Introduction to Vacuum Science and Technology

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Defining Vacuum

- Ideal
  - Classical metaphysics: a space containing nothing
- Real
  - Any subatmospheric pressure
- Practical
  - any volume which has fewer gas molecules than the same size volume in the surrounding atmosphere

A Brief History of Vacuum: the Classical View

- From the Greeks through the Renaissance absolute vacuum (ie, space containing nothing) was believed to be non-existent

"*horror vacui-nature abhors a vacuum*" – Aristotle

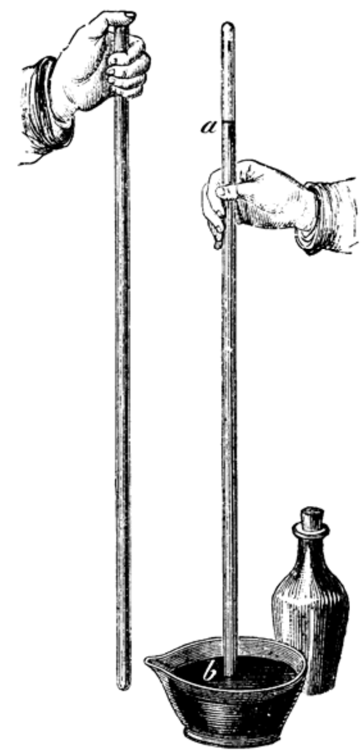
- conflicted with early ideas of the universe being comprised of countless, individual particles
- would a perfect vacuum imply unimpeded motion
- upheld by Renaissance writers (Descartes) and the Church

A Brief History of Vacuum: Vacuum Technology is Born

- **Galileo** (1564—1642) attempted to measure the force that a partial vacuum imparted piston

- **Torricelli** (1608—1647) first to produce a vacuum with an inverted Hg column (the first vacuum gauge, barometer, altimeter)

- **Pascal** (1623—1662) put the concept of "horror vacui" to rest by measuring the force of atmospheric pressure on an evacuated space



ISI Unit of Pressure:

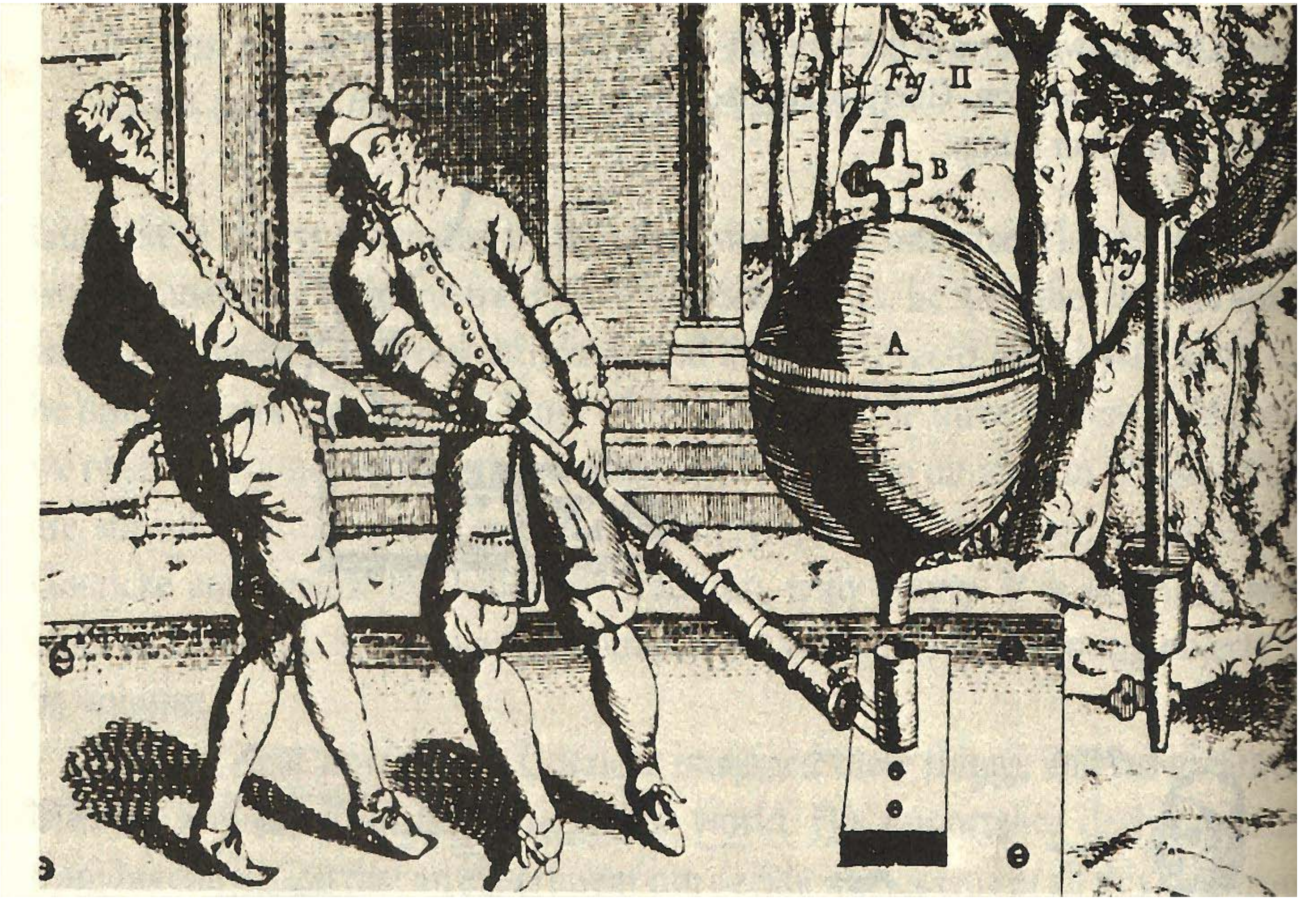
1 Pa = 1N/m^2 =7.501 x10 $^{-3}$ Torr = 10^{-2} mbar

Otto von Guericke (1602-1686)

Burgermeister of Magdeburg

- Experimenter in vacuum and electrostatics
- Modified water pumps, invented the air pump (1650) and the first manometer (1661)
- “Magdeburg Hemispheres” experiment (1654)

Mechanical Air Pump (O. von Guerke, 1640)



Compressing the History of Vacuum:1800-2000

– the pioneer period, Charles, Boyle, etc.

  -fundamental gas laws

– late 1800's
  - McLeod gauge
  - 0.1 to 1 mTorr (mbar)
  - Geissler, Thomson, Edison, "cathode ray" studies, pumps, gauges

– early 1900's
  - diffusion pump
  - capacitance manometer, Pirani gauge
  - 10^{-6} Torr (mbar)

– mid 1900's
  - Bayard-Alpert gauge, ion pump
  - UHV and UHV hardware

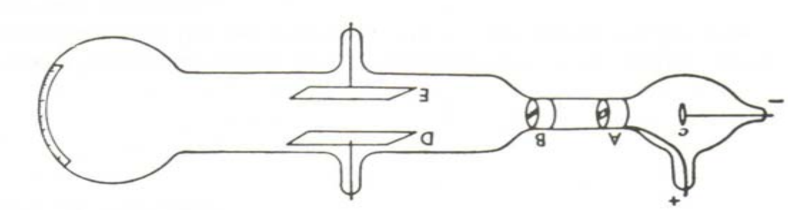
– 1970—1990
  - Commercial turbopumps and cryopumps
  - dry pumping (getters)

Edison's Vacuum Pump for His First Lamps: 1879

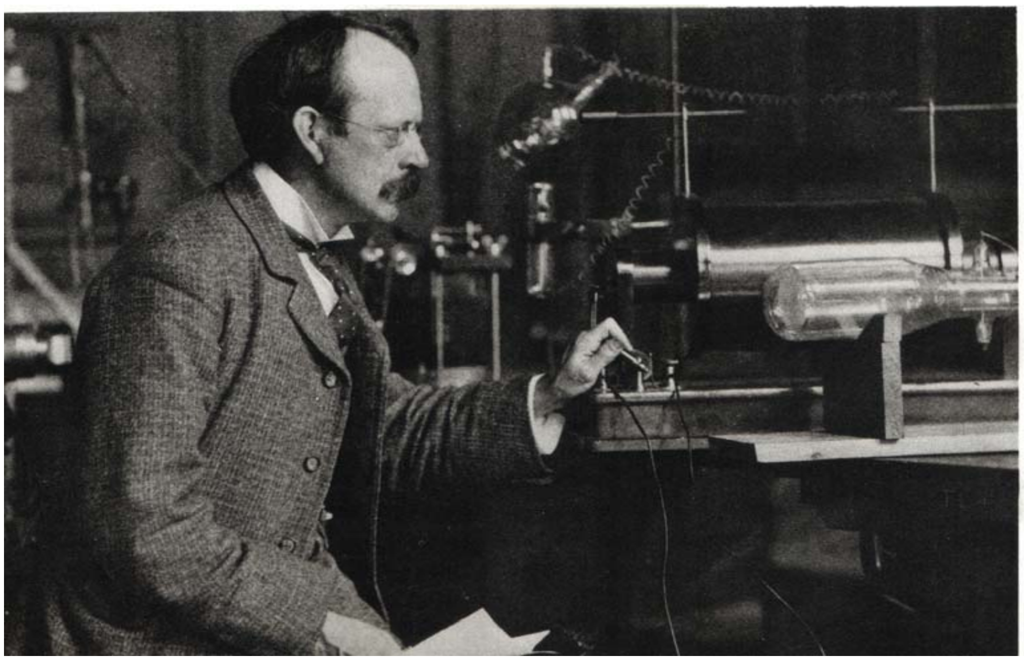
- **Mercury Drop Pump developed by Geissler and improved by Sprengel**
- **Modified by Thomas Edison for his early experiments and then first production of electric lamps**
- **Likely to have produced vacuum conditions <10^{-3} mbar with chemical gettering of water**

Thompson’s Discovery of the Electron (1897)

Thomson incorporated Crooke’s improvements to Sprengel’s pumps and sealing technology to produce the first electron beam unshielded by background ions



