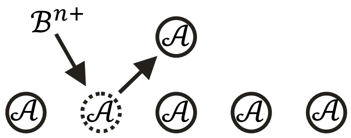
Ion Creation and –Confinement

Ion Creation

- supply neutral atoms $\mathcal{A}$ by:
  - injection of gas
  - vaporing
  - sputtering, i.e. bombard surface with other ion species $\mathcal{B}^{n+}$



- collide atoms with photons or electrons e^-

$$\begin{matrix} e^- & & & & \mathcal{A}^+ + e^- + e^- & \text{, most efficient} \\ \text{or} & \longrightarrow & \mathcal{A} & \longrightarrow & & \\ \gamma & & & & \mathcal{A}^+ + e^- & \text{, creates free } e^- \end{matrix}$$

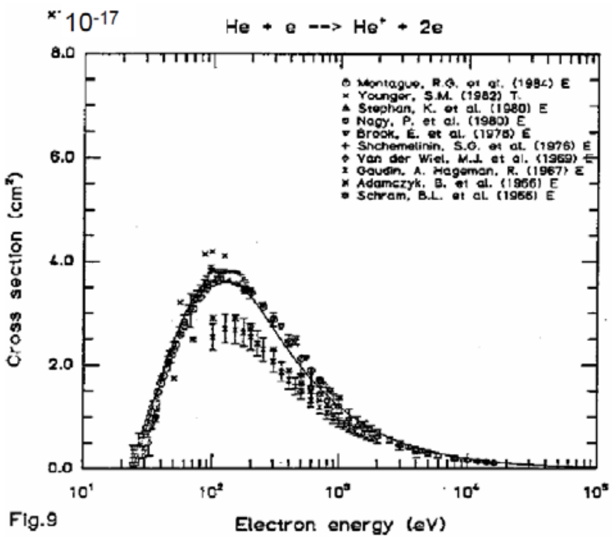
cross section of e^-- impact ionization (Lotz - formular):

$$\sigma_{\Delta q=1} = 4.5 \cdot 10^{-14}\ (\text{eV cm})^2 \cdot \sum_{i=1}^{N} \frac{ln[E_{kin}/P_i]}{E_{kin} \cdot P_i}$$

$E_{kin} = e^-$ kin. energy

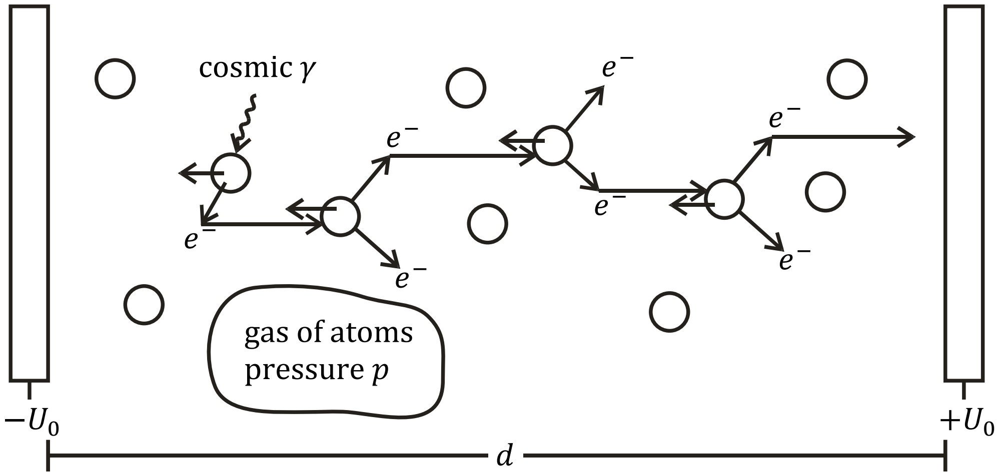
P_i = ionisation energy for e^- in orbit i

