Vacuum II

G. Franchetti

CAS - Bilbao

Index

Creating Vacuum (continuation)

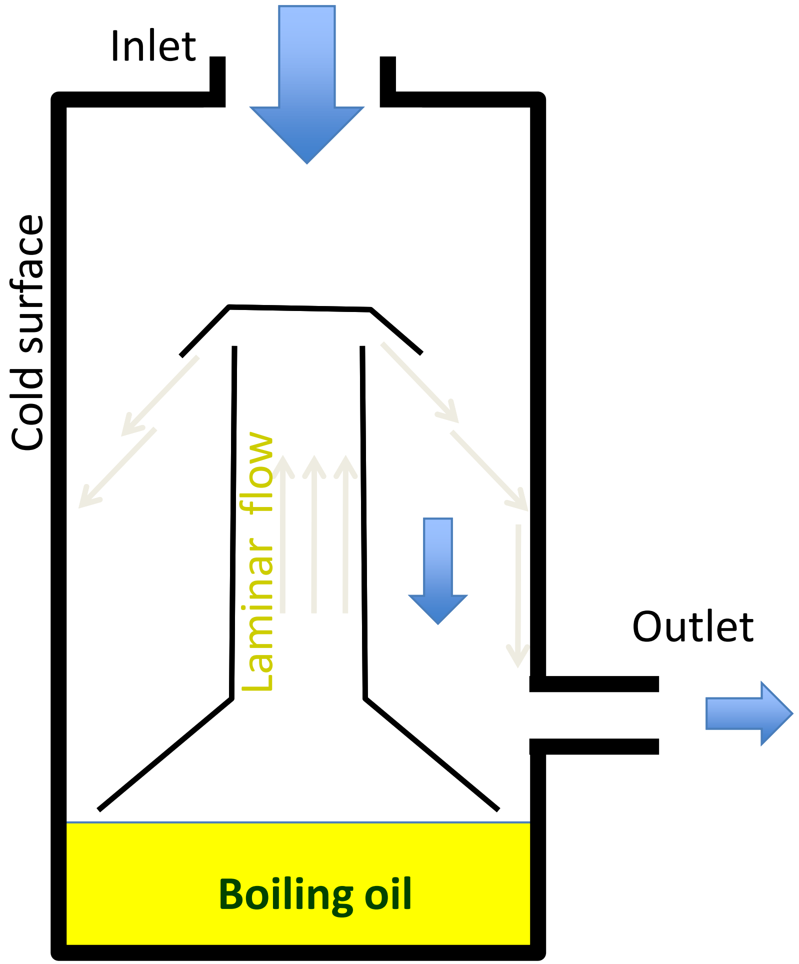
Measuring Vacuum

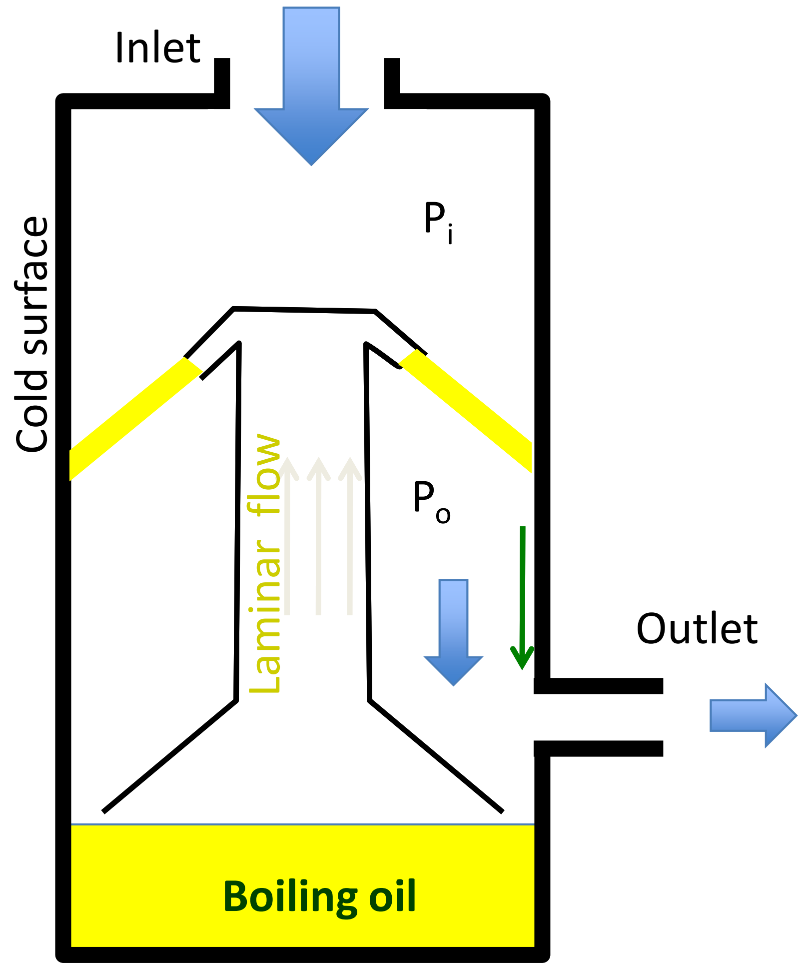
Partial Pressure Measurements

Diffusion Ejector pump

Schematic of the pump

operating pressure: $10^{-3} - 10^{-8}$ mbar

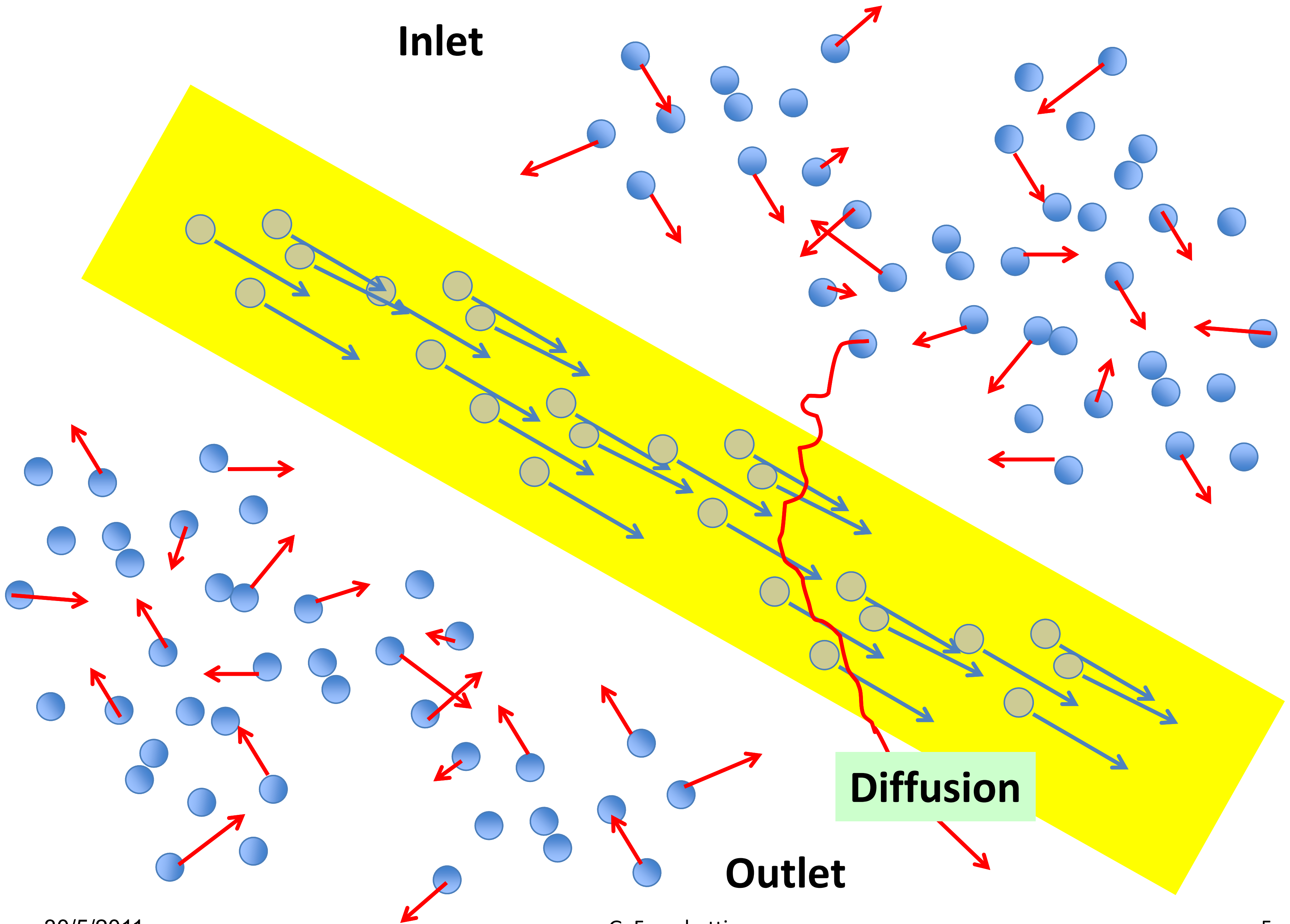




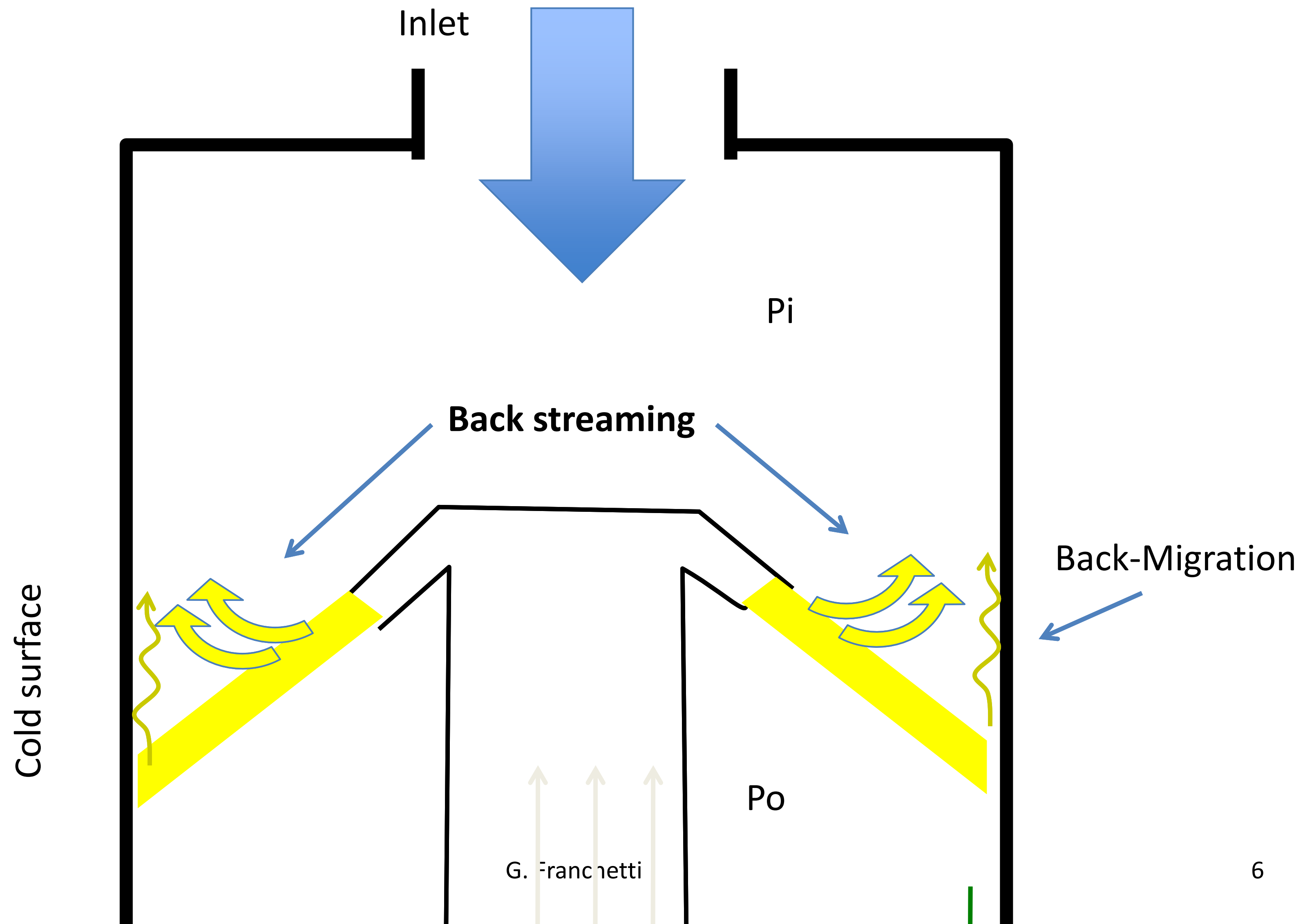
Pump principle:

The vacuum gas diffuses into the jet and gets kicked by the oil molecules imprinting a downward momentum

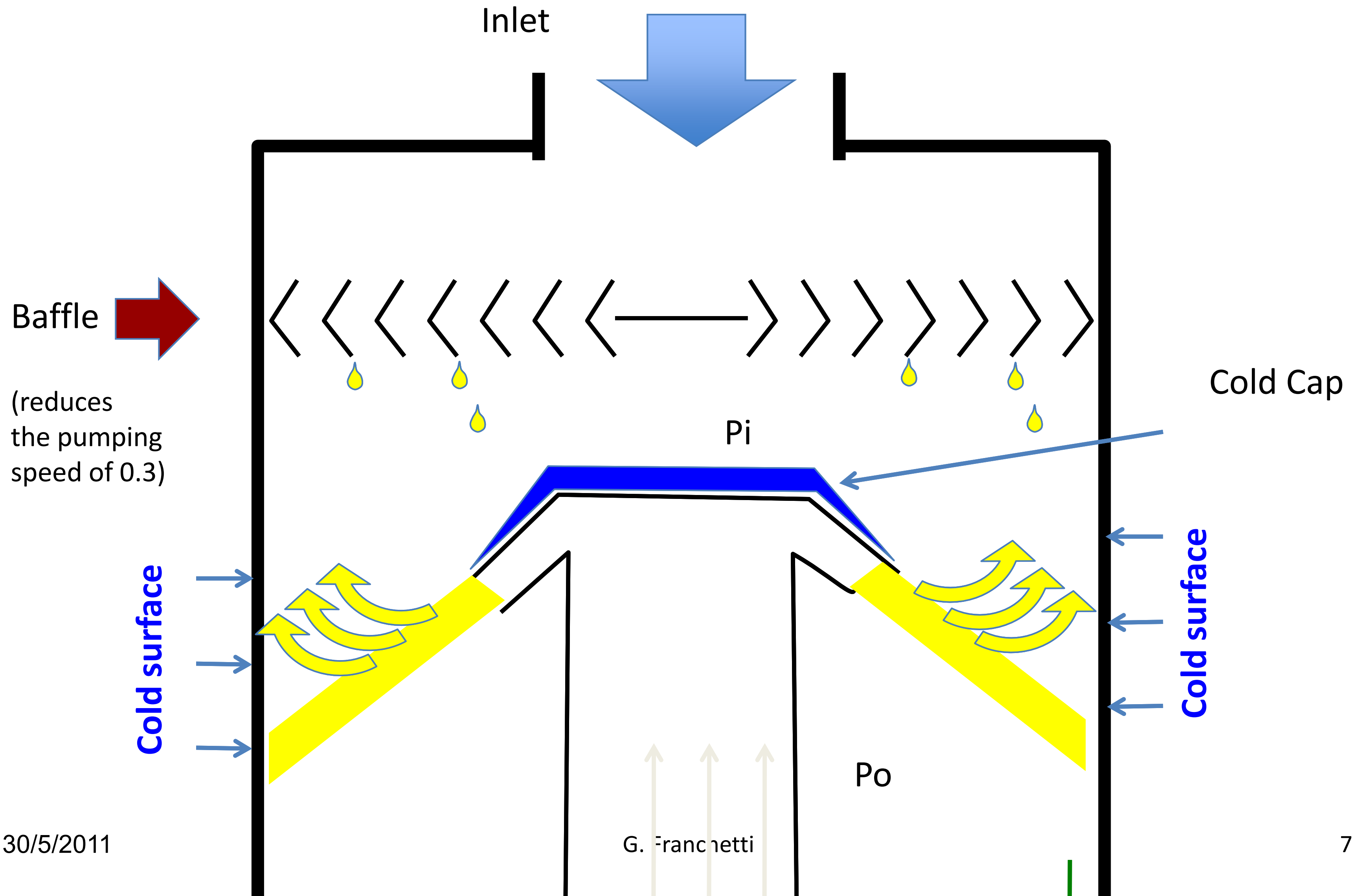
The oil jets produces a skirt which separate the inlet from the outlet


Inlet
Diffusion
Outlet

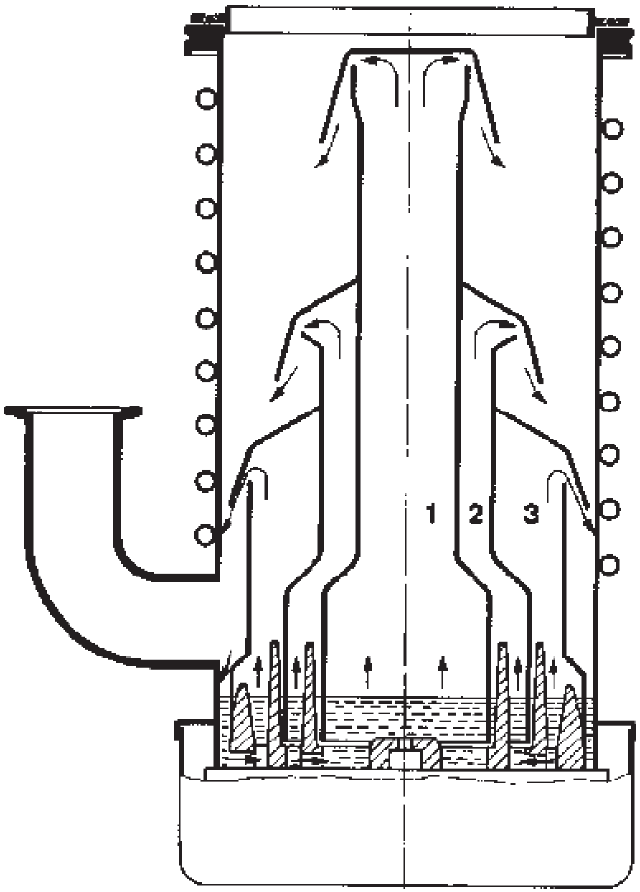
Problems



Cures



Inlet
Baffle
(reduces
the pumping
speed of 0.3)
Pi
Cold Cap
Cold surface
Cold surface
Po

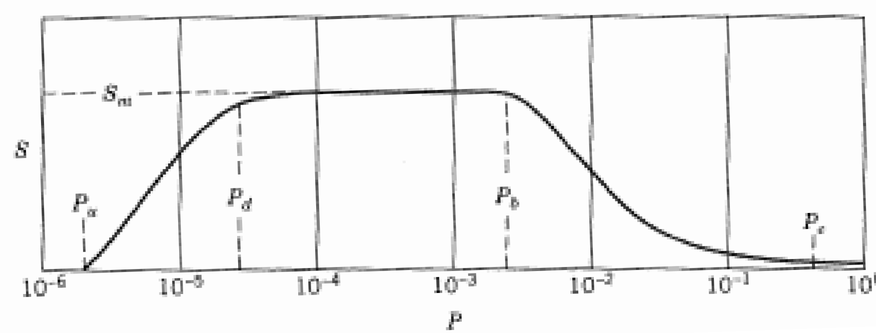


LEYBOLD (LEYBODIFF)

with $p_u \sim 10^{-6}\,\mathrm{mbar}$

The pumping speed S_m is proportional to the area of the inlet port

100 mm diameter → S_m = ~ 250 l/s for N_2



Capture Vacuum Pumps

Principle

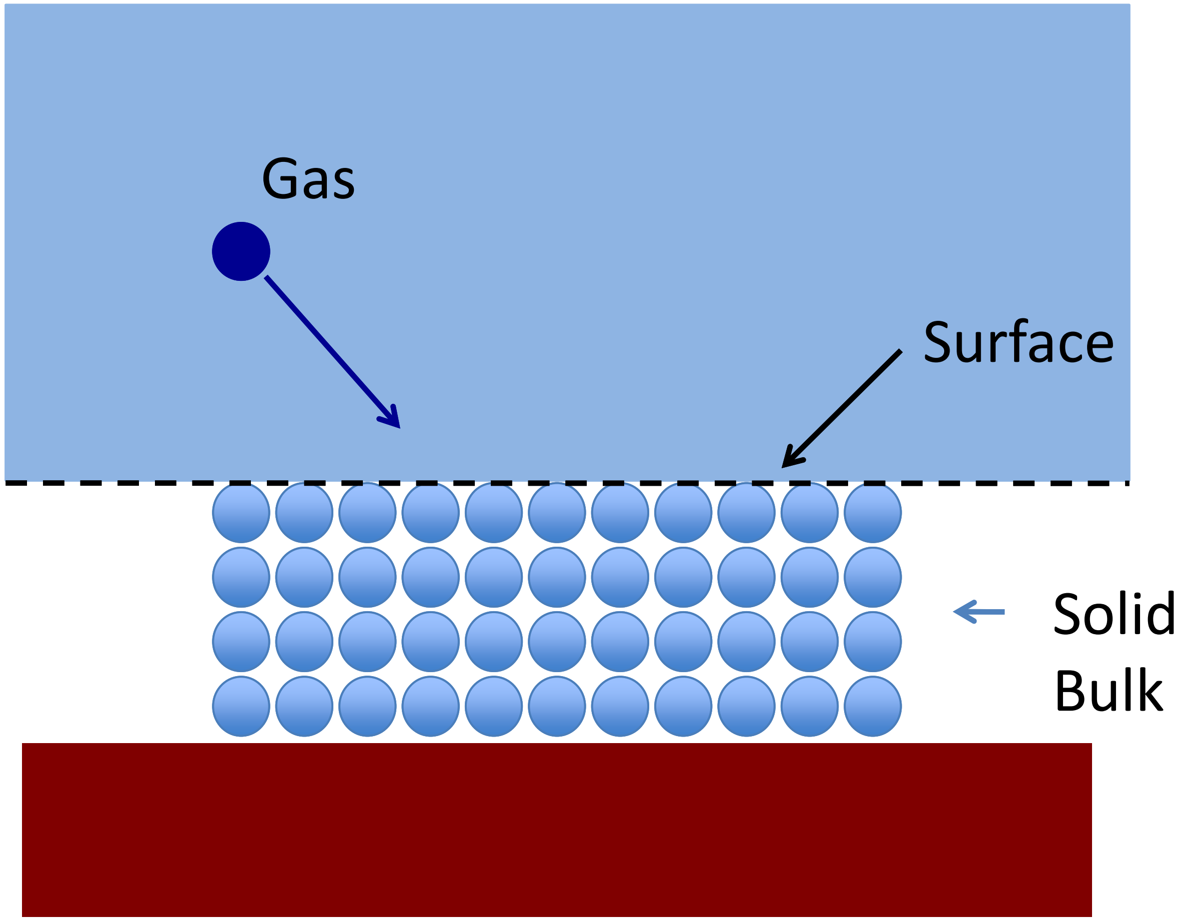
Capture vacuum pumps are based on the process of capture of vacuum molecules by surfaces

