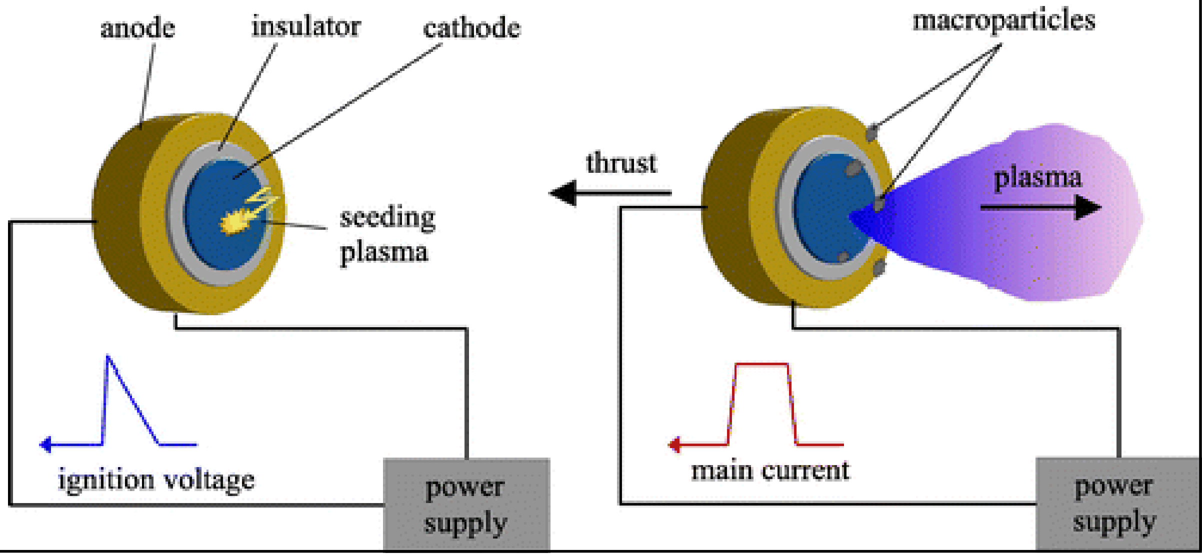
– The plasma is **ignited in the metal vapors that are emitted from the cathode**

– Vacuum arcs have been ignited at pressures of 10^{-4} or even 10^{-6} Pa



Vacuum arcs

- Vacuum arcs are very different from conventional arcs that operate at 1000 Pa – 1 atm.
- In the cathode spot, the plasma density can reach **10^{25}-10^{26} m^{-3}** (yes, over 1 atm of plasma) even if it is surrounded by high vacuum
- The remarkable gradient in plasma properties causes hypersonic expansion of the plasma plume, which attains the drift velocity of **10 – 50 km/s (Mach 20 – Mach 120)**
- It has been extensively researched for satellite electric propulsion, but the main applications are PVD coatings.



Applications of arc plasmas

Application – Lighting

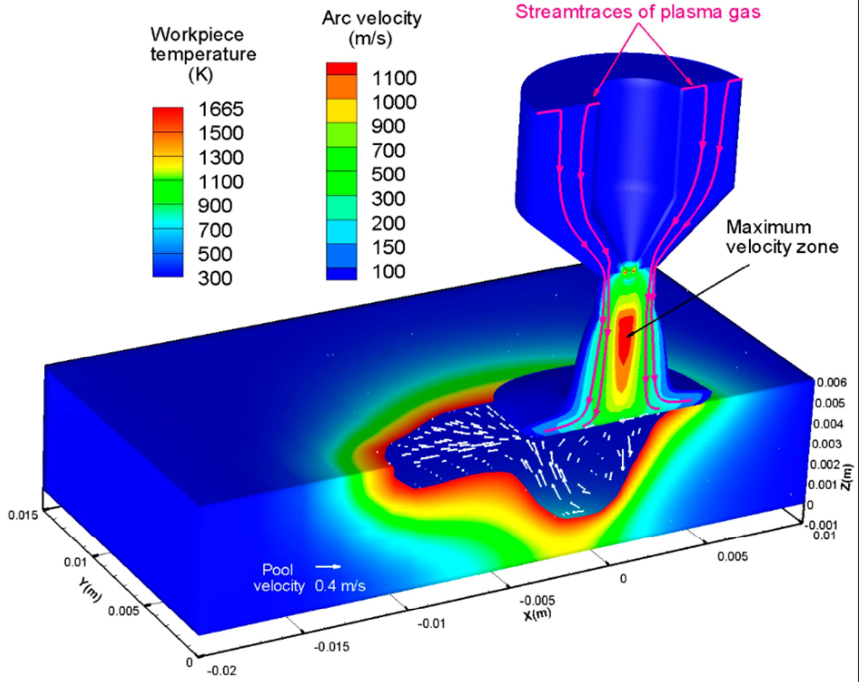
- Sodium arc lamps – only scalable source of large-area lighting before the recent scaling of LEDs. **Low ionization potential of sodium and pleasant emission current made them the most energy efficient source of lighting until ca 2020**