- **Thompson’s second tube**



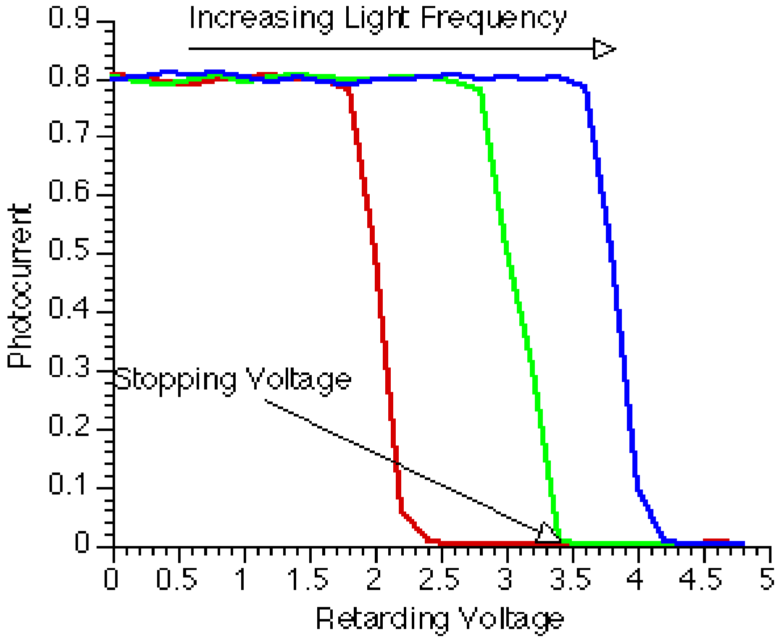
J. J. Thompson in his Cavendish Laboratory

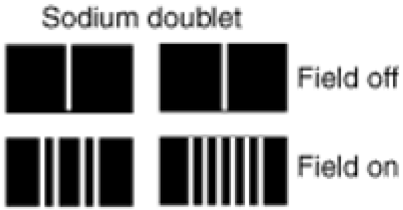
From Early Vacuum Tubes: the Dawn of Modern Physics

The physics we learned from the low pressure discharges:

The first observed sub-atomic particles (electrons and nucleons)
Energetic radiation (x-rays)
Physical measurements which heralded the birth of quantum mechanics

the photoelectric effect:





atomic spectra observed in high magnetic and electric fields

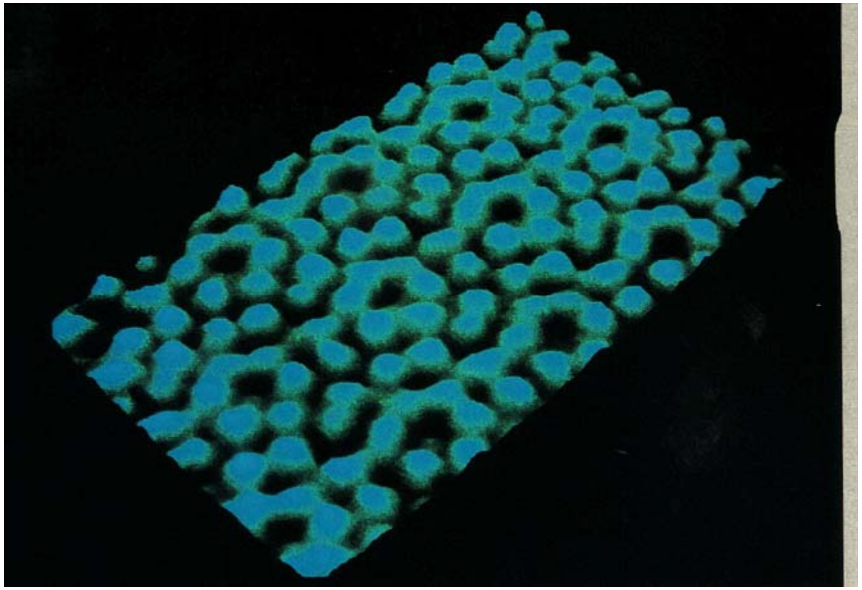
Uses of Vacuum for Science and Technology

- **To extend (and maintain) molecular Mean-Free-Paths**
  - Electron tubes
  - Early generation particle accelerators and CTR devices
  - Mass spectrometers and vacuum instruments
  - Vacuum coaters
  - High voltage and thermal insulation
- **To obtain (and maintain) clean surfaces**
  - Surface analysis and instrumentation
  - Cleaning prior to film deposition
  - Molecular Beam Epitaxy (MBE) devices
  - Contemporary accelerators and magnetic fusion devices

Vacuum Technology's Key Role in Materials Science

Tools for materials analysis

- electron spectroscopy (AES/ESCA)
- scanning probe techniques



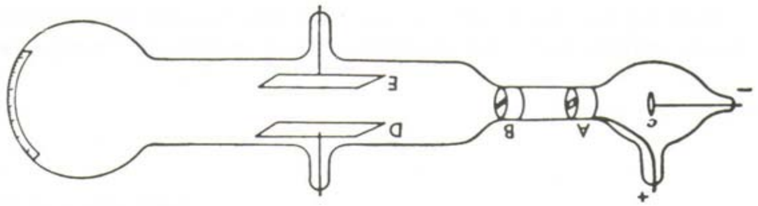
(IBM)

From Millivolts to Teravolts

The primitive “Thomson Tube” has evolved to TV-class accelerators used to probe sub-nuclear to stellar dimensions and timescales

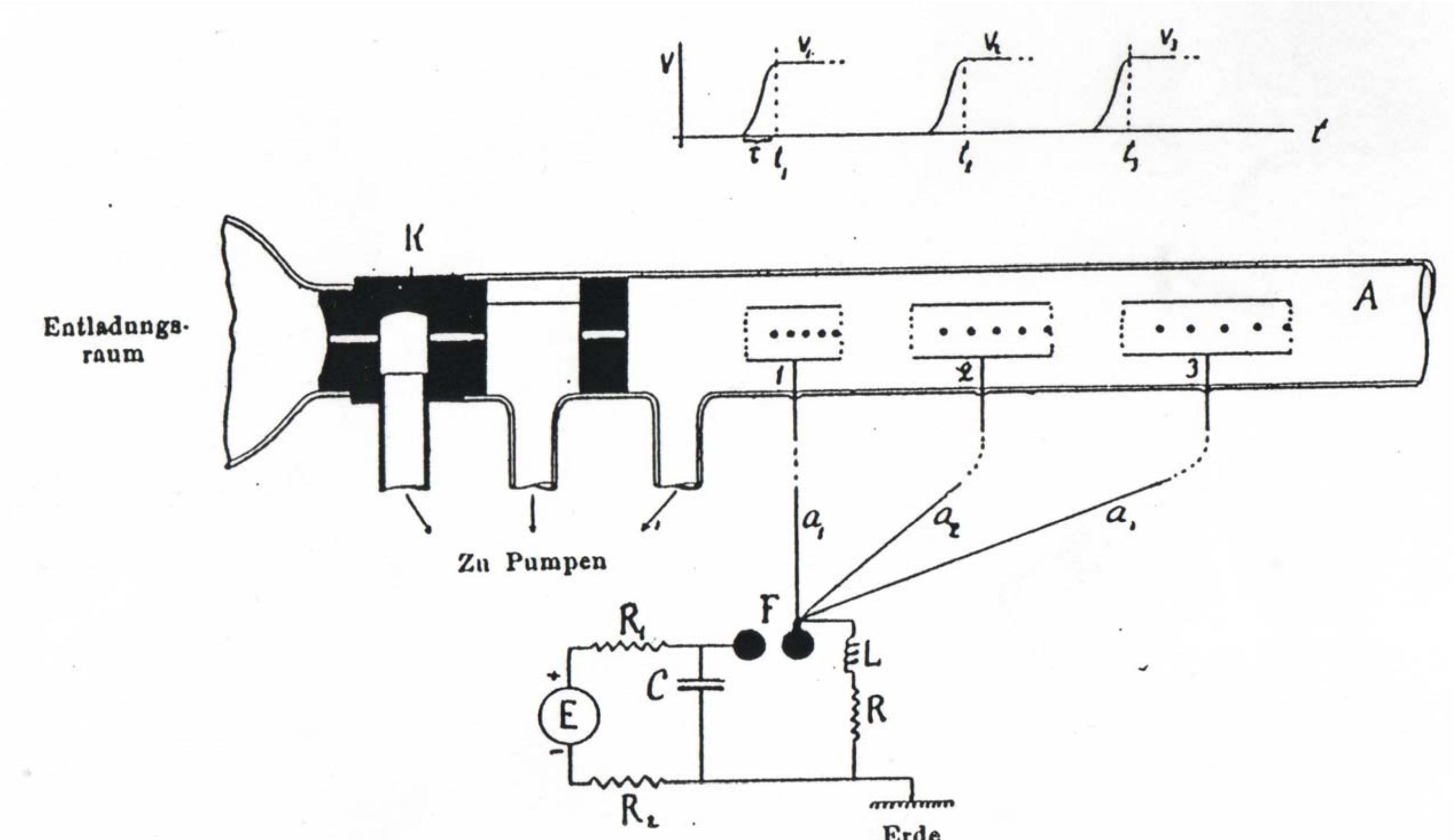
Accelerators at the turn of the last century:

- **the Thomson and Roentgen tubes were electron and ion accelerators at the kV range**



First Generation of Accelerators

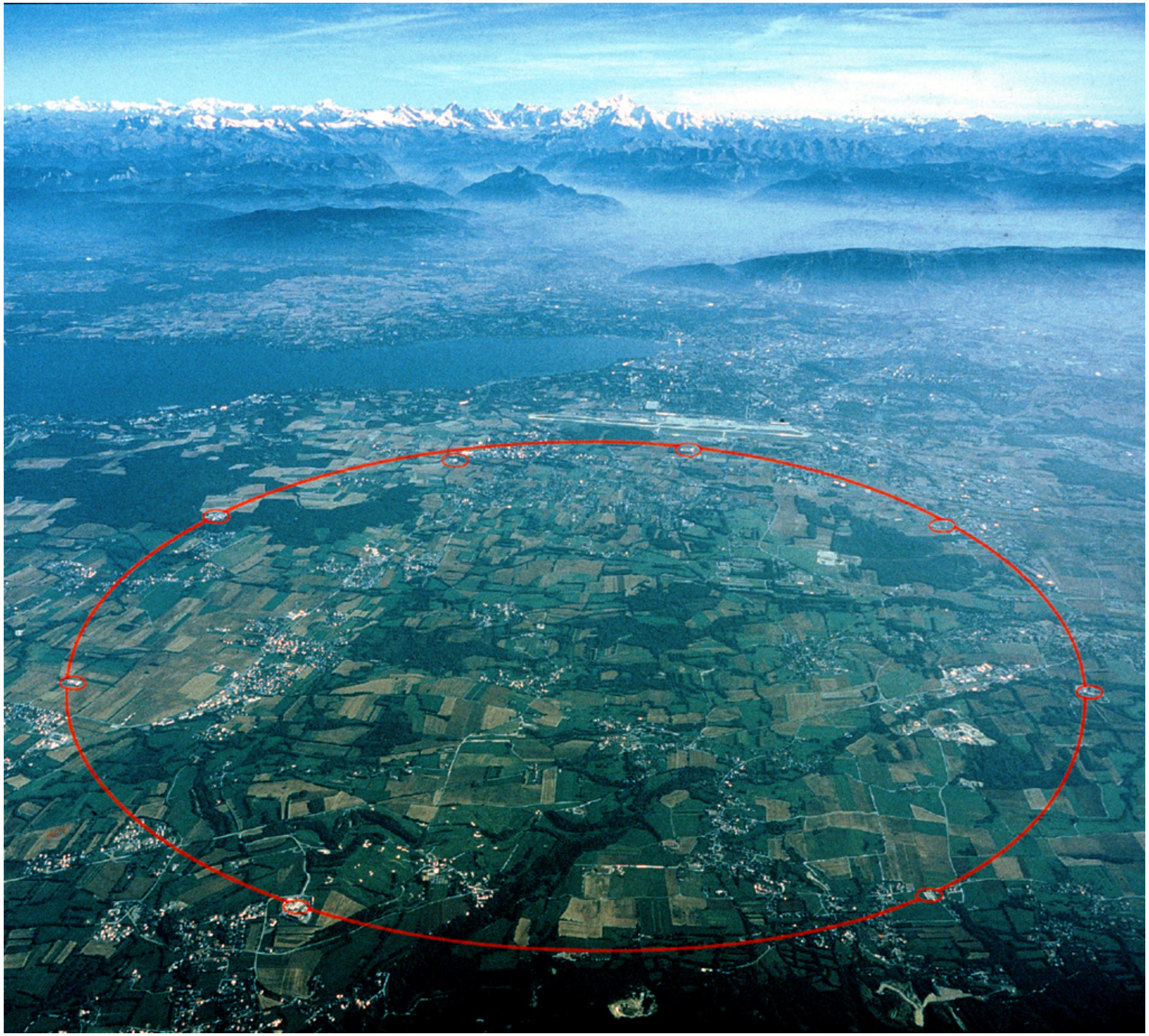
- **G. Ising's pioneering RF Linear Accelerator (1924)**



