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ASTeC

The Cockcroft Institute of Accelerator Science and Technology

# Vacuum Science and Technology in Accelerators


Lecturers are the members of ASTeC Vacuum Solutions Group:

- *Dr. Oleg Malyshev (Lectures 1,6)*
- *Dr. Keith Middleman (Lectures 2,3)*
- *Dr. Stuart Wilde (Lecture 4)*
- *Dr. Reza Valizadeh (Lecture 5)*


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# Session 6

Part 1: Sources of gas in vacuum system
Part 2: Basic vacuum design of accelerators.
Calculations to support the design
Examples and Revie

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# Session 6

## Part 1:
## Sources of gas in vacuum system

# Aims of Part 1: Vacuum Requirements of Accelerators

- To give a brief overview of sources of gas in vacuum systems
- To understand which materials can be used for particle accelerators

# Some Suitable Materials

## Vessels

- Metals
  - Stainless Steel – AISI 304, L, LN; 316, L, LN
  - Aluminium – 4043 (5% Si)
    5052 (2.5% Mg, 0.25% Cr)
    6061(0.25% Cu, 0.6% Si; 1% Mg, 0.2% Cr)
    6063 (0.5% Si, 0.1% Cu, Mn, Zn, Ti, Cr, 0.8% Mg)
  - Copper
    especially high strength with e.g. 2% Be
  - Titanium
- Ceramics
  - Fully vitrified electrical Porclean and vitrified Alumina, Beryllia
- Glass
- GRP Epoxy (low vacuum machines)

## Internal

- All materials shown for vessels
- All refractory metals (extraordinarily resistant to heat and wear)
- OFHC and OFS Copper
- Copper and aluminium bronzes
- Glidcop®
- Gold, many alloys,
- Silica (SiO2) (ex.: quartz glass)
- Glass (Borosilicate Glass ,a.k.a. Pyrex)
- etc.

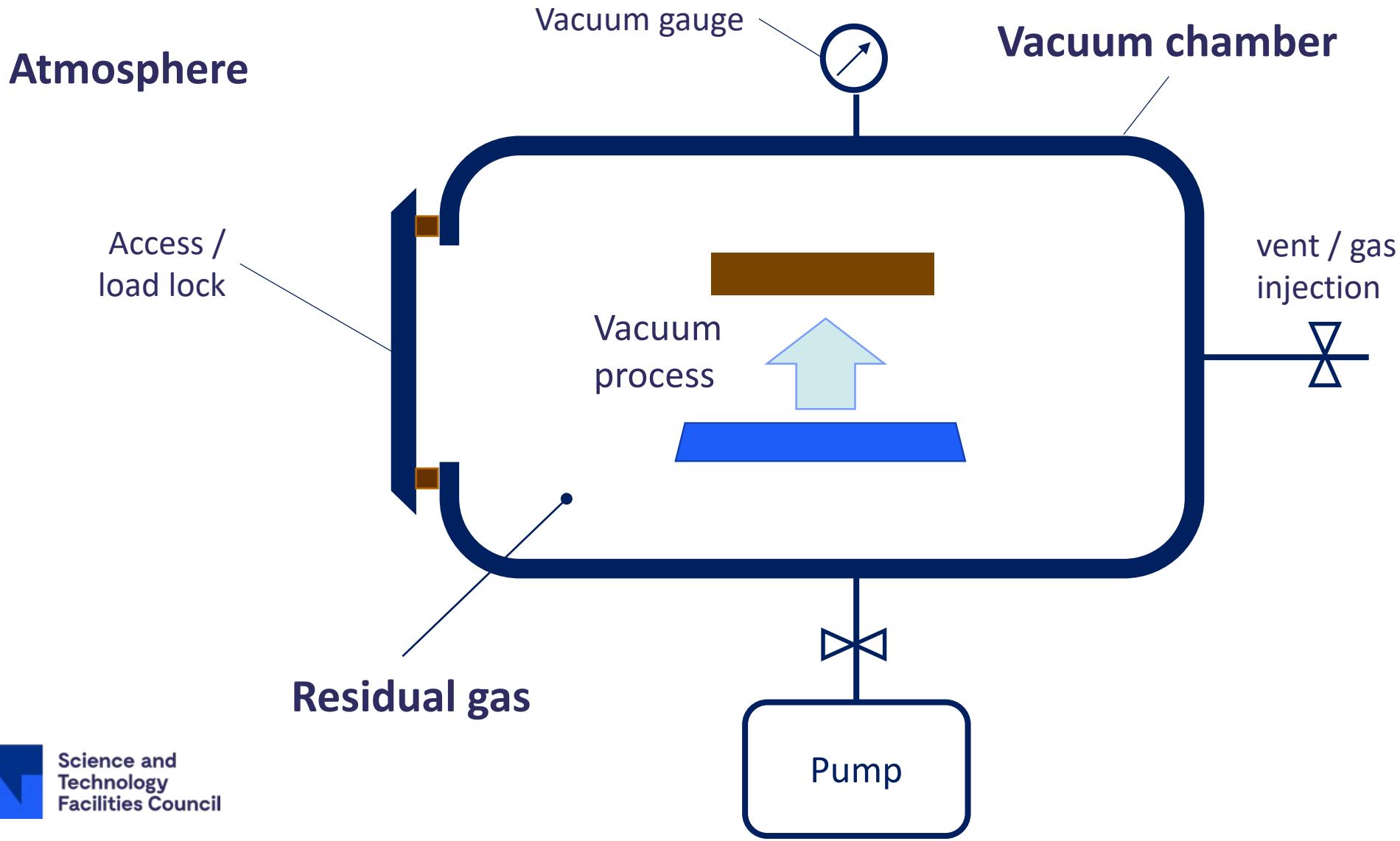
# Materials that shouldn’t be used in vacuum

- This list should include just about everything not listed above, **the general rule being if in doubt don't use it**. Some common materials (nasties) that are not suitable for vacuum:
  - Brass, high sulphur and phosphorus containing alloys.
  - Cadmium Plating, often used for small screws.
  - Small screws used in the chamber can be nickel plated brass or plain copper, and should be drilled or relieved (i.e. file off one side of the threaded area.) to prevent virtual leaks.
  - PVC insulated wire (high outgassing rate)
    - and should be replaced with Teflon insulated wire.
  - Paint Yellow Transformer
    - can be replaced with ordinary (plumbers) Teflon tape.

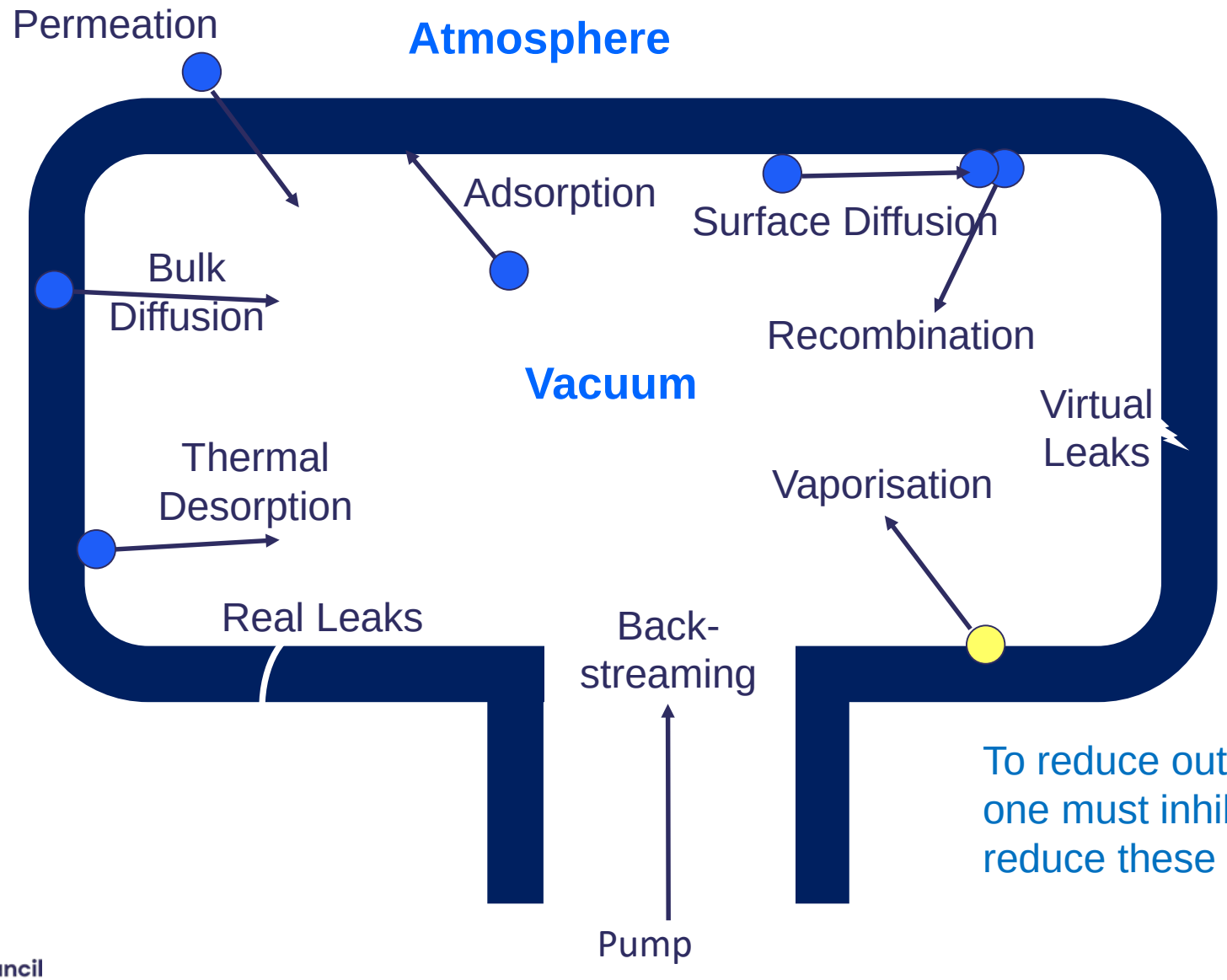
# Properties which influence on vacuum

- Outgassing
  - Thermal induced desorption
- Desorption
  - Photon stimulated desorption (PSD)
  - Electron stimulated desorption (ESD)
  - Ion stimulated desorption (ISD)
  - Other particle stimulated (or induced) desorption
- Photon and Secondary Electron Yield (PEY and SEY)

# Schematic layout of a typical vacuum system



# Mechanisms Contributing to Outgassing




To reduce outgassing, one must inhibit or reduce these processes

# Sources of Gas in a Vacuum System

- Gas injection — It is usually well controlled
- Residual gas from atmosphere — It is not a source of gas for the most of UHV systems
- Leaks (from atmosphere or trapped volumes) — there must be no leaks
- Thermal outgassing
  - Vacuum chamber
  - Components and samples inside the vacuum chamber
- Equilibrium vapour pressure
  - $H_2O$ and Hg at RT,
  - $H_2$ at LHe, $CO_2$ at $LN_2$, etc.
- Products or by-product of a processing in vacuum
- Induced gas desorption
  - Photon, electron and ion simulated desorption
  - Cryogenic vacuum chamber: recycling and cracking
- Back streaming from the pump

The major sources of gas in UHV system

# Sources of Gas in a Vacuum System: Vacuum Leaks

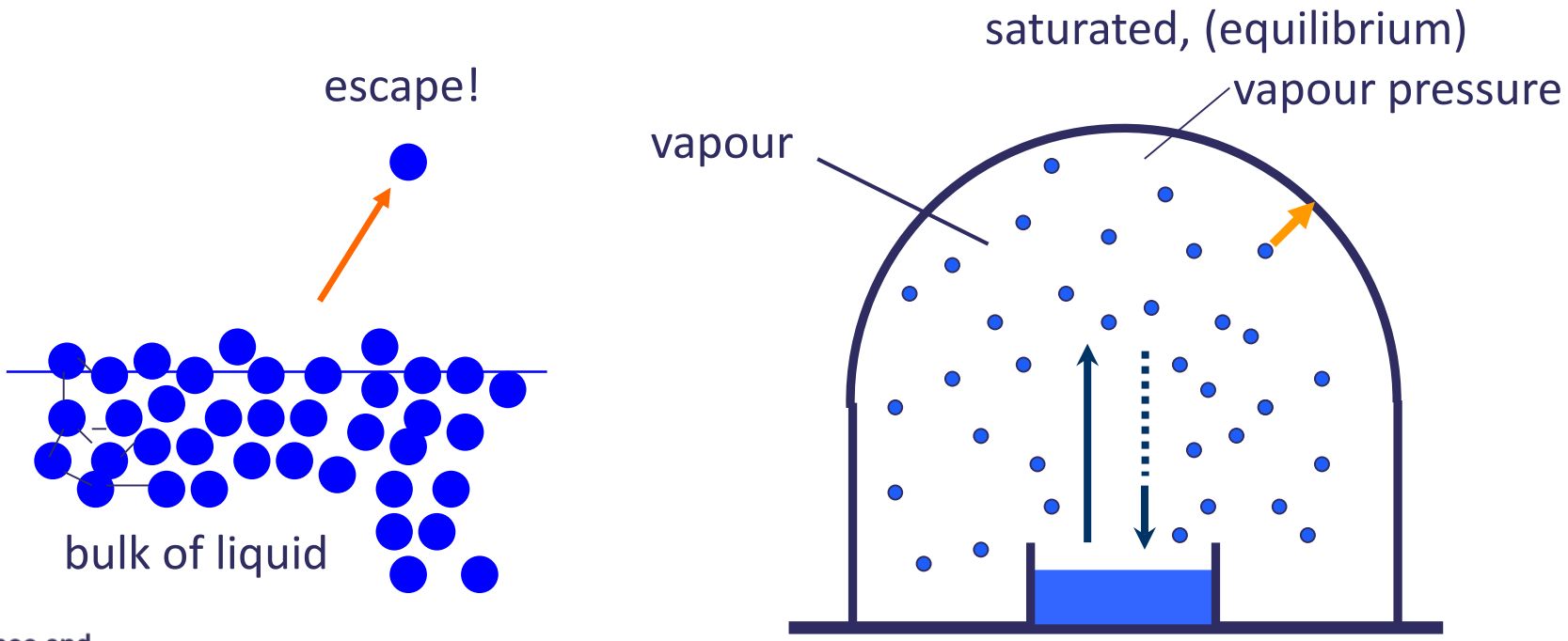
- The aim is building a vacuum-tight vessel, i.e. no gas from atmosphere should be able to find its way into the vessel, *there must be no leaks to atmosphere.*
- To minimise the possible leaks it is necessary:
  - to engineer an appropriate design (both mechanical and vacuum)
  - to use vacuum-tight components (checked by vacuum support)
  - to perform quality welding and careful assembly of components
  - to use tested types of valves and flanges, only new gaskets

After the production of the vacuum vessel, assembly of components and installation, a leak detection is needed to locate possible leaks and to guarantee the required pressure will be reached.