Single-ionisation: He + e → He⁺ + 2e



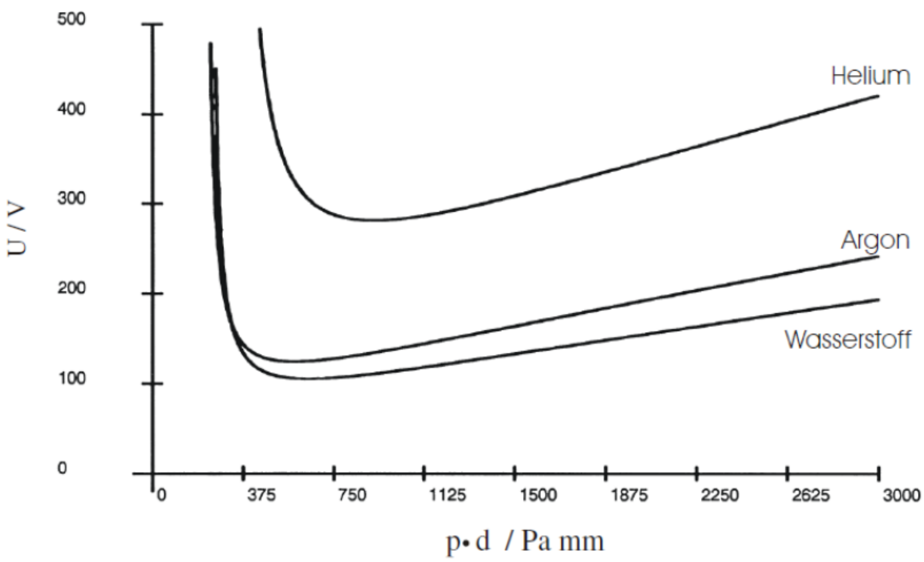
Ion Sources

Electron & Ion Production by controlled Discharge



if p & d are properly chosen
→ contineous e^- & ion production

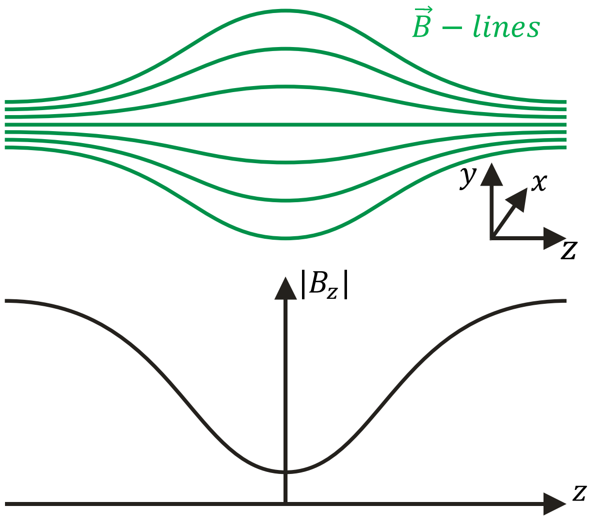
condition for discharge ignition (Paschen curve)



Ion (Plasma) Confinement

- without confinement ions & e^- move towards electrodes and get lost
- higher ion intensities require to confine ions inside "production" volume
- confinement by magnetic bottle:

Ion Sources



$$\frac{{v_x}^2 + {v_y}^2}{|B_z|} = \text{const}$$

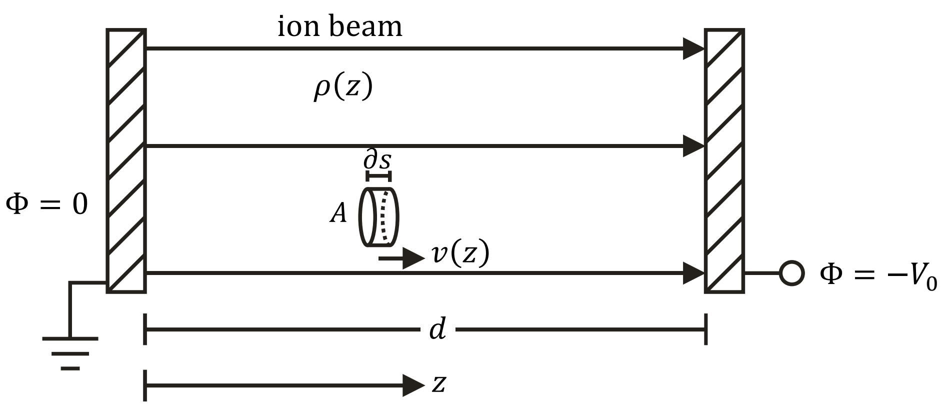
(see Jackson "class el. dyn.")