Getter Pumps
(evaporable, non-evaporable)

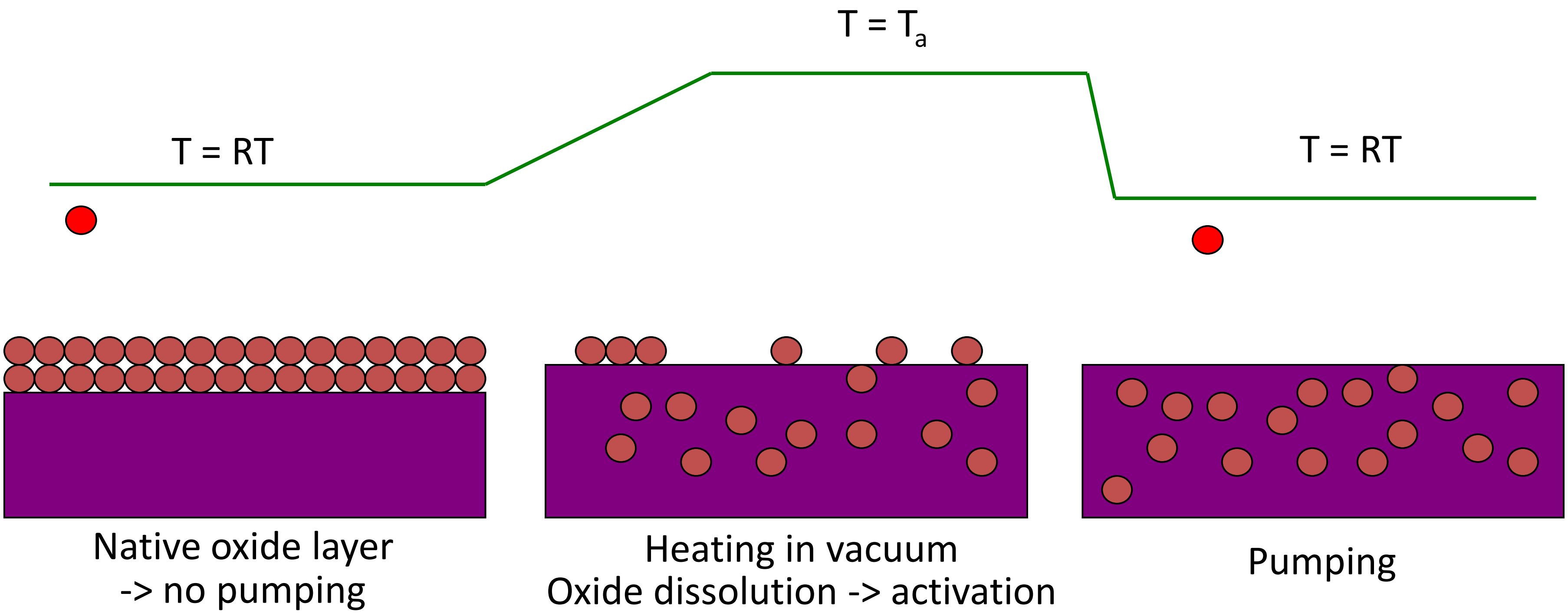
Sputter ion Pumps

Cryo Pumps

Getter Pumps



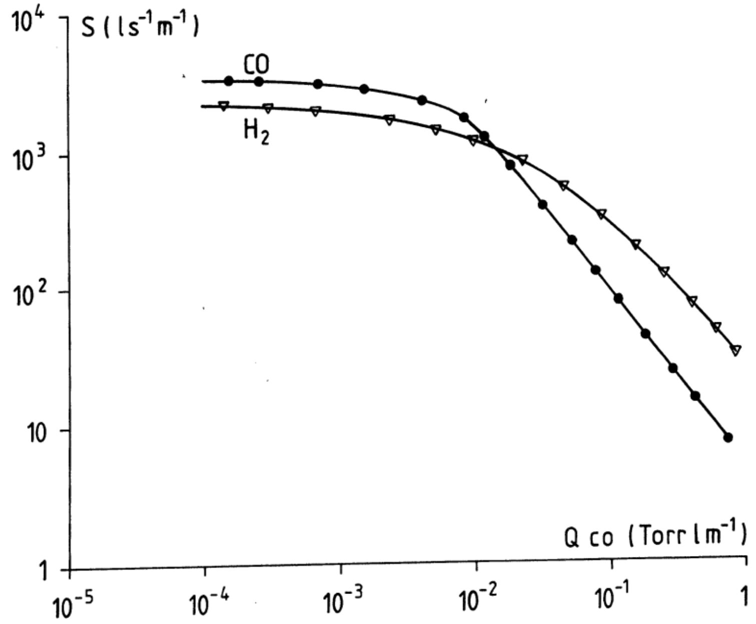
Getters are materials capable of chemically adsorbing gas molecules. To do so their surface must be clean. For Non-Evaporable Getters a clean surface is obtained by heating to a temperature high enough to dissolve the native oxide layer into the bulk.



P. Chiggiato

NEGs pump most of the gas except rare gases and methane at room temperature

Sorption Speed and Sorption Capacity



C.Benvenuti, CAS 2007

Choice of the coating technique for thin film: **sputtering**

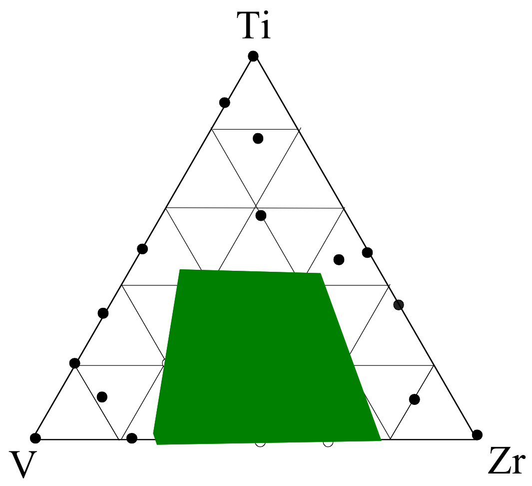
substrate to coat: ***vacuum chamber***

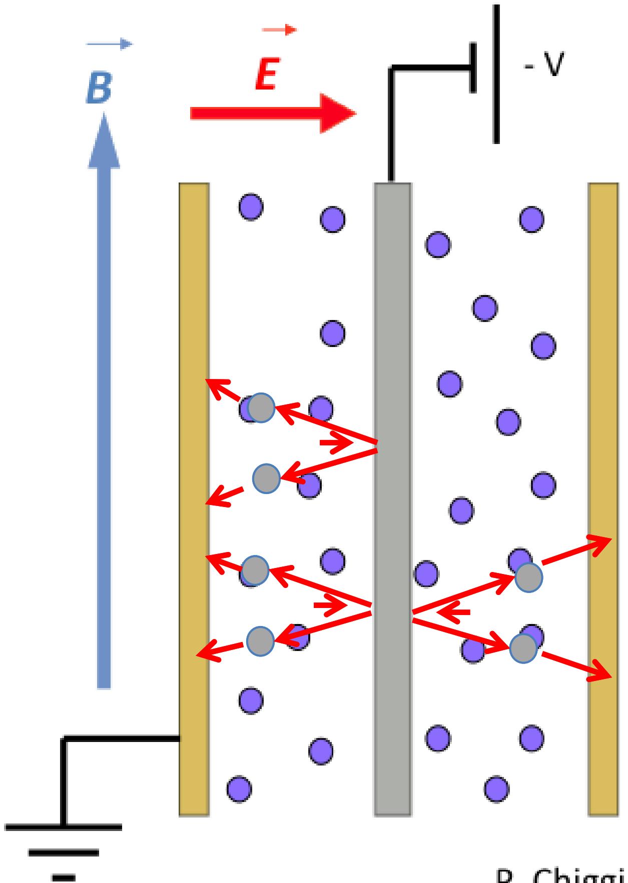
target material: ***NEG (cathode)***

driving force: ***electrostatic***

energy carrier: ***noble gas ions***

NEG composition





P. Chiggiato

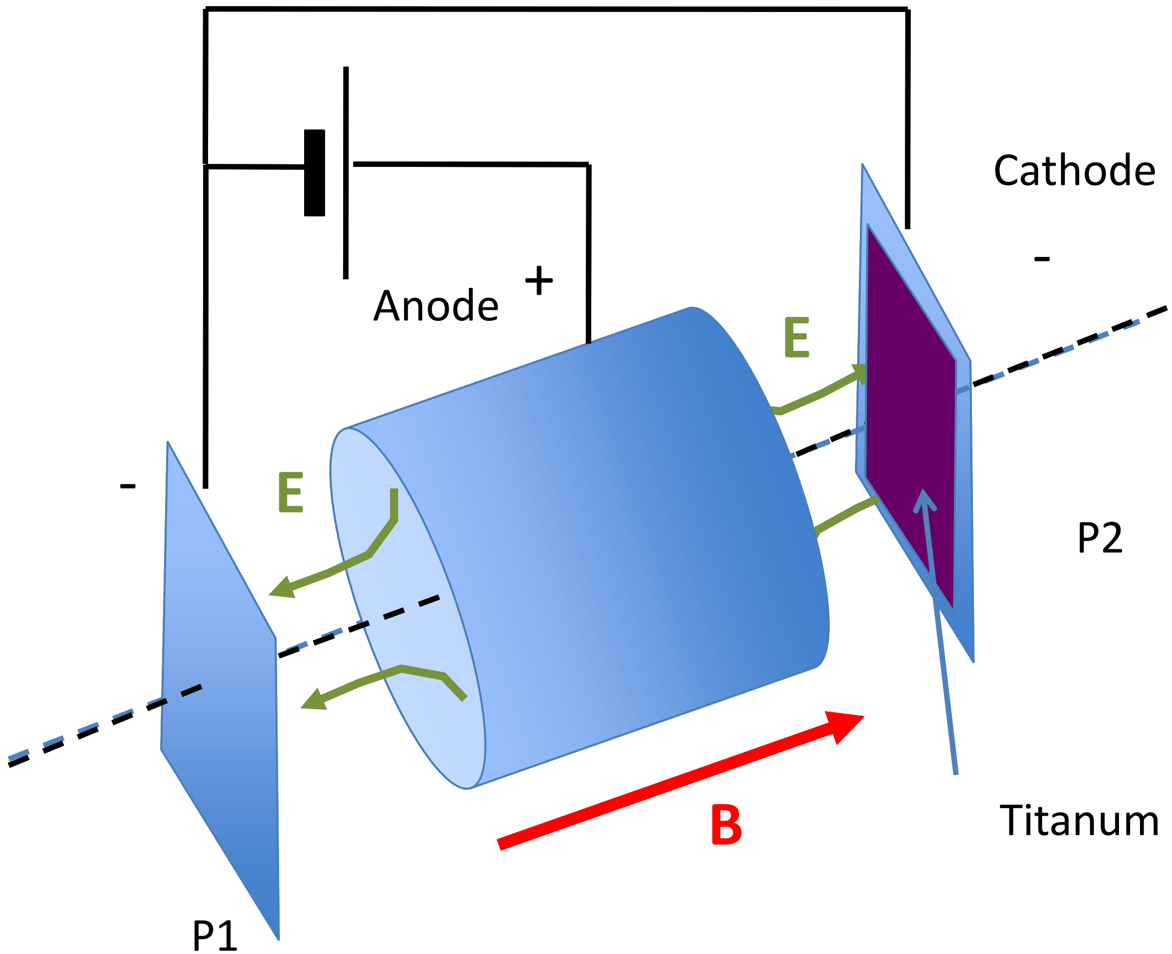
- The trend in vacuum technology consists in moving the pump progressively closer to the vacuum chamber wall.
- The ultimate step of this process consists of transforming the vacuum chamber from a gas source into a pump.
- One way to do this is by **"ex-situ" coating** the vacuum chamber with a NEG thin film that will be activated during the "in situ" bakeout of the vacuum system.

Dipole Coating Facility

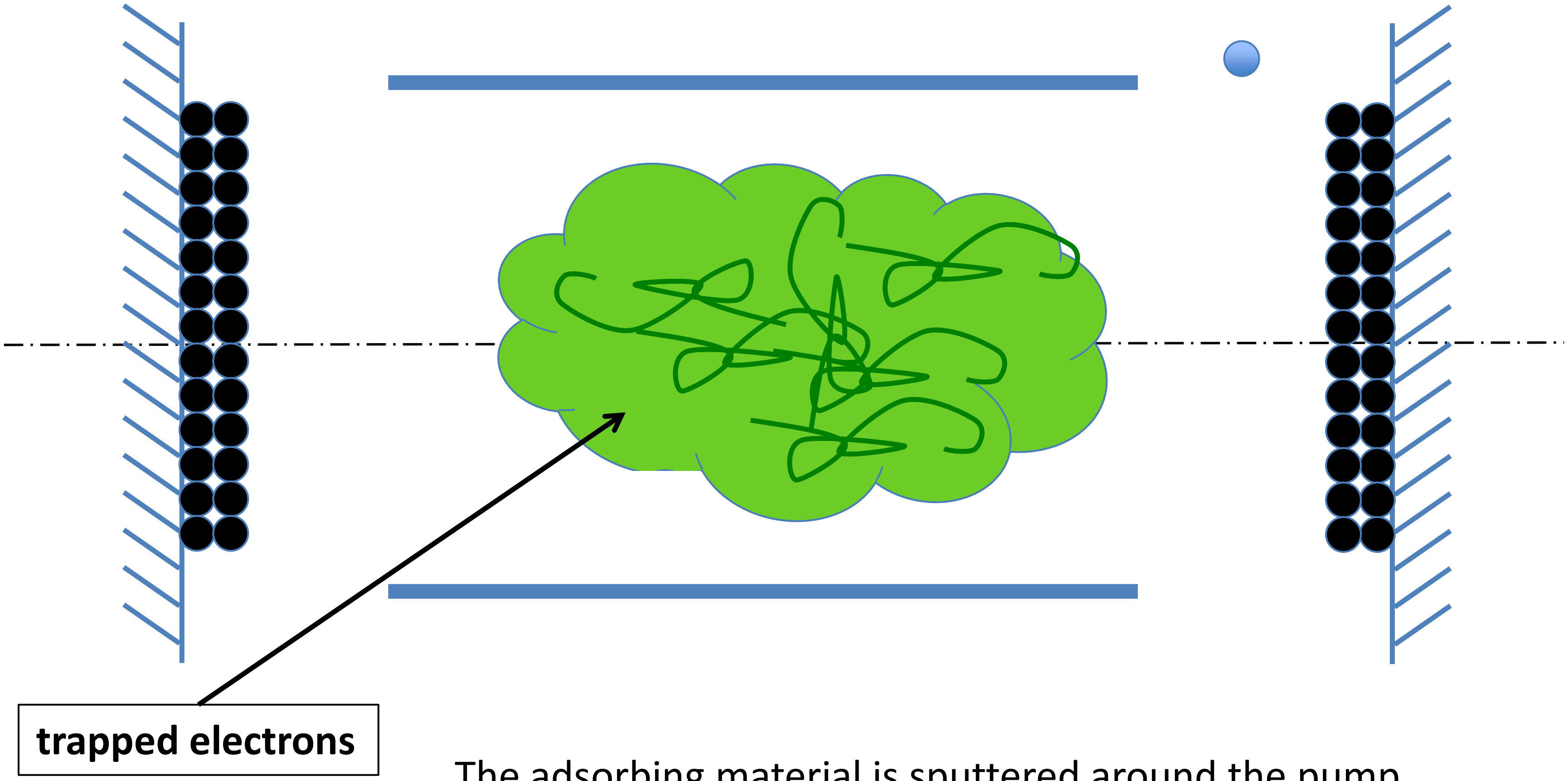
Quadrupole Coating Facility

M.C. Bellachioma (GSI)

Sputter ion pumps

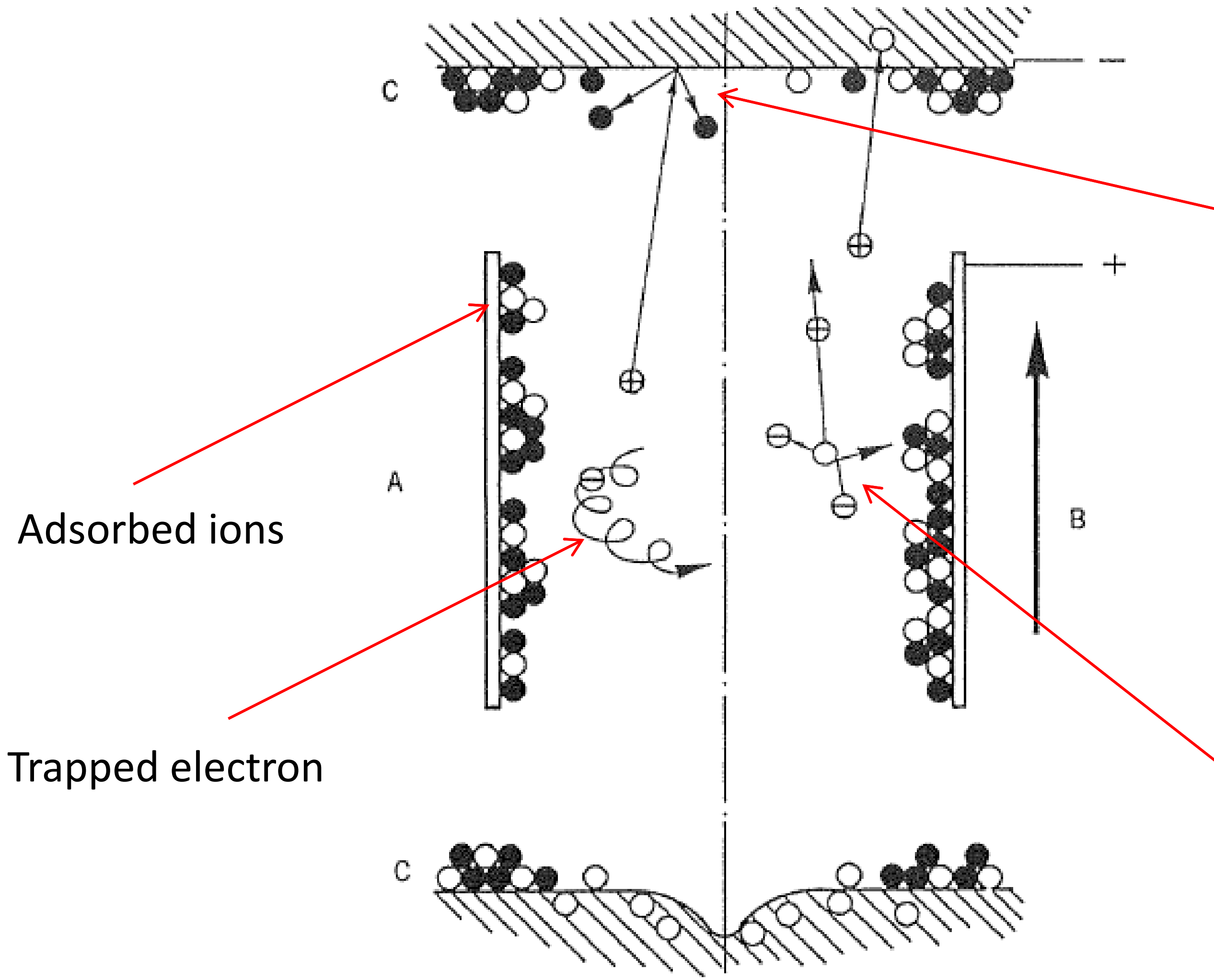


Sputtering process



The adsorbing material is sputtered around the pump

A glimpse to the complexity



Example of Pumping speed

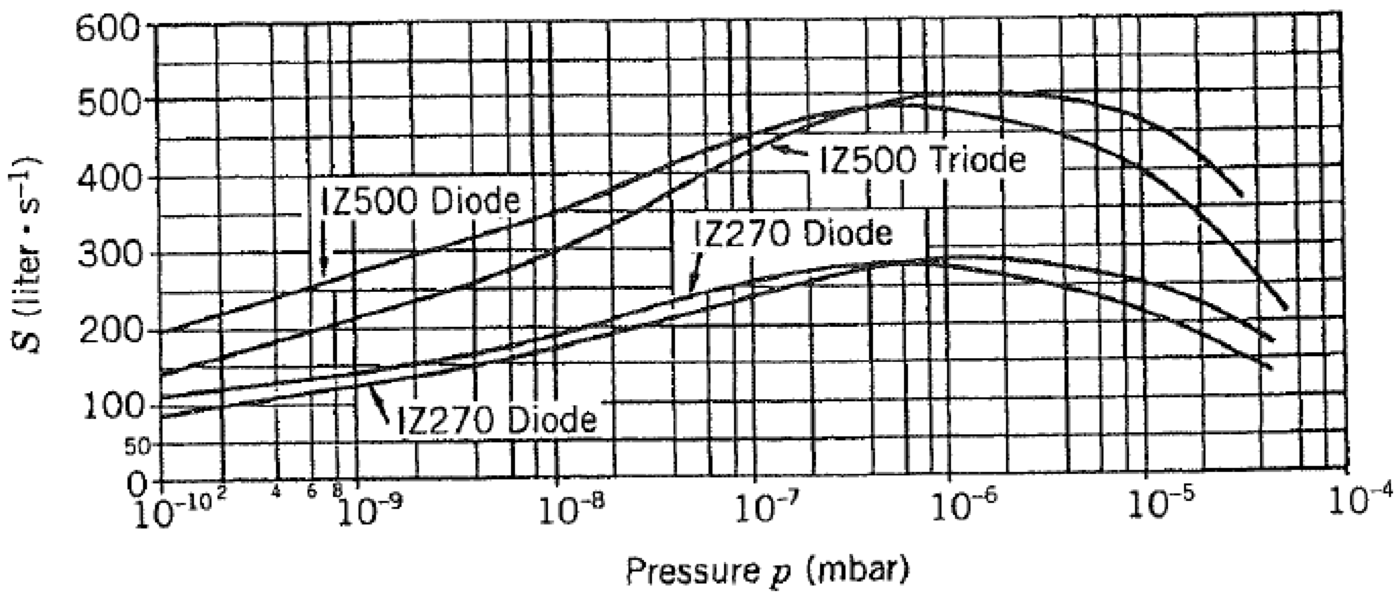
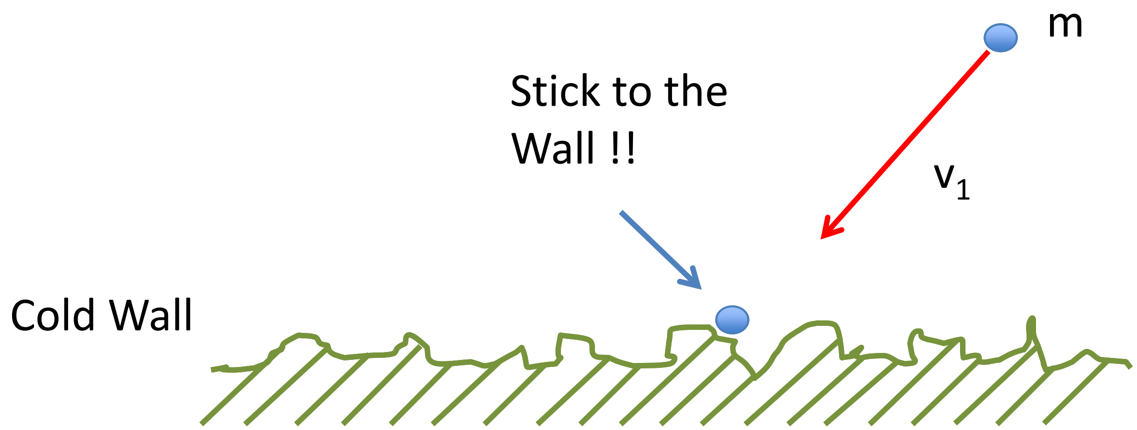


Fig. 5.67. Volume throughput (VTP) of sputter ion pumps for nitrogen as a function of pressure. IZ270 is a pump with nominal VTP, $S = 270$ liter·s^{-1}, diode and triode; IZ500 is a pump with nominal VTP, $S = 500$ liter·s^{-1}, diode and triode.