R. Wideroe demonstrated device in 1928 with 50 keV K+

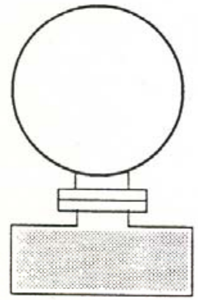
Accelerators: the Current Generation

CERN, showing the LEP/LHC ring

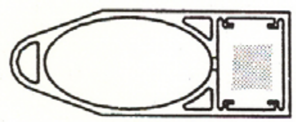


(CERN)

Vacuum system configuration



appendage pump



inserted "linear" pump

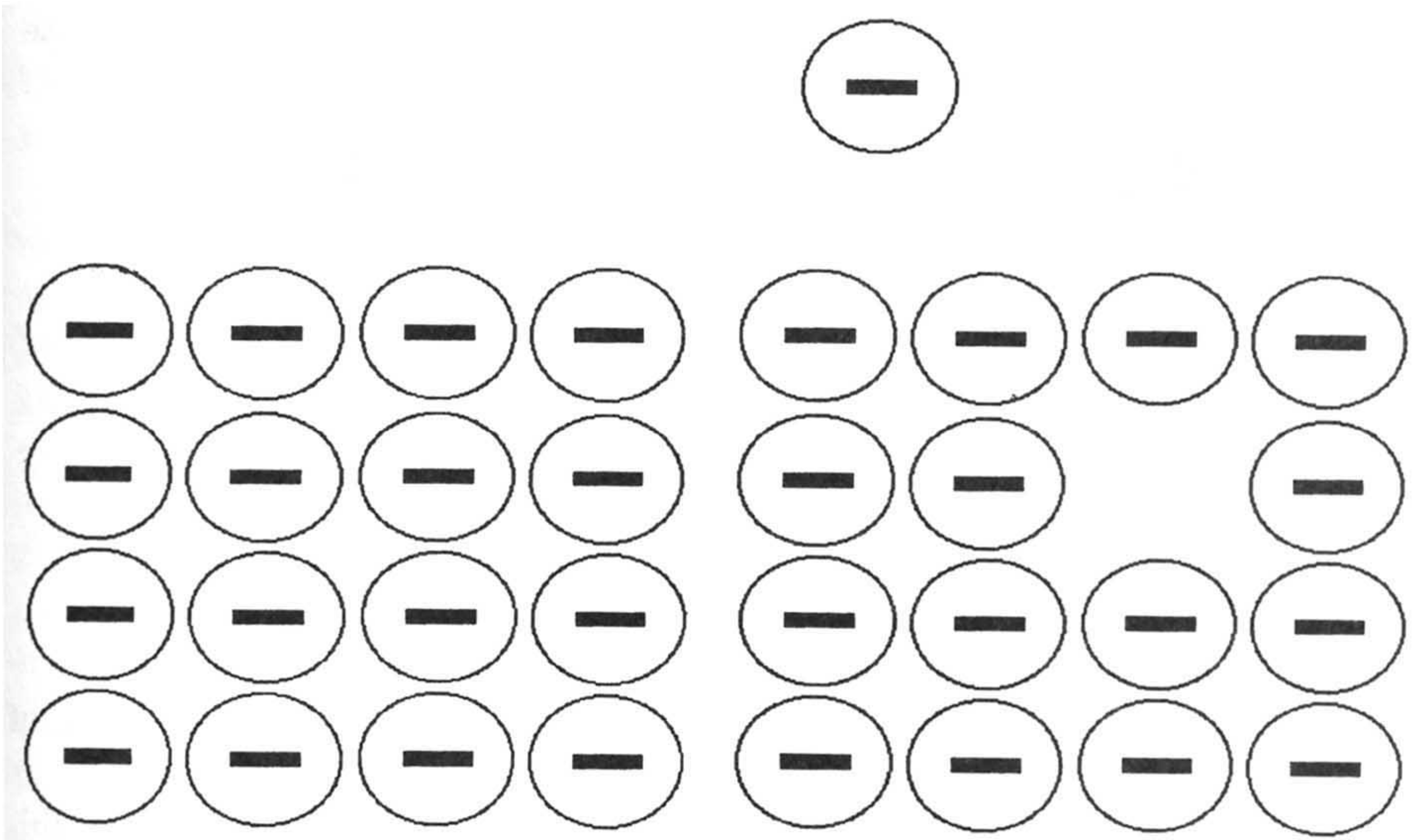
inserted "total" pump

surface pump/diffusion barrier

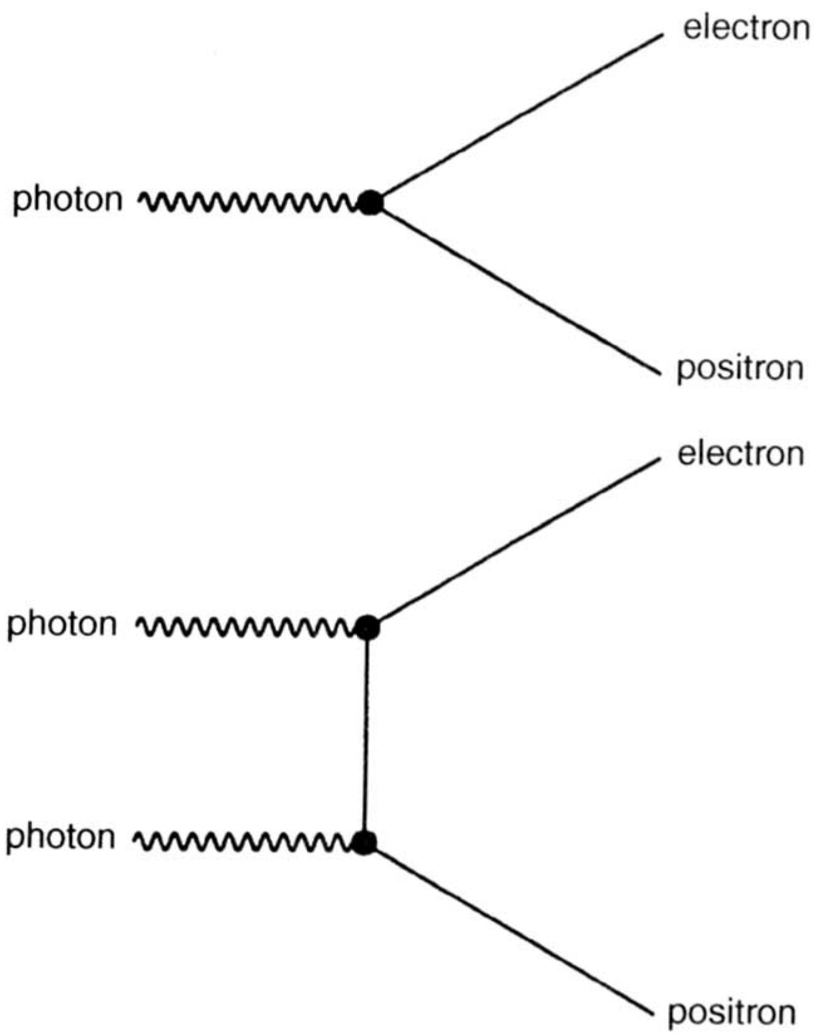
Ref: Benvenuti

Vacuum: the Modern View

The vacuum really isn't empty!
Dirac's sea of e^-e^+ pairs (1928)

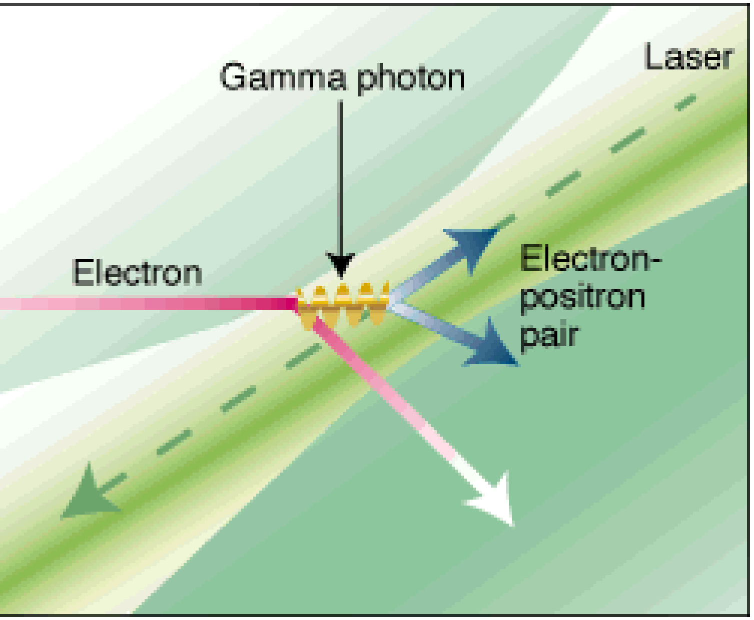


Electron-Positron Pair Production



Sparking the Vacuum

- **Stanford's sparking the vacuum experiment by K.T. McDonald, et al (*Science* <u>5330</u>,** 1202, 1997**)**