# Sources of Gas in a Vacuum System: Vapours

In the condensed state of a substance, either solid or liquid, the *bonds* that hold its atoms (or molecules) together are opposed by *thermal agitation,* whose measure is *temperature.*

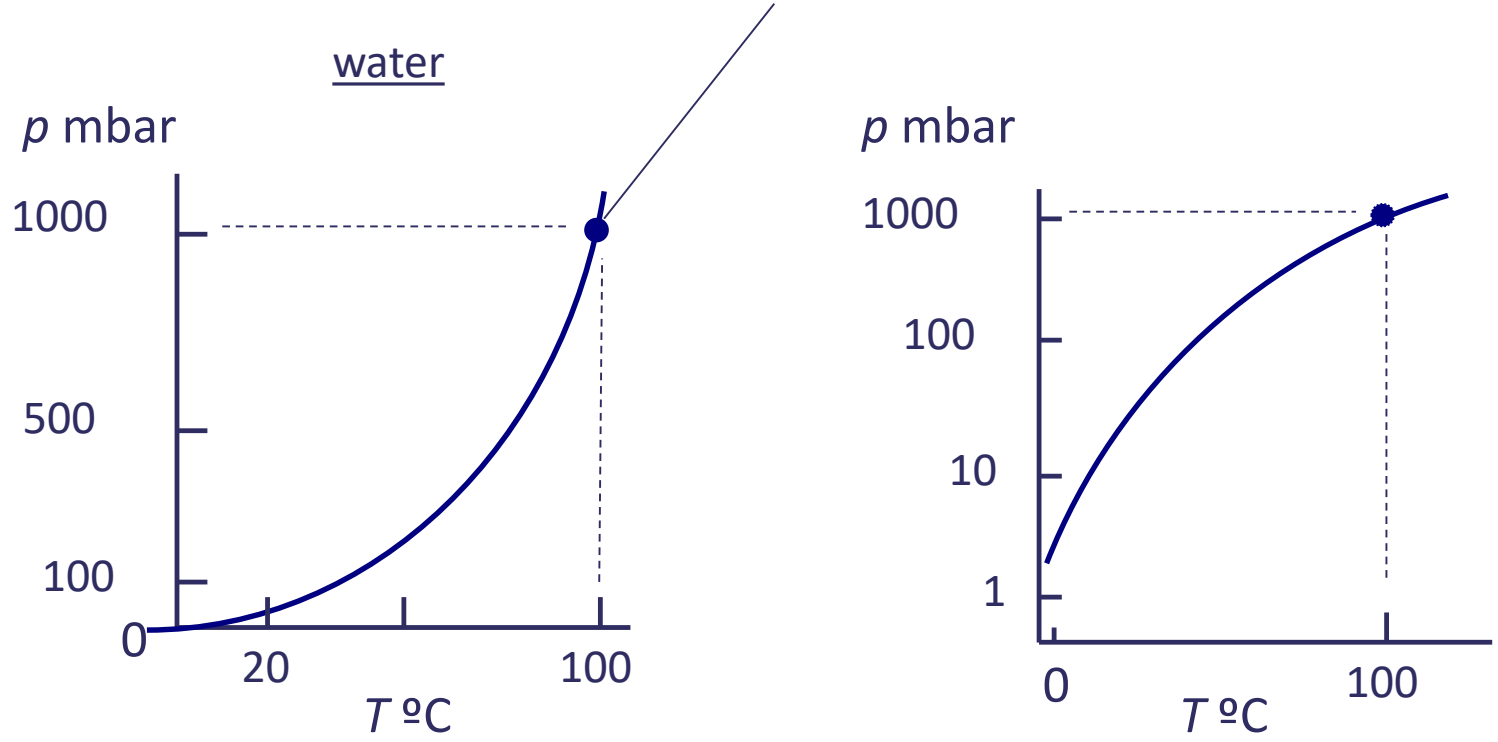
*Bonding* versus *temperature*




At equilibrium, departure and arrival fluxes at liquid surface balance

# How does vapour pressure depend on temperature?

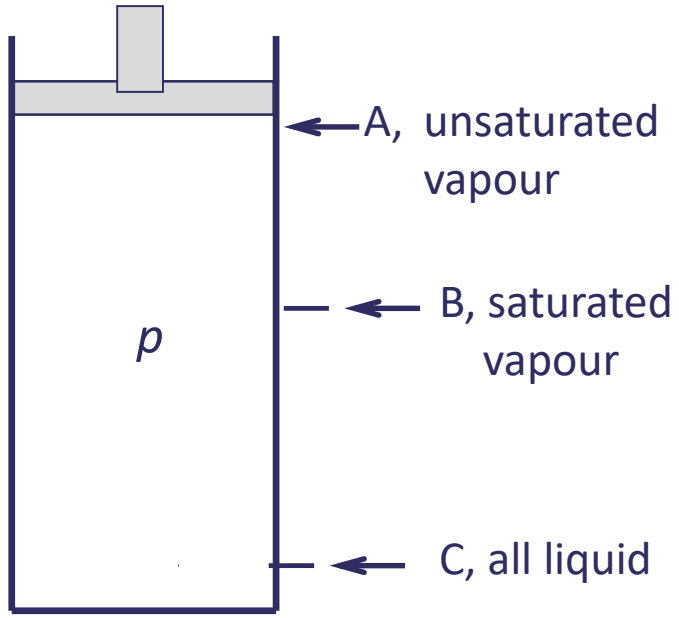
- …… strongly, it is a *thermally activated* process – so the higher the temperature, the greater the thermal agitation that causes the escape of molecules from the surface.
- *Water boils at T = 100°C at P = 1013 mbar.*

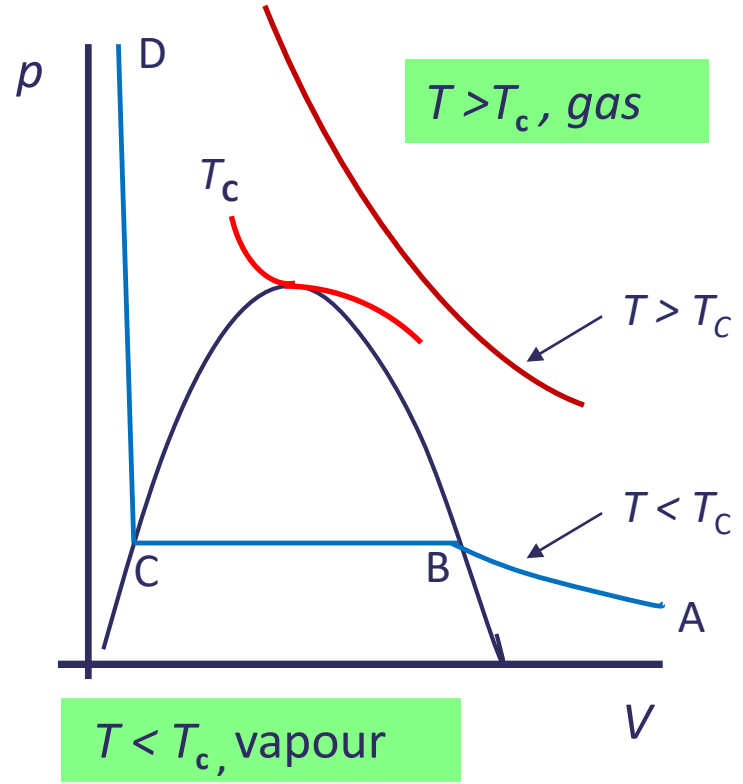



worth remembering …. at room temperature T = 22 °C
vapour pressure of water is P = 26 mbar

# Distinction between gas and vapour

by the *critical temperature*, $T_c$ …




$T > T_c$, gas

$T < T_c$, vapour

Critical temperatures: $T_c$(water) = 647 K (374 °C),
$T_c$(nitrogen) 126 K (-147 °C)

Definition (Oxford Dictionaries):

- Gas is a gaseous substance that cannot be liquefied by the application of pressure alone.
- A gaseous substance that is below its critical temperature, and can therefore be liquefied by pressure alone.

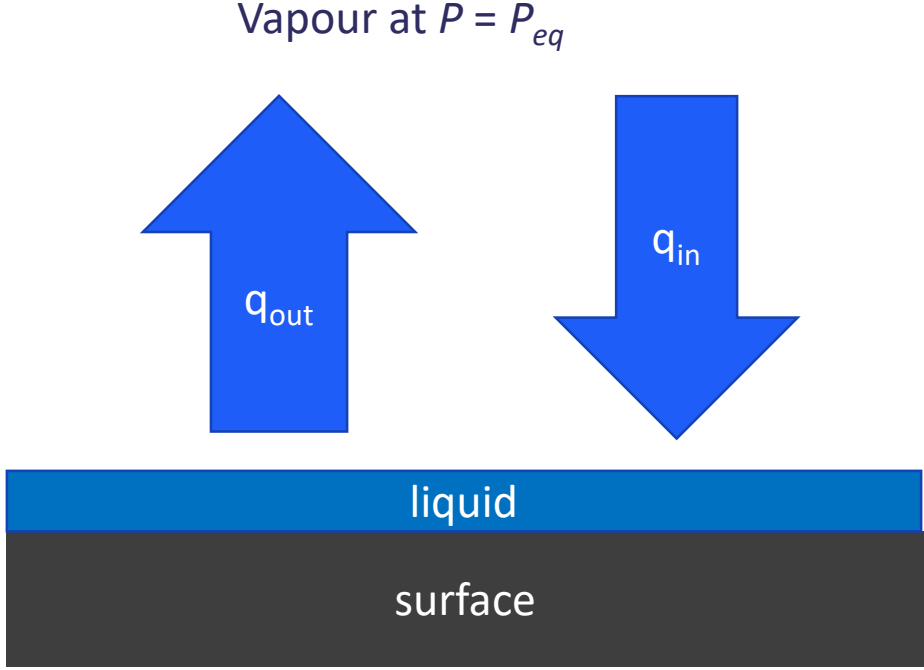
# Sources of Gas in a Vacuum System:

## Equilibrium Vapour Pressure without pumping.

When liquid, condensed gas or a very porous material is present in a vacuum chamber the pressure is limited by the equilibrium vapour pressure:

| Material | Temperature, T [K] | Equilibrium pressure, $P_{eq}$ [mbar] |
|---|---|---|
| Mercury | 293 | $2 \cdot 10^{-3}$ |
| Pump oil | 293 | $10^{-6}$ to $10^{-8}$ |
| Water | 293 | 20 |
| $H_2$ | 4.2 | $8 \cdot 10^{-7}$ |
| $CO_2$ | 77.8 | $2 \cdot 10^{-8}$ |

There are two gas flows: from and to liquid surface




$$q_{in} = q_{out} = n_{eq}\frac{\bar{v}}{4} = \frac{P_{eq}\bar{v}}{4k_B T}$$

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# Sources of Gas in a Vacuum System:

## Equilibrium Vapour Pressure with pumping.

When liquid, condensed gas or a very porous material is present in a vacuum chamber the pressure is limited by the equilibrium vapour pressure:

| Material | Temperature, T [K] | Equilibrium pressure, $P_{eq}$ [mbar] |
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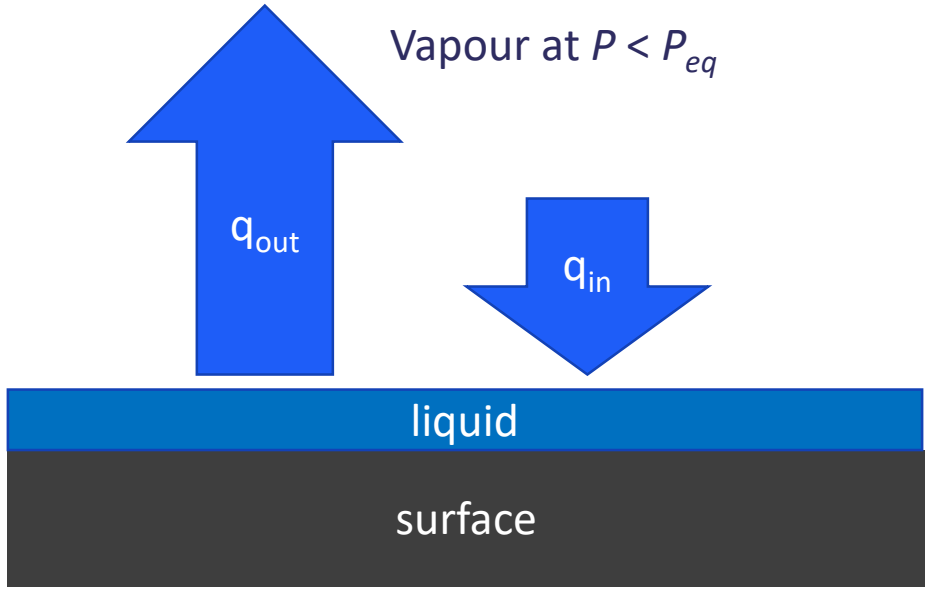