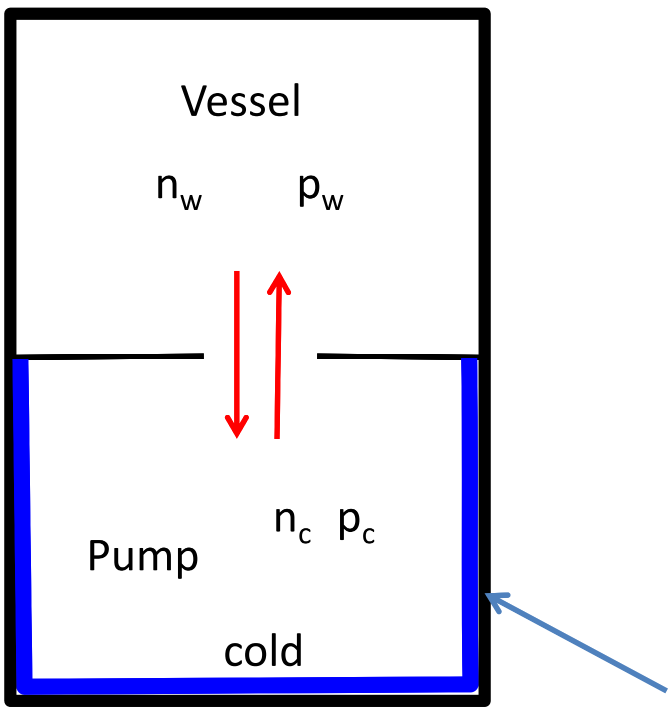
J.M. Laffterty, Vacuum Science, J. Wiley & Son, 1998

Cryo Pumps



Dispersion forces between molecules and surface are stronger then forces between molecules

Schematic of a cryo pump



P_w = pressure warm
P_c = pressure in the cold
I_w = flux Vessel → Pump
I_c = flux Pump → Vessel

Now $I_w = \frac{1}{4}\tilde{n}_w v_w A$ → By using the state equation → $I_w = \frac{P_w A}{4 k_B T_w} v_w$

In the same way → $I_c = \frac{P_c A}{4 k_B T_c} v_c$

If $I_c = I_w$ no pumping although $P_c \neq P_w$

Relation between pressures

Thermal Transpiration $\frac{P_c}{\sqrt{T_c}} = \frac{P_w}{\sqrt{T_w}}$

When the two pressures breaks the thermal transpiration condition a particle flow starts

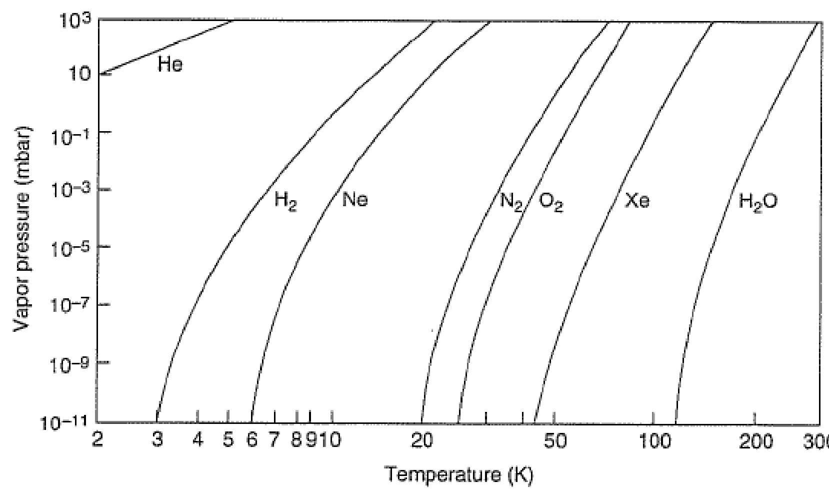
$$I_{net} = I_w - I_c = \frac{AP_w v_w}{4k_B T_w}\left[1 - \frac{P_c}{P_w}\frac{v_c T_w}{v_w T_c}\right]$$

We define $I_{max} = \dfrac{AP_w v_w}{4k_B T_w}$ and $P_w(ult) = P_c\sqrt{\dfrac{T_w}{T_c}}$

We find $I_{net} = I_{max}\left[1 - \dfrac{P_w(ult)}{P_w}\right]$

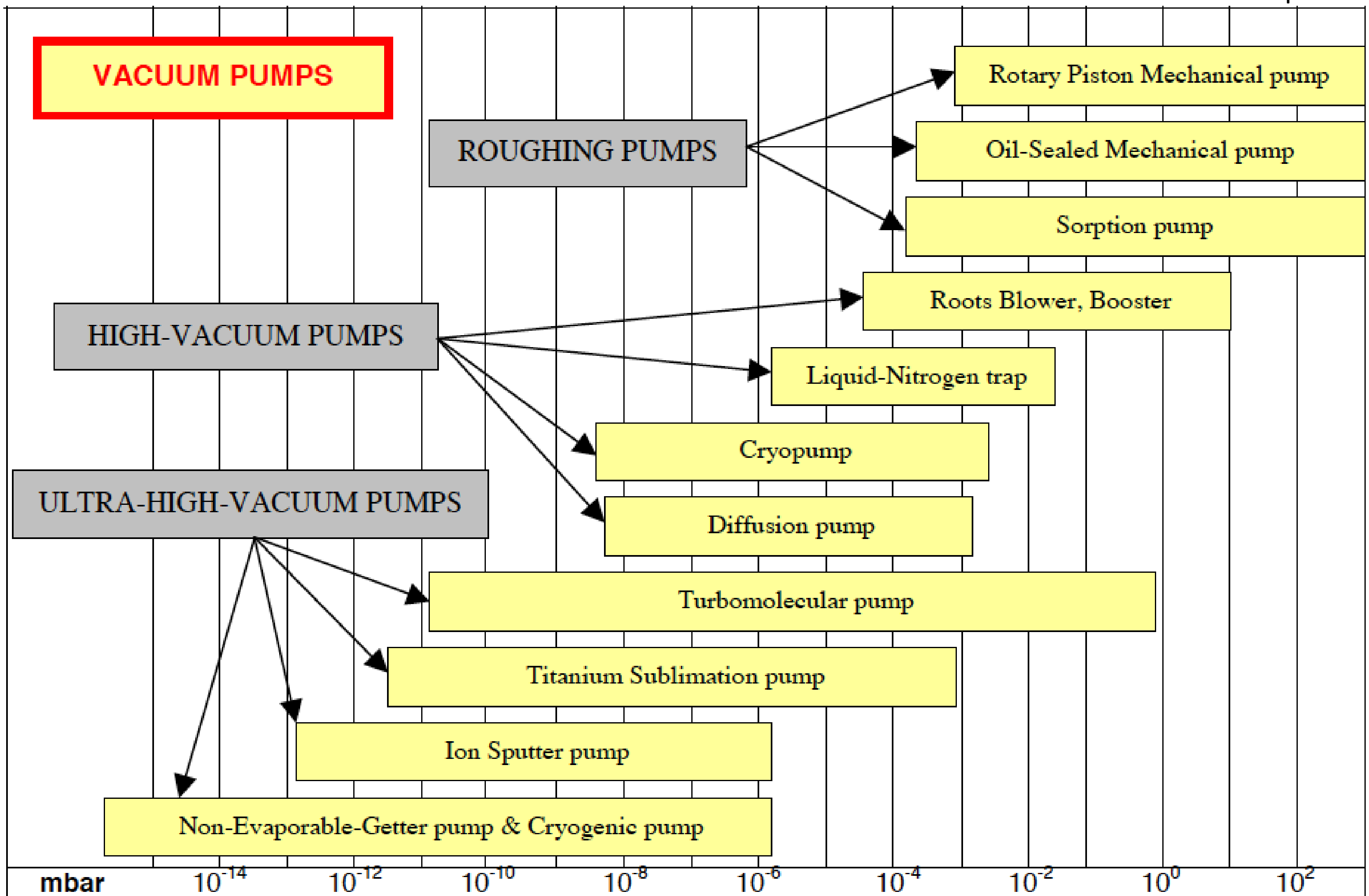
P_c depends on the capture process

Cryocondensation: P_w is the vapor pressure of the gas at T_c



Summary on Pumps

N. Marquardt



Gauges

Liquid Manometers

MacLeod Gauges

Viscosity Gauges

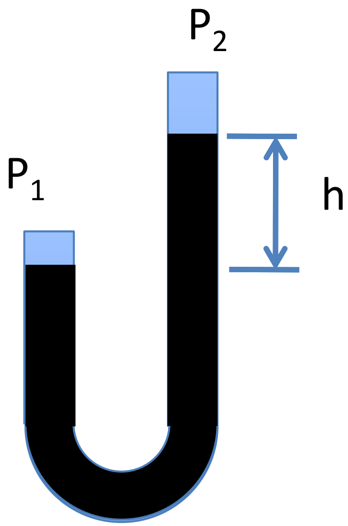
Thermal conductivity Gauges

Hot Cathode Gauges

Alpert-Bayard Gauges

Penning Gauges

Liquid Manometers



Relation between the two pressure

$$P_1 - P_2 = h\rho g$$

issue: measure precisely “h”   by eye +/- 0.1 mm

but with mercury surface tension depress liquid surface

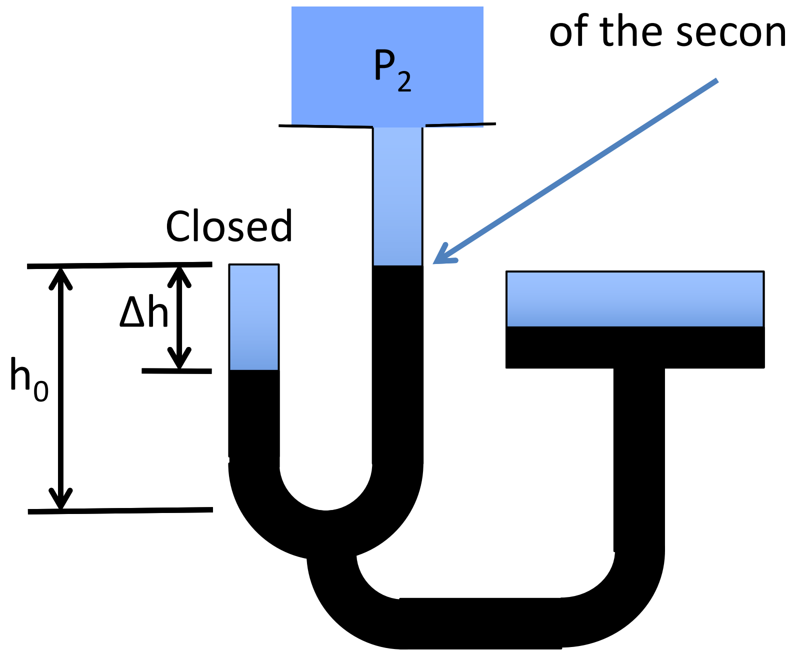
High accuracy is reached by knowing the liquid density

<u>Mercury should be handled with care: **serious health hazard**</u>

McLeod Gauge

First mode of use:

The reservoir is raised till the mercury reaches the level of the second branch (which is closed)

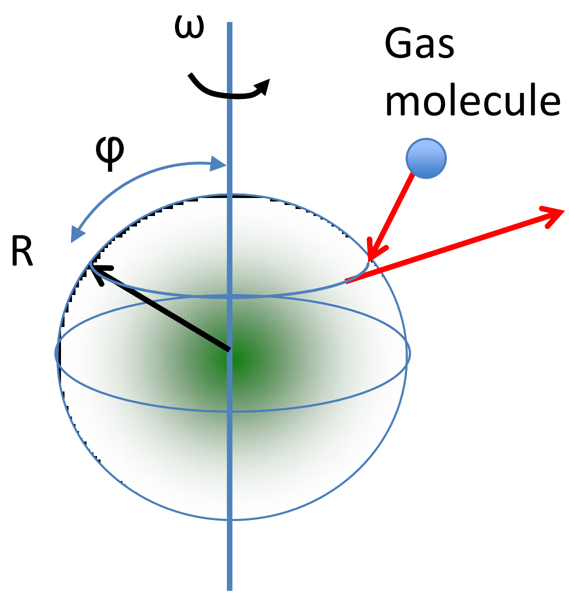


$$P_2 = \rho g \frac{\Delta h^2}{h_0 - \Delta h}$$

Quadratic response to P_2

Second mode of use: keep the distance Δh constant and measure the distance of the two capillaries → linear response in Δh

Viscosity Gauges



It is based on the principle that gas molecules hitting the sphere surface take away rotational momentum

The angular velocity of the sphere decreases

$$P = \frac{\pi}{10}\rho R v_a \left(\frac{1}{\omega}\frac{d\omega}{dt} + 2\alpha \frac{dT}{dt} \right)$$

ρ = sphere density
α = coefficient of thermal dilatation
T = temperature
v_a = thermal velocity

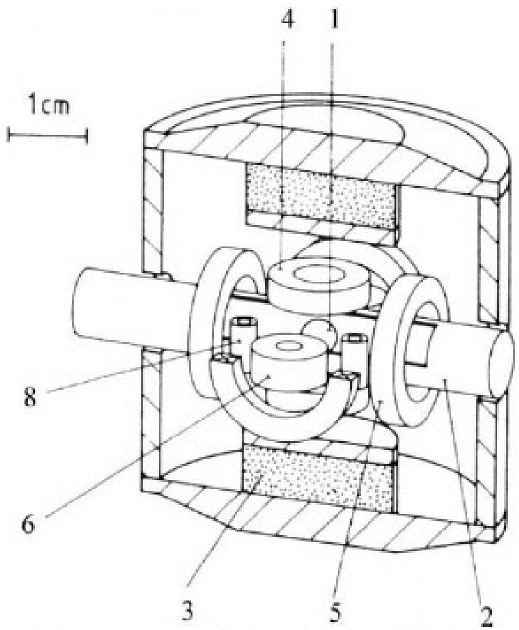
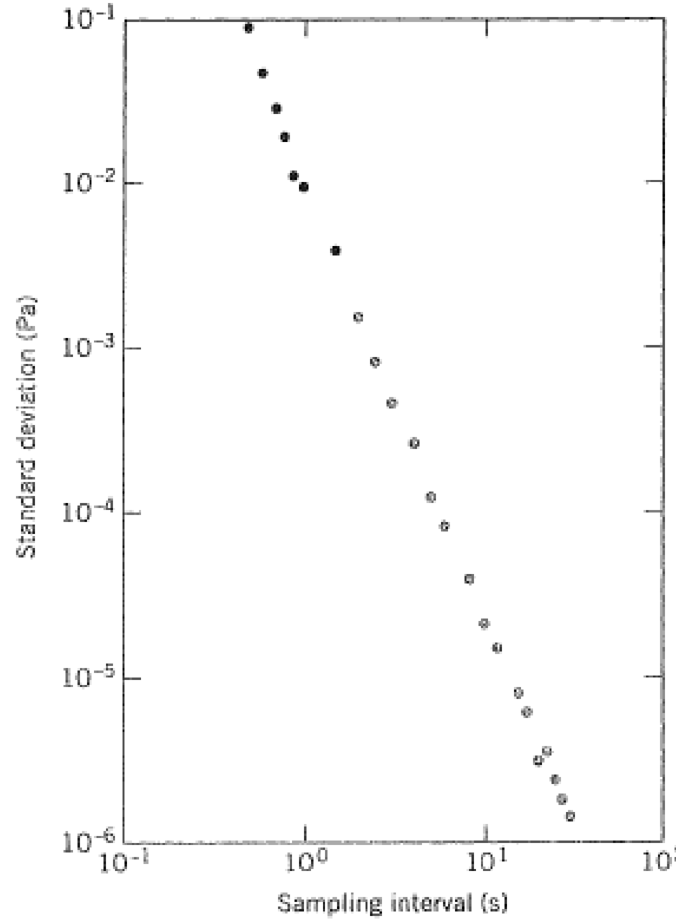


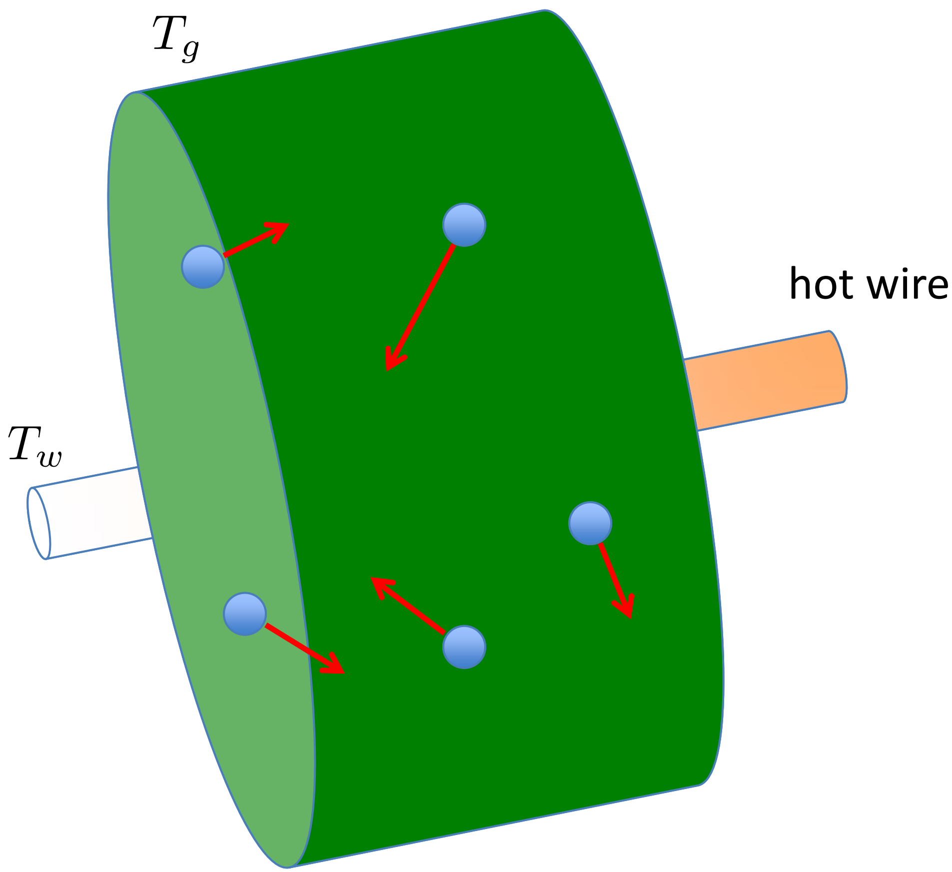
Fig. 24: Schematic of a spinning rotor gauge. 1 rotor; 2 vacuum tube; 3 permanent magnets; 4 two coils for vertical stabilization; 5 four drive coils; 6 two detection coils; 8 four coils for horizontal stabilization. From *Wutz Handbuch Vakuumtechnik* by K. Jousten (ed.), Vieweg Verlag.