$${v_{tot}}^2 - {v_z}^2 = |B_z| \cdot \text{const}$$

$${v_z}^2 = \frac{2}{m} E_{kin} - |B_z| \cdot \text{const}$$

$\rightarrow |B_z| > B_c \rightarrow$ ion reflection along z-axis

Extraction of ions from planar surface



$$I(z) = \frac{\partial q}{\partial t} = \frac{\rho(z) \cdot A \cdot \partial s}{\partial t} = \text{const!}$$

$$\frac{I}{A} := J = \rho(z) \cdot v(z) = \rho \cdot \dot{z} = \text{const!} \quad (*)$$

$$\Rightarrow \underline{\frac{\partial J}{\partial z} = 0} \quad \text{continuity equation} \quad (1)$$

$$\vec{\nabla}\vec{E} = \frac{\rho}{\varepsilon_0}, \quad \vec{E} = -\vec{\nabla}\Phi$$

$$\Rightarrow \underline{\Delta\Phi = \frac{\delta^2\Phi}{\delta z^2} = -\frac{\rho}{\varepsilon_0}} \quad \text{Poisson equation} \quad (2)$$

$$\underline{\frac{m}{2}\dot{z}^2 = -q\Phi(z)} \quad \text{energy preservation} \quad (3)$$

$$\Rightarrow \frac{\delta^2\Phi}{\delta z^2} = \Phi'' = -\frac{\rho}{\varepsilon_0} \overset{(*)}{=} -\frac{1}{\varepsilon_0} \cdot \frac{J}{\dot{z}} \overset{(3)}{=} \frac{J}{\varepsilon_0}\sqrt{\frac{m}{2q}} \cdot \frac{-1}{\sqrt{-\Phi}} \quad \Big| \int(\ )\Phi'\,\delta\Phi$$

$$\frac{\delta^2\Phi}{\delta z^2} := \Phi'' = \frac{J}{\varepsilon_0}\sqrt{\frac{m}{2q}} \cdot \frac{-1}{\sqrt{-\Phi}}$$

$$\Phi'^2 = \frac{4J}{\varepsilon_0}\sqrt{\frac{m}{2q}}\sqrt{-\Phi} + C$$

$$\Phi(z=0) = 0\,,\ \Phi'(z=0) = 0 \quad \rightarrow \quad C = 0$$

$$\Phi' = 2\sqrt{\frac{J}{\varepsilon_0}}\sqrt[4]{\frac{m}{2q}} \cdot \sqrt[4]{-\Phi}$$

$$-\frac{4}{3}(-\Phi)^{3/4} = 2\sqrt{\frac{J}{\varepsilon_0}} \cdot \sqrt[4]{\frac{m}{2q}} \cdot z \qquad (a)$$

$$\Phi(z=d) = -V_0$$

$$\Longrightarrow\ -\frac{4}{3}{V_0}^{3/4} = 2\sqrt{\frac{J}{\varepsilon_0}} \cdot \sqrt[4]{\frac{m}{2q}} \cdot d \qquad (b)$$

from $\frac{(a)}{(b)} \Longrightarrow \Phi(z) = -V_0\left(\frac{z}{d}\right)^{4/3}$

$$\Longrightarrow \boxed{J = \frac{4}{9}\varepsilon_0\sqrt{\frac{2q}{m}} \cdot \frac{{V_0}^{3/2}}{d^2}}$$ **Child-Langmuir Law** of space charge limited extraction