That means that there are two gas flow from and to liquid surface:

$$q_{out} = n_{eq}\frac{\bar{v}}{4} = \frac{P_{eq}\bar{v}}{4k_BT}; \quad q_{in} = n\frac{\bar{v}}{4} = \frac{P\bar{v}}{4k_BT};$$

$P_{eq}$ and $n_{eq}$ are equilibrium pressure and gas density; $P$ and $n$ are the actual pressure and gas density in vacuum chamber

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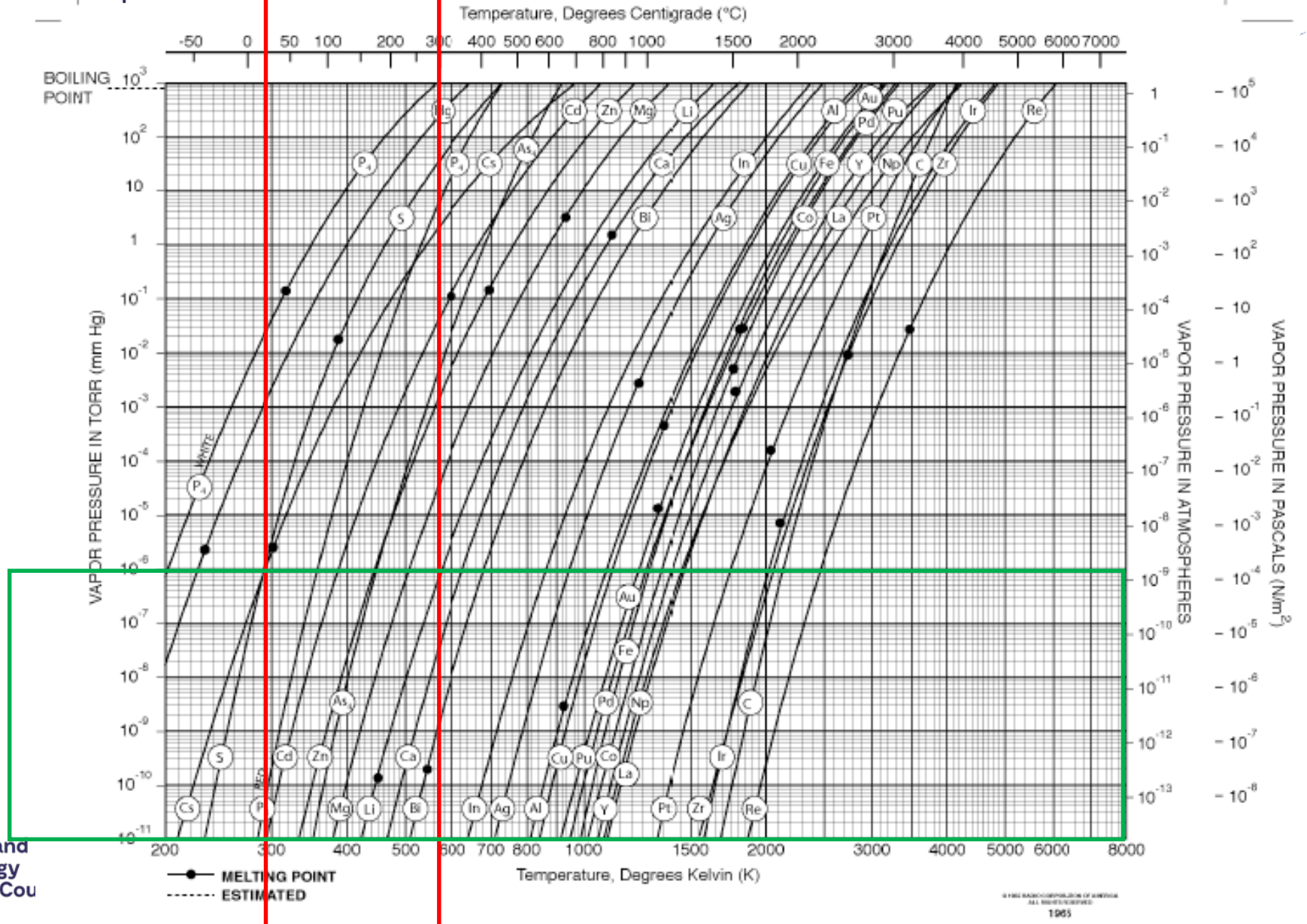
# Vapour Pressure

Room => temperature

<= Bakeout temperature




Range of pressures in particle accelerators =>

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# Sources of Gas in a Vacuum System:
## Equilibrium Vapour Pressure

When liquid, condensed gas or a very porous material is present in a vacuum chamber the pressure is limited by the equilibrium vapour pressure

| Material | Temperature, K | Equilibrium pressure, mbar |
|---|---|---|
| Mercury | 293 | $2 \cdot 10^{-3}$ |
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| Water | 293 | 20 |
| $H_2$ | 4.2 | $8 \cdot 10^{-7}$ |
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# Gas composition in the atmosphere and in vacuum

| Atmosphere (at sea level) | Unbaked vacuum chamber | Baked vacuum chamber | NEG coated vacuum chamber | At cryogenic temperatures (1 to 80 K) |
|---|---|---|---|---|
| $N_2$ (78.1%) | $H_2$ | $H_2$ | $H_2$ | $H_2$ |
| $O_2$ (20.9%) | $H_2O$ | CO | $CH_4$ | CO |
| $H_2O$ (0.1-5.0%) | CO | $CO_2$ | $C_xH_y$ | $CH_4$ |
| Ar (0.93%) | $CO_2$ | $CH_4$ | CO | $CO_2$ |
| $CO_2$ (0.033%) | $CH_4$ | $C_xH_y$ | | |

- **Atmospheric air** is a mixture of gases with over 99% of **nitrogen** and **oxygen**, while the rest of gas in **UHV** consist mainly of **hydrogen.**
- The gas composition is varied depending on many factors: choice of material, cleaning, baking, pumping system design, type of pumps, temperature, photon, electron or ion bombardment of the surface and many others.

# Thermal Desorption

**Thermal desorption (or thermal outgassing) means:**

- Molecules adsorbed on the surface (initially or after the air venting) and desorbing when vacuum chamber is pumped
- Molecules diffusing through the bulk material of the vacuum chamber, entering the surface, (recombining) and desorbing from it

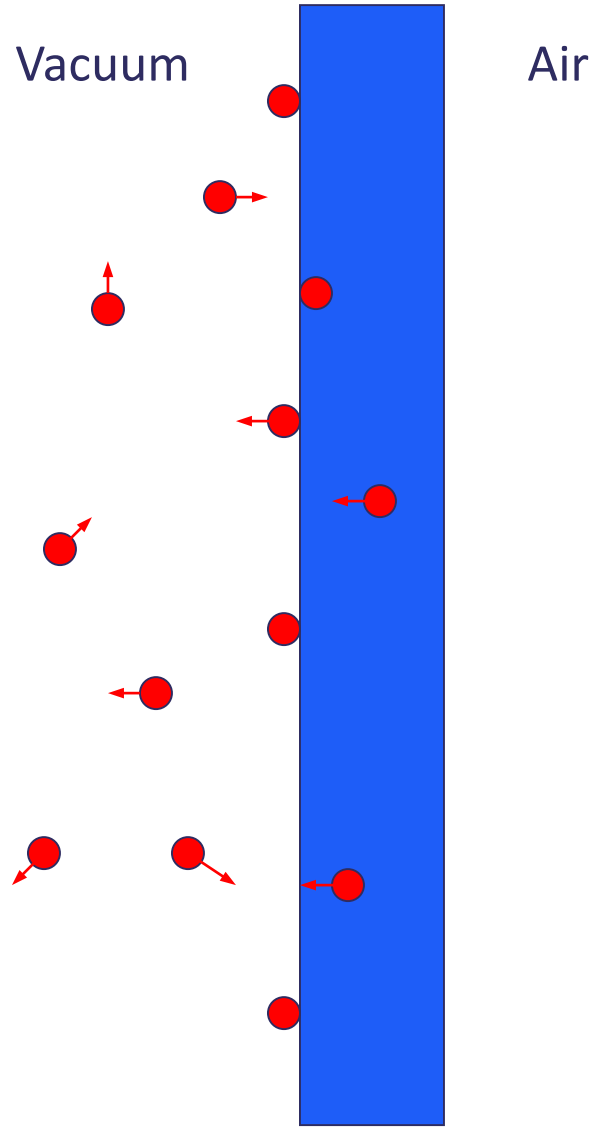
**Outgassing rate** depends on many factors: choice of material, cleaning procedure, baking, pumping time, etc...

Ex.: $\eta_{316\,LN} \Rightarrow (10^{-15} – 10^{-8})$ mbar·l/(s·cm$^2$)

$\Rightarrow$ Input data for a gas dynamic model are very approximate

$\Rightarrow$ UNFORTUNATELY, water molecules adsorbed in large amounts (from ambient surroundings when surfaces are at atmospheric pressure), and with a bond strength that causes its release at a problematic rate:

outgassing rate, $\eta \sim 10^{-7}$ mbar·l/(s·cm$^2$) (after 1 hour pumping)



# Choice of Material for UHV System

- **The outgassing rates may vary in order of magnitudes** depending on factors: choice of material, cleaning procedure, history of material, pumping time, etc...
- Not all materials are compatible with UHV and XHV system!
- **The example** of the outgassing rates after one hour pumping:

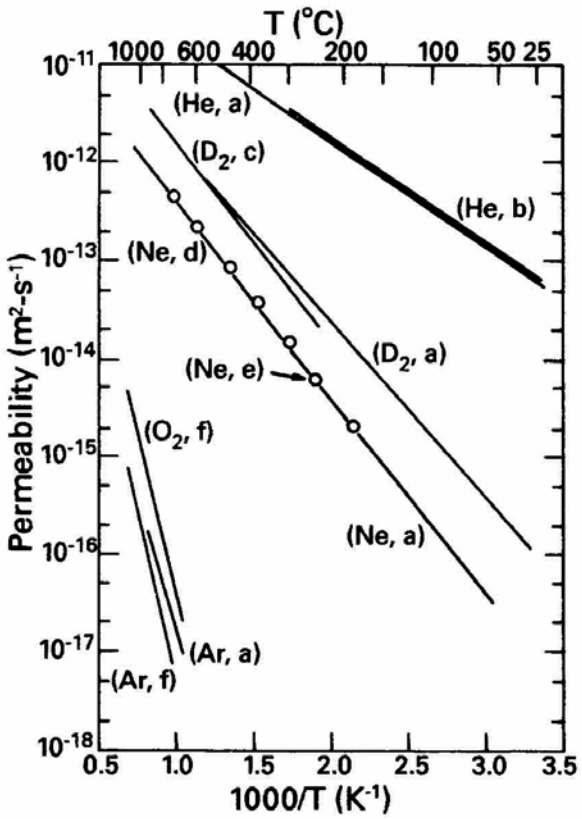
| Material | $\eta_t$ [mbar·l/(s·cm$^2$)] |
|---|---|
| Aluminium (fresh ) | $9 \cdot 10^{-9}$ |
| Aluminium (20h at 150°C) | $5 \cdot 10^{-13}$ |
| Cupper (24h at 150°C) | $6 \cdot 10^{-12}$ |
| Stainless steel (304) | $2 \cdot 10^{-8}$ |
| Stainless steel (304, electropolished) | $6 \cdot 10^{-9}$ |
| Stainless steel (304, mechanically polished) | $2 \cdot 10^{-9}$ |
| Stainless steel (304, electropolished, 30h at 250°C ) | $4 \cdot 10^{-12}$ |
| Perbunan | $5 \cdot 10^{-6}$ |
| Pyrex | $1 \cdot 10^{-8}$ |
| Teflon | $8 \cdot 10^{-8}$ |
| Viton A (fresh) | $2 \cdot 10^{-6}$ |

# What can be achieved for stainless steel?

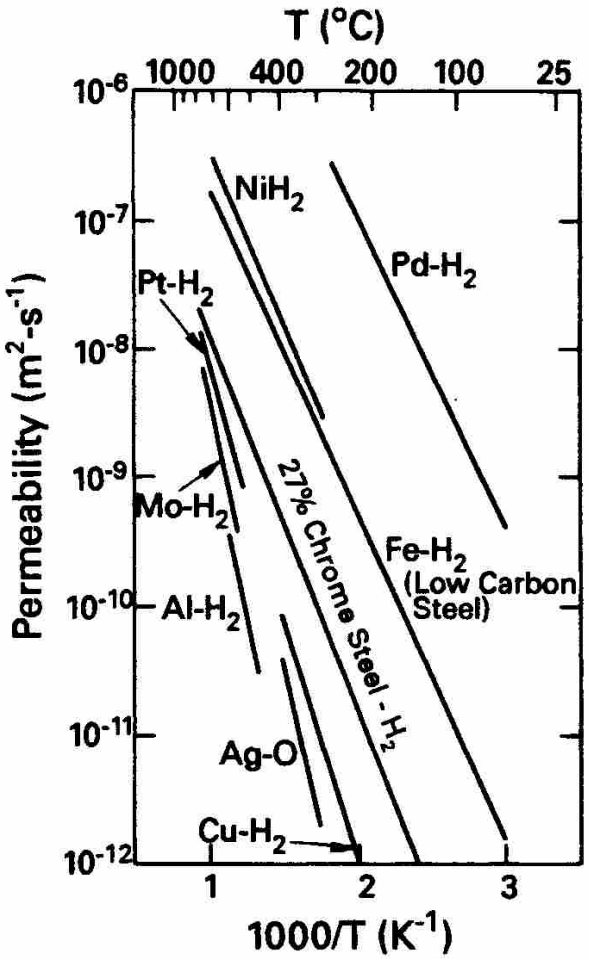
- Experience shows that an outgassing rate of the order of $10^{-11}$ mbar·l/(s·cm$^2$) can be obtained after bakeout to 250 °C
- An outgassing rate of $10^{-13}$ mbar·l/(s·cm$^2$) is achievable with conventional techniques
- Rates lower than $10^{-14}$ mbar·l/(s·cm$^2$) are achievable with care, particularly in thin walled vessels, or on polished and vacuum fired surfaces