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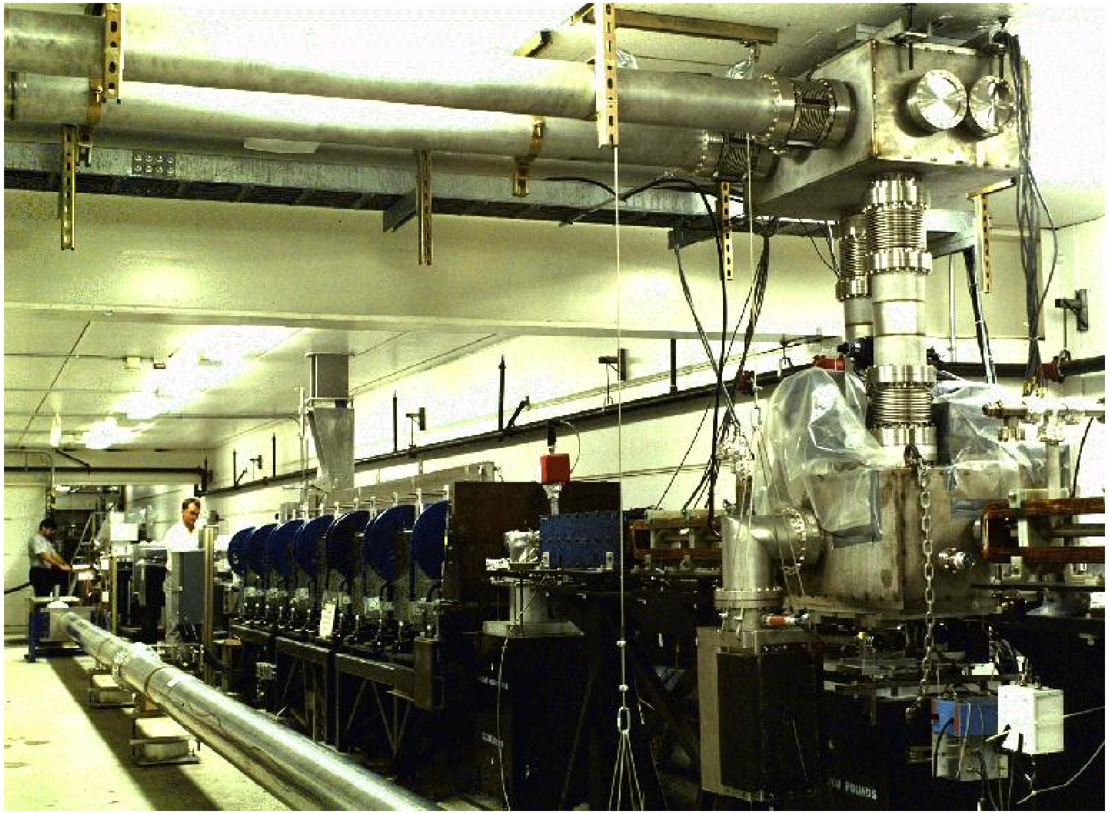

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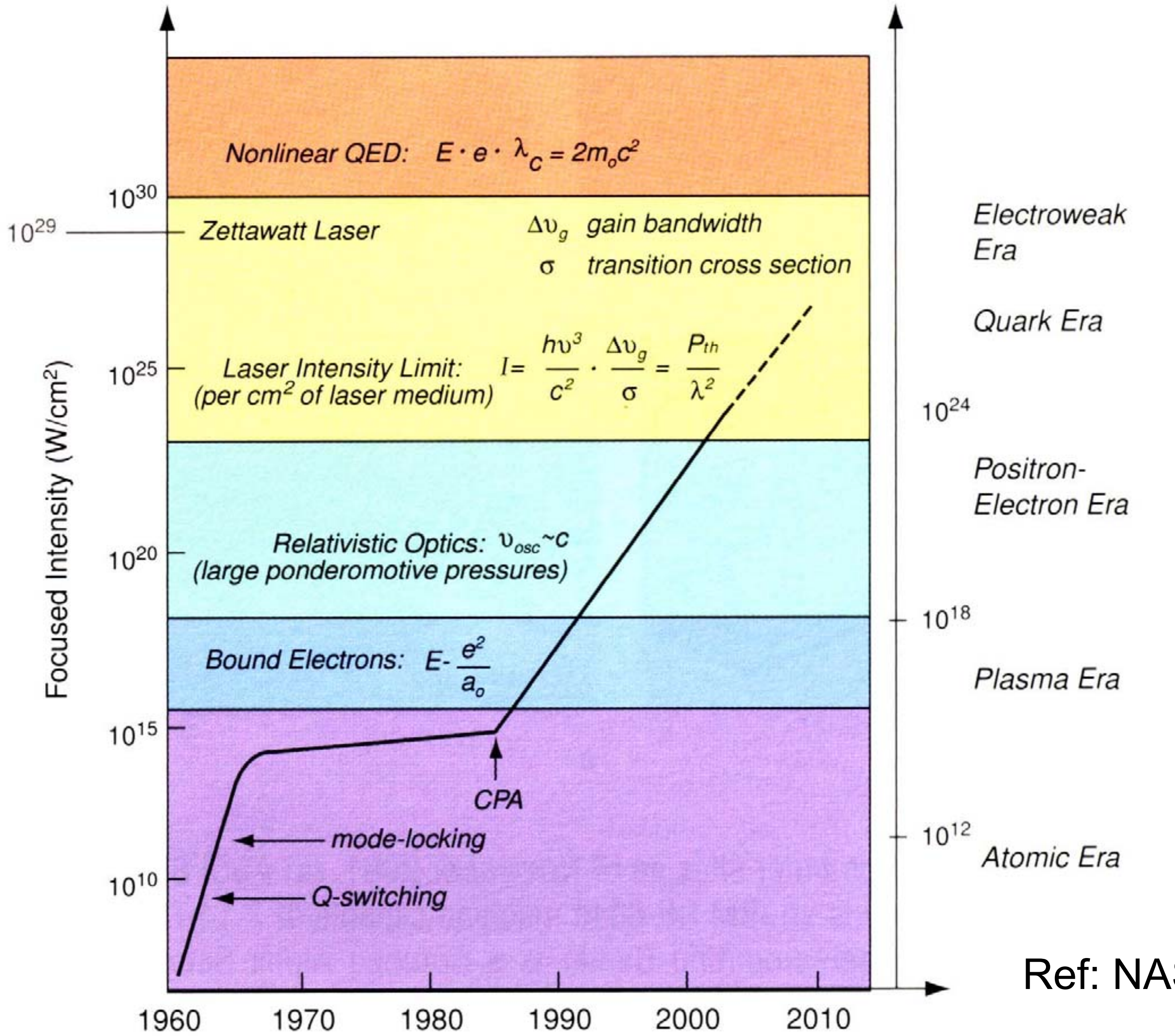
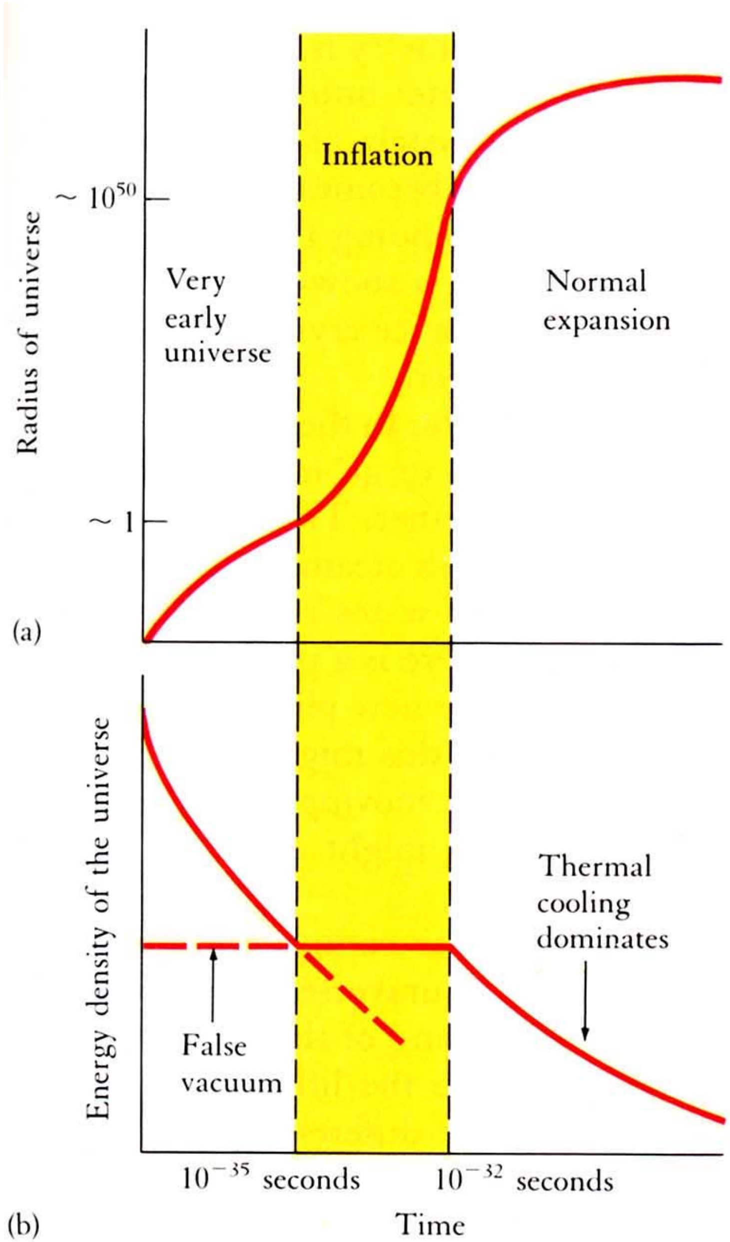
Back to the Beginning



Ref: NAS (2003)