- used simplification of planar plates (electrodes)
- real electrodes:
  - are curved
  - have beam holes (extraction electrode @ -V_0)

→ real currents may be lower (ions)

but scaling law $J \sim {V_0}^{3/4} \cdot d^{-2}$ holds

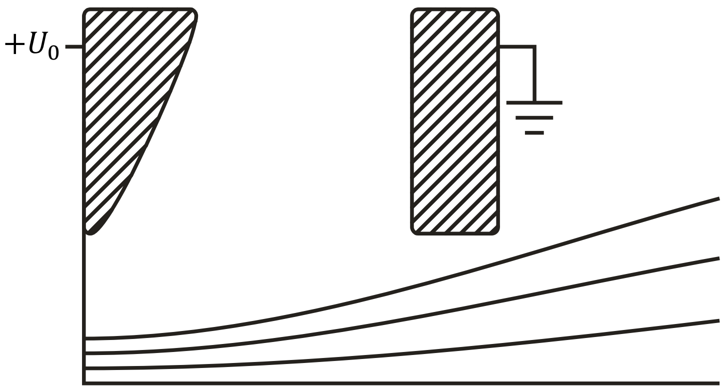
$I = A \cdot J := P \cdot \frac{A_{\text{cathode}}}{d^2} \cdot V^{3/2}$, P is "Perveance"

$P(\text{Child-Langmuir}, e^-) = 2.33 \cdot 10^{-6}\ \frac{A}{V^{3/2}} := 2.33\ \mu\text{Perv}$

<u>ion–energy and –current are coupled!</u>

extraction with one electrode is called "diode" extraction
"di" ≙ 2 → 1. emitting electrode, 2. grounded electrode

diode extraction:



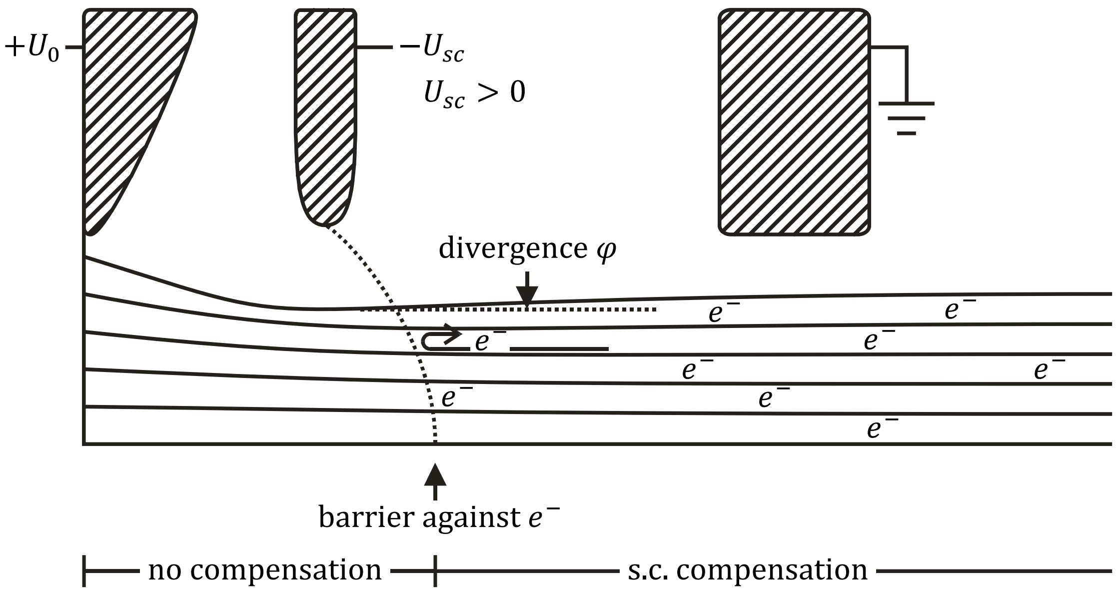
- I and E_{kin} are coupled, i.e. can't be set independently
- beam has strong repulsing self forces, called space charge (s.c.) forces
- space charge decreases beam quality (causes beam divergence)

beam ions collide with neutral residual gas atoms → e^- creation

- e^- reduce s.c.
- but e^- are pulled towards emitter → e^- are removed from beam
  → s.c. is re-installed