# Permeability

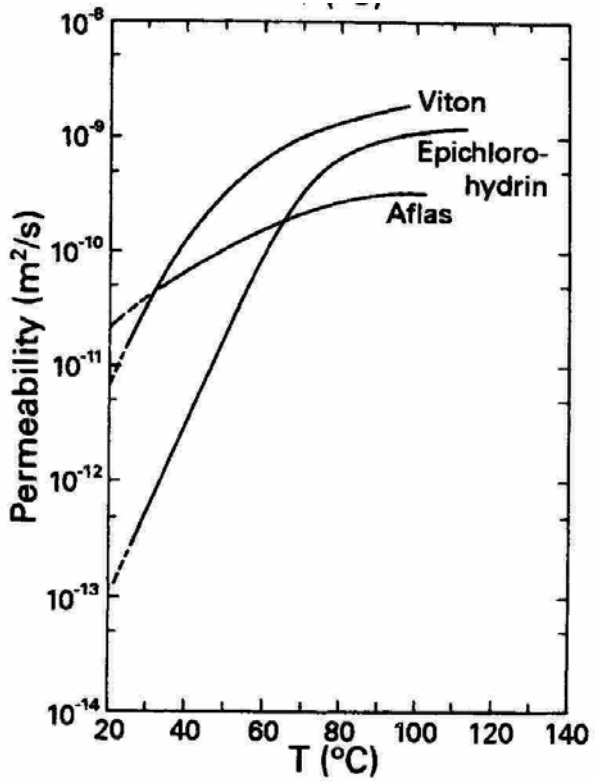
Permeability of gasses through glass



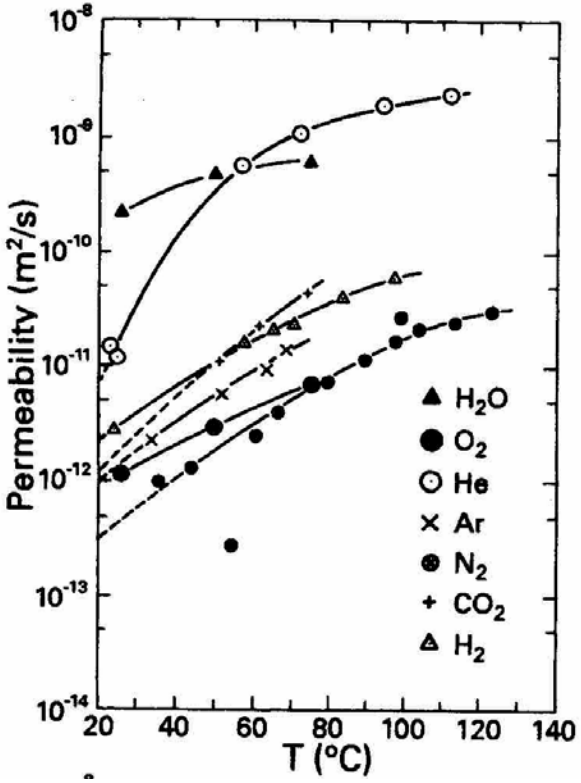

$H_2$ permeability through metals




Viton®




Elastomers

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# Strategies for reducing of outgassing

- Permeation:
  - wall thickness
  - barrier layer on surface
    - coating, oxide, nitride, etc.
    - internal or external
  - preferred orientation of grains
    - should be parallel to the surface (rolled sheets)
    - forged flanges (to minimise normal to surface)
- Bulk diffusion :
  - reduce dissolved hydrogen
    - vacuum melt, vacuum firing, air bake, induce trapping states (bulk or surface)
  - grain boundary density
- Recombination :
  - reduce surface mobility by introducing surface trapping sites

- Desorption:
  - reduce surface concentration
    - surface cleaning and vacuum bakeout
  - reduce physical surface area
    - by design and by surface polishing
- Adsorption:
  - reduce exposure to air and sorbing gases
  - fill surface binding sites
    - surface polishing, air-bake

**References:**


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- M Suemitsu et al. Vacuum 44 (1993), 425.
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- M. Bernardini et al. J. Vac. Sci. Technol. A16 (1988), 188.
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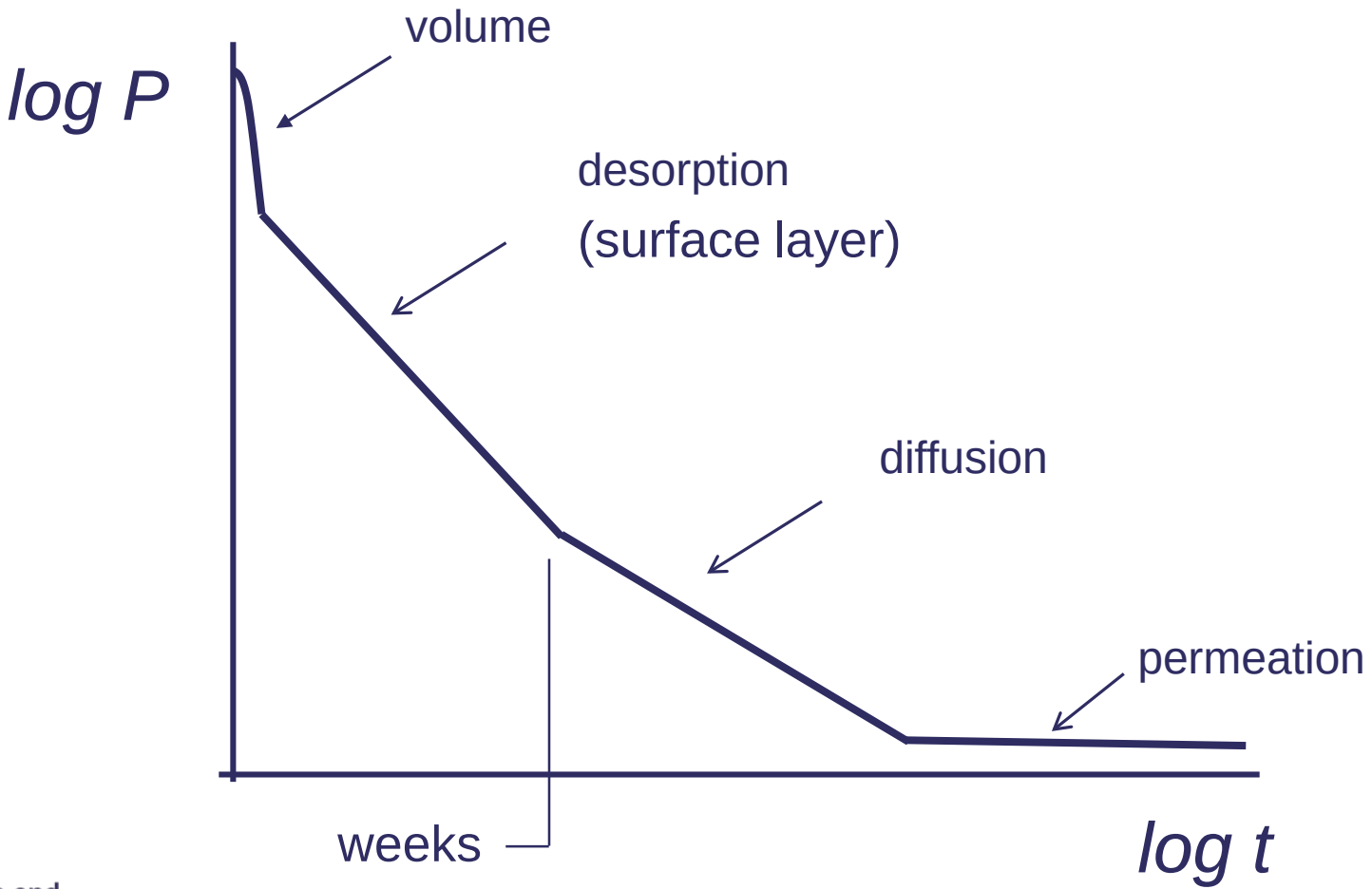
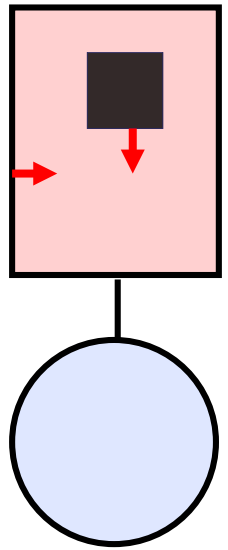
- Y. Tito Sasaki. J. Vac. Sci. Technol. A25 (2007), 1309.
- C. Benvenuti. Proc. of PAC'01, p.602.

# Pumpdown time

(after O'Hanlon)



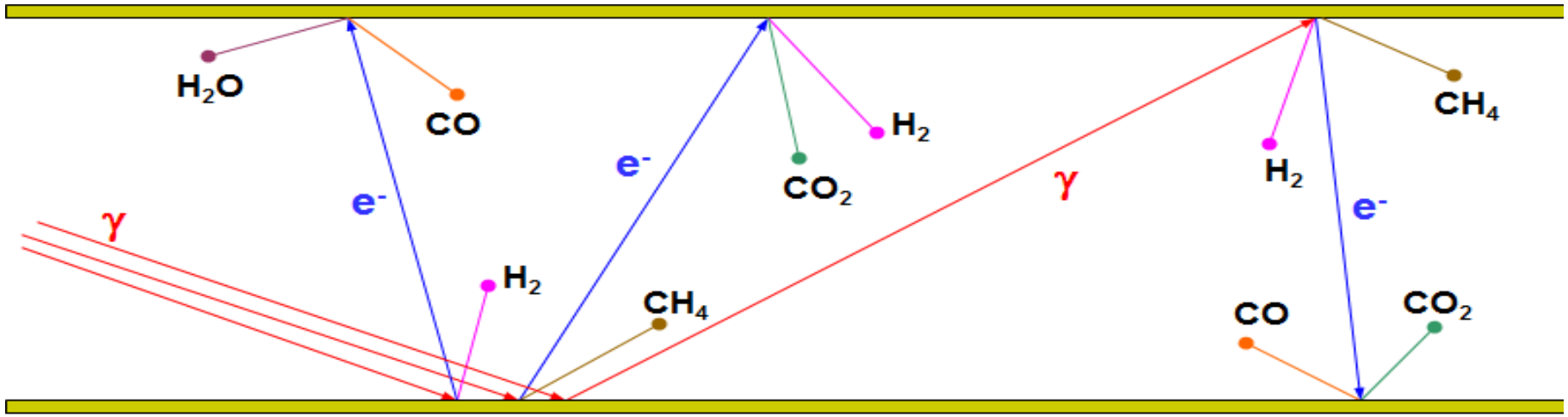
# Photon stimulated desorption (PSD)

# Photon stimulated desorption

**Photon stimulated desorption (PSD)** is one of the most important sources of gas ***in the presence of synchrotron radiation (SR)*** *or any photons with E > 5-10 eV*.

PSD can be considered as a two-step process:

- first, photons with energy >5-10 eV cause the photoelectron emission,
- then the photoelectron stimulate gas desorption.