False Vacuum and the Real Vacuum

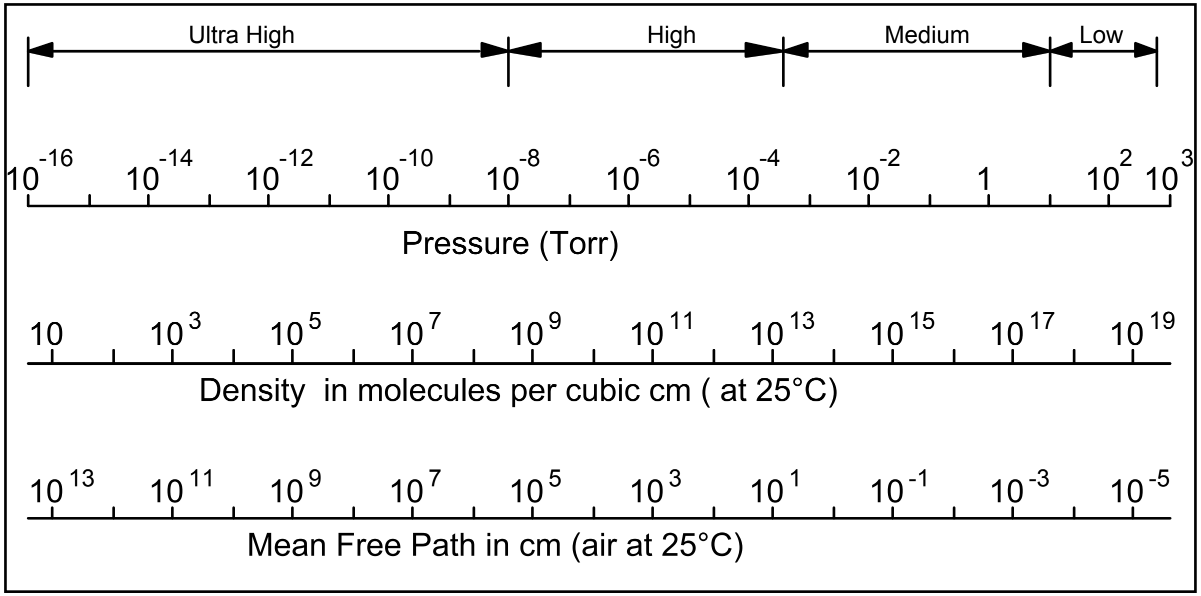


A.Guth (MIT)

Vacuum Physics: An Introduction

- Ideal gas laws and real gas corrections
- Kinetic theory: velocity distributions and gas temperatures
- Thermal conductivity and energy transport
- Gas flow regimes and transport phenomena
- Gas loads and ultimate pressures

Describing a Vacuum

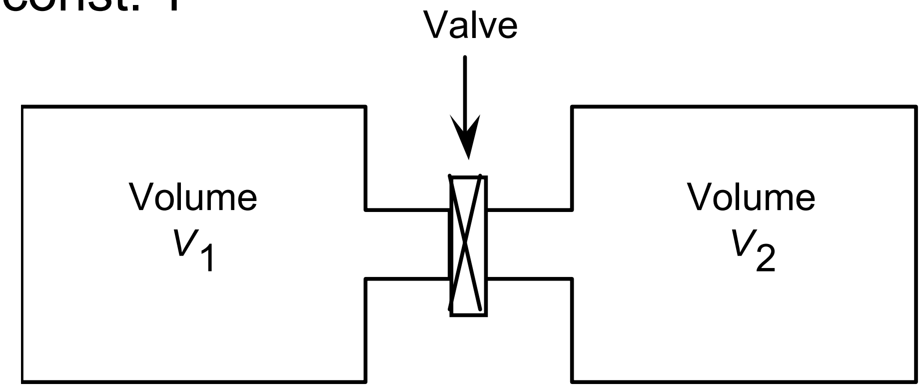


Gas Laws: Macroscopic Properties of a Low Pressure Gas

- Boyle's Law

$PV = nRT$ = constant at const. T

or $P_a V_a = P_b V_b$



- assumes constant temperature
  - wait for it to equilibrate
- assumes constant amount
  - you didn’t loose any to condensation

Gas Laws: Macroscopic Properties of a Low Pressure Gas

- Amontons' Law
  - Pressure is proportional to absolute temperature, for constant volume and amount

$$\frac{P}{T} = \text{constant} \qquad \text{or} \qquad \frac{P_1}{T_1} = \frac{P_2}{T_2}$$

- Charles' Law
  - Volume is proportional to absolute temperature, for constant pressure and amount

$$\frac{V}{T} = \text{constant} \qquad \text{or} \qquad \frac{V_1}{T_1} = \frac{V_2}{T_2}$$

Macroscopic Properties of a Low Pressure Gas

- Dalton's Law
  - in a mixture, each gas exerts its own pressure independently. Total pressure is the sum of the partial pressures.

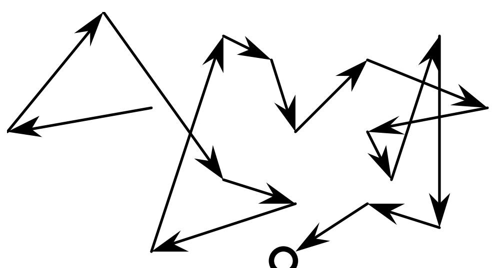
- Partial Pressure of Air (in Torr)

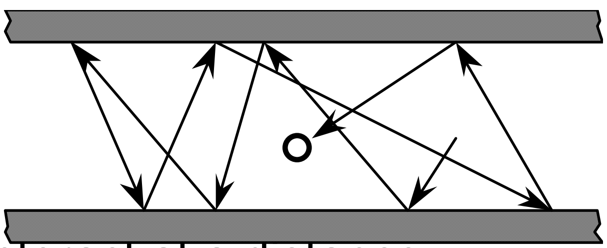
– N_2	593
– O_2	159
– Ar	7.1
– CO_2	0.25
– Ne	0.014
– He	0.004
– CH_4	0.0015
– H_2O	variable (to 17.5)

Kinetic Theory of Gas Molecules

Postulates

- Ideal gas laws (ie, non-interacting molecules) work well for most vacuum situations
- ramifications
  - separation vs. size of molecules
    - solids, about the same
    - gas, 1 atm, ≈ 300 times
    - gas, 1 mbar, ≈ 200 million times
  - “chaotic”

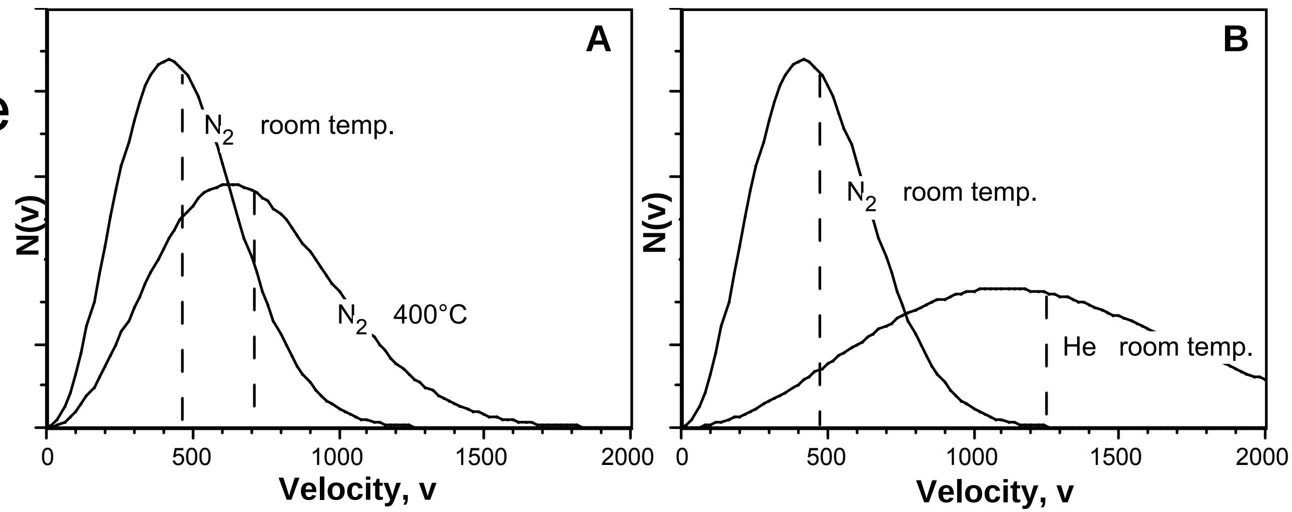




- theory does not apply when molecules interact at a distance
- behavior of the gas is the sum of the individual behaviors

Kinetic Theory of the Gas Molecules: The Maxwell-Boltzmann Distribution

- Velocity of a gas molecule



$$v_{\max} = \sqrt{\frac{2kT}{m}}$$

$$v_{\mathrm{av}} = \sqrt{\frac{8kT}{\pi m}}$$

$$v_{\mathrm{rms}} = \sqrt{\frac{3kT}{m}}$$

Ave. Molecular Velocities (at room temp)

H_2	1693 m/sec
He	1201
H_2O	566
N_2	454
Ar	380

Kinetic Theory of the Gas Molecules

– Mean Free Path

$$L = \frac{1}{\sqrt{2}\pi N d^2}$$

L (mm) = 6.6/P (Pa)

– Collision Rate with Surfaces

$$I = \frac{Nv}{4}$$

I (cm^2/s) $=2.63 \times 10^{24}$ P/√MT P(Pa)

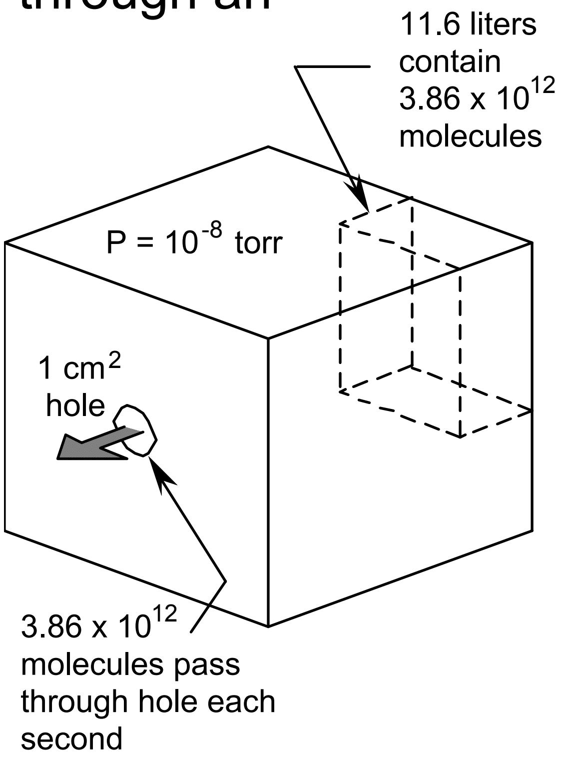
– Monolayer Formation Time

$$t_m = \frac{1}{Id^2} = \frac{4}{Nvd^2}$$

t_m (s) = *2.5 x* 10^{-4} */ P* (Pa)

Kinetic Theory of the Gas Molecules

Volumetric Flow through an Orifice



Gas Flow Regimes

- Flow Regimes
  - turbulent
  - laminar
  - molecular
- Knudsen Number
  - $Kn = L/d$
- Viscous flow
  - $Kn < 0.01$
  - gas-gas collisions
- Transition region
  - $1 > Kn > 0.01$
- Molecular flow
  - $Kn > 1$
  - gas-wall collisions