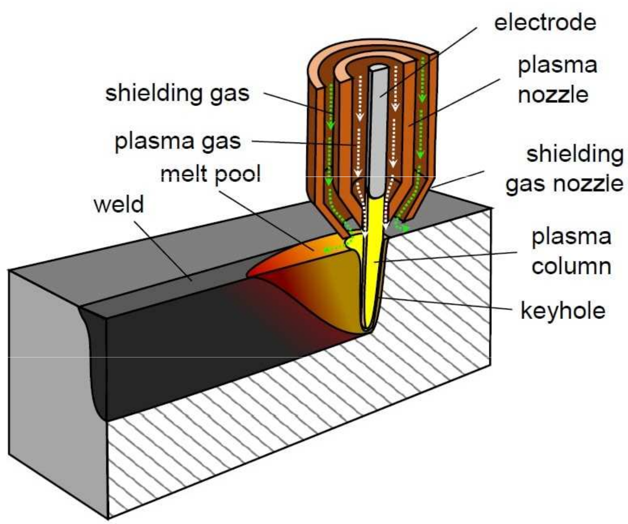
- Xenon arc lamps for automotive applications – also surpassed by LEDs.

- HID lamps (high-intensity discharge) – typically operated in mercury vapors with dopants. But mercury does not produce UV, it **emits through blackbody radiation**.

Application – Welding

- Plasma welding is probably the most widely used application of arcs.
- Apart from regular welding machines that you can find in every dad’s garage, there are highly specialized devices for industrial use.
- These devices typically combine arc cathode with the welded piece as an anode and there is active gas flow through the cathode.
- **Enables high-precision welding and joining.**





Application – Circuit breakers

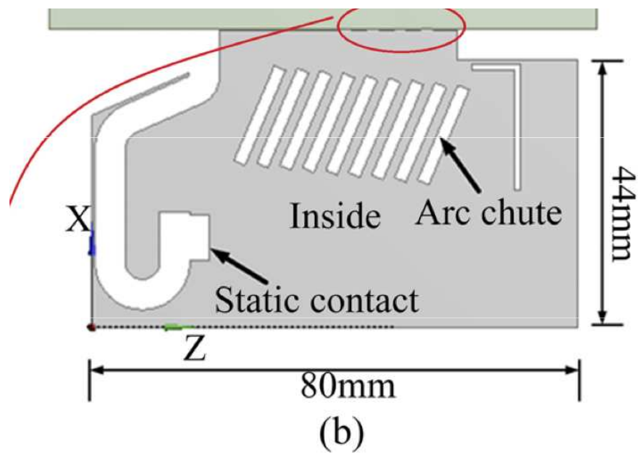
– If a high-power circuit is disconnected, there is a lot of energy that needs to be dissipated.