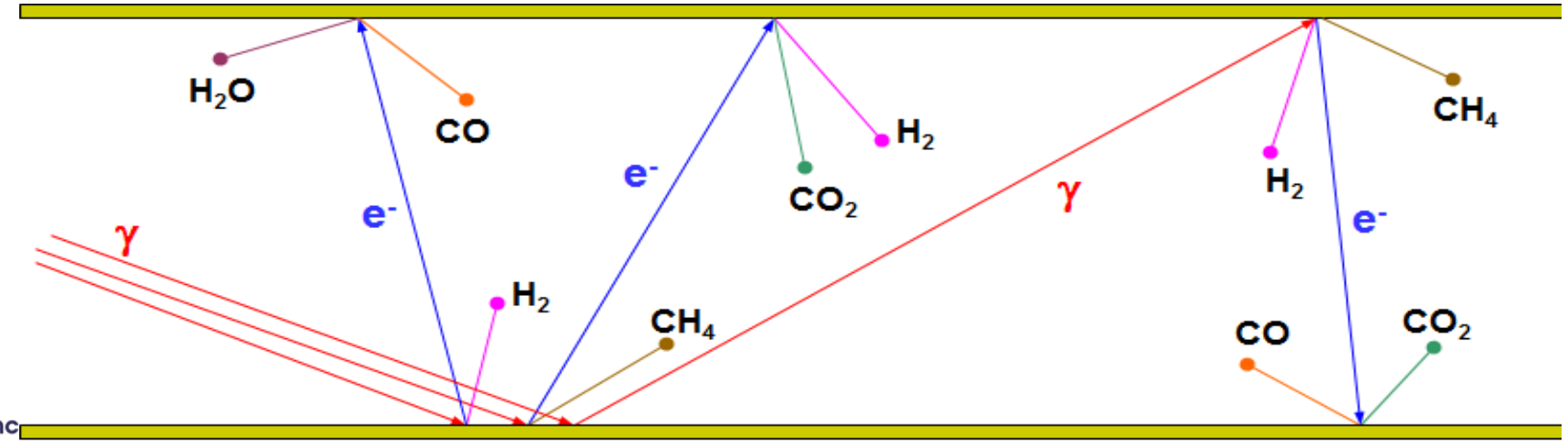



Gas molecules may desorb from a surface when and where *photoelectrons* leave and arrive at a surface

# PSD yields

PSD yields are defined as a number of gas molecules desorbed from the surface per incident photon, $\eta_\gamma$ [molecules/photon]:

$$\eta_\gamma \left[ \frac{molecules}{photon} \right] = \frac{Q\left[ Pa \cdot m^3/s \right]}{k_B T\left[ K \right] \Gamma\left[ photon/s \right]},$$



# What PSD depend on?

Similarly to thermal desorption,

PSD depends on:

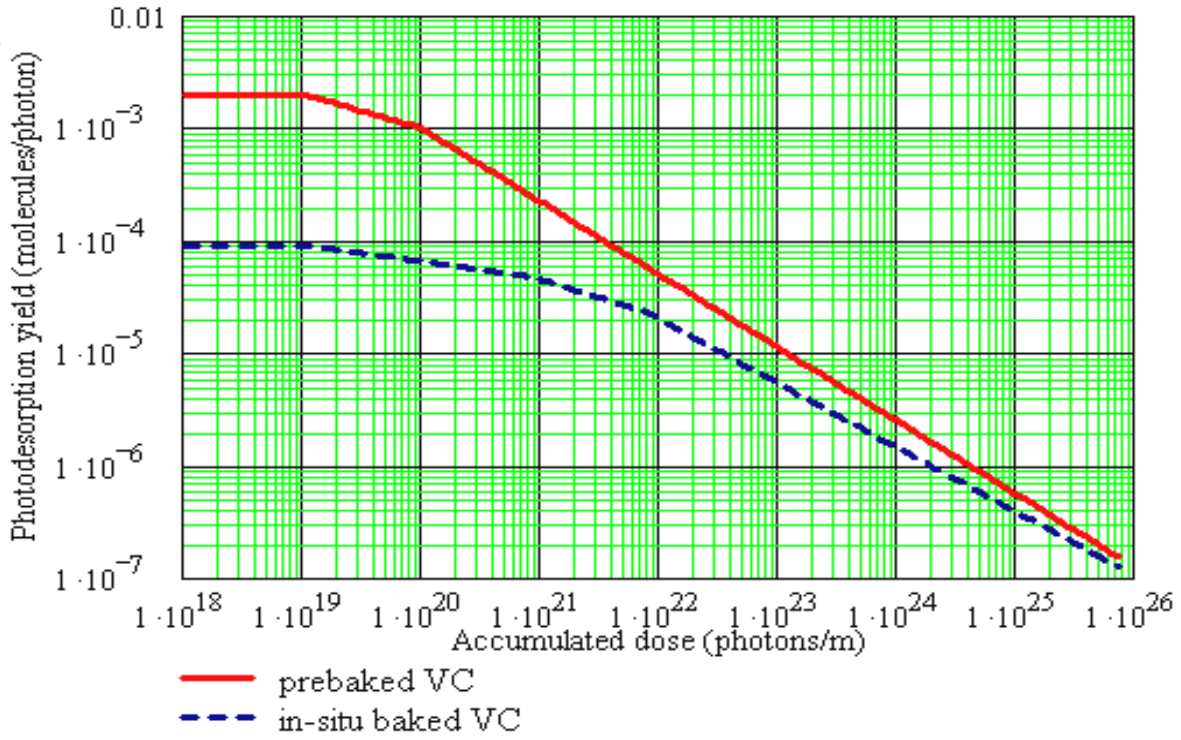
- Choice of material
- Cleaning procedure
- History of material
- Bakeout and vacuum firing
- Pumping time

**Additionally it depends on**

- **Energy of photons**
- **Photon flux**
- **Integral photon dose**
- **Temperature**

# PSD as a function of dose

Photodesorption yields, $\eta$ **(molecules/photon),** as a function of accumulated photon dose, ***D***, for different materials measured up to certain doses, these results are extrapolated for use in the design of new machines



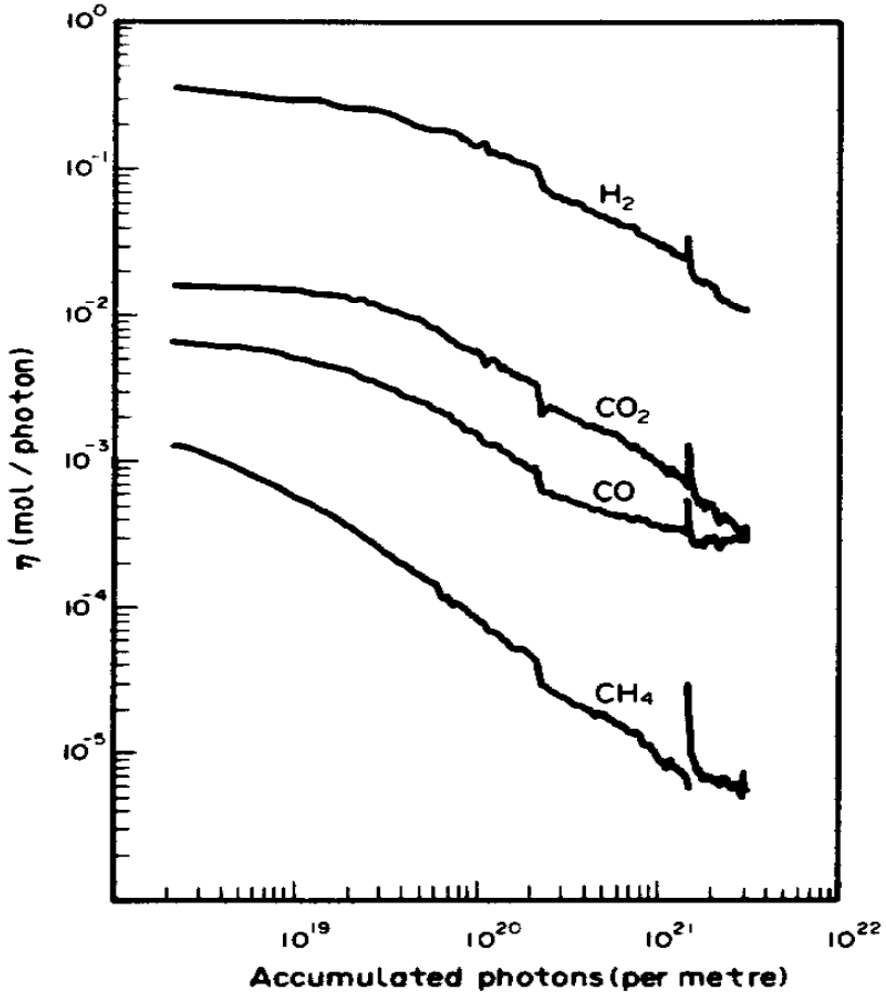

Photodesorption yield as function of accumulated photon dose can be described as:

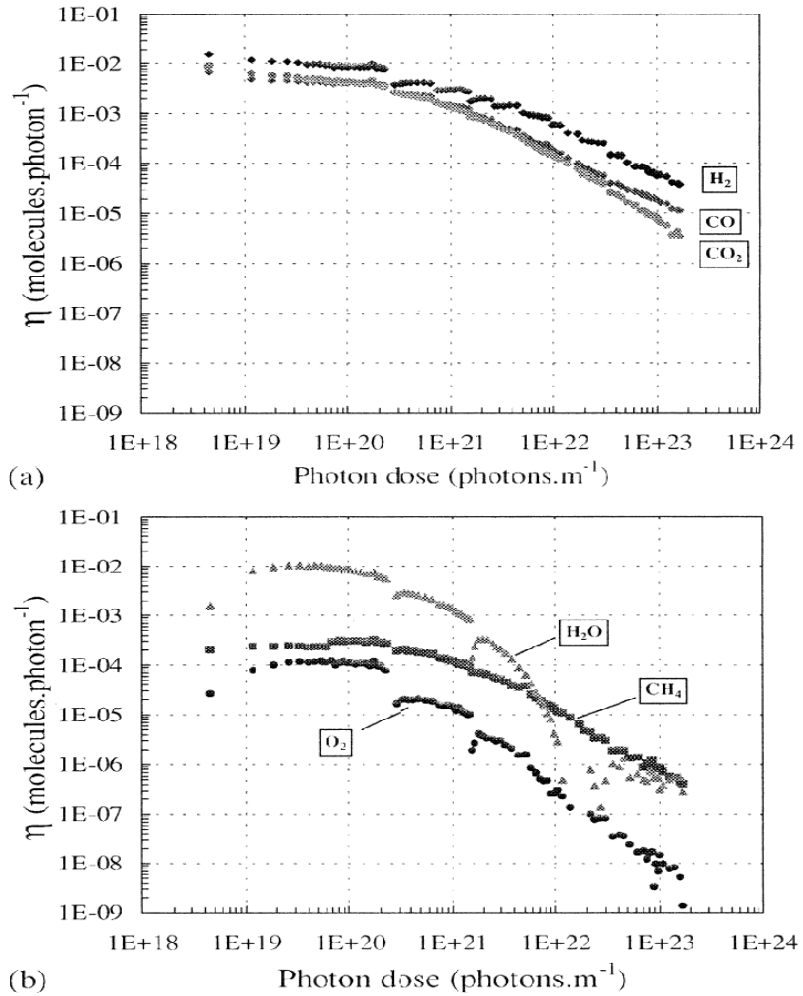
$$\eta = \eta_0 \left( \frac{D_0}{D} \right)^{\alpha}, \quad 0.65 < \alpha < 1$$

PSD yield for CO for prebaked and *in-situ* baked stainless steel vacuum chambers.
Yields for doses higher then $10^{23}$ photons/m (1 to 10 Amp·hrs for diamond) are extrapolations.

# PSD as a function of dose

The PSD yield $\eta$ for various gas species as a function of the accumulated photon dose at $\varepsilon_c$ = 3.75 keV at DCI



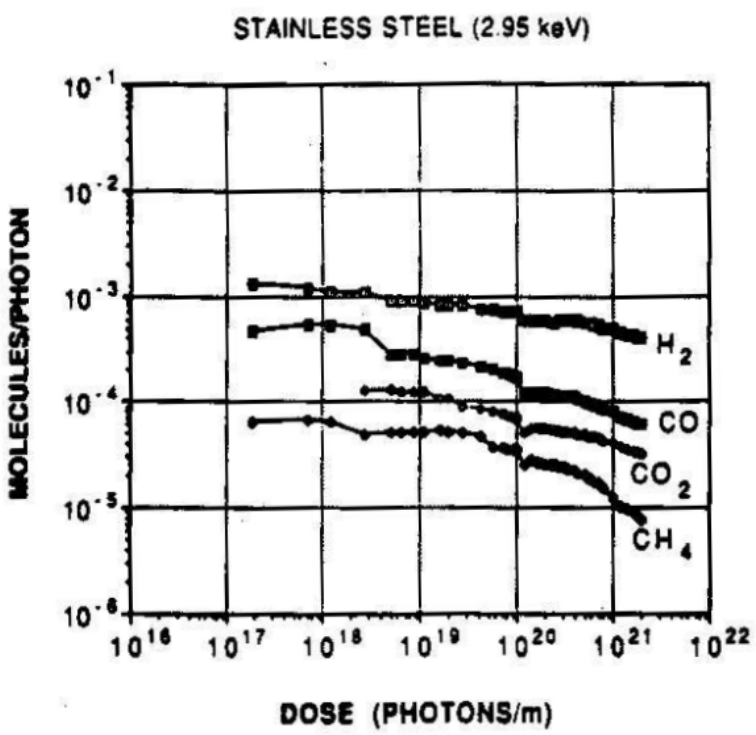



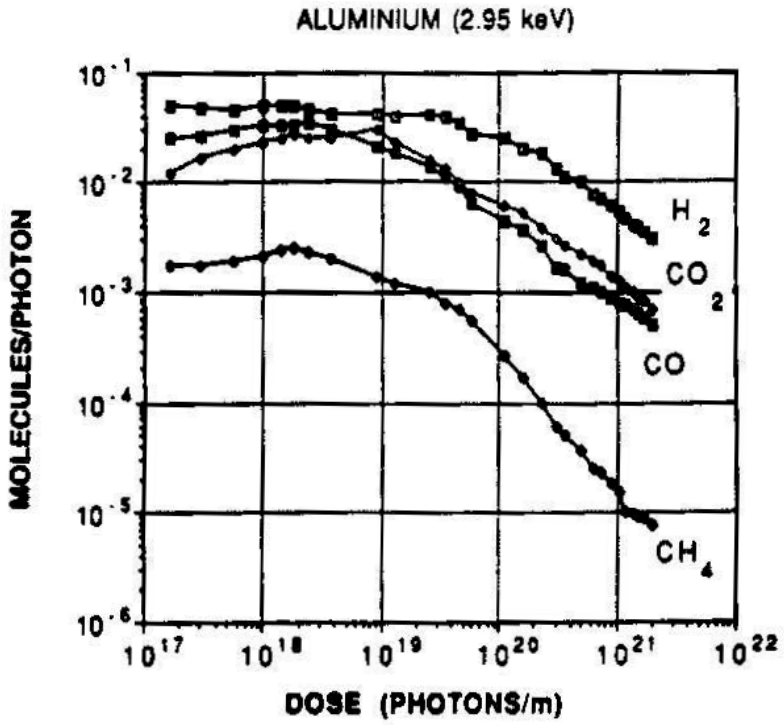

aluminium vacuum chamber
(Vacuum 33, 397 (1983))