(K. Jousten, CAS 2007)



F.J. Redgrave, S.P. Downes, “Some comments on the stability of Spinning Rotor Gauges”, Vacuum, Vol. 38, 839-842

Thermal conductivity Gauges



A hot wire is cooled by the energy transport operated by the vacuum gas

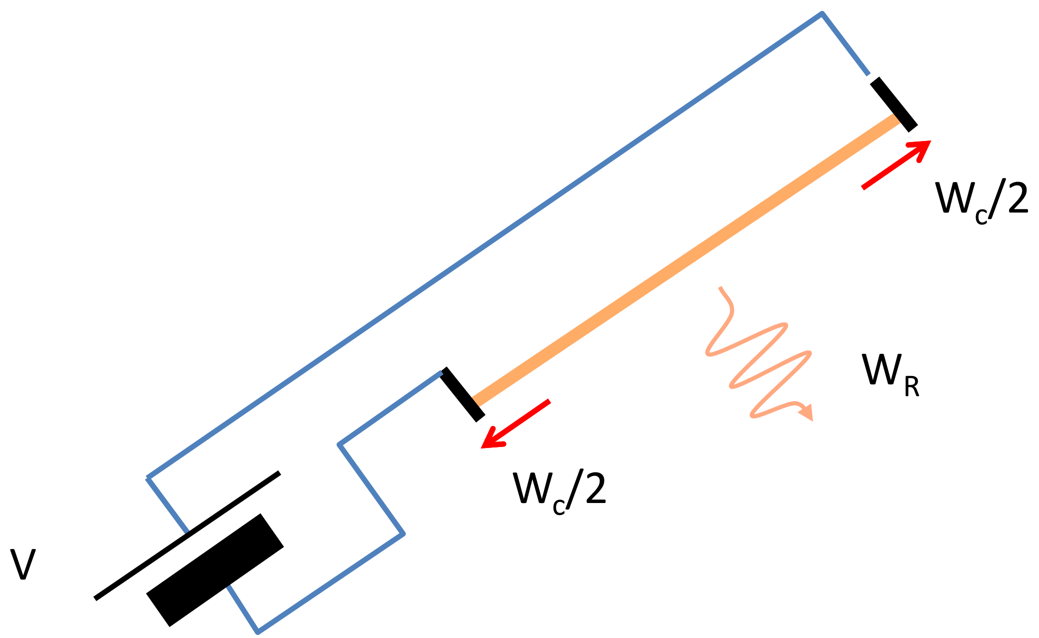
$$\dot{E} = \sqrt{\frac{2k}{\pi m T_g}}\alpha(T_w - T_g)P$$

Accommodation factor

$$\alpha = \frac{T_d - T_g}{T_w - T_g}$$

By measuring dE/dt we measure P

Energy Balance



- Energy loss by gas molecules

$$\dot{E} = \sqrt{\frac{2k}{\pi m T_g}}\alpha(T_w - T_g)P$$

- Energy loss by Radiation

$$W_R = \epsilon\sigma(T_w^4 - T_g^4)$$

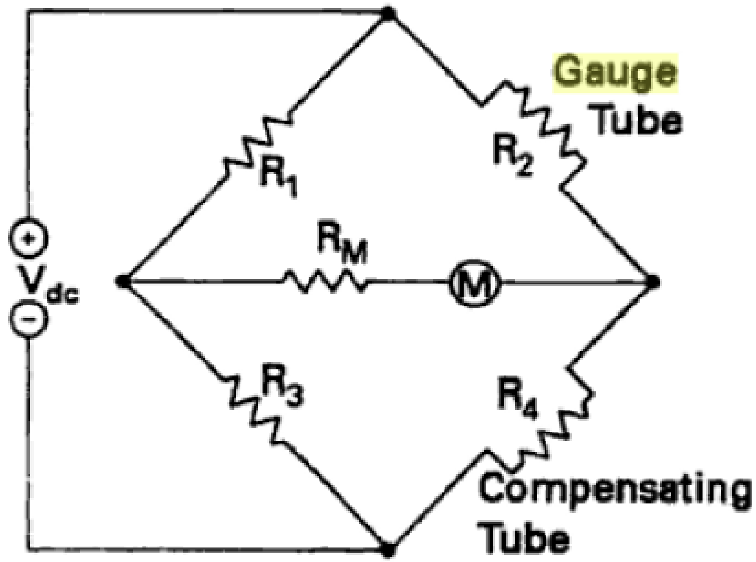
$\sigma = 5.673 \times 10^{-8}\ \mathrm{W\ m^{-2}K^{-4}}$

ε = emissivity

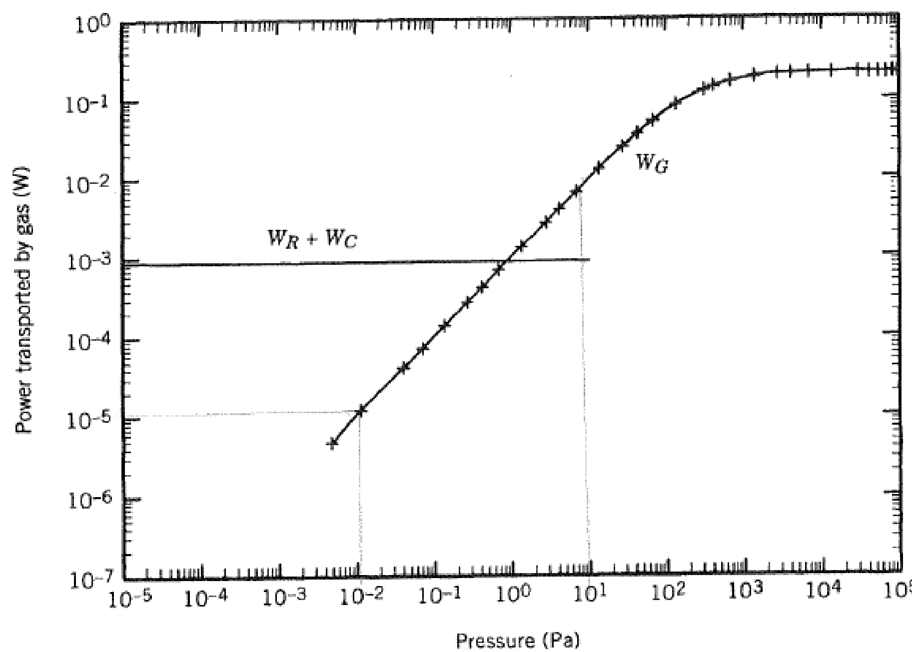
- Energy loss by heat conduction

When the energy loss by gas molecule is dominant
P can be predicted with contained systematic error

Pirani Gauge



Example of power dissipated by a Pirani Gauge vs Vacuum pressure



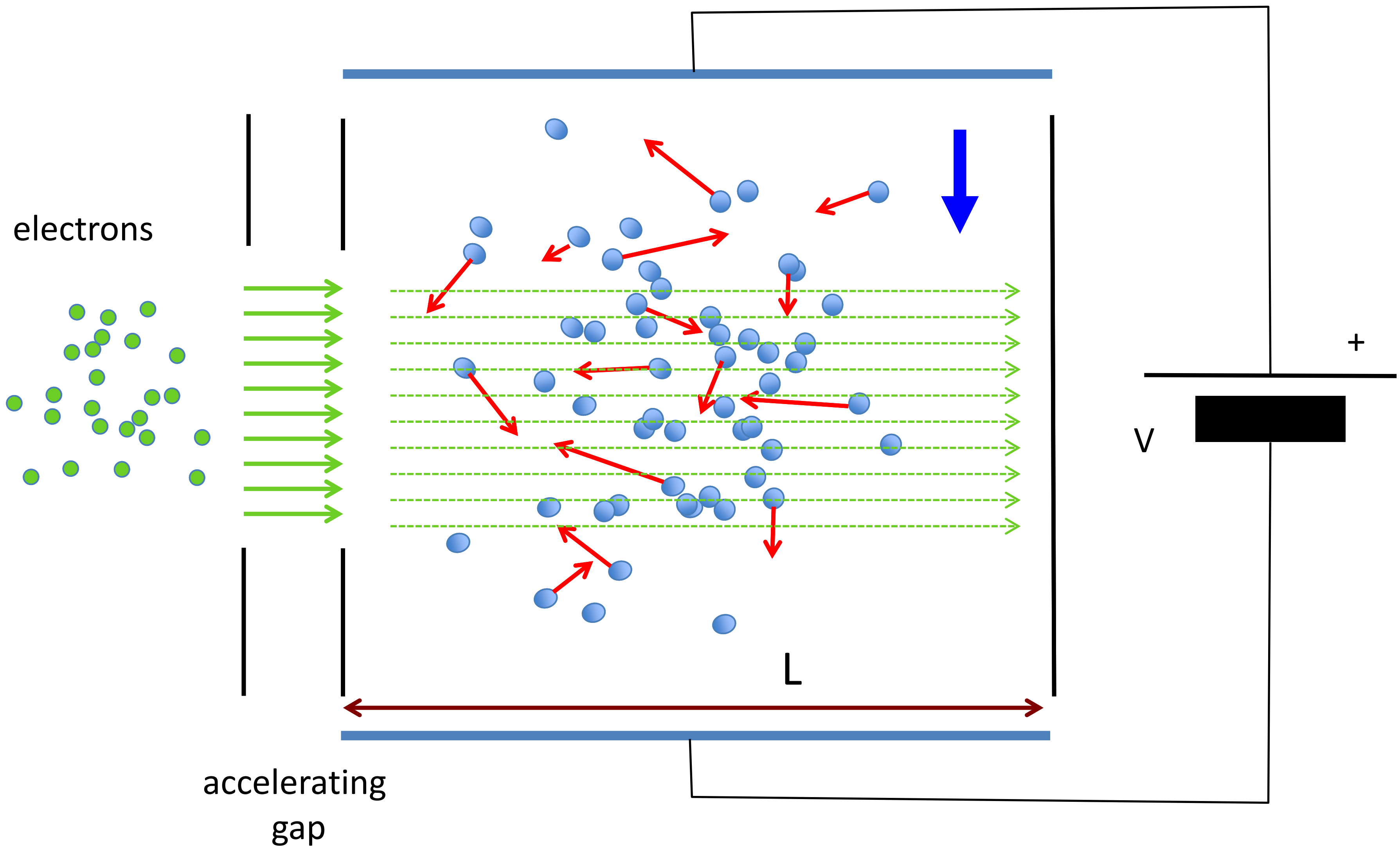
The Gauge tube is kept at constant temperature and the current is measured

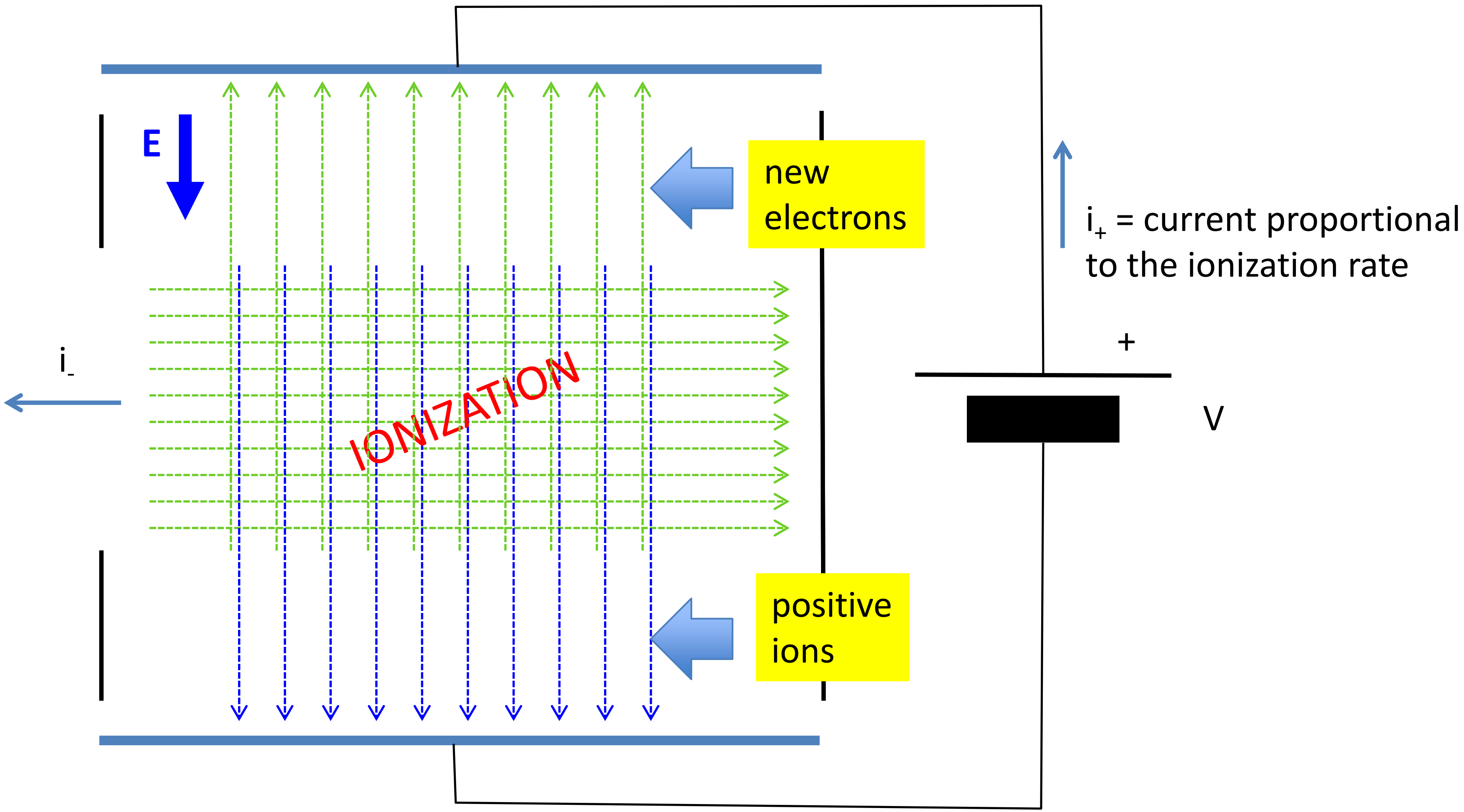
So that

$$W = \frac{V^2}{4R}$$

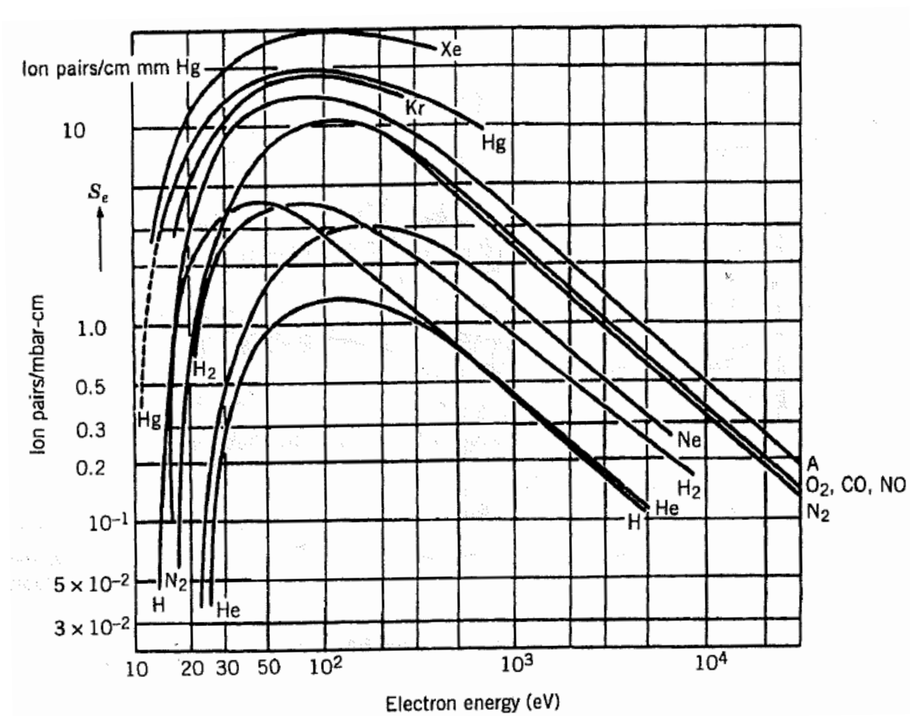
Through this value → $\dot{E}$

Ionization Gauges Principle




E
new electrons
positive ions
IONIZATION
i_
i+ = current proportional to the ionization rate
+
V

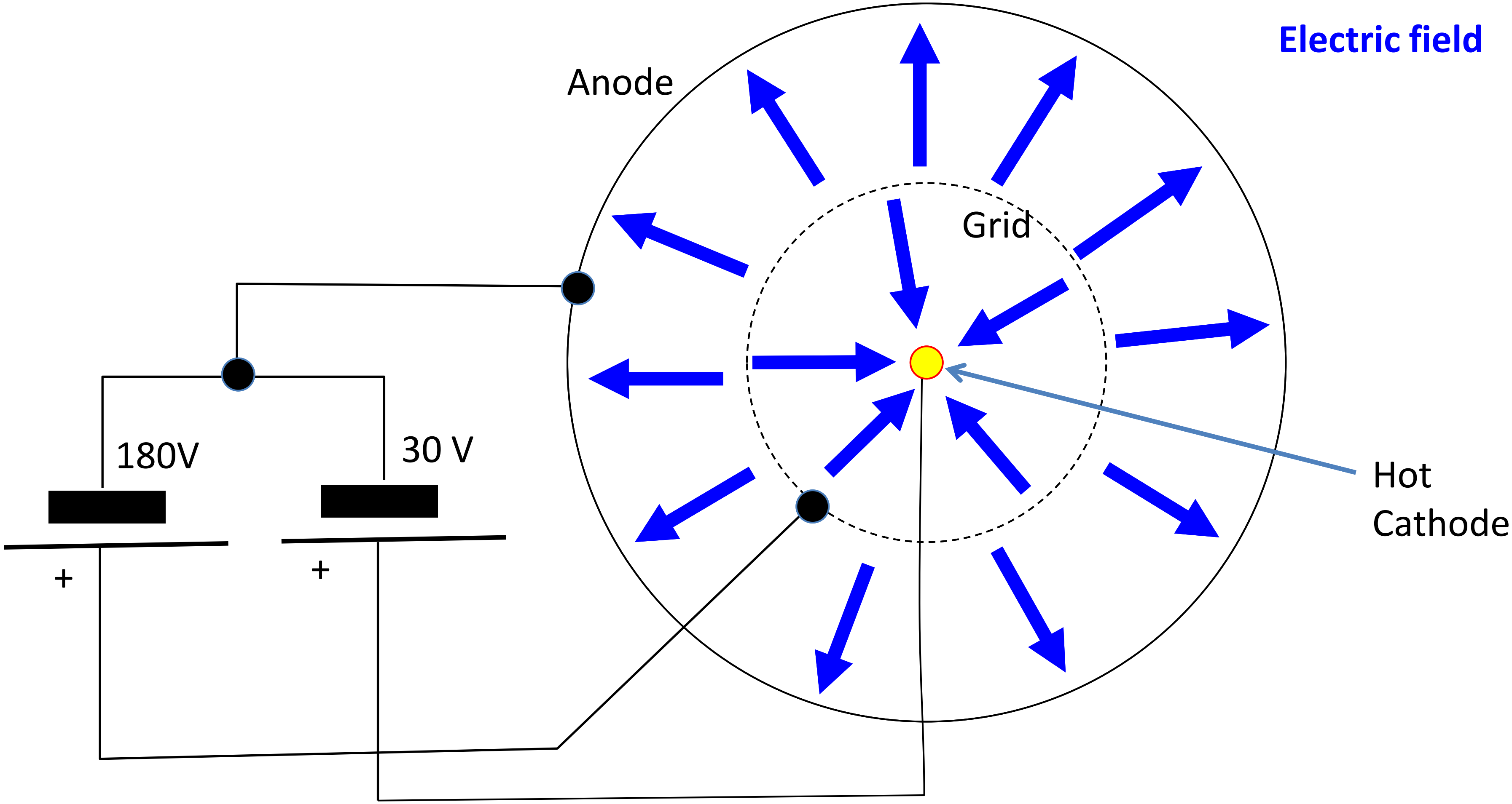
Electrons ionization rate



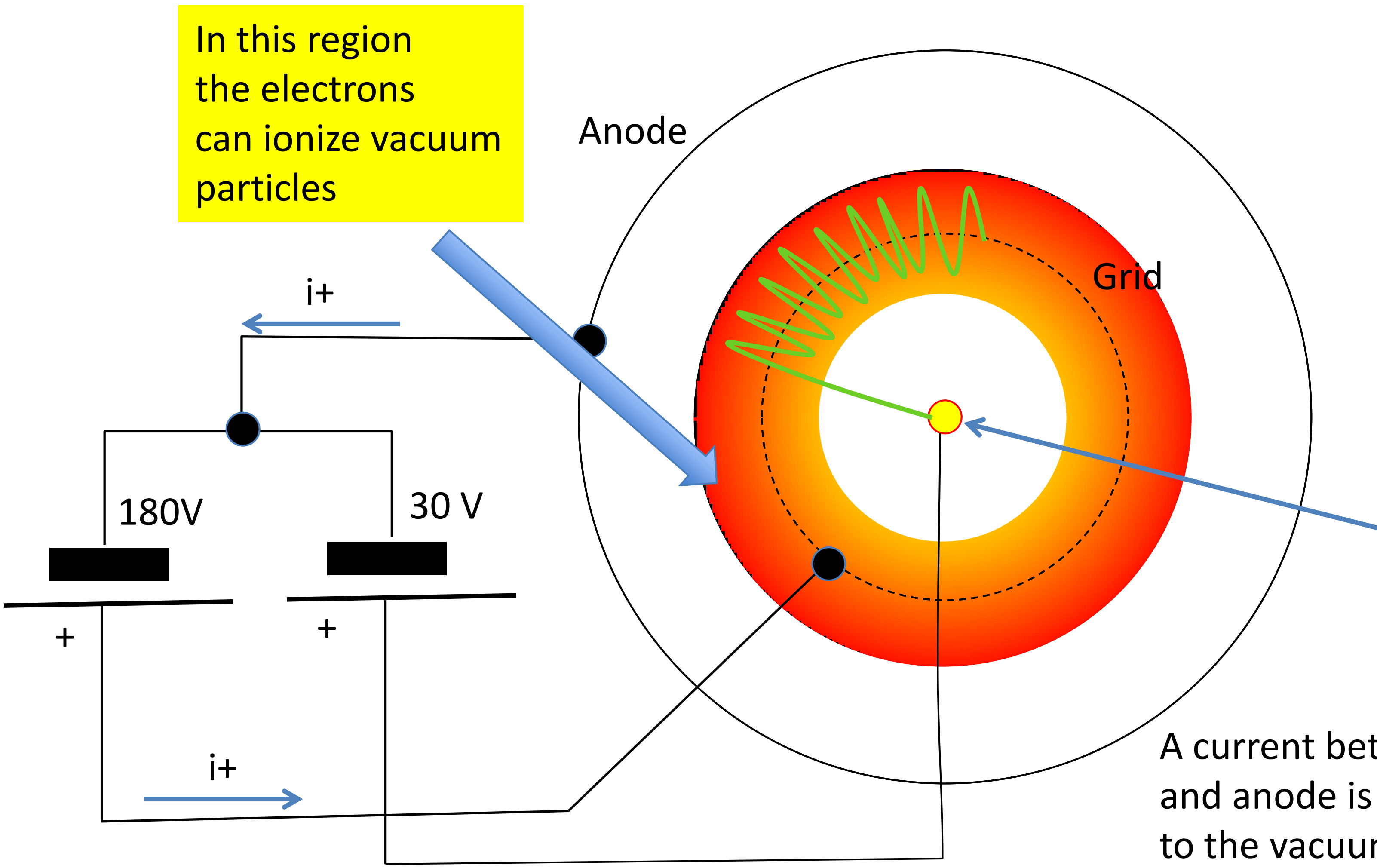
$$\frac{i_+}{i_-} = \frac{\sigma_i L}{k_B T} P$$