Thermal Conductivity of Gases

- Heat transfer by
  - convection, conduction, radiation

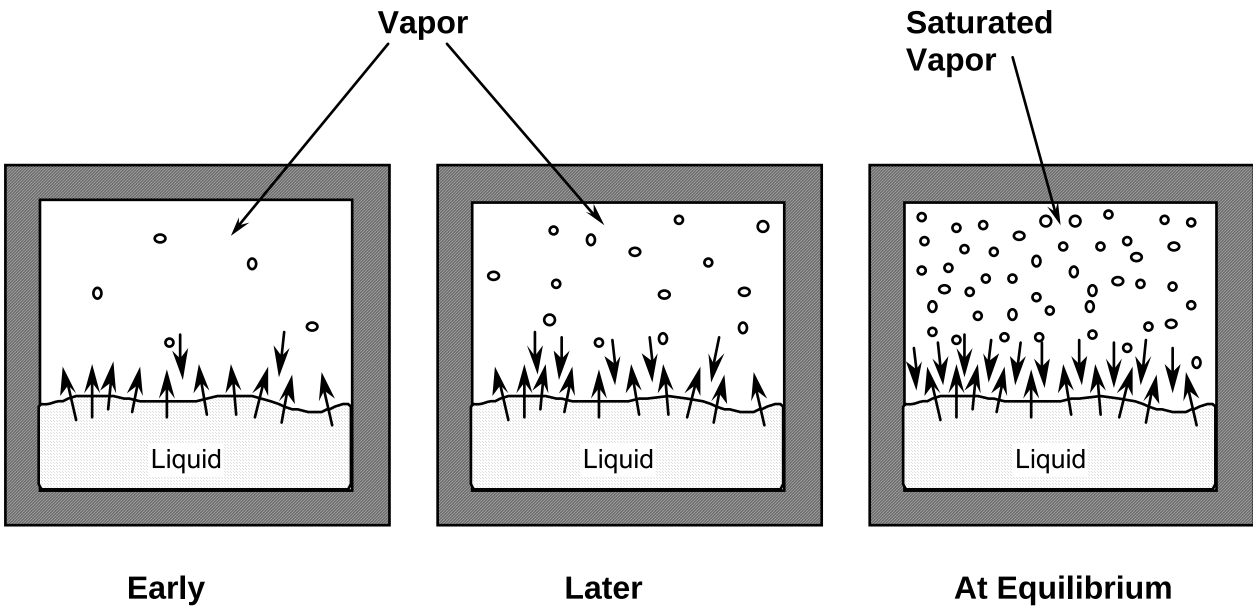
- at atm pressure, convection dominates

- below ~ 1 mbar, convection currents disappear and conduction predominates

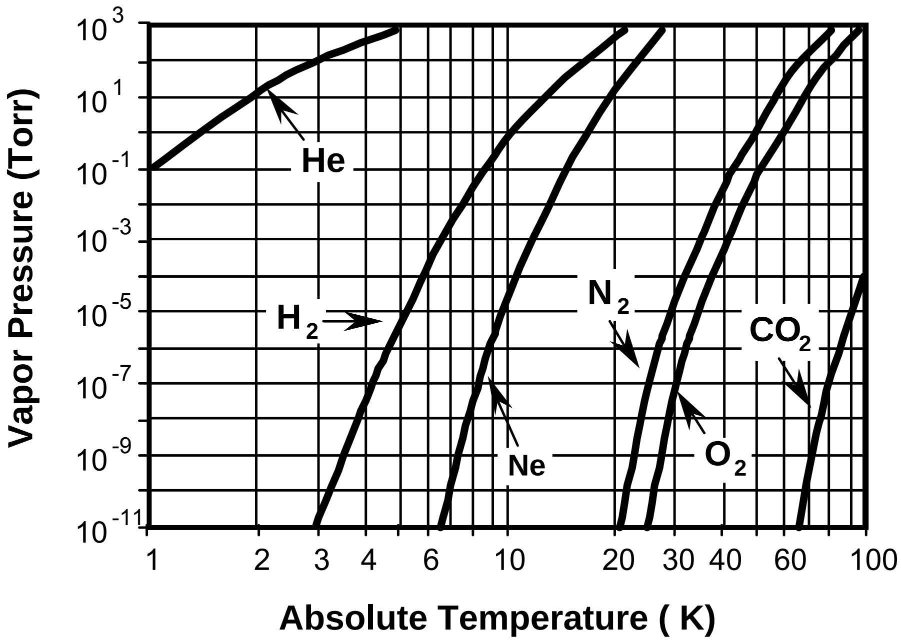
- for conduction,
  - while mfp short, molecule-molecule interaction
    - heat transfer a function of ΔT, but not of pressure
  - longer mfp, molecule-surface interaction
    - heat transfer depends on pressure
    - phenomena applied to low vacuum (thermocouple) gauging
  - when heat transfer is negligible, no longer a function of pressure
  - valid while $0.01 < Kn < 10$ or 1 mbar $< P < 1$ bar
    - can be extended, with effort (look-up tables)

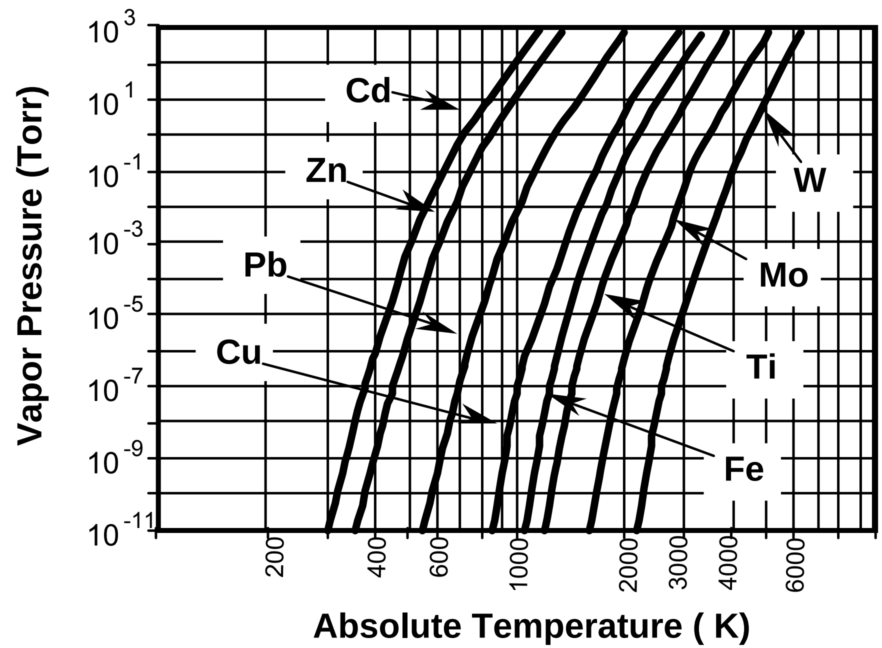
Vapor Pressure

- “vapor pressure” vs “saturation vapor pressure”
- for solids, sublimation instead of evaporation



Vapor Pressure

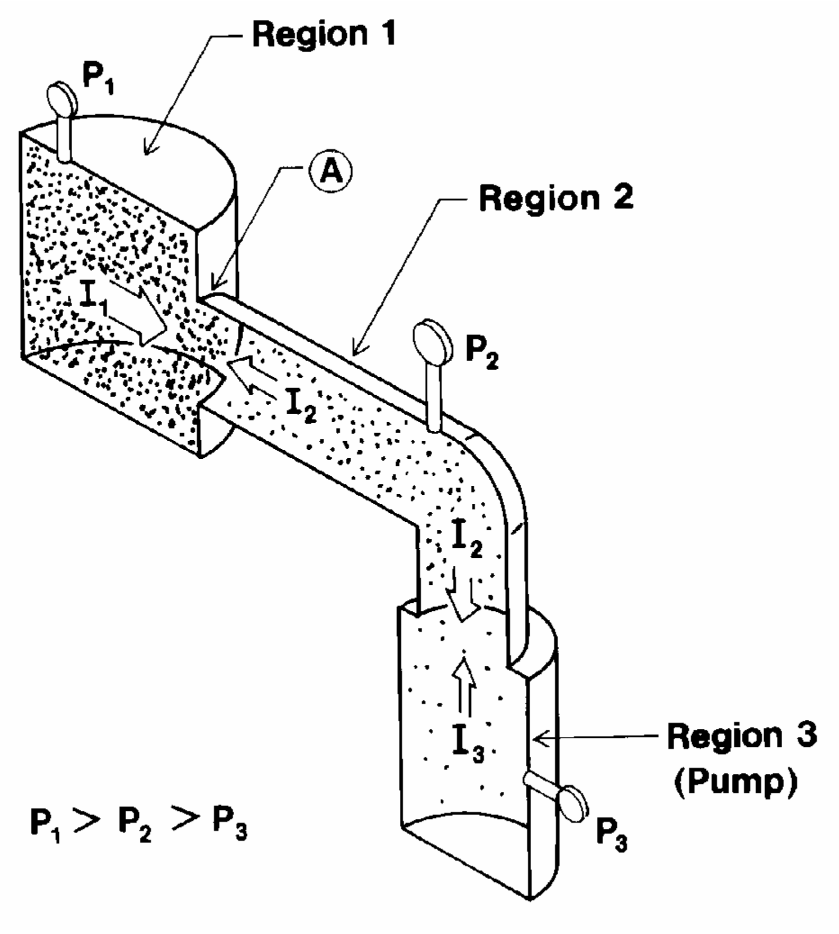




– data from R. E. Honig and D. A. Kramer, *RCA Rev.*, **30**, 285 (1969)

Gas Flow

- Molecular Flow



Gas Flow

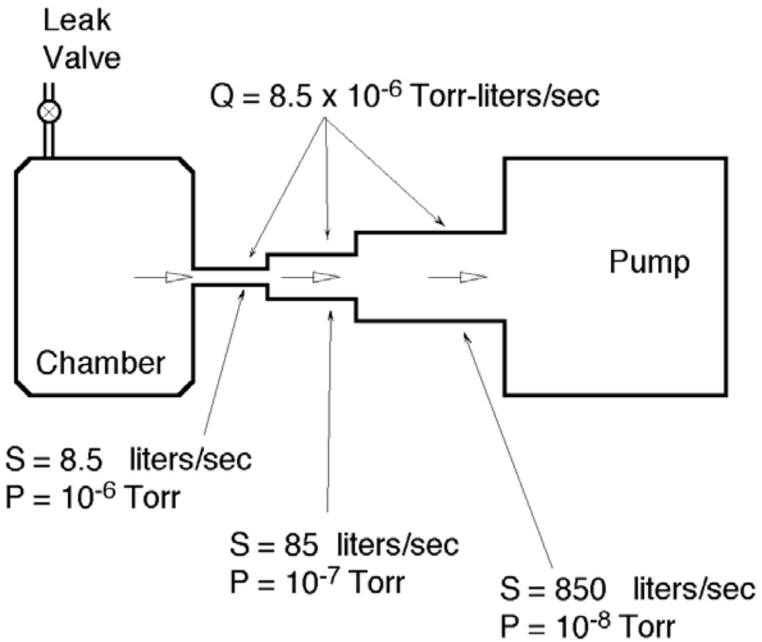
- Definition, Throughput and Pumping Speed

  rate of flow is influenced by:
  - capacity of pump
  - shape and dimensions of passage
  - type of flow (laminar, molecular, etc.)
  - gas characteristics

  flow rates are expressed in two ways:
  - Mass flow rate, Q
  - Volumetric flow rate, S