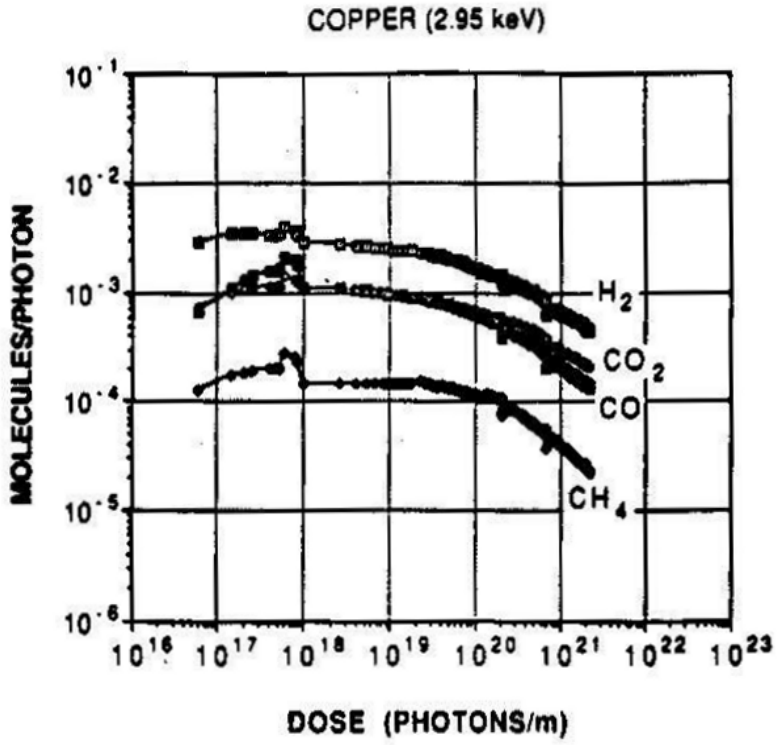
stainless steel vacuum chamber
(Vacuum 60, 113 (2001)).

# PSD yields from different materials as a function of photon dose

Photodesorption yields, **η(molecules/photon),** as a function of accumulated photon dose for different materials for vacuum chamber (A. Mathewson, AIP Conf. Proc. 236 (1), 313 (1991))



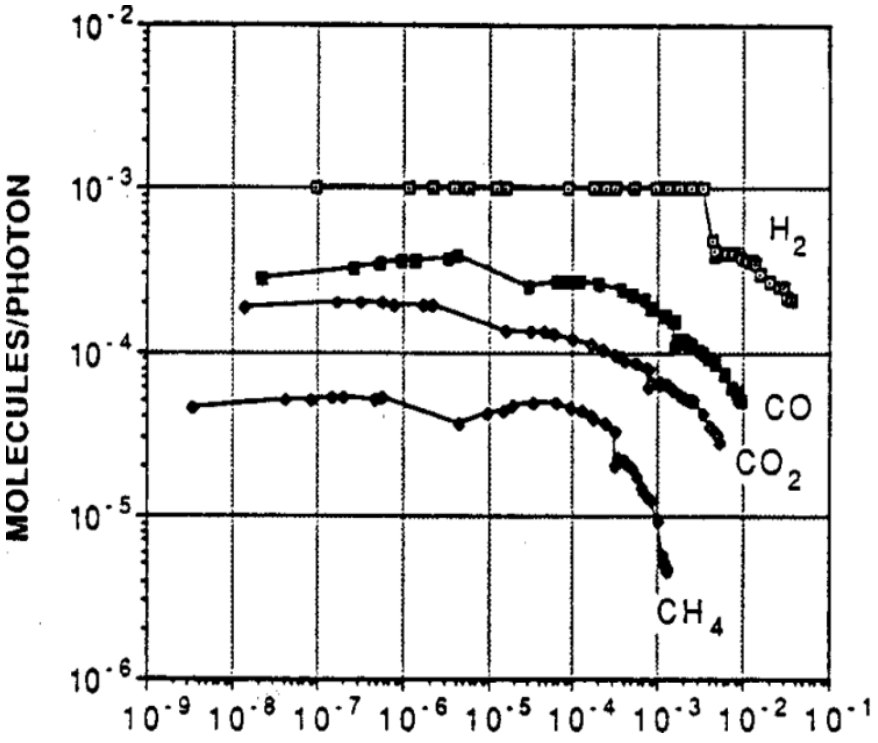



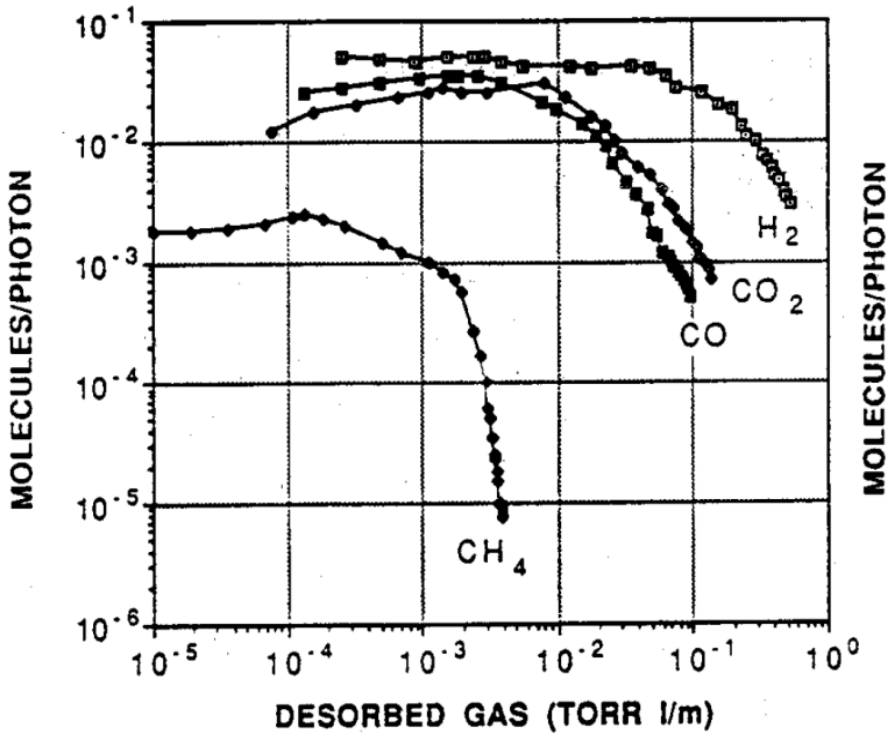
# PSD as a function of amount of desorbed gas

The same data can be plotted differently:

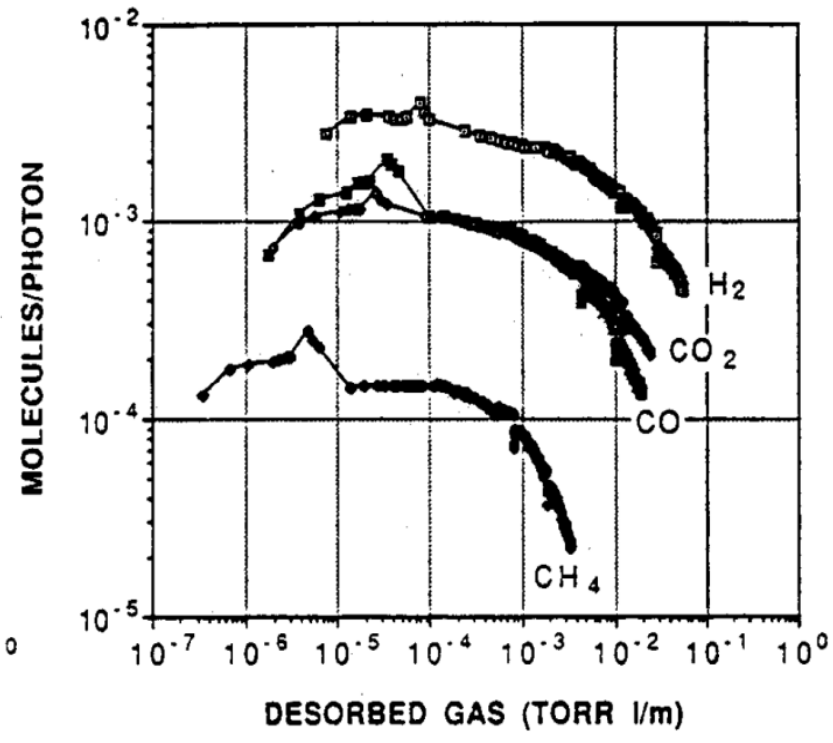
Stainless steel



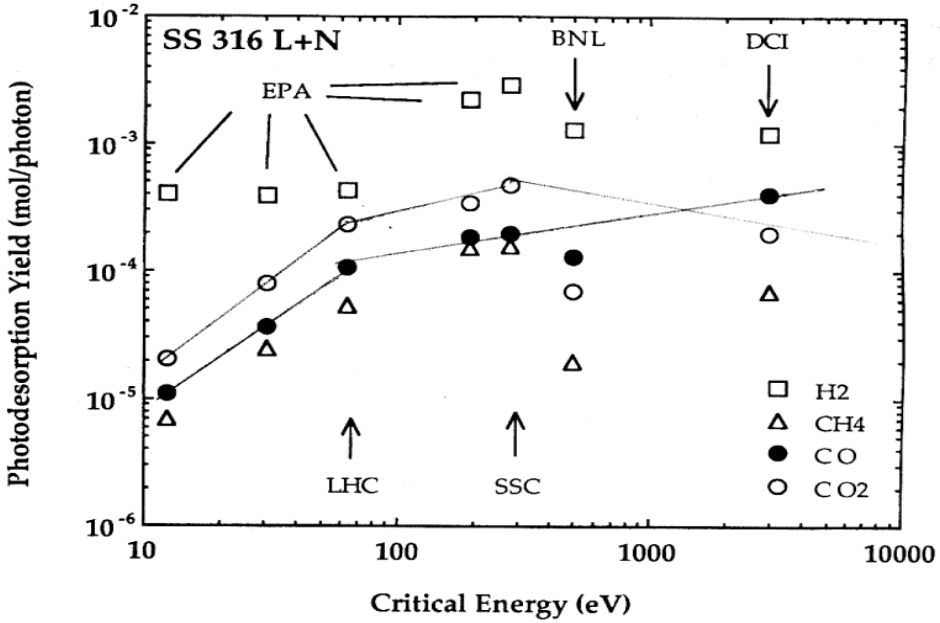

Aluminium



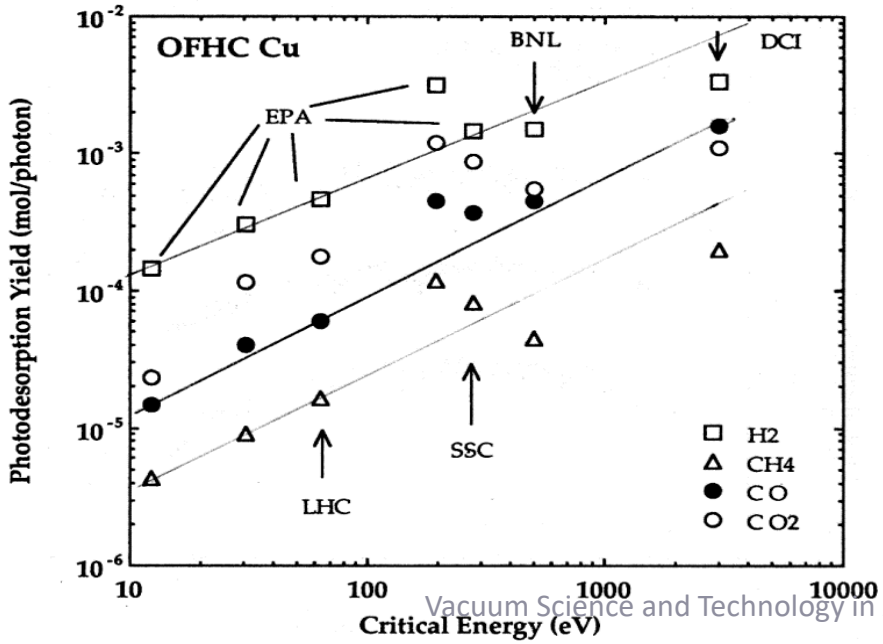

Copper



# PSD as a function of critical energy of SR




- $\varepsilon_c$ = 10-1000 eV




$\varepsilon_c$ = 0.1-1.4 MeV

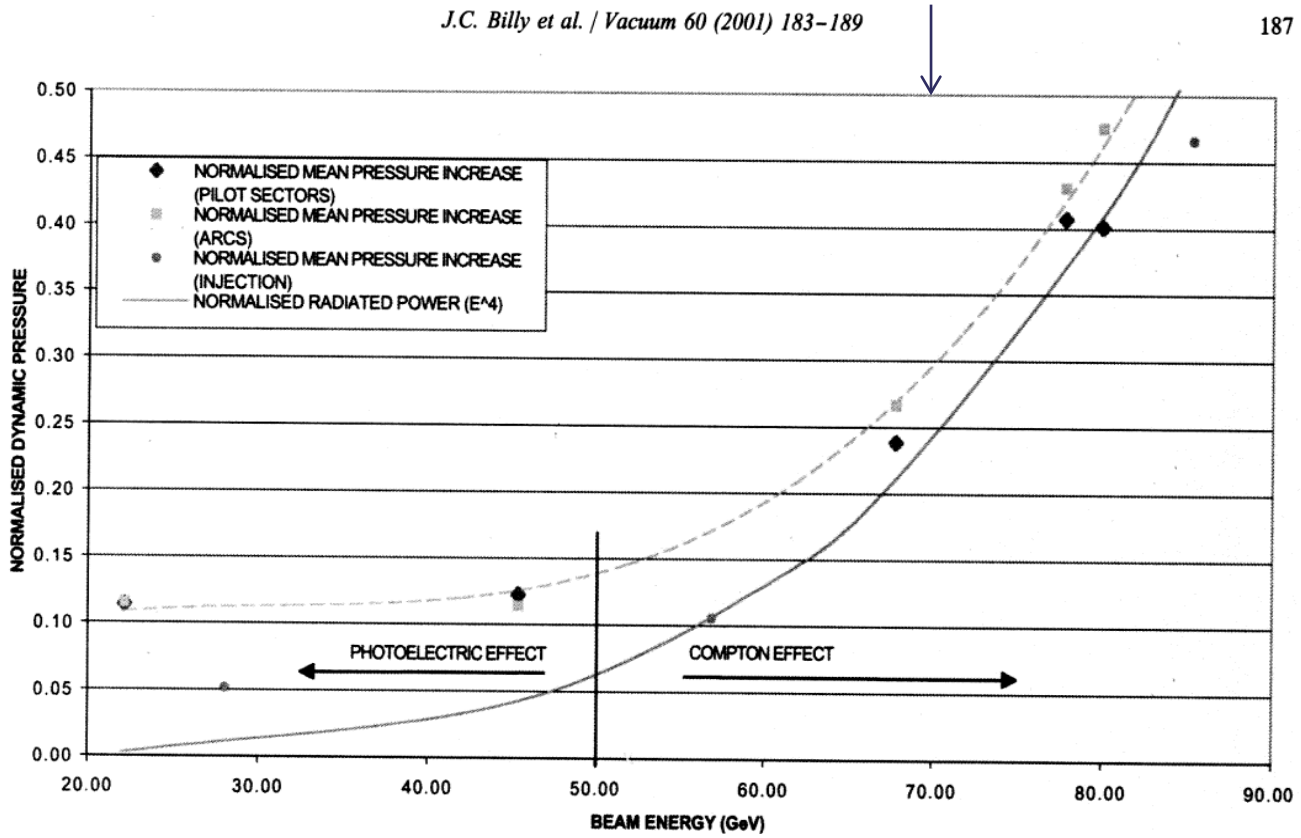
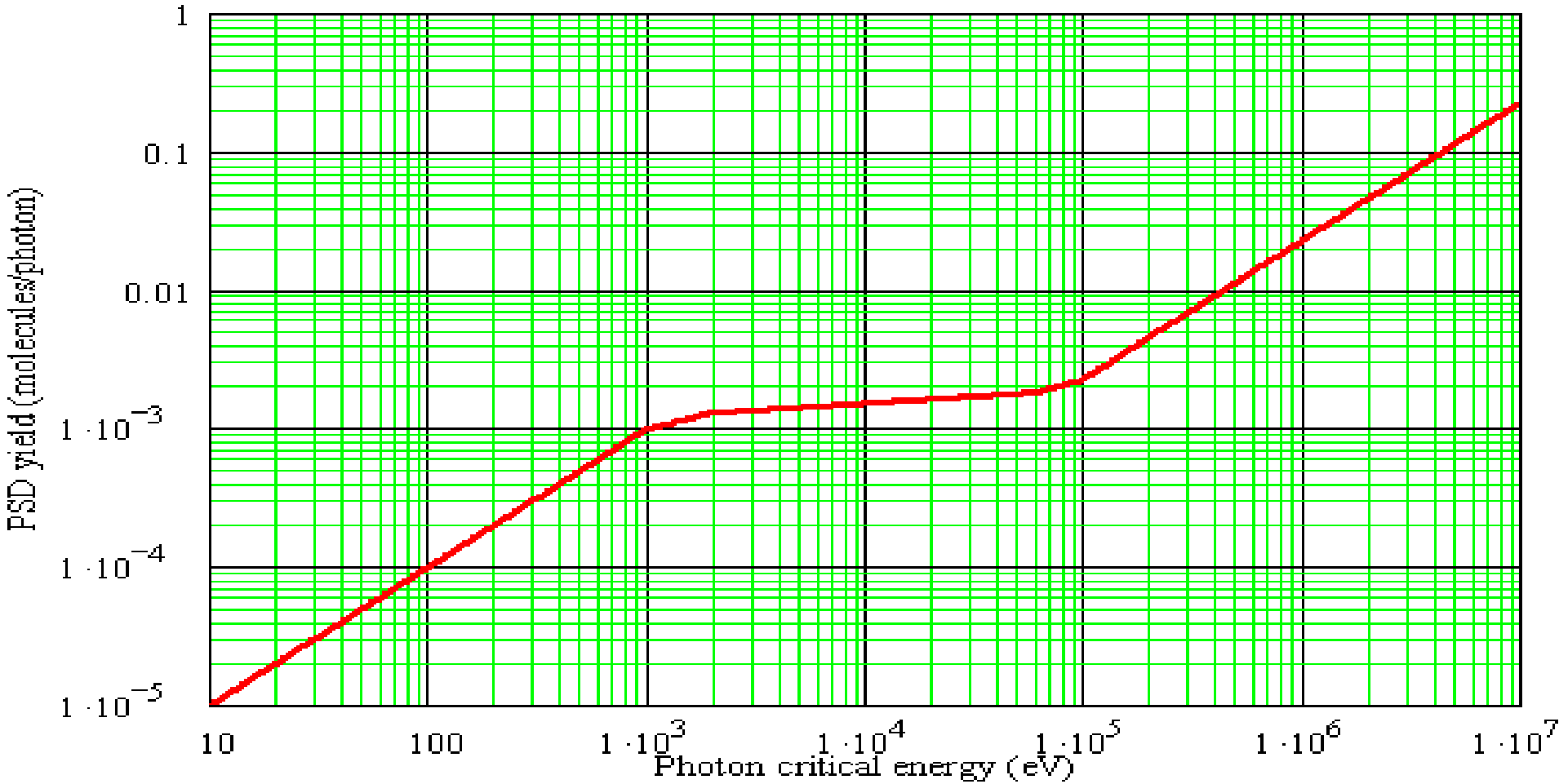



Fig. 5. Normalised pressure increase (low beam energy, measured in LEP arcs, 1999).

J. Gomez-Goni, O. Gröbner, and A. G. Mathewson, J. Vac. Sci. Technol. **A12**, 1714, (1994)

# PSD as a function of critical energy of SR

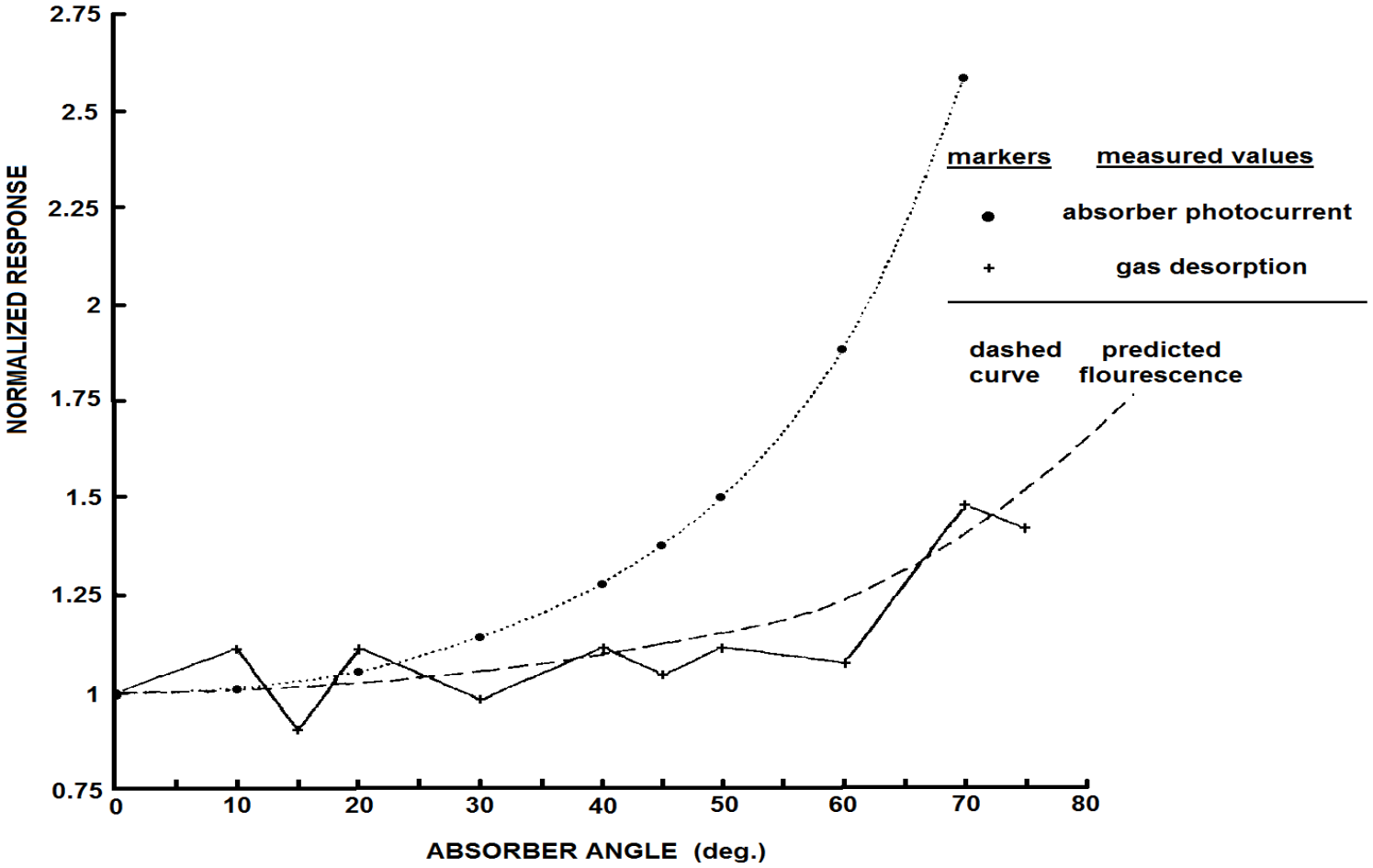


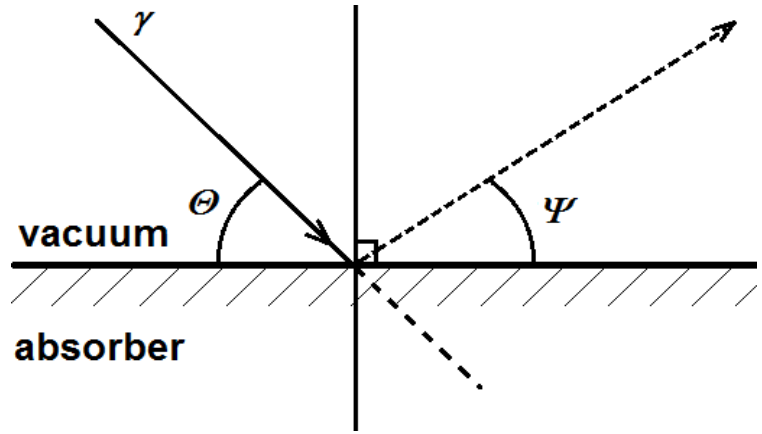

J. Vac. Sci. Technol. A 25(2007): 791-801

# Reducing PSD by bakeout

| Bakeout | Impact | Comment |
|---|---|---|
| In-situ at 150 °C for 24 hrs | reduction of $\eta_{H2O}$ by 5-10 times; reduction of initial PSD yields for other species by 2-4 times | Reducing bakeout temperature to 120 °C requires increasing of bakeout duration to a few days. |
| In-situ at 300-350 °C for 24 hrs: | reduction of initial $\eta_{H2}$ by 10-20 times, for other species by 7-15 times | - |
| Ex-situ at 250-300 °C for 24 hrs | reduction of initial $\eta_{H2}$ by 5-10 times, for other species by 4-8 times | keep in vacuum; minimise vent to air during installation; purge with dry air, $N_2$ or noble gases |
| Vacuum firing at 950 °C for 1-2 hrs at P < $10^{-5}$ mbar | hydrogen depletion in the bulk of vacuum chamber material | Keep in vacuum or fill with $N_2$ or noble gas. |
| No in-situ bakeout after vacuum firing | reduction of $\eta_{H2}$ by ~1.5-2 times | |
| In-situ bakeout after vacuum firing | reduction of $\eta_{H2}$ by ~20-50 times | |

# Effect of incident angle on PSD



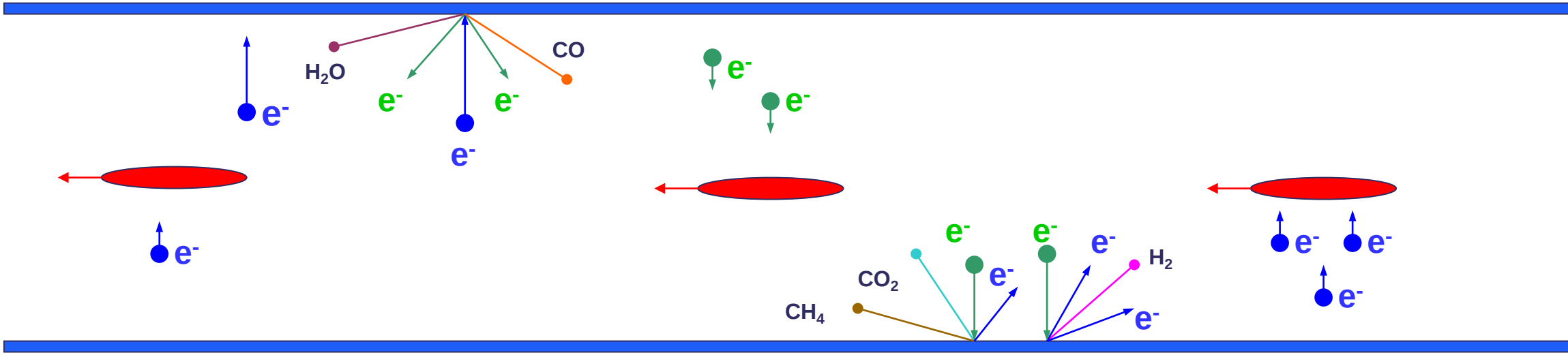

PSD and PEY as a function of absorber angle (90°–Θ) normalised to response at normal incidence for copper surface

[B. A. Trickett, D. Schmied and E. M. Williams. Hard synchrotron radiation and gas desorption processes at a copper absorber J. Vac. Sci. Technol. A10 (1992) 217]

# Electron stimulated desorption (ESD)

# ESD

**Electron stimulated desorption (ESD)** could be an important sources of gas in case of electron beam bombardment, beam induced electron multipacting, or as a part of the PSD process ***in the presence of SR***.