Sensitivity

Hot Cathode Gauges



Hot Cathode Gauges

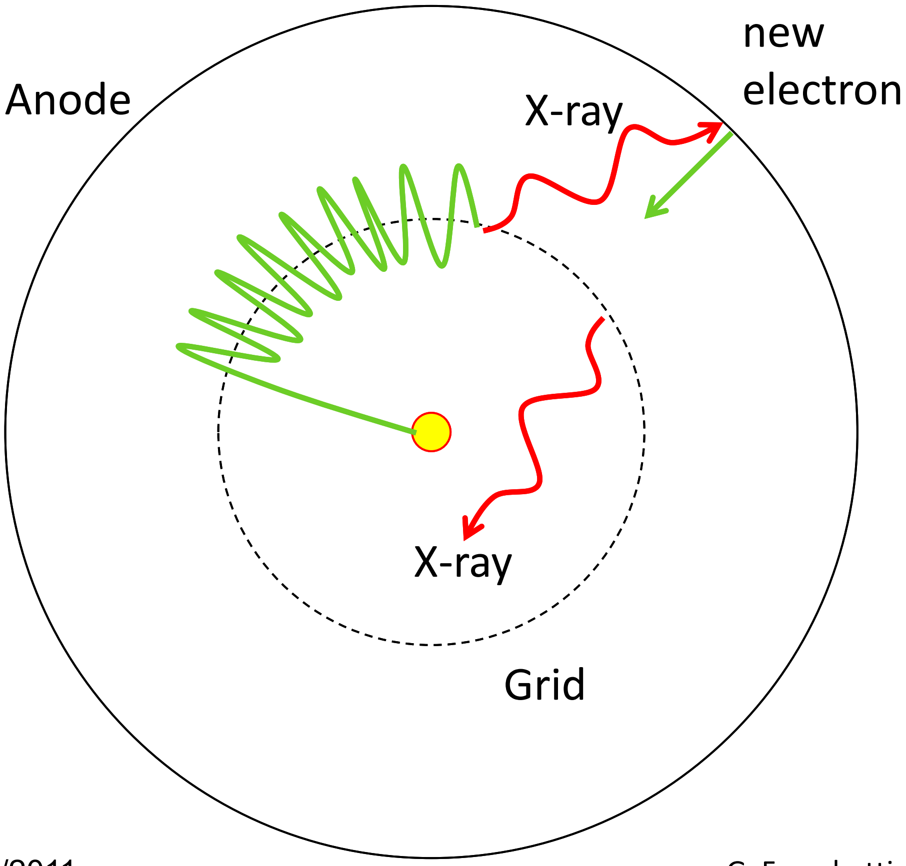


A current between grid
and anode is proportional
to the vacuum pressure

Limit of use

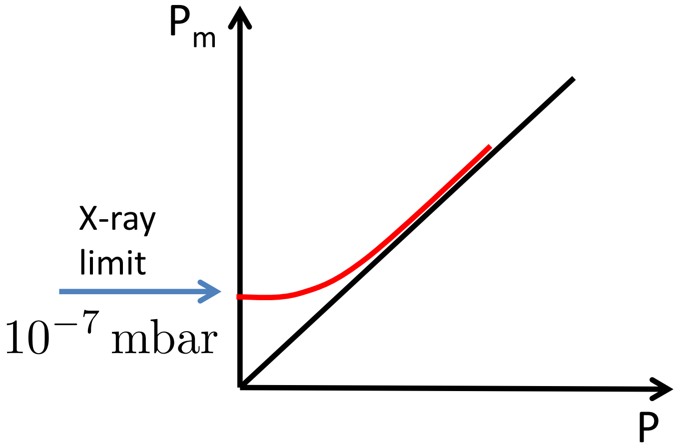
Upper limit: it is roughly the limit of the linear response

Lower limit: X-ray limit

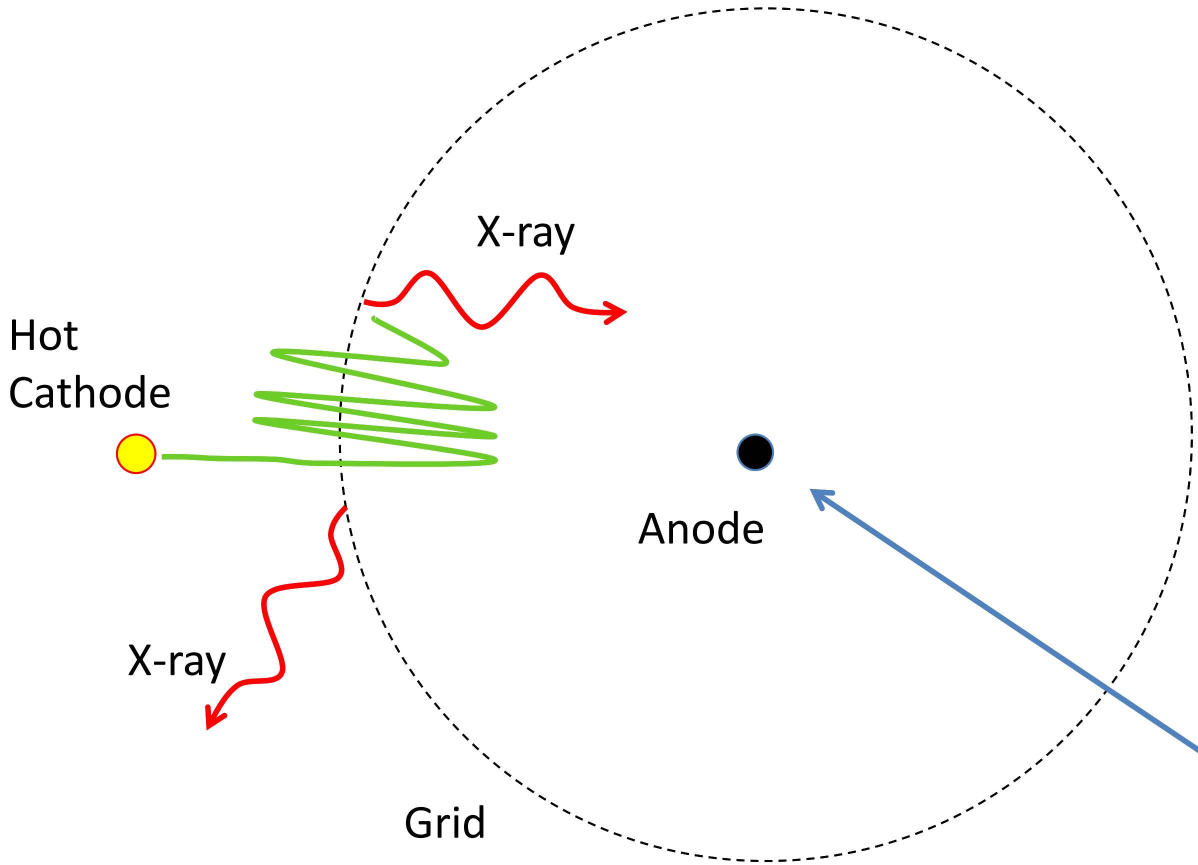


The new electron change the ionization current

$$i_+ + i_r = KPi_- + i_r$$



Alpert-Bayard Gauge



The X-ray limit is easily suppressed by a factor ~100-1000

the probability that a new electron hits the anode is now very small

Schematic of the original design (K. Jousten, CAS 2007)

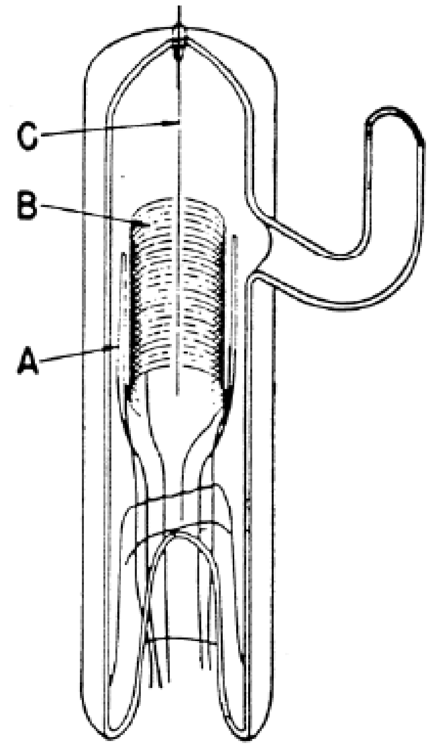
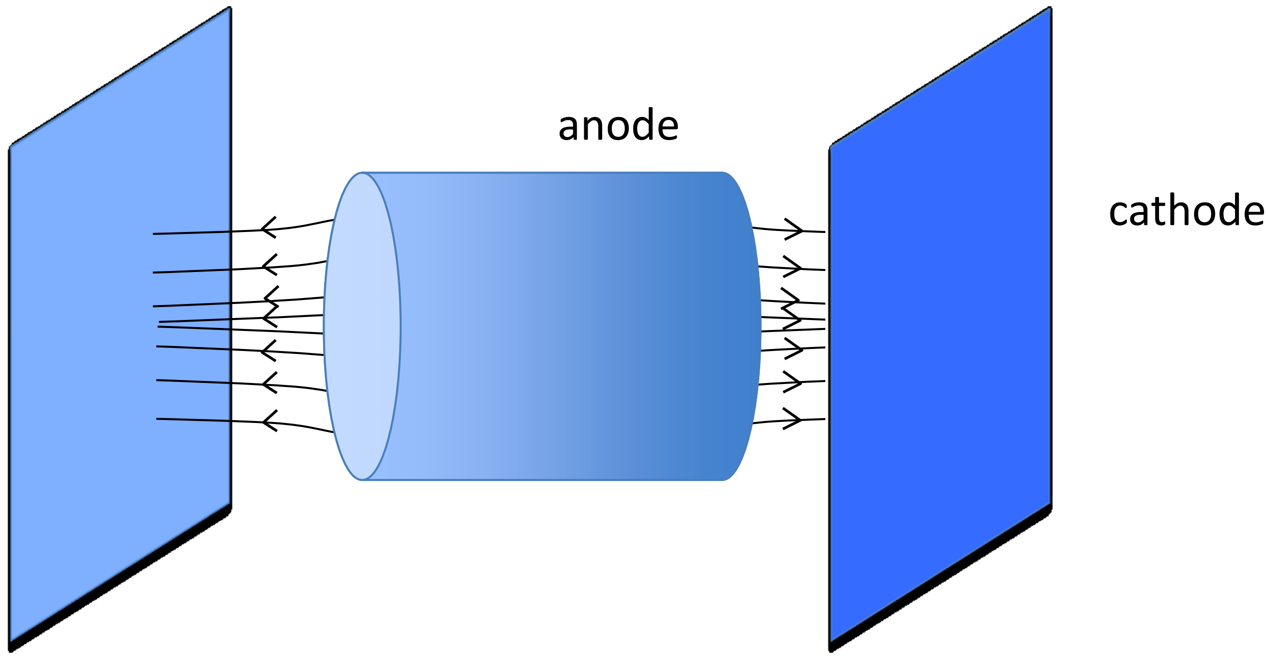


Fig. 11: The original design of the Bayard–Alpert gauge. From R.T. Bayard and D. Alpert, *Rev. Sci. Instrum.* **21** (1950) 571.

Penning Gauge (cold cathode gauges)

E = electric field

B = magnetic field

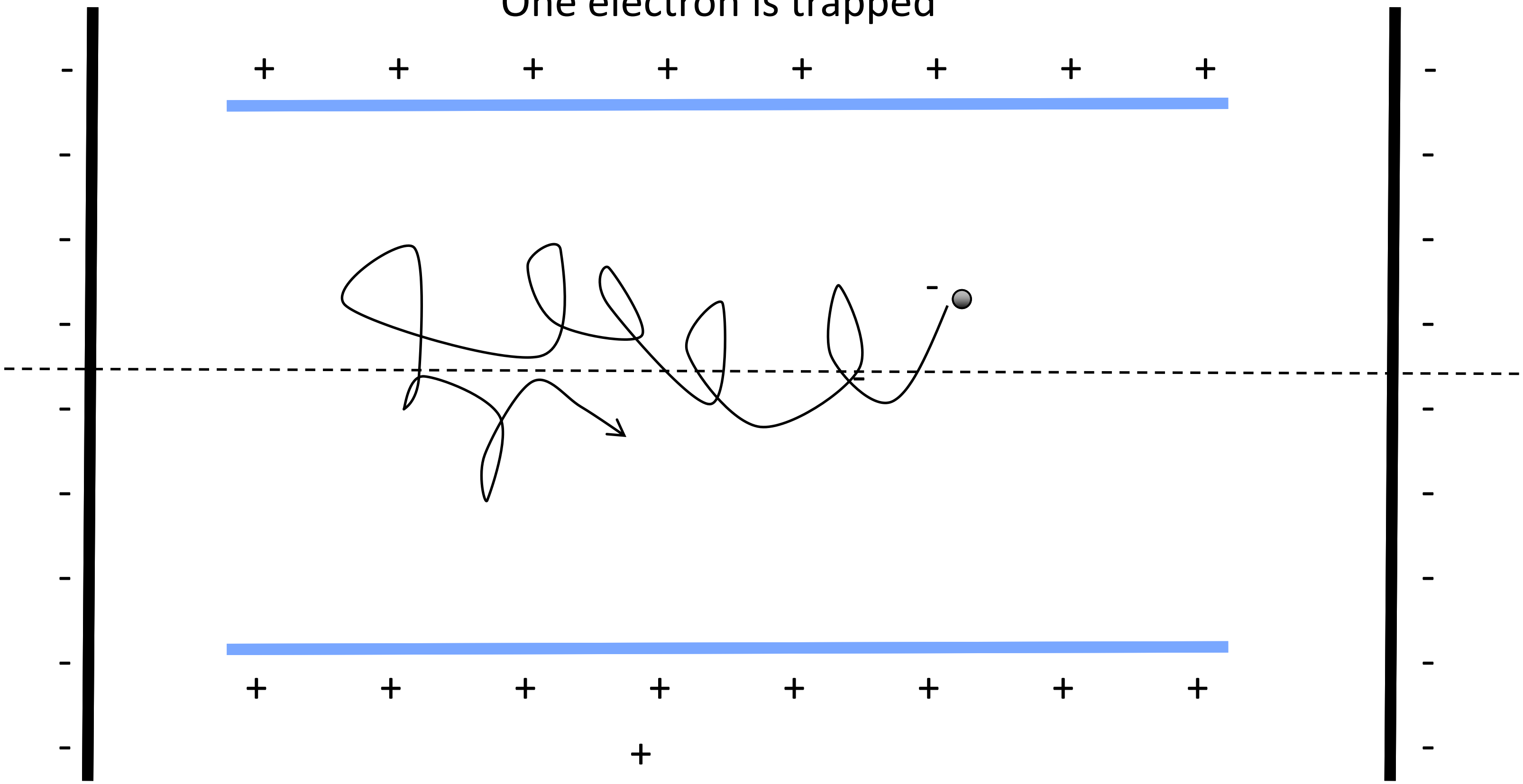


Electrons motion

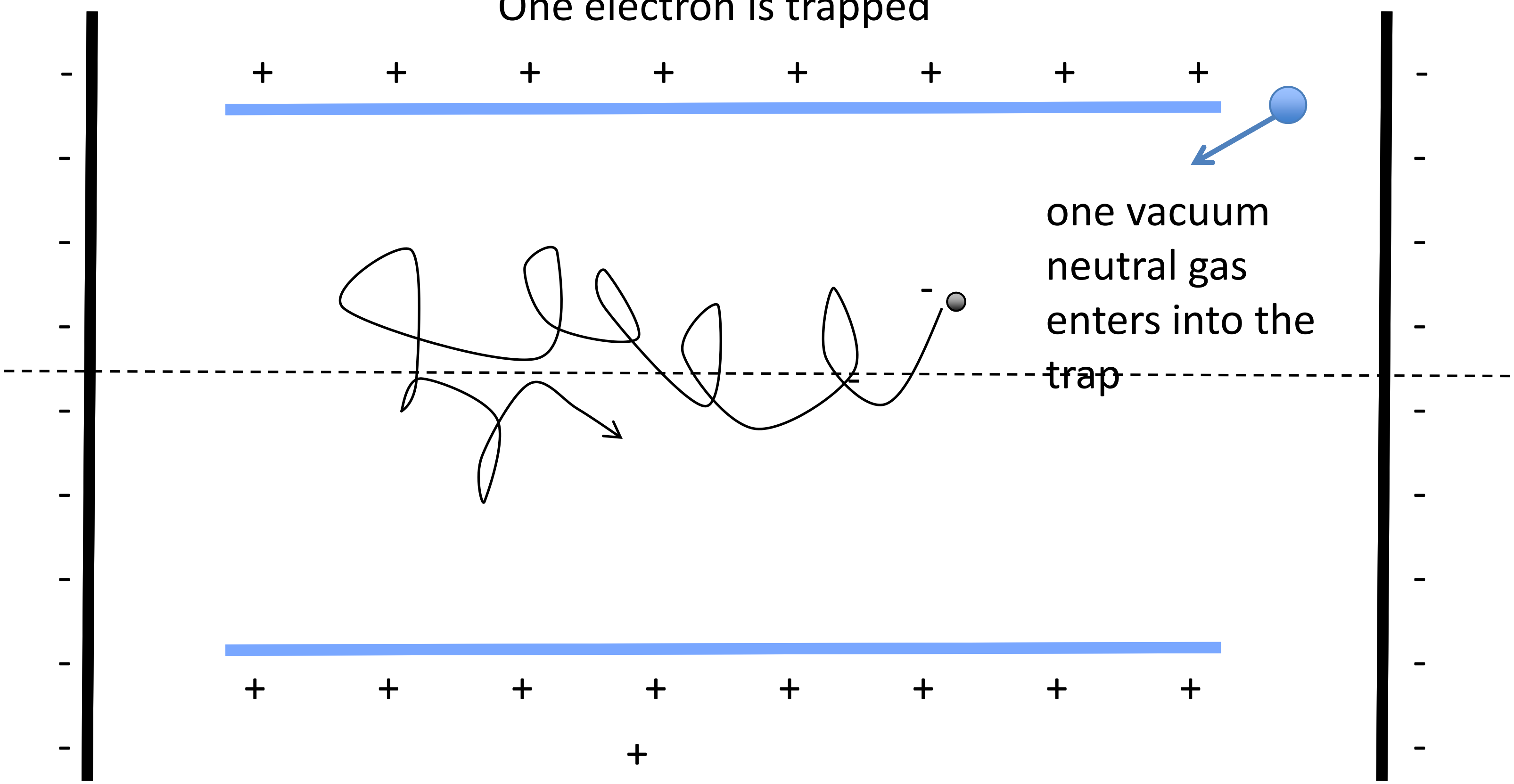
$$\frac{dm\gamma\vec{v}}{dt} = e\vec{E} + e\vec{v} \times \vec{B}$$