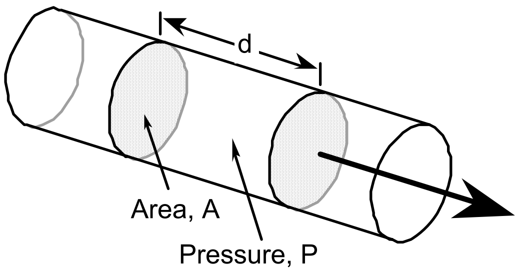
Gas Flow: Throughput and Pumping Speed

- mass flow rate, Q
  - called "throughput"
  - essentially the net number of molecules passing a given plane per unit time
  - By the ideal gas law equal to P-V per second
  - same throughout the circuit



Gas Flow: Throughput and Pumping Speed

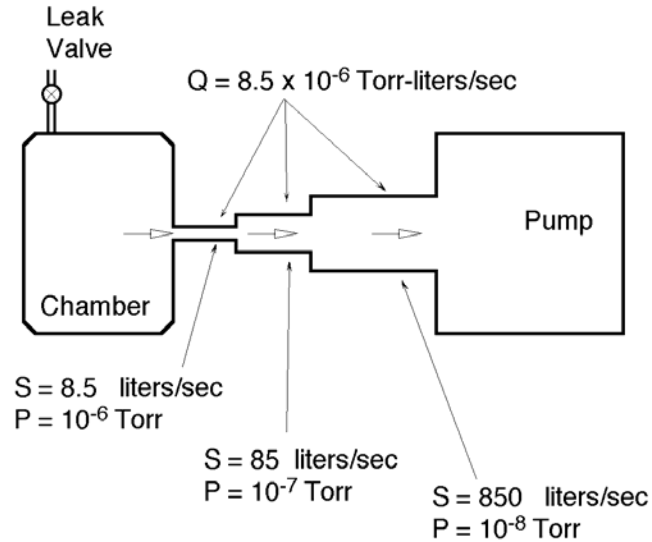
- Volumetric flow rate S
  - called “pumping speed” (sometimes misleading)
  - units are volume per unit time (e.g. liter/sec or cfm)
  - number of molecules depends on pressure
  - laminar flow, visualize volume moving along
    - regardless of pressure



  - molecular flow, not so easy to visualize
  - “volume” is the volume needed to contain the net number of molecules passing the plane per second
  - S is different throughout the circuit (next foil)

Gas Flow: Throughput and Pumping Speed

- Volumetric Flow Rate
  - S is different throughout the circuit



- Relationship between Q and S
  - Q = S x P
  - Q, S, P associated with a given plane or point
  - use of the term “pumping speed” will be made clearer in a later section

Gas Flow: Conductance

- Definitions
  - resistance

$$\left(P_1 - P_2\right) = ZQ$$

  - conductance

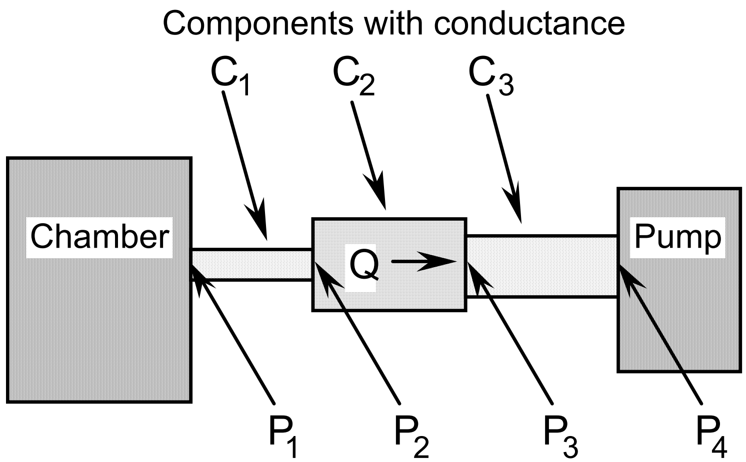
$$C = \frac{Q}{P_1 - P_2}$$

  - C, S, same units, but not the same quantity

Gas Flow: Combining Conductances

– in series

$$\frac{1}{C_t} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$



– in parallel

$$C_t = C_1 + C_2 + C_3$$

Conductance Example: Orifice

Conductance for a thin orifice:

$C = \frac{1}{4} v A$

For air at 22C:

$C(m^3/s) = 116\ A\ (m^2)$

$C(l/s) = 11.6\ A\ (cm^2)$

Note: this is the maximum conductance for an orifice;
for any structure with a thickness that can't be ignored
the conductance decreases by a transmission factor *a'* :

$C(l/s) = 11.6\ a'\ A\ (cm^2)$

Conductance Example: Long Tubes

Conductance under molecular flow conditions:

$$C = \frac{\pi}{12} v \frac{d^3}{L}$$

For air at 22C:

$$C\ (m^3/s) = 121 \frac{d^3}{L}$$

Therefore, for large d, short L --> large conductance

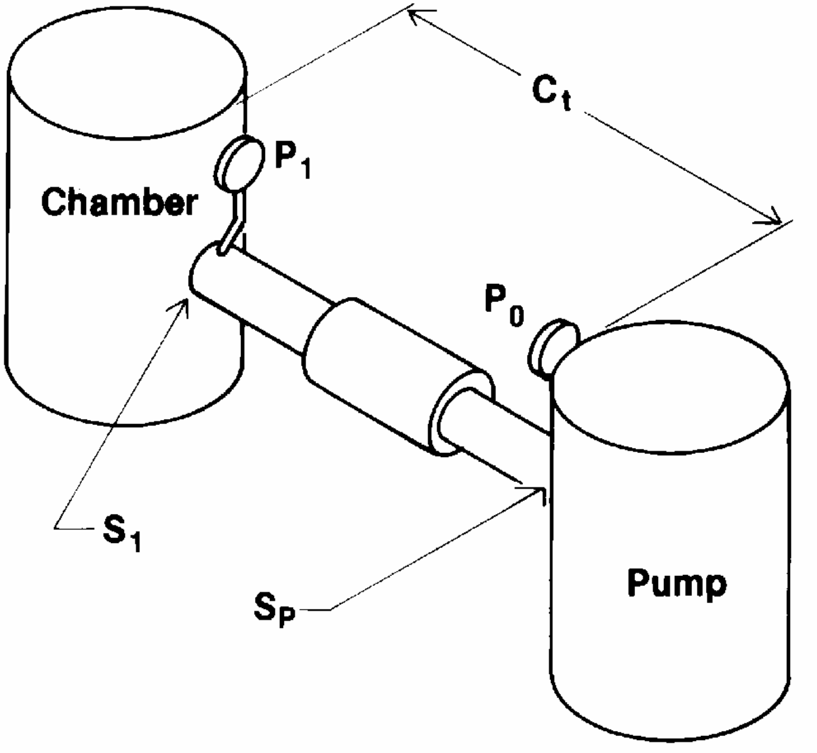
Pumping Speed/ Conductance Calculations

- Calculating Pumping Speed at different locations

Note: we have generalized the term “pump”

It is now reasonable to talk about “pumping speed” at places away from the pump

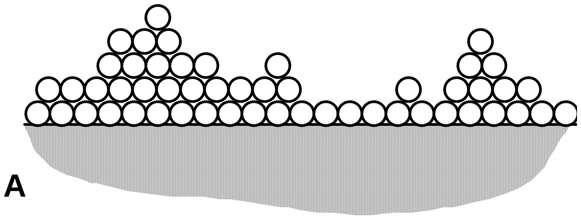
The pumping speed at any given point is no larger than the smallest conductance between the point and the pump



$$\frac{1}{S_1} = \frac{1}{S_P} + \frac{1}{C_t}$$

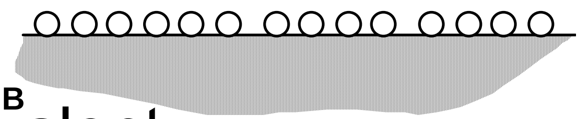
Surface Interactions

- Physisorption
  - dipole interaction
  - weaker bonding
  - non-selective
  - first stages of condensation



A

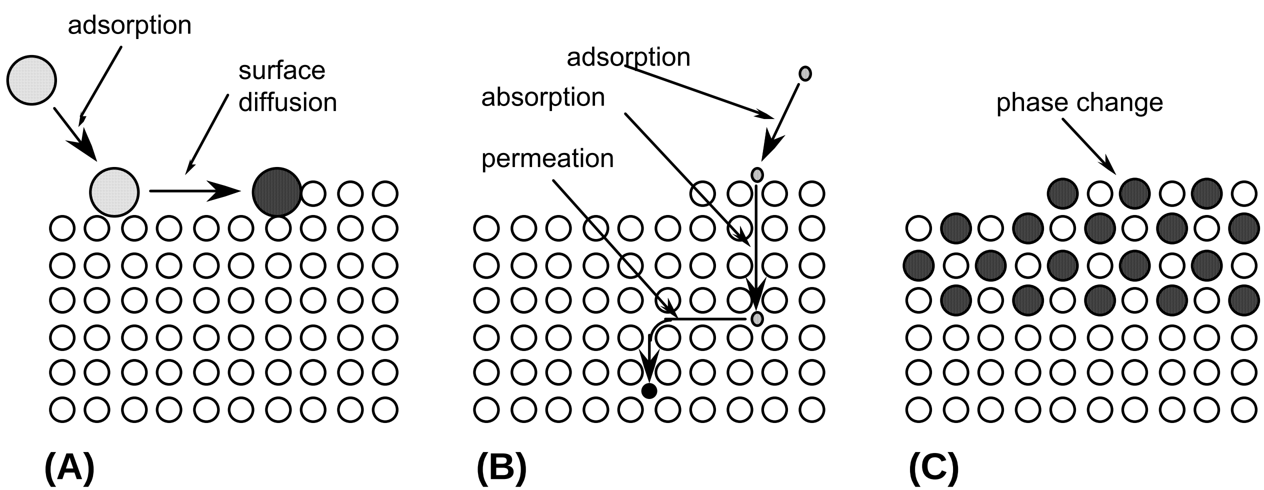
- Chemisorption
  - stronger interaction
  - chemical bonds, ionic or covalent
  - selective