Triode Extraction:

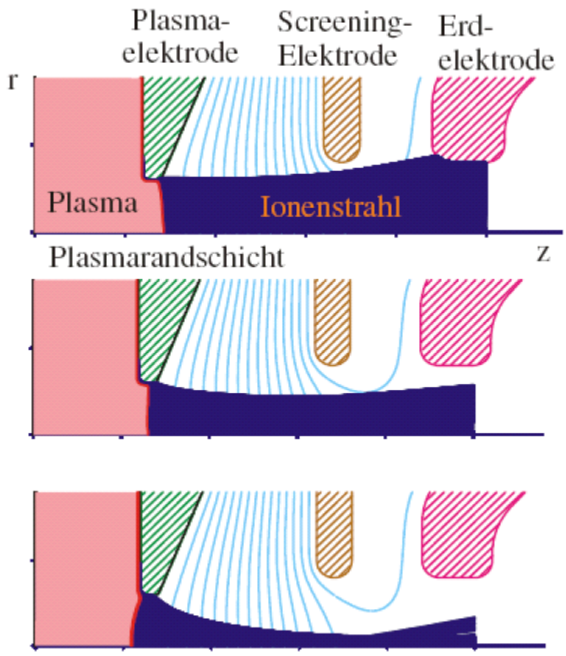
insert a screening (sc) electrode that keeps e^- off from emitter



- beam current from $U_0 - (-U_{sc}) = U_{ext,eff}$; effective extraction voltage
- beam energy from $U_0 - 0 = U_0$

measure for beam quality:

- beam envelope divergence angle φ at e^--barrier
- φ minimized → matched case, $\varphi = \varphi(U_0, U_{sc})$



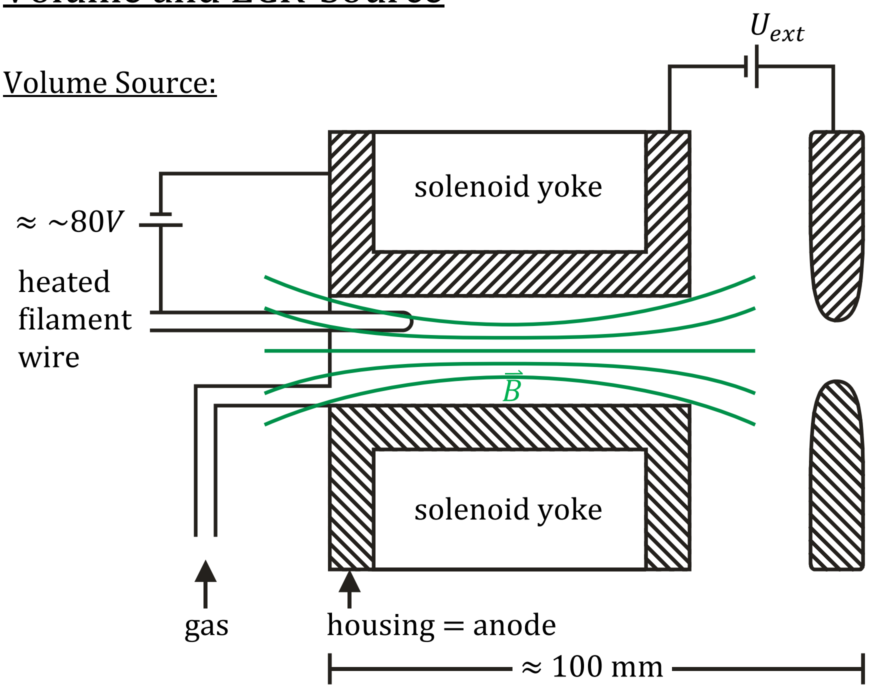
U_{ext} too low

U_{ext} ok, matched

U_{ext} too high

Volume and ECR-Source

Volume Source:



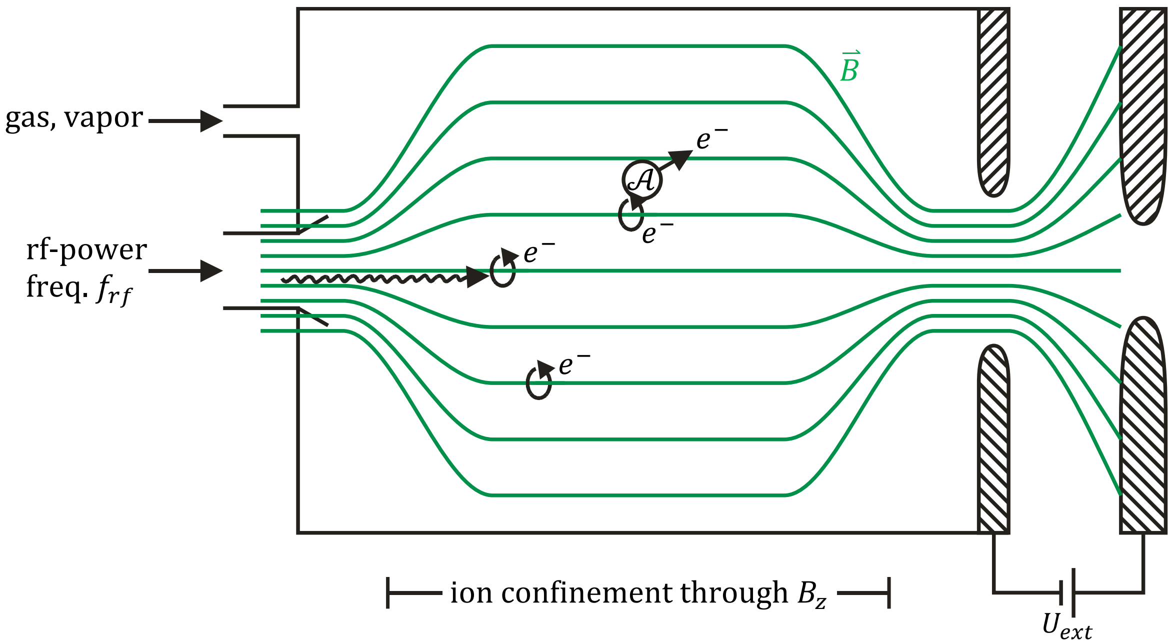
Ions: H^+, D^+

I: ≈ some 100 mA

B_{sol}: ≈ 0.02 T

- filament provides free e^- for discharge
- solenoid field guides electrons

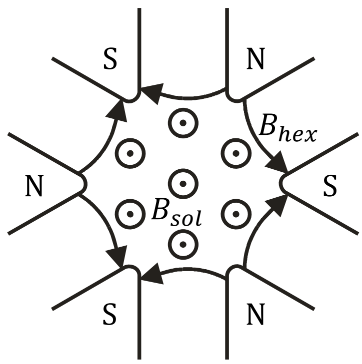
Electron-Cyclotron-Resonance (ECR) Source:



- rf-photons are absorbed by few free e^-
- absorbtion just if photon-frequency equal to cyclotron-frequency of e^- around field lines:

  $e \cdot v \cdot B_z = m_e \cdot \frac{v^2}{R} = m \cdot \omega_c \cdot v \quad \Longrightarrow \quad \underline{\omega_c = \frac{e \cdot B_z}{m_e} \stackrel{!}{=} 2\pi f_{rf}}$

- repeated absorbtion by same e^- increases its E_{kin}
- e^- can ionize atoms to high charge states and create additional free e^-
- for intermediate and heavy mass ions → additional hexapole-field for confinement



transverse hexapole-fields
improve confinement