Under proper condition of (E,B) electrons get trapped in the Penning Gauge

One electron is trapped



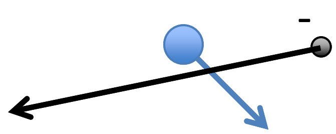
One electron is trapped



Ionization process

Before Collision

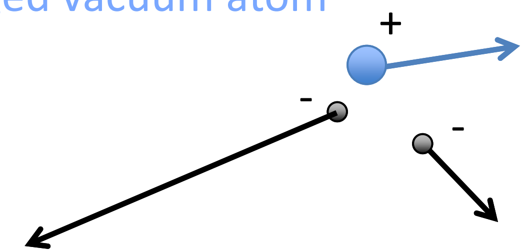
Neutral vacuum atom



Electron at ionization speed

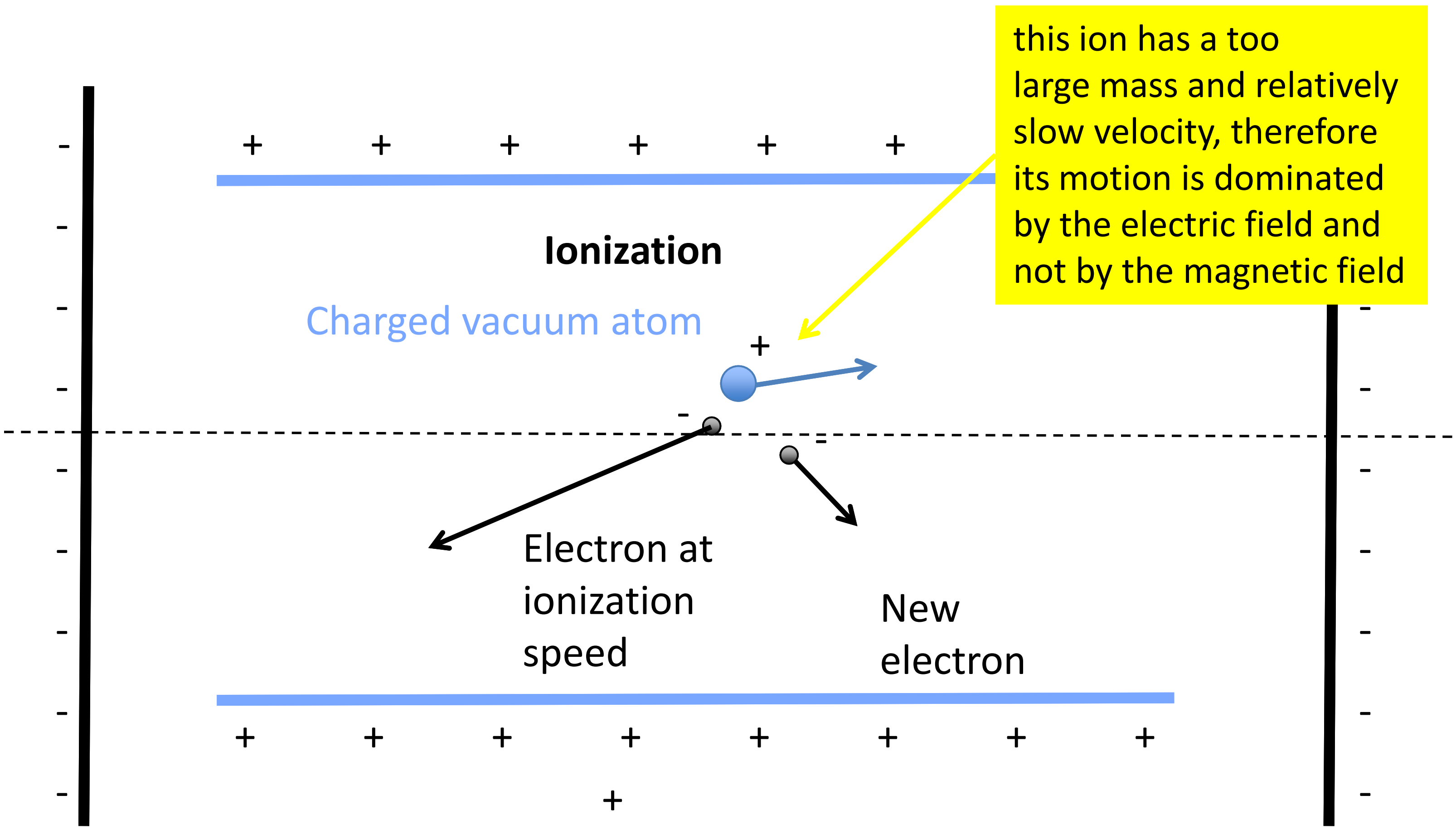
Collision → Ionization

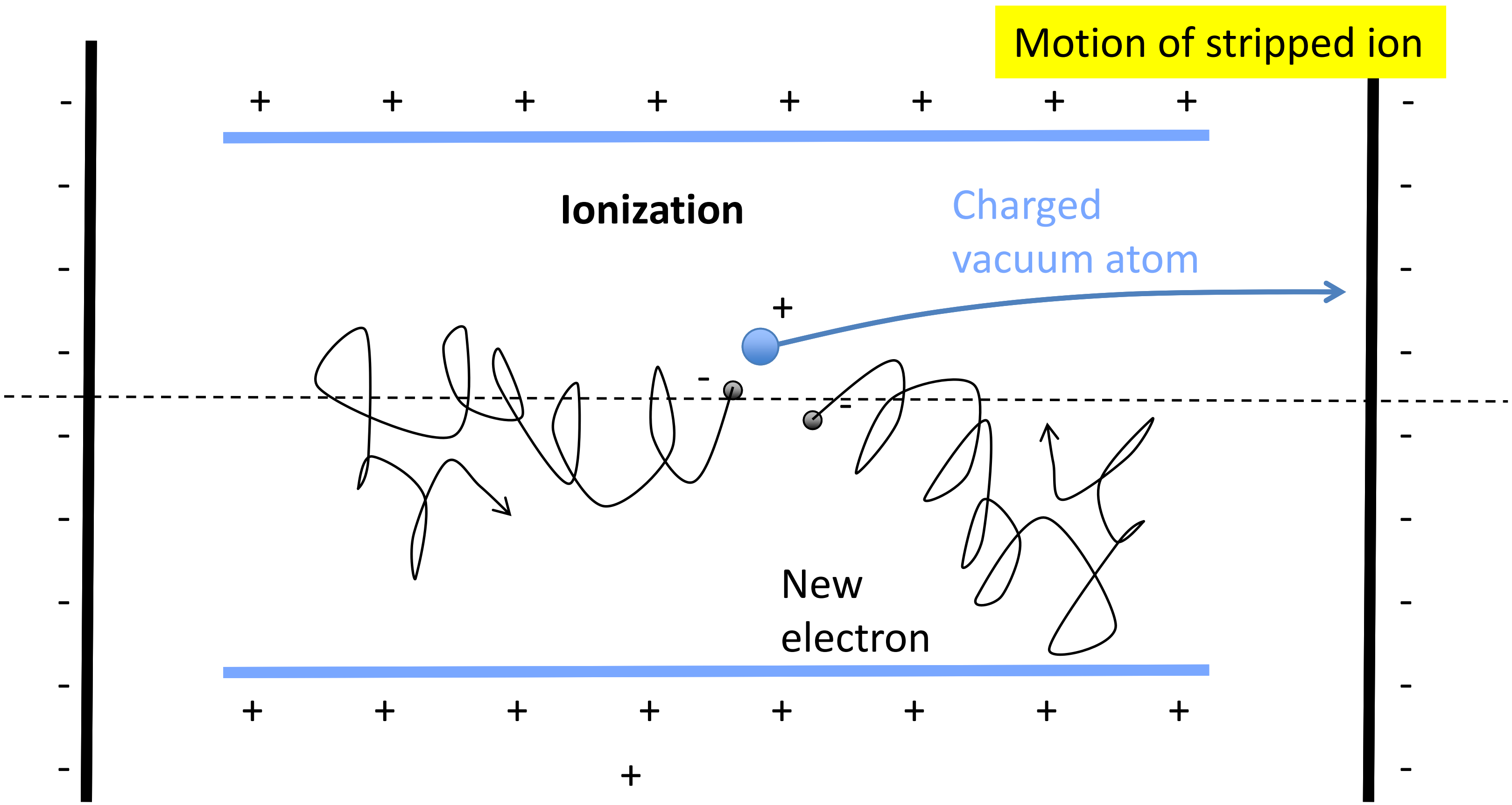
Charged vacuum atom



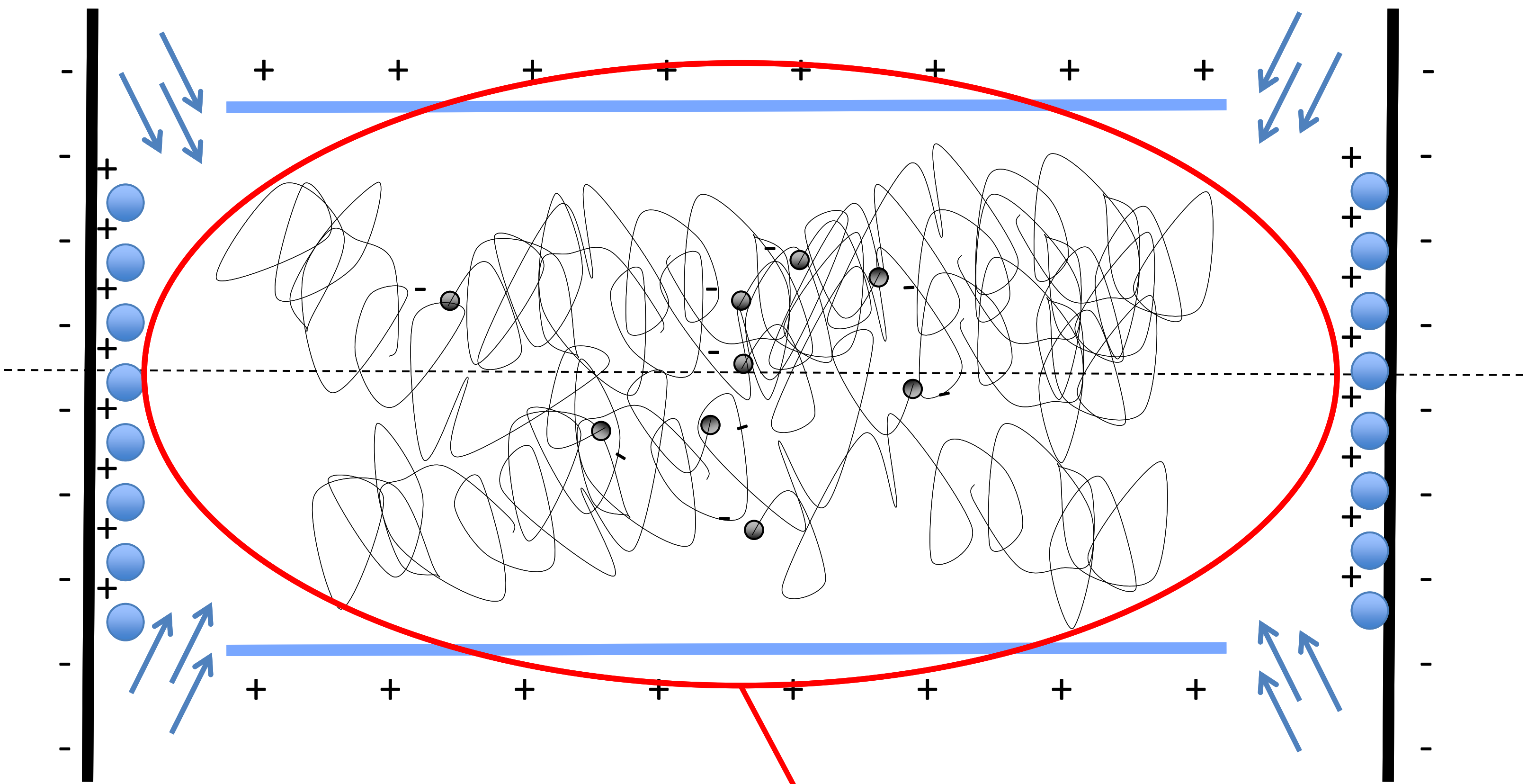
Electron at ionization speed

New electron


this ion has a too large mass and relatively slow velocity, therefore its motion is dominated by the electric field and not by the magnetic field
Ionization
Charged vacuum atom
Electron at ionization speed
New electron

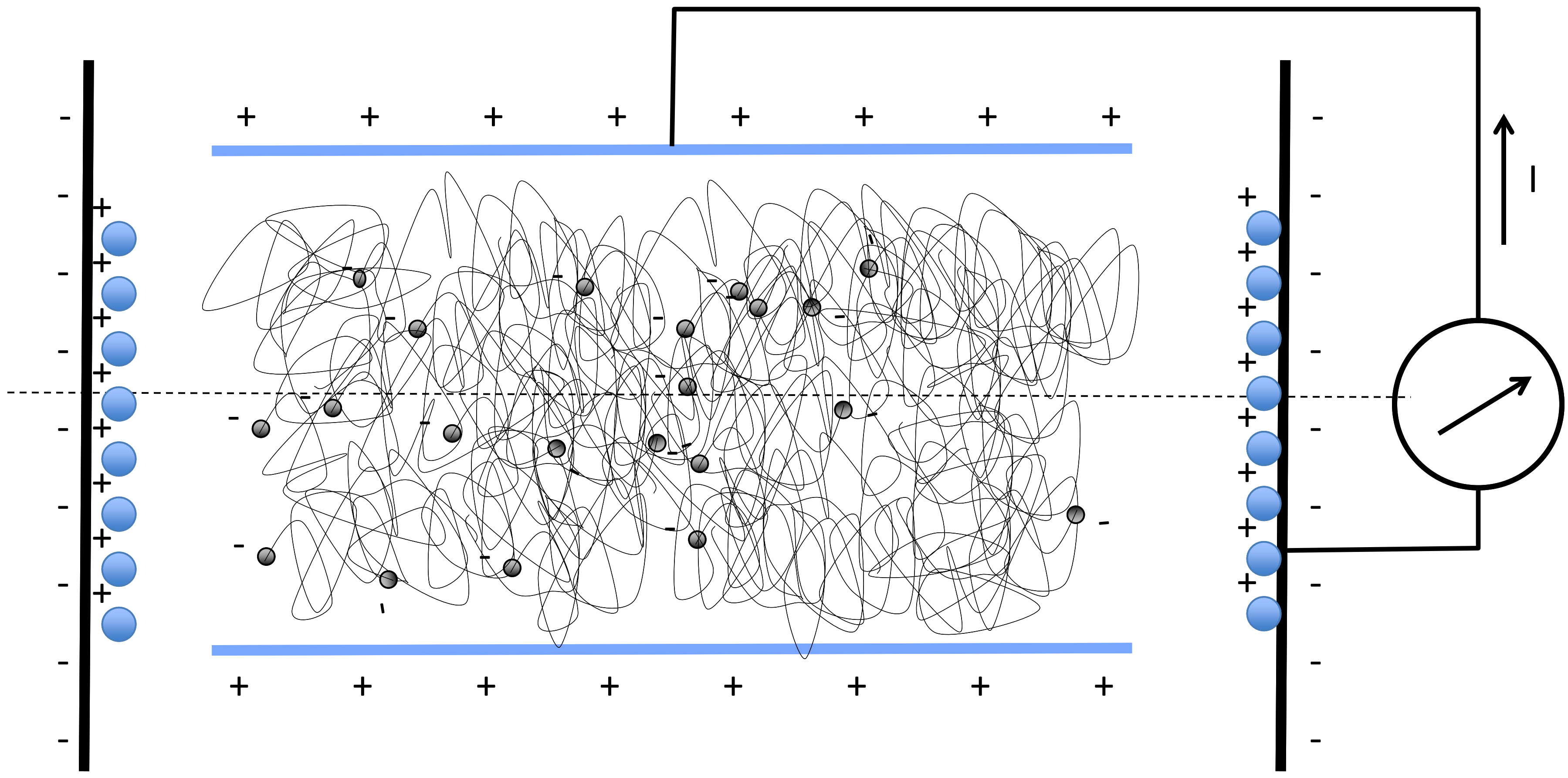

Motion of stripped ion
Ionization
Charged
vacuum atom
New
electron

More electrons are formed through the ionization of the vacuum gas and remains inside the trap



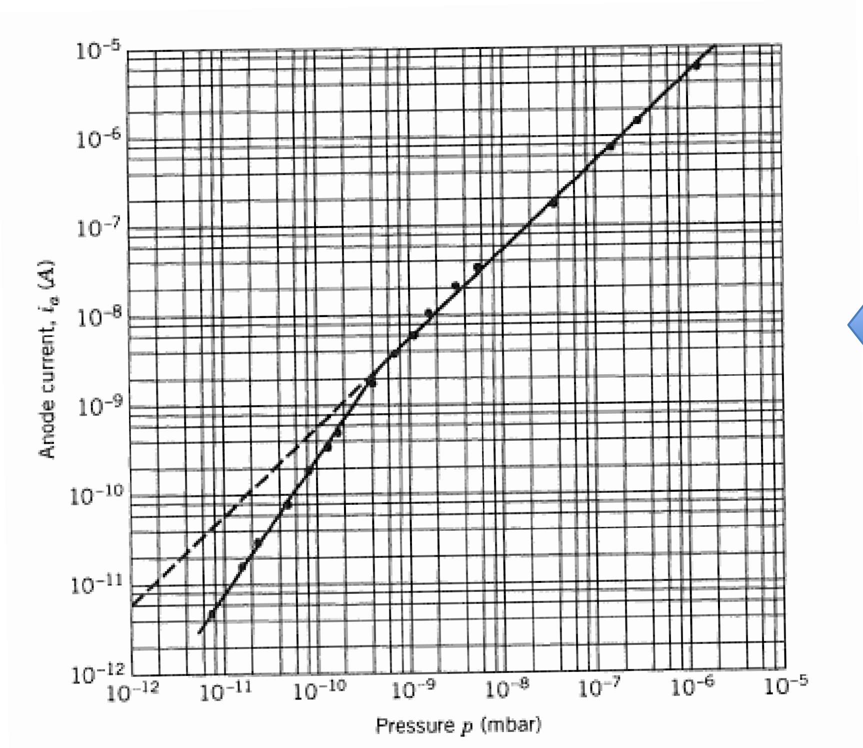
Negative space charge formation

When the discharge gets saturated each new ionization produce a current



The time necessary for the discharge formation depends upon the level of the vacuum

lower pressure → longer time of formation

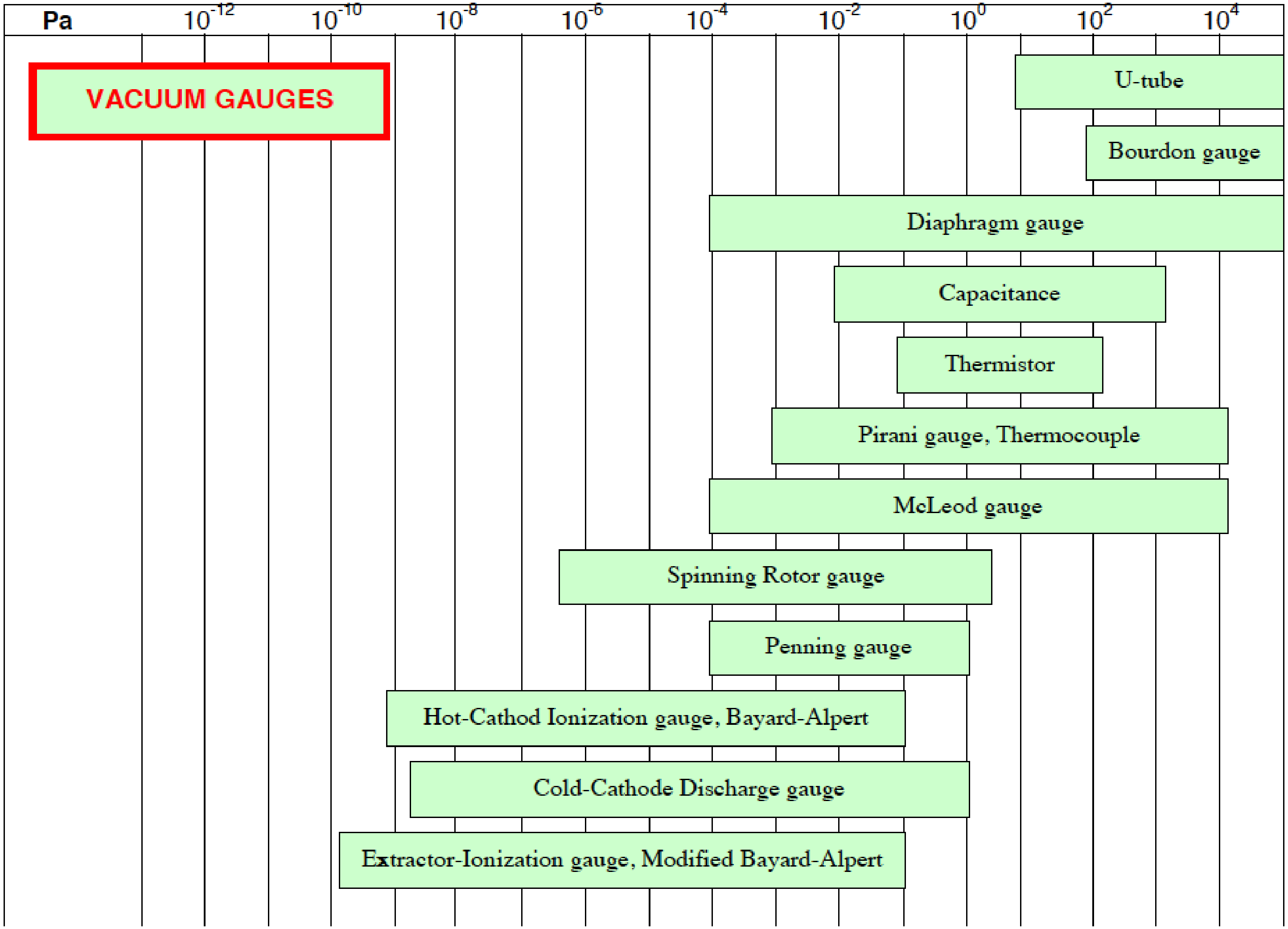


J.M. Lafferty, Vacuum Science,p. 322

Sensitivity of a SIP (the same as for the Penning Gauge).