B

Surface Interactions

- surface diffusion (in plane)
- absorption, permeation, and diffusion (in bulk)
- phase changes



Surface Interactions: Outgassing

- Gas leaving a surface depends on your viewpoint:
  "desorption phenomena" (surface scientist)
  "outgassing" (vacuum technologist)

- Outgassing is the dominant problem in HV/UHV/XHV systems

- After the volume gas is pumped away, the gas load from outgassing determines the system pressure
- Sources of outgassing:
  - from surfaces
  - from grain boundaries
  - diffusing out of the vacuum envelope
  - permeating through parts of the vacuum envelope

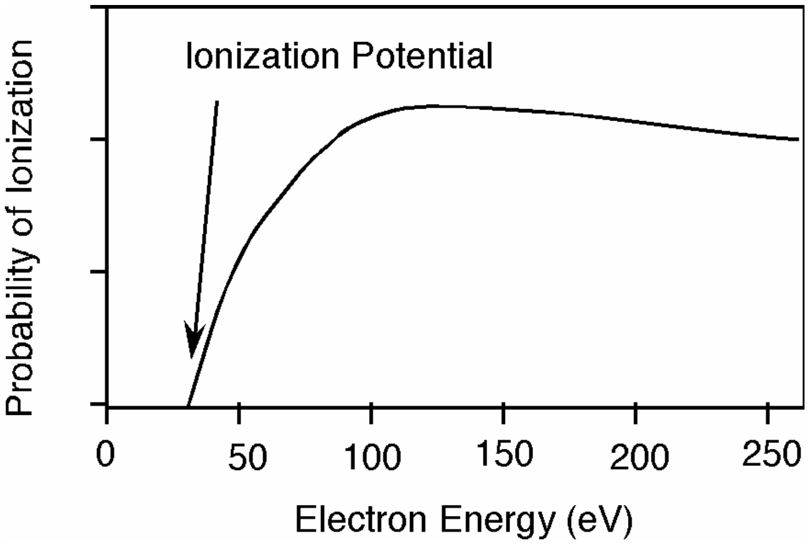
Outgassing Rates

Outgassing Rate for various Materials after 1 hr under vacuum

Material	Outgassing Rate (Torr-liters/sec-cm^2)
Aluminum (fresh)	6.3×10^{-9}
OFHC Copper (mech. polished	3.5×10^{-9}
Stainless Steel	
(mechanically polished)	1.7×10^{-9}
(vacuum baked at 250°C for 30 hrs)	3.0×10^{-12}
Aluminum	
(vacuum baked at 250°C for 15 hrs)	4.0×10^{-13}
Pyrex (fresh)	7.4×10^{-9}
Neoprene	3.0×10^{-5}
Polystyrene	2.0×10^{-5}
Plexiglas	3.1×10^{-6}
Viton A	1.1×10^{-6}
PVC (24 hr at 95% RH)	8.5×10^{-7}
Teflon	6.5×10^{-8}
Viton A (baked)	8.0×10^{-9}

Ionization of Gases

- Plot of probability of ionization (or number of ions created) vs. electron energy
- Important for design and operation of electron-impact ion sources for ion gauges, residual gas analyzers, and ion pumps
- Also important for beam-gas instabilities in accelerators



The Vacuum Environment

- After the initial pumpdown
  - all real vacuum chambers have gas sources such as outgassing and inleakage
  - all real pumps have some backflow
  - as P is reduced, the composition of the residual gas changes
    - selectivity of pump
    - desorption from walls no longer negligible
    - some gases created *in situ*
  - at <1 mbar, main species is water vapor
  - at and below 10^{-9} mbar, H_2, CH_4, CO, CO_2
  - very little N_2 or O_2 if system is “leak tight”
  - work being done in the system can generate sizeable amounts of gas
    - Heating or particle bombardment
    - mechanical motion

Gas Sources

- Outgassing
  - sublimation of the actual surface
  - desorption of physically adsorbed or chemisorbed molecules
  - release of gas diffusing out of grain boundaries
  - permeation of gases through walls or O-rings
- Inleakage
  - gas entering the system through holes in the wall
    - seals, porous welds or brazes, porous metals, etc
- Backflow
  - an ideal pump only removes molecules
  - a real pump gives some gases back
    - residual gas molecules, organic vapors, rare gases, etc.

The Vacuum Environment

The Gas Load

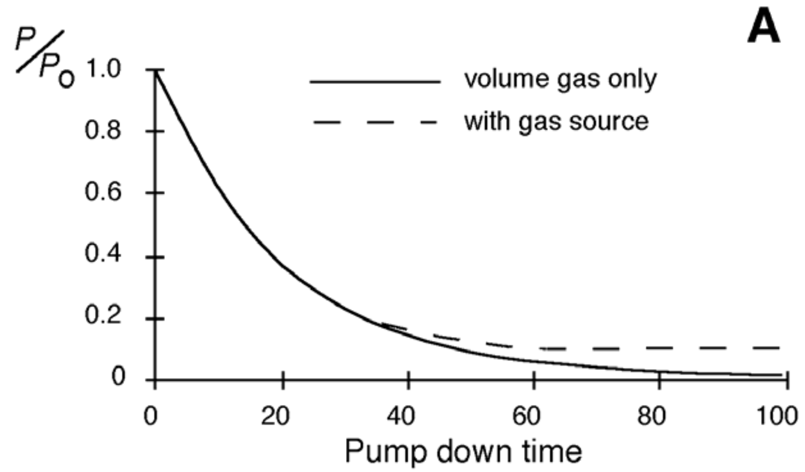
- First part of pumpdown
  - volume gas
- Later on
  - desorbed gas
- Mass balance equation

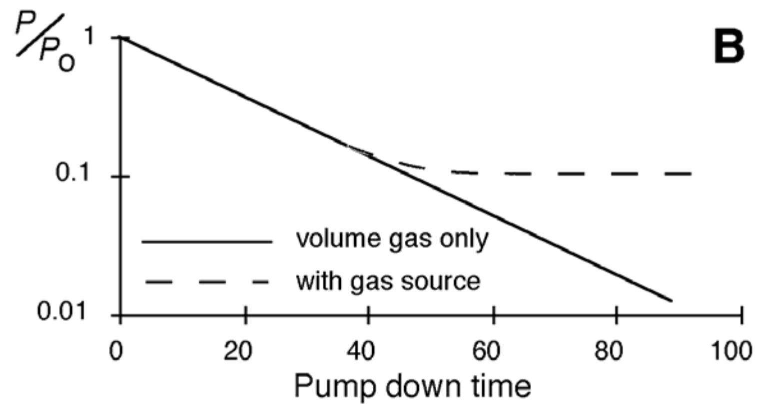
$$\frac{d(PV)}{dt} = -SP + Q_w$$

- the "Gas Load" sums

outgassing, in-leakage and sources from in-perfect pumps and gauges
  - "equilibrium" $-SP + Q_w = 0$
  - slow time dependence

$$P(t) = \frac{Q_w(t)}{S}$$

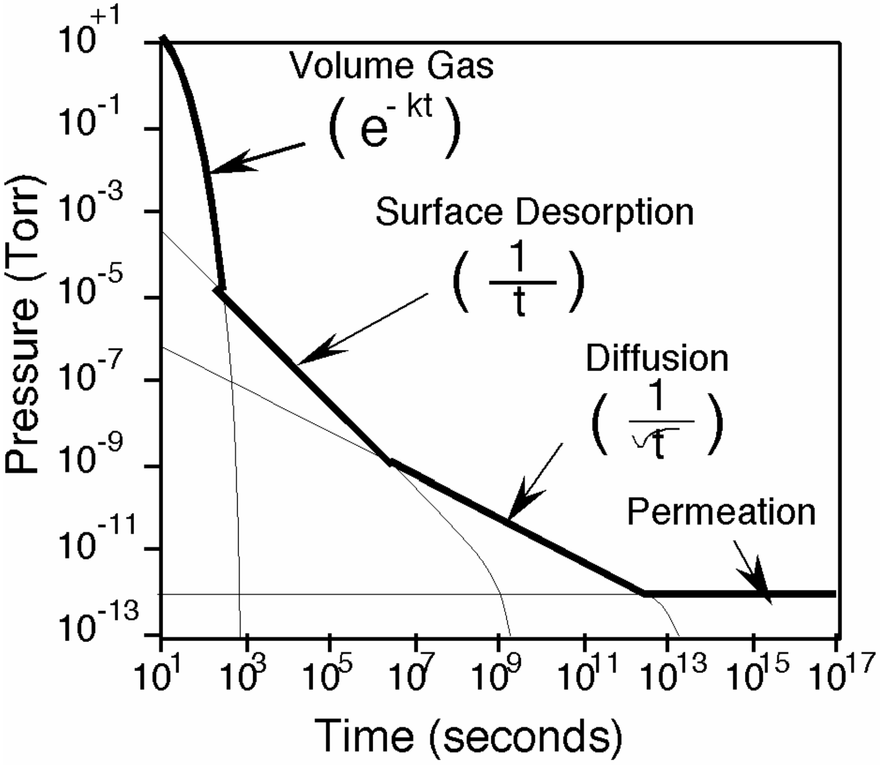




The Vacuum Environment

Limiting Mechanisms

- Early on
  - negative exponential
- Later
  - inverse time
- for UHV
  - inverse sq rt of time
- finally for UHV
  - Permeation and gas generation at the surface
- For O-ring systems
  - permeation line moves up



Coming Attractions in this Course

Context:

- *Introduction to Accelerators* –Brandt
- *Development History of UHV and XHV* - Dylla

Vacuum Physics

- *Outgassing* (thermal and non-thermal)-Chiggiato, Hilleret, Dylla
- *Gas Dynamics, Calculations, Design Rules-* Sharipov, Hauviller, Kersevan
- *Interactions with Matter*- Schou
- *Beam-Vacuum Interactions* – Graefstrom, Grobner

Coming Attractions in this Course

Vacuum Technology:

- *Cryogenics and cryogenic systems-* Lebrun, Baglin
- *Cryo-,Mechanical,Ion and Getter Pumps-* Day,Chew,Audi,Mazzolini,Benvenuti
- *Pressure and Partial Pressure Measurements* -Jousten, Peter
- *Vacuum Materials and Seals* –Sgobba, Sonderegger
- *Leak Detection* –Zapfe
- *Surface Conditioning* -Taborelli

Coming Attractions in this Course

Vacuum Systems:

- *Control Systems* – Strubin
- *Large System Commissioning* – Zapfe
- *Misconceptions and Problems* – Hilleret
- *Synchrotron Light Sources* – Reid
- *ITER* – Wykes
- *Industrial Applications* – Mueller

Challenges

- *XHV* – Dylla
- *Future Machines* - Reid

References

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A.Roth, “*Vacuum Technology*”, North-Holland, Amsterdam (1976)

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Acknowledgements

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