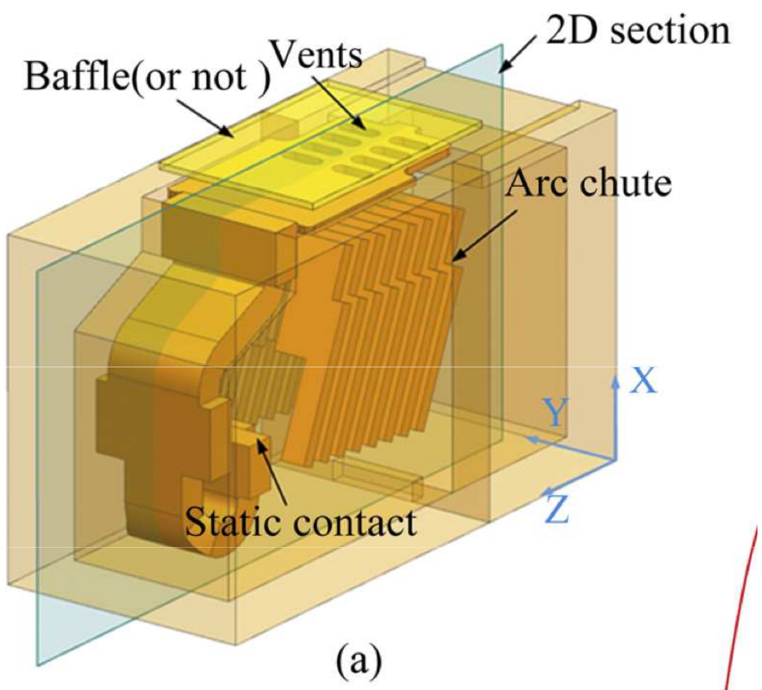
– That energy can be dissipated into forming a plasma discharge.

– Obviously, the discharge is parasitic, unwanted => people use gases which are really bad for generating plasma. **Typically SF6**

– These gases are called “electronegative” gases, because they prefer to form negative ions rather than positive.

– **In Prague, there is a big research centre of EATON working on these – job opprotunity.**