Summary on Gauges

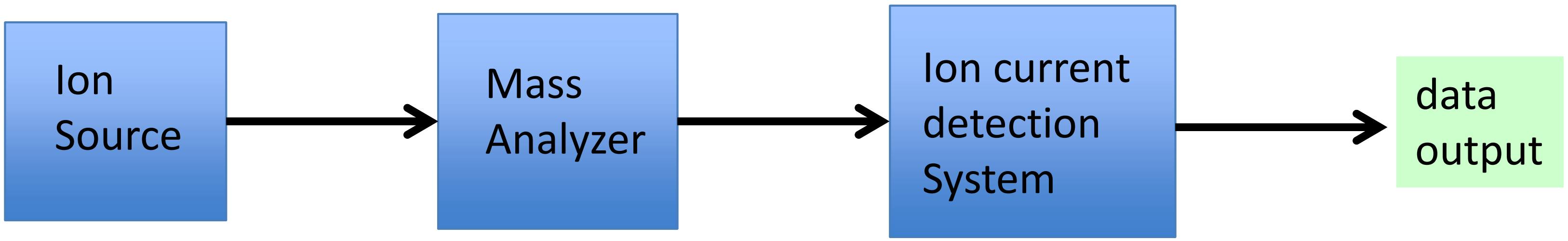
N. Marquardt



Partial Pressure Measurements

These gauges allow the determination of the gas components

Partial pressure gauges are composed

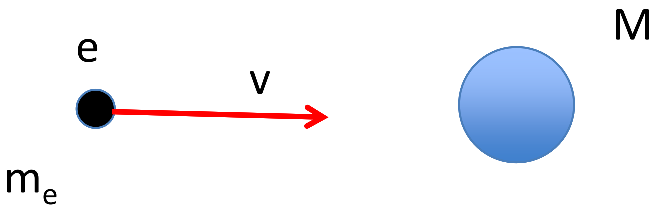


Ion Sources

Vacuum gas is ionized via electron-impact → **the rate of production of ions is proportional to each ion species**

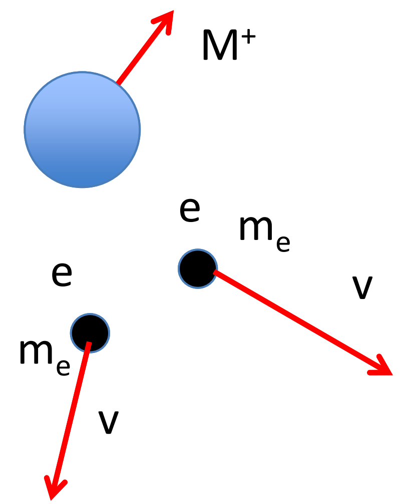
Electron-impact ionization process

Before Impact



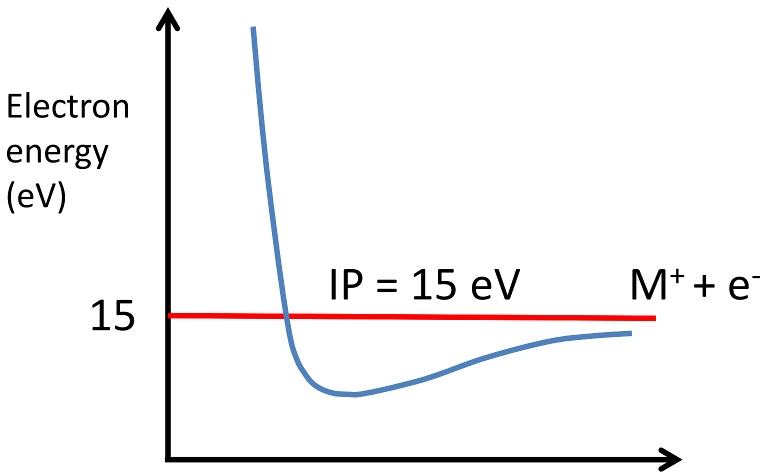
inelastic scattering: kinetic energy transfer from the electron to the molecule

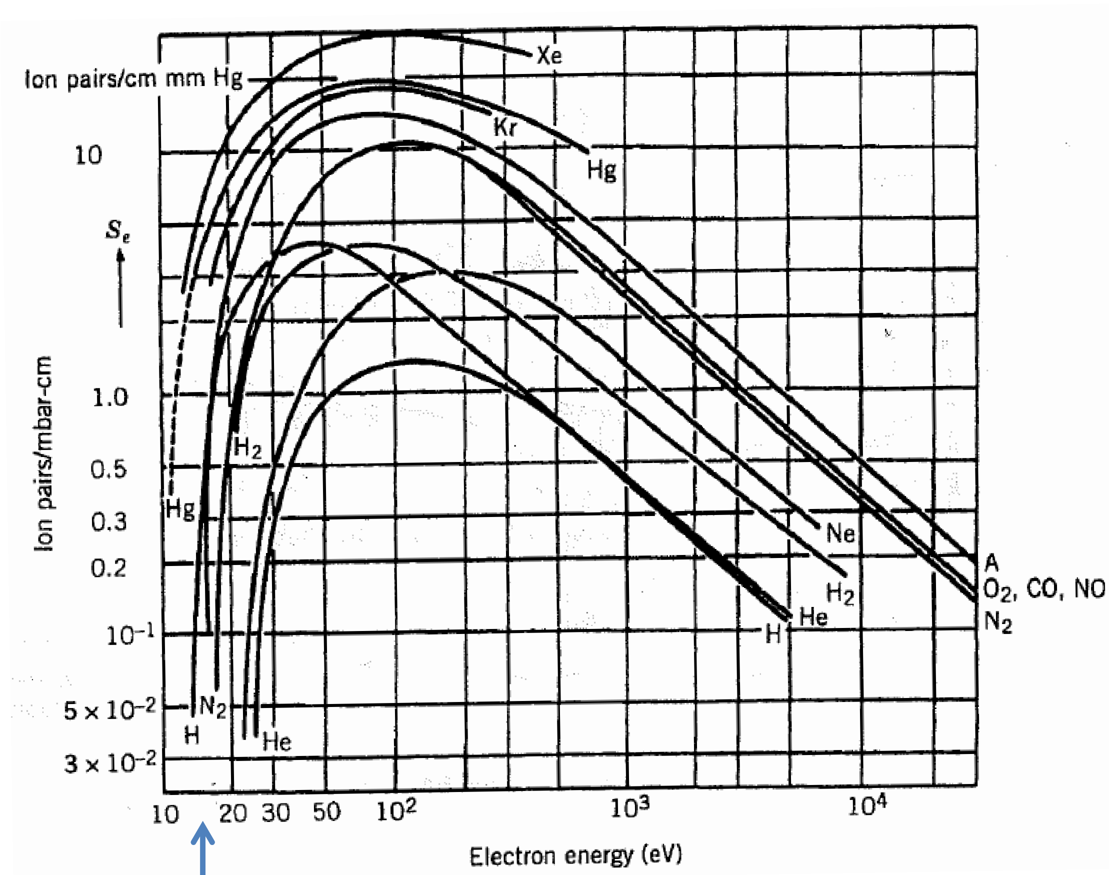
After impact



At the appearance potential the production rate is low

The minimum energy to ionize M is called "appearance potential"



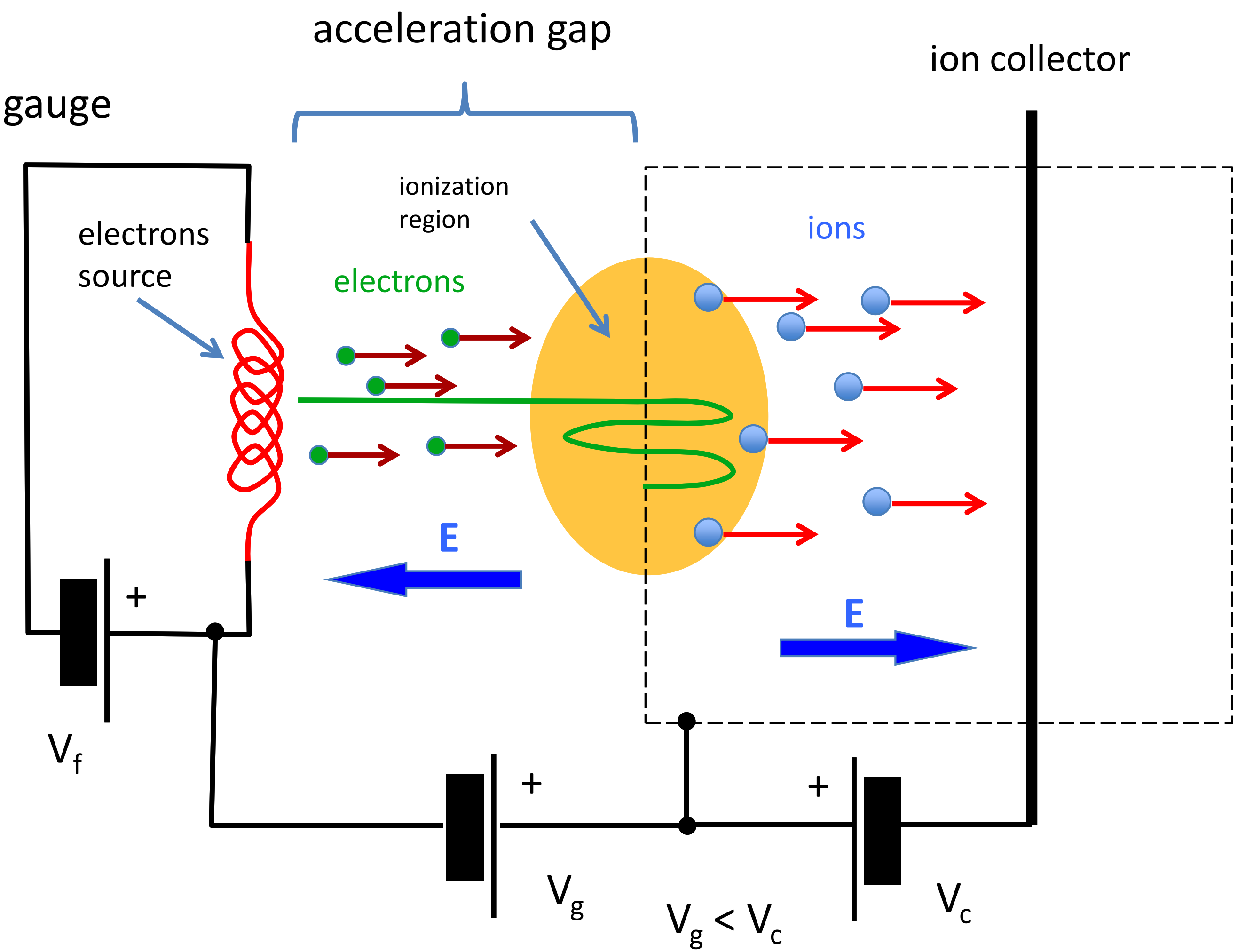


appearance potential

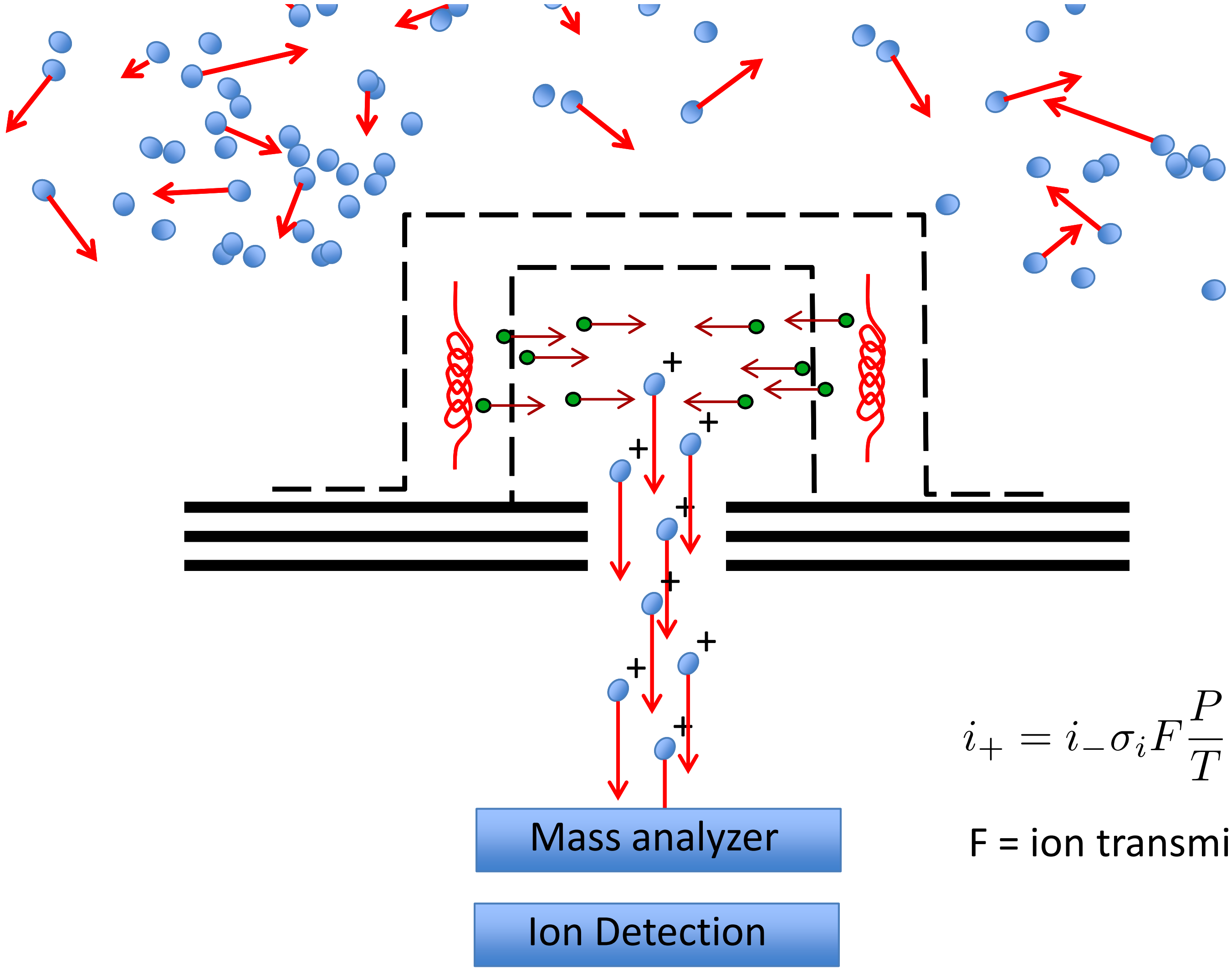
A. von Engel, Ionized Gases, AVS Classics Ser., p. 63. AIP Press, 1994

Ion source

Open source
Bayard-Alpert gauge



A schematic



$$i_+ = i_- \sigma_i F \frac{P}{T}$$

F = ion transmission factor

Ion Detection

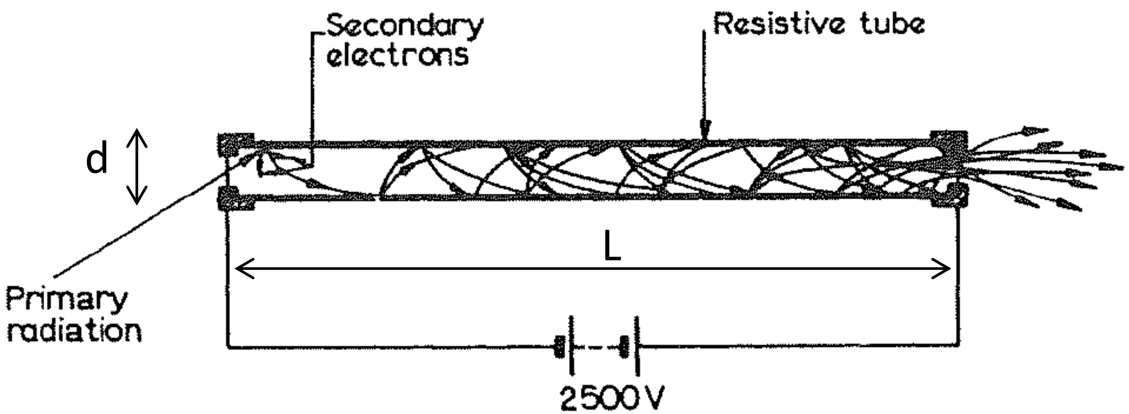
- Faraday Cup
- Secondary electron Multiplier (SEM)

Gain

$$G = \frac{\#\ \text{electrons output}}{\#\ \text{ion input}}$$

$$G = \left(\frac{KV_0^2}{4V\alpha^2}\right)^{\left(\frac{4V\alpha^2}{V_0}\right)}$$

Idea: an ion enters into the tube, and due to the potential is accelerated to the walls. At each collision new electrons are produced in an avalanche process



J.Adams, B.W. Manley IEEE Transactions on Nuclear Science, vol. 13, issue 3, 1966. p. 88

$\alpha = L/d$

V_0 = applied voltage

V = initial energy of the electron

$K = \delta V_c$

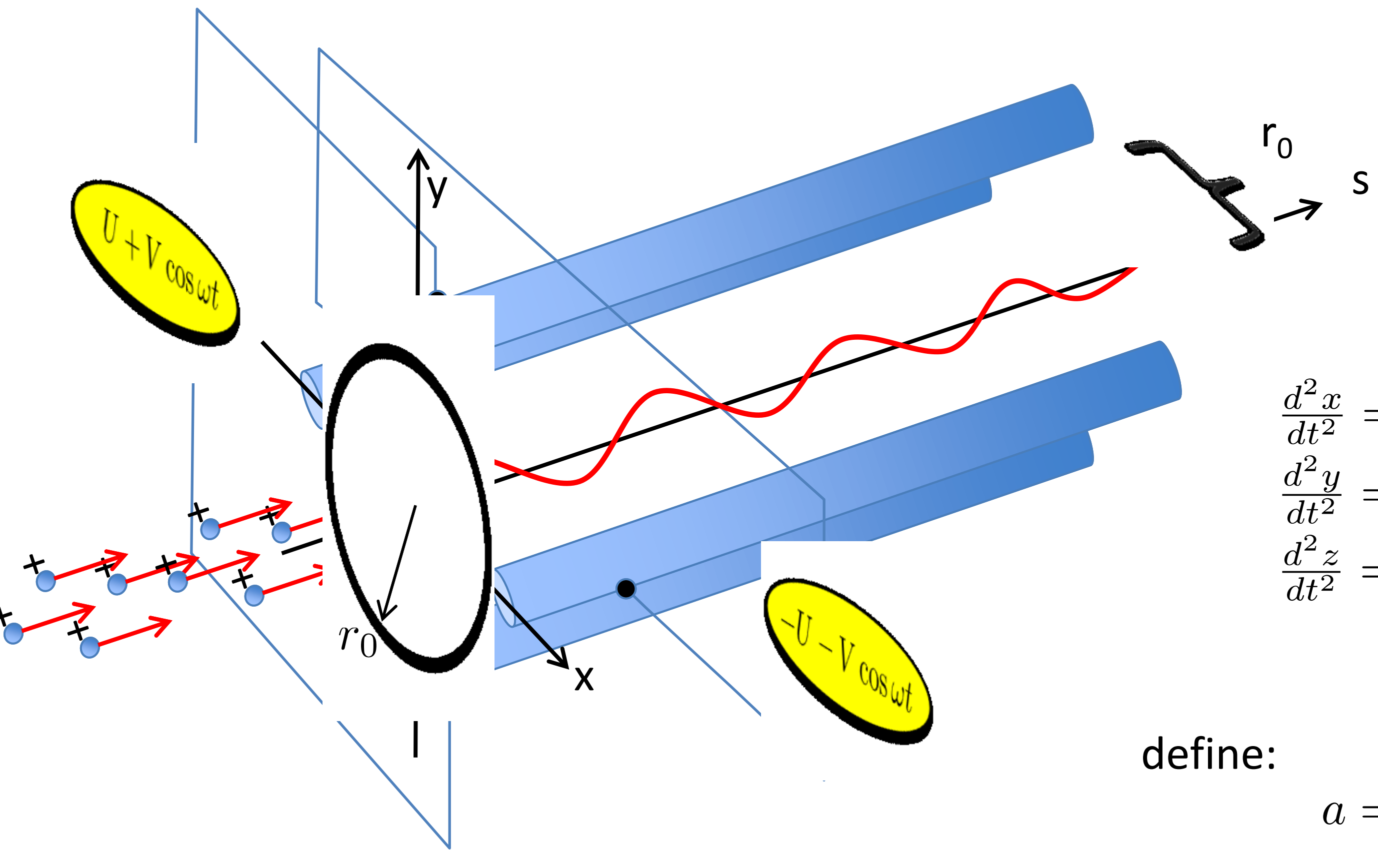
where

δ = secondary emission coefficient

V_c = collision energy

Mass Analyzers

Quadrupolar mass spectrometer



Ion equation of motion

$$\frac{d^2x}{dt^2} = +\frac{e}{m}\frac{1}{r_0^2}(U+V\cos\omega t)x$$
$$\frac{d^2y}{dt^2} = -\frac{e}{m}\frac{1}{r_0^2}(U+V\cos\omega t)y$$
$$\frac{d^2z}{dt^2} = 0$$

U, V constant

define:

$$a = \frac{4eU}{Mr_0^2\omega^2} \quad q = \frac{2eV}{Mr_0^2\omega^2}$$

By rescaling of the coordinates the equation of motion becomes

$$\frac{d^2x}{d\theta^2} = (a + 2q\cos 2\theta)x$$
$$\frac{d^2y}{d\theta^2} = -(a + 2q\cos 2\theta)y$$
$$\frac{d^2z}{d\theta^2} = 0$$

← Mathieu Equation

The ion motion can be stable or unstable

Stability of motion

	horizontal	**vertical**
q=0, a>0	unstable	stable
q=0, a<0	stable	unstable

The presence of the term q, changes the stability condition

Development of stable motion

Stable or unstable motion is referred to a channel which is infinitely long, but typically a length correspondent to 100 linear oscillation is considered enough

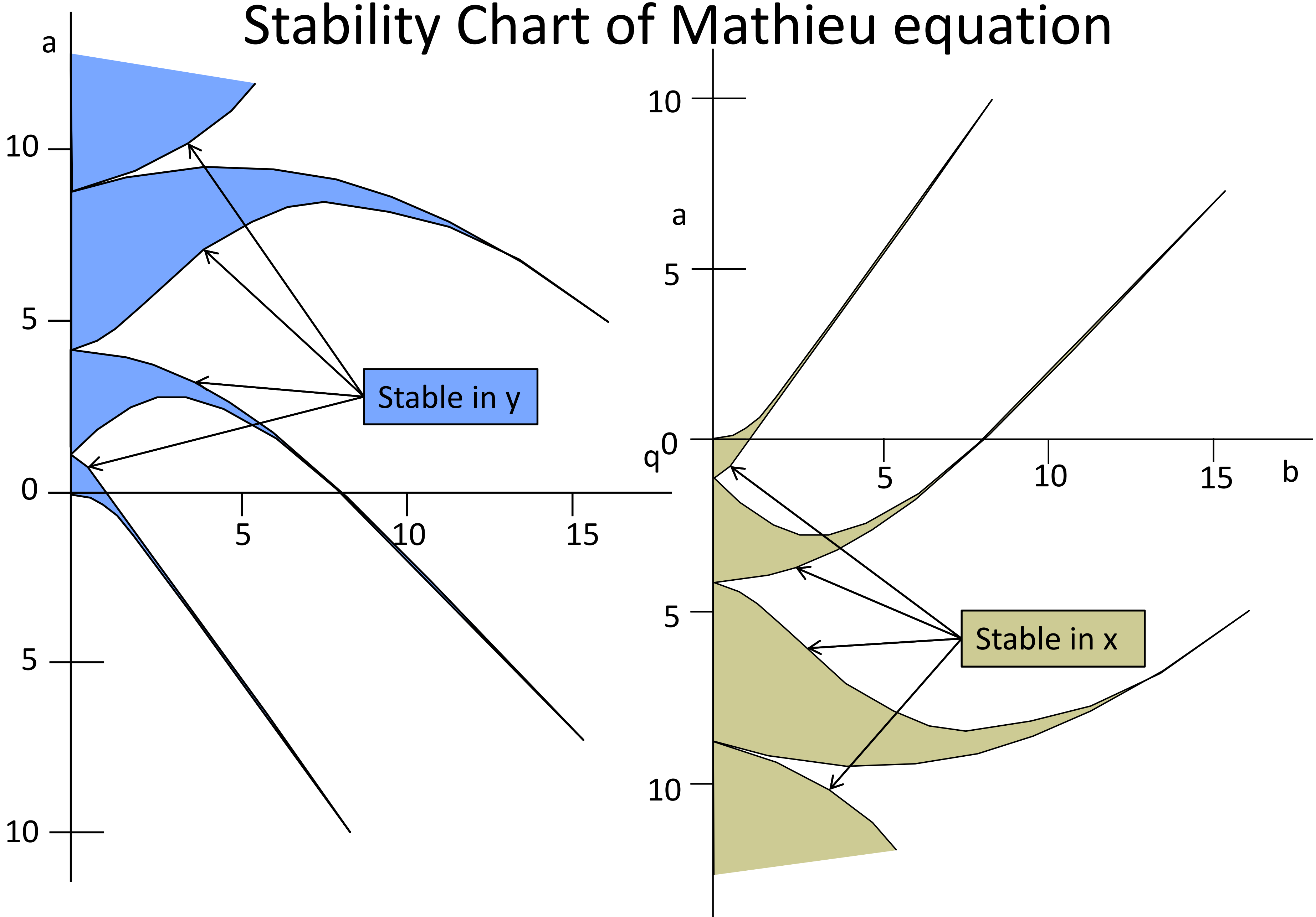
Example:

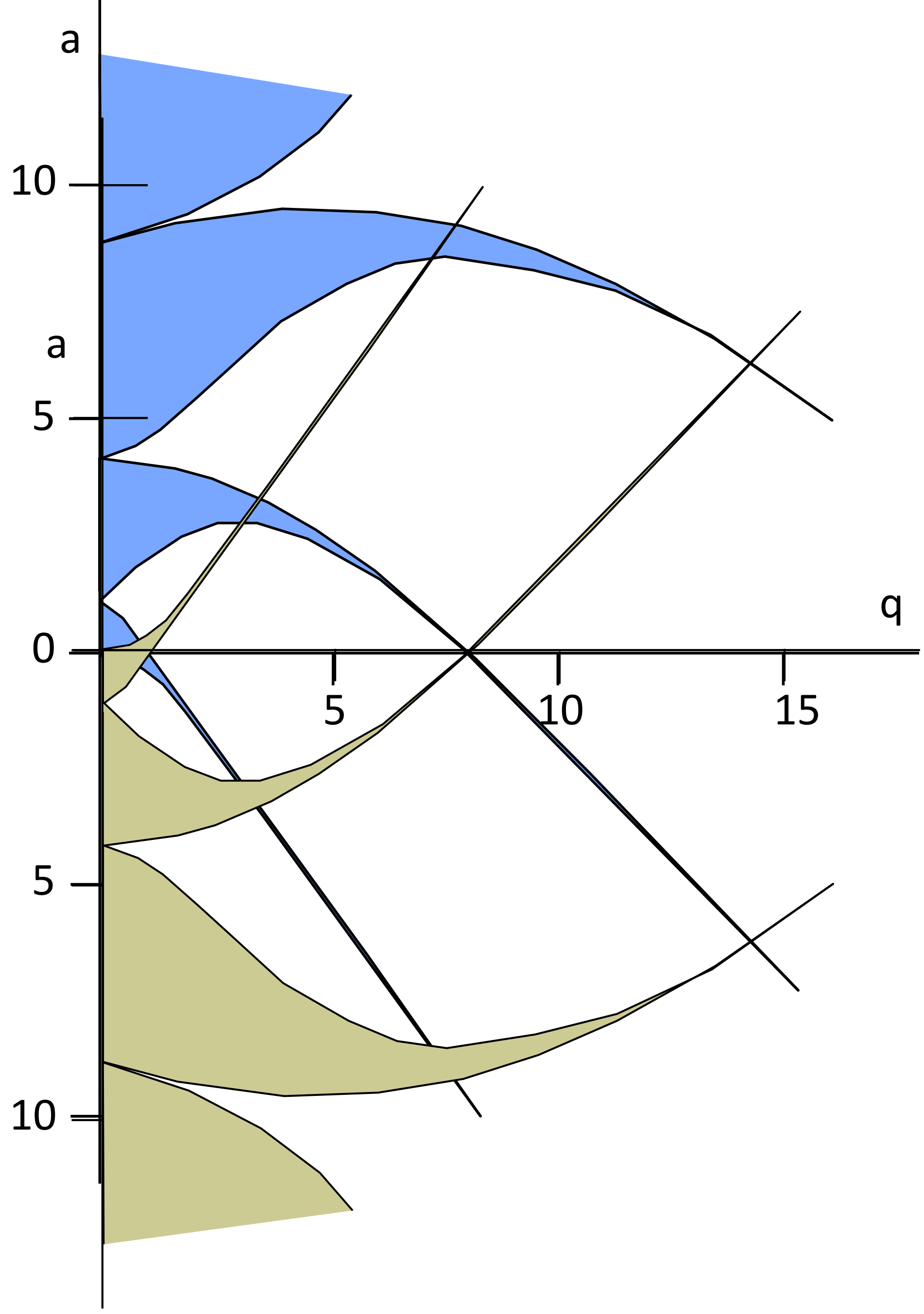
For N_2 at E_k = 10 eV → v_s = 8301 m/s

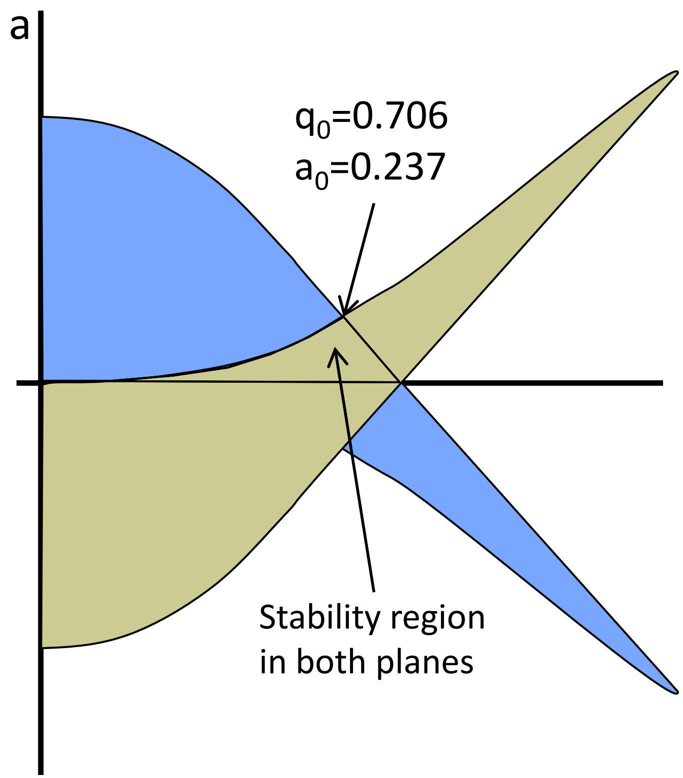
For a length of L = 100 mm
100 rf oscillation ⇒ f = 8.3 MHz

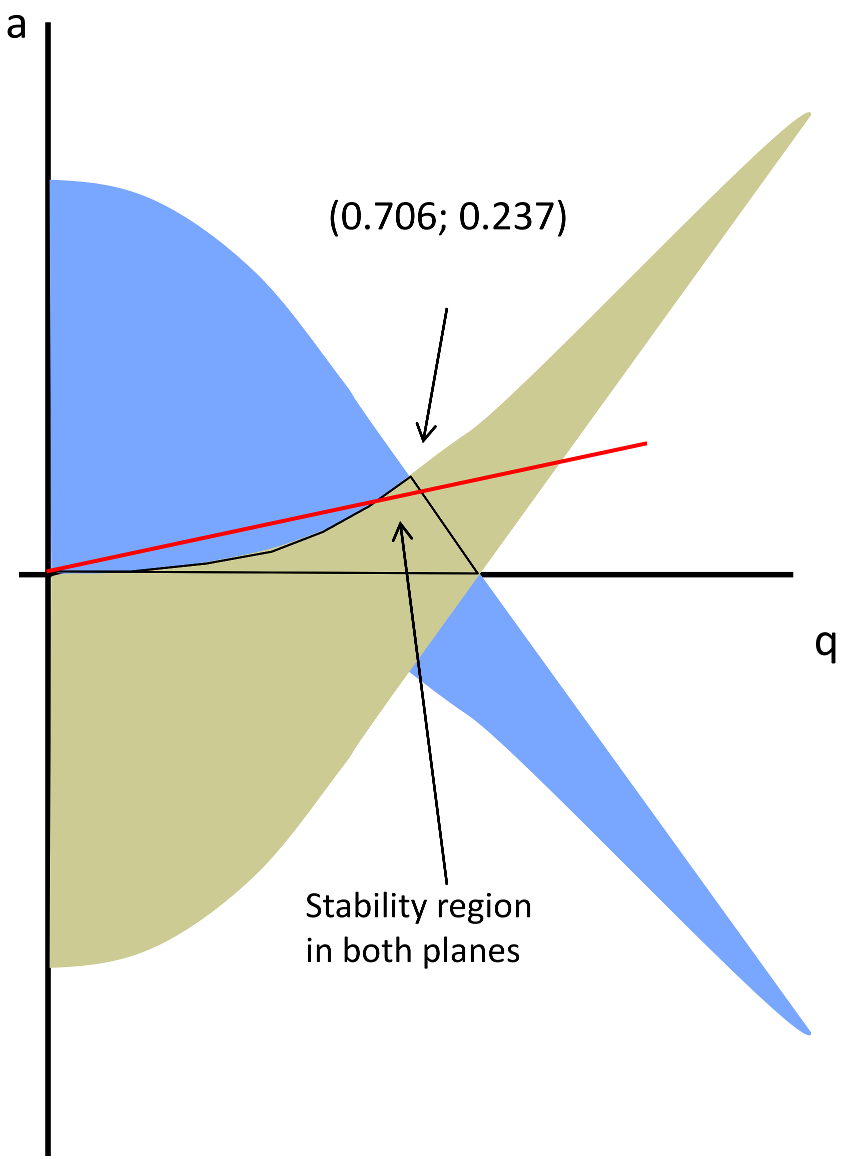
typically
f ~ 2 MHz

Stability Chart of Mathieu equation




a
10
a
5
0
q
5
10
15
5
10

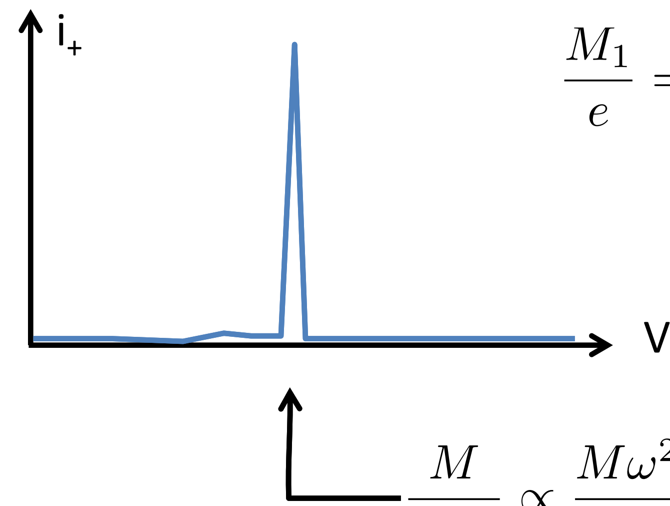

a
q_0=0.706
a_0=0.237
q
Stability region
in both planes



Given a certain species of mass M_1 there are two values U_1, V_1 so that $q=q_0$ and $a=a_0$

By varying V and keeping the ratio V/U constant, the tip of the stability is crossed and a current is measured at $V=V_1$

$$\frac{M_1}{e} = \frac{2V_1}{q_0 r_0^2 \omega^2}$$



$$\frac{M}{\Delta M} \propto \frac{M\omega^2 L^2}{2eV_z}$$

Magnetic Sector Analyzer

Example: A 90^0 magnetic sector mass spectrometer

B is varied and when a current is detected then

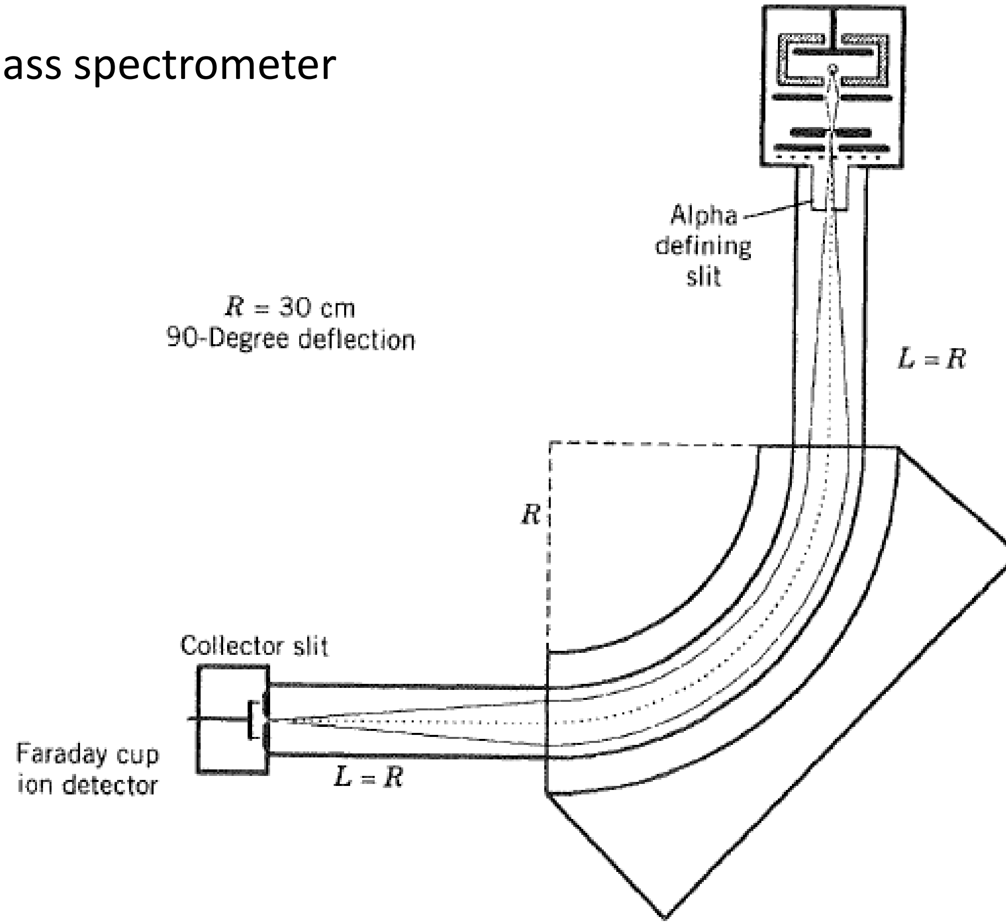
$$\frac{M}{q} = \frac{R^2 B^2}{2E_z/q}$$

E_z is the ions kinetic energy

Resolving power

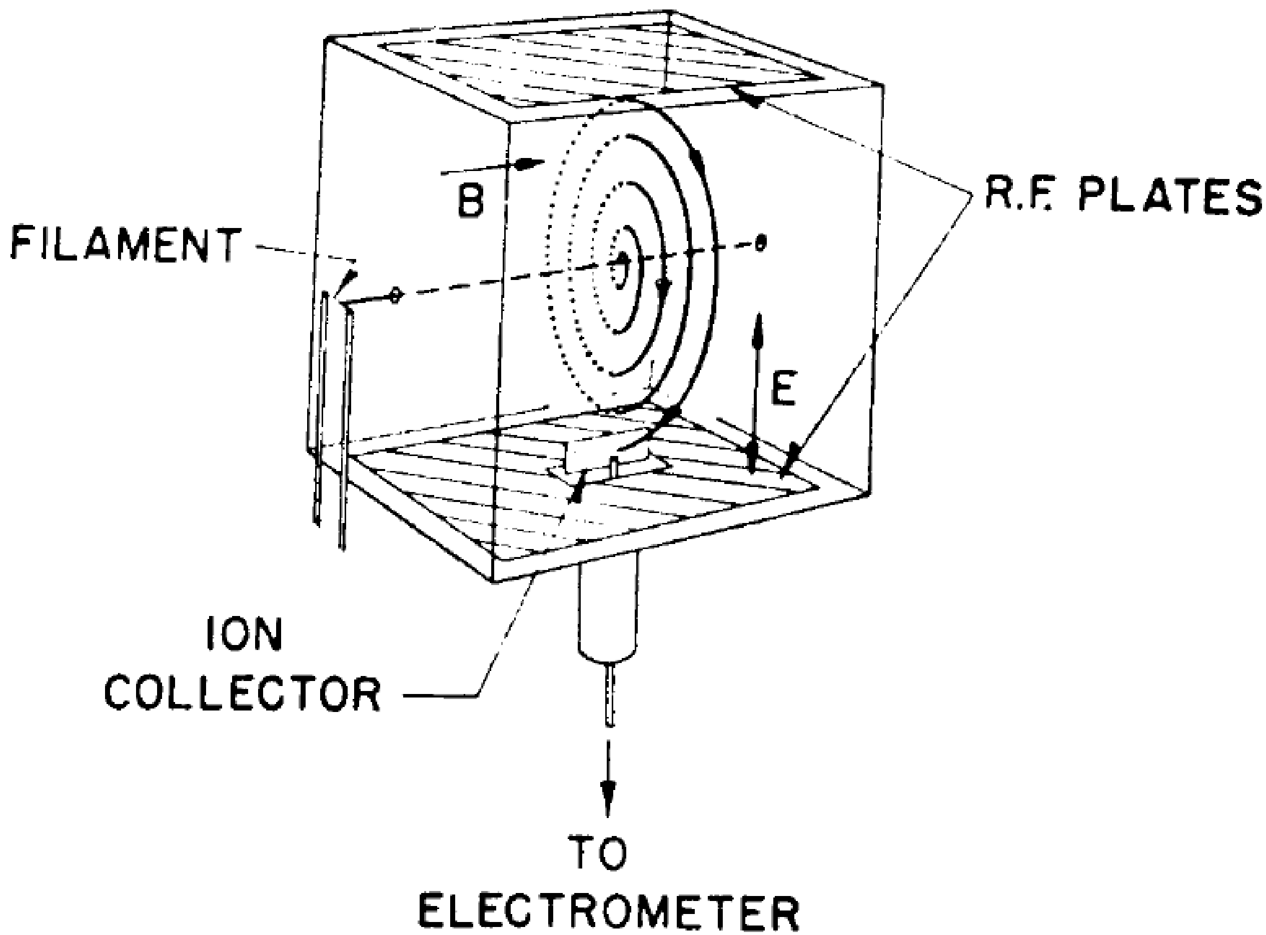
$$RP \simeq \frac{R}{W_{source} + W_{collector}}$$

W_{source} = source slit width
$W_{collector}$ = collector slit width



J.M. Lafferty, Vacuum Science, p. 462

Omegatron



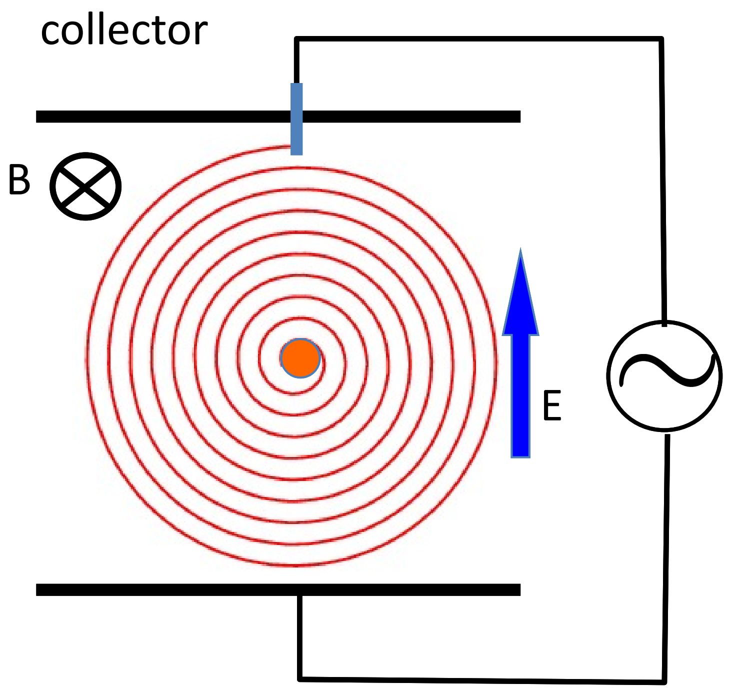
The revolution time is independent from ion energy

$$\tau = \frac{2\pi}{B}\frac{M}{q}$$

If the frequency of the RF is 1/τ a resonant process takes place and particle spiral out

Resolving power

$$\frac{M}{\Delta M} = 4.8 \times 10^{-5}\frac{R_0 B^2}{E_0}\frac{e}{M}$$

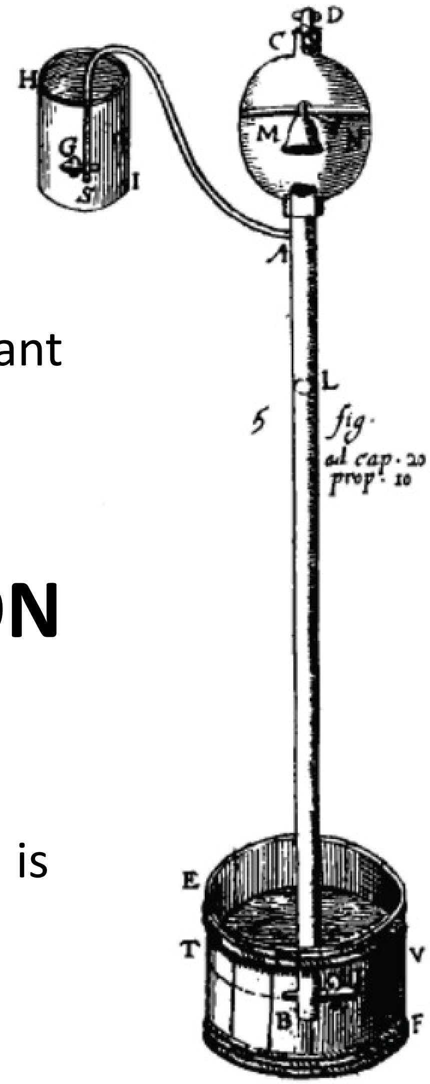


Conclusion

Creating and controlling vacuum will always be a relevant part of any accelerator new development.

THANK YOU FOR YOUR ATTENTION

These two lectures provides an introduction to the topic, which is very extensive: further reading material is reported in the following bibliography



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