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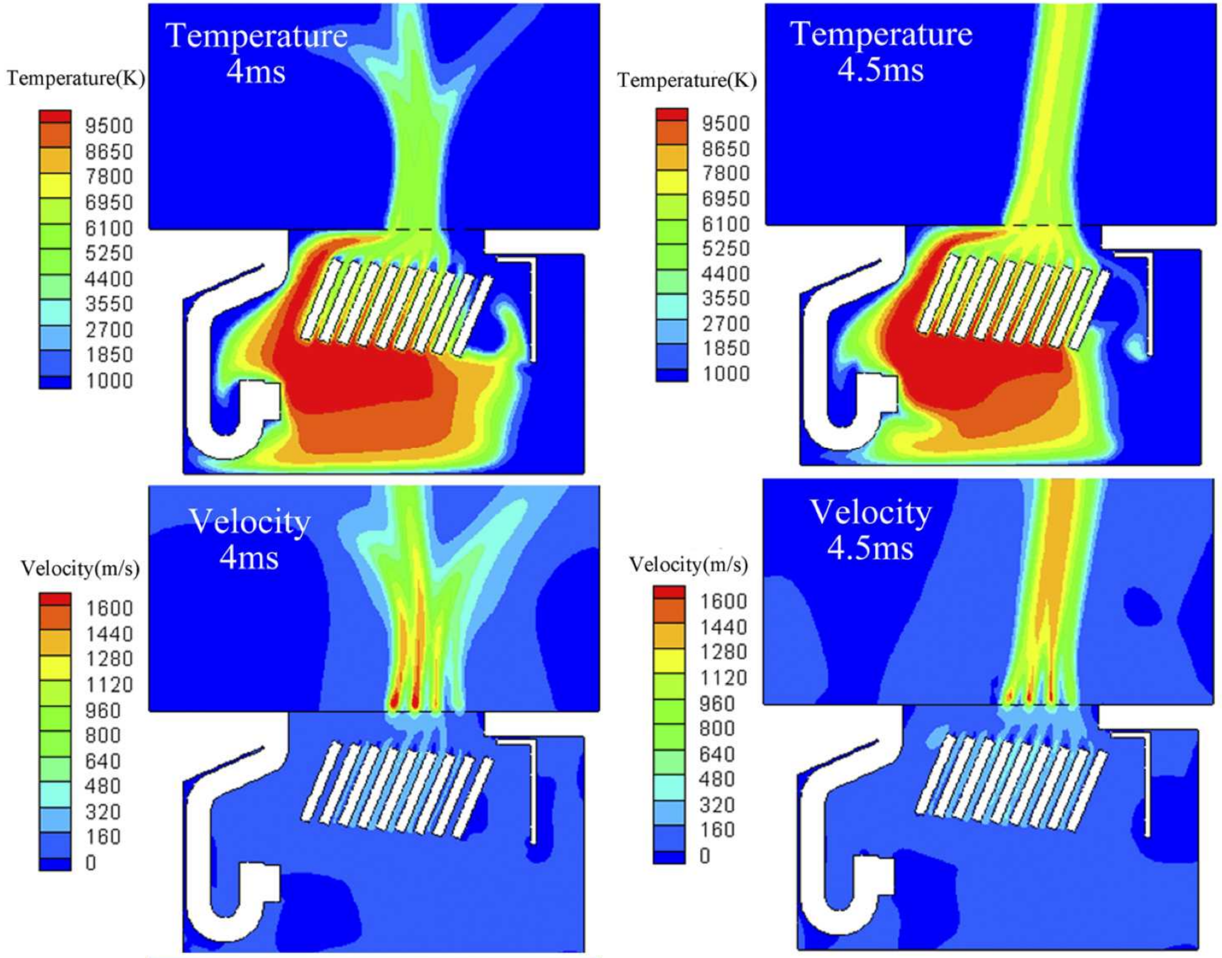
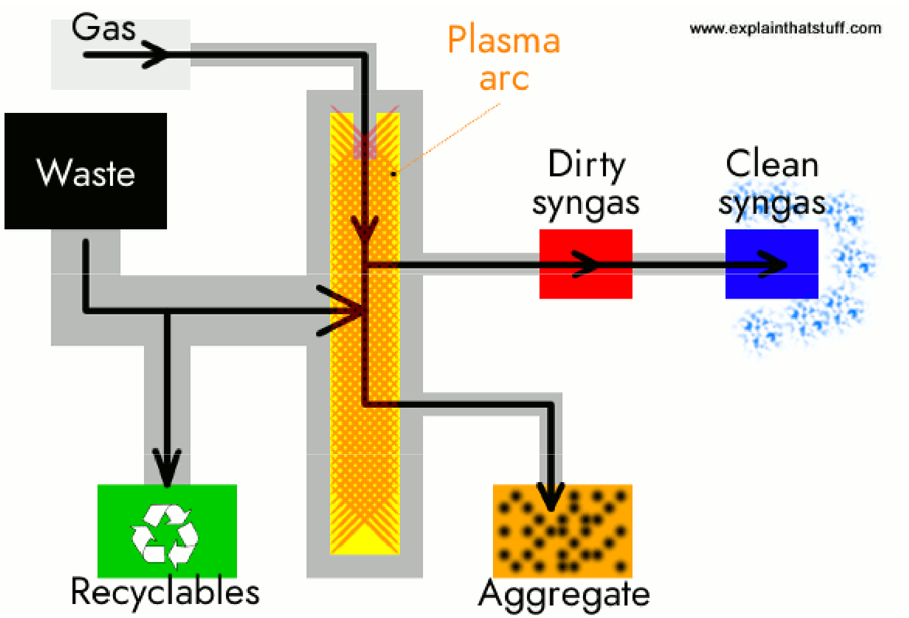
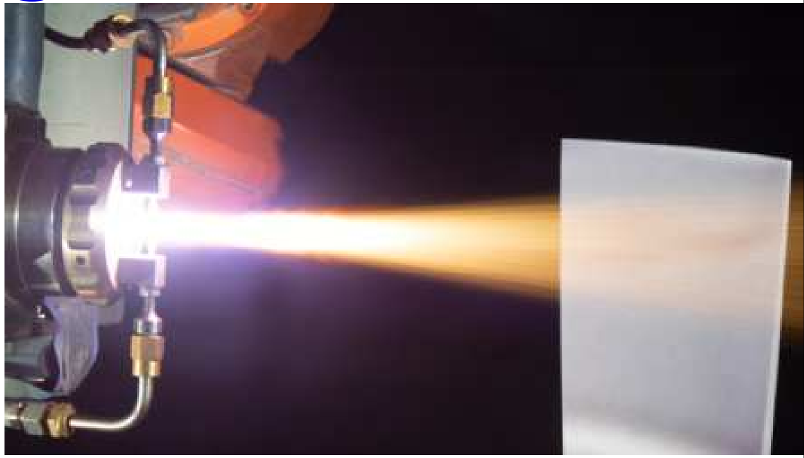


Application – Plasma Catalysis

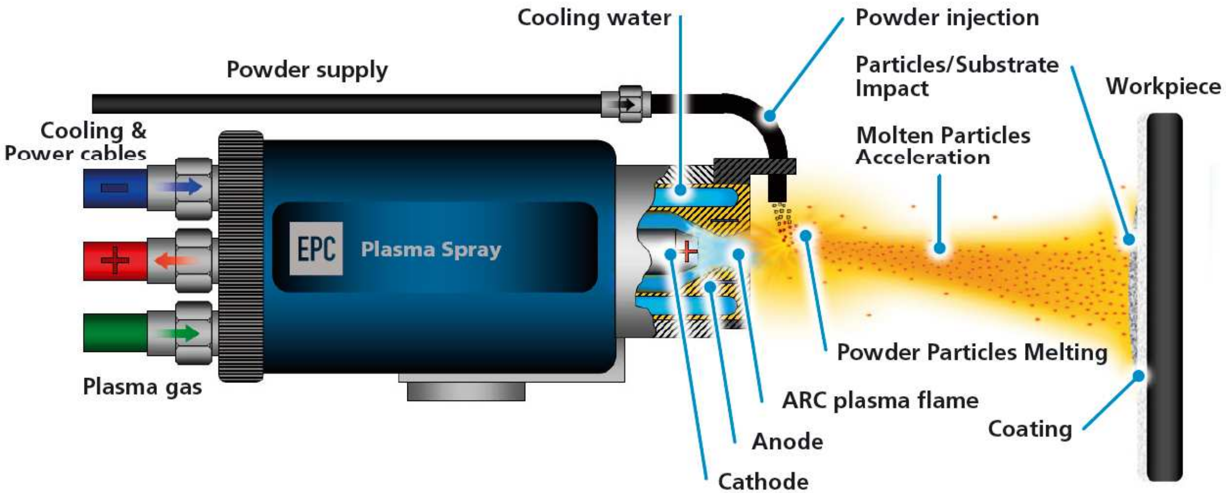
- Plasma catalysis is an emerging “green” application. Where not only arc plasmas ar used.
- The idea is converting waste gases to value-added chemicals, e.g. converting CH_4 from biomass to H_2 or converting CO_2 to syngas, that can be re-used as fuel.
- **Arc plasmas are used rather often in this type of projects because of their scalability, fast switching times, robustness, and off-the-shelf availability**.



Application – Plasma Spraying



- Extremely important in all mechanical industries
- Solid microparticles melted or evaporated in the plasma and deposited onto substrates to form hard / low friction / thermal barrier coatings.
- This is used especially for jet engine turbine blades or for mechanically stressed components in power generation applications.
- Alternative/parallel to low pressure PVD – **plasma spraying is much faster but produces much "dirtier" and rougher materials.**



Take aways

- Mechanisms of arc plasma formation
- Surface phenomena – thermoemission and field emission and what they depend on.
- Properties of an arc discharge
- Modeling strategies for high power LTE arcs – Saha, Ellenbaas-Heller, non-linear thermodynamic properties.
- Overview of applications

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