Gas molecules may desorb from a surface when and where *electrons* arrive at a surface

**ESD** could also be an important sources of gas in case of measurements with an electron beam, electron beam treatment, electron beam welding, and other processes with electrons.

# ESD yields

ESD yields are defined as a number of gas molecules desorbed from the surface per incident electron, $\eta_e$ [molecules/e$^-$]:

$$\eta_e\left[\frac{molecules}{e^-}\right]=\frac{N_{molecules}}{N_{electrons}}=\frac{Q\left[Pa\cdot m^3/s\right]q_e\left[C\right]}{k_BT\left[K\right]I\left[A\right]},$$

where

- $Q$ is a flux of molecules desorbed due to electron bombardment,
- $I$ is the electron current,
- $q_e$ is the elementary charge

# What ESD depend on?

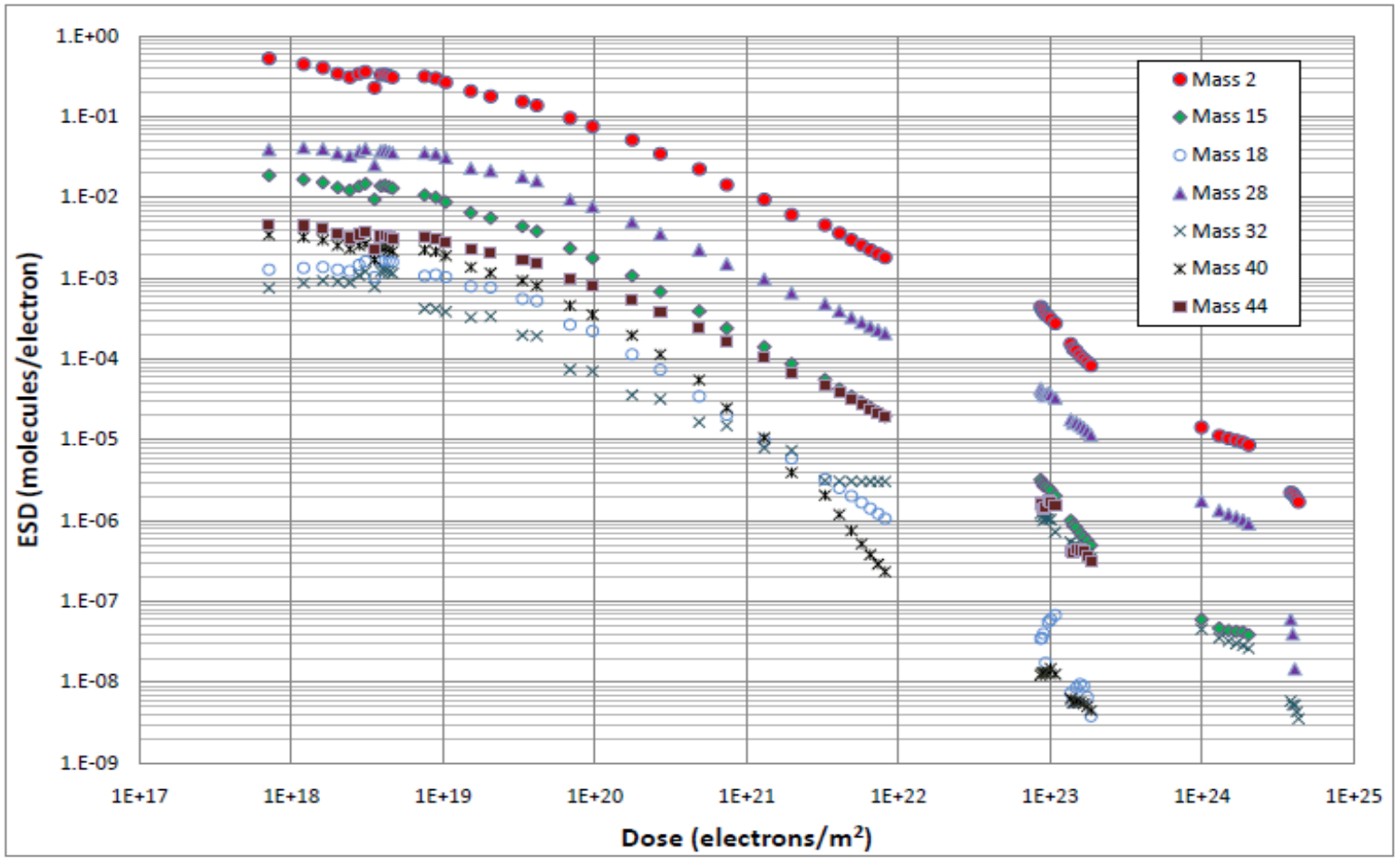
Similarly to PSD and thermal desorption, ESD depends on:

- Choice of material
- Cleaning procedure
- History of material
- Bakeout and vacuum firing
- Pumping time

**Additionally it depends on**

- Energy of electrons impinging the surface
- Electron flux to the surface
- Integral electron dose
- Temperature

# ESD as a function of dose




ESD yield as function of accumulated photon dose can be described as:

$$\eta = \eta_0 \left( \frac{D_0}{D} \right)^{\alpha}$$

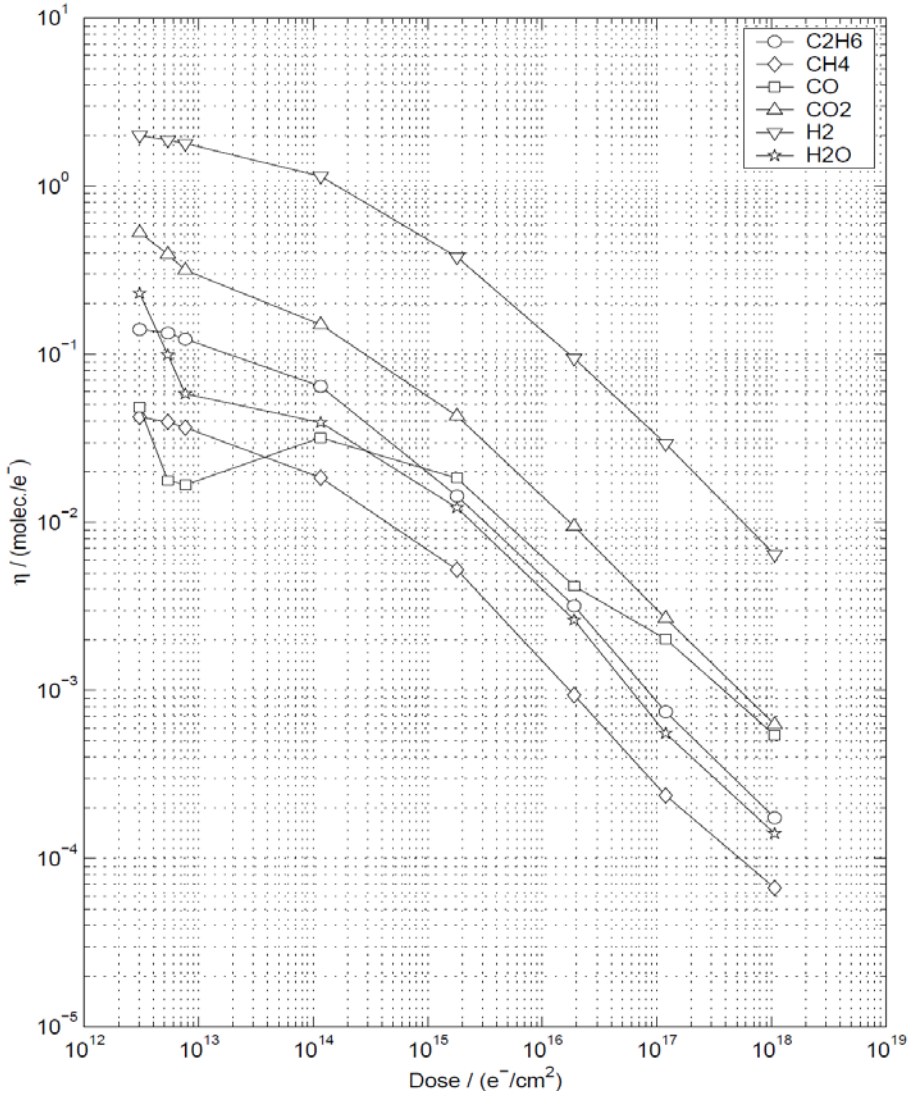
the exponent $\alpha$ lies between $0.5 \leq a \leq 1$

ESD yields of 316 LN stainless steel baked to 250 ºC for 24 hours as a function of electron dose at electron energy $E_e$ = 500 eV.

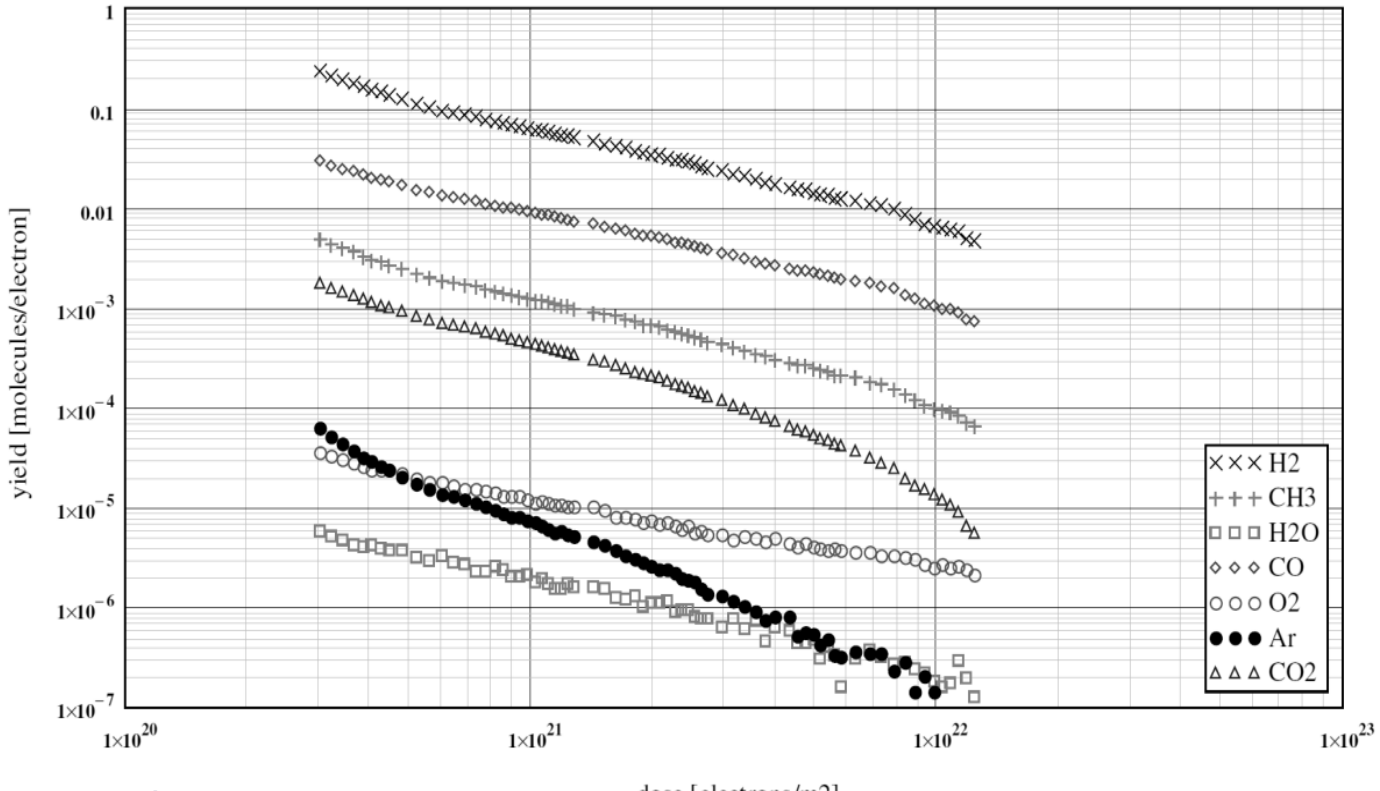
O.B. Malyshev and C. Naran. Vacuum **86** (2012), 1363-1366.

# ESD from different materials

ESD yields of unbaked OFHC copper after 24-hour pumping as a function of electron dose at $E_e$ = 300 eV




ESD yields of aluminium alloy baked to 220 ºC for 24 hours as a function of electron dose at electron energy $E_e$ = 500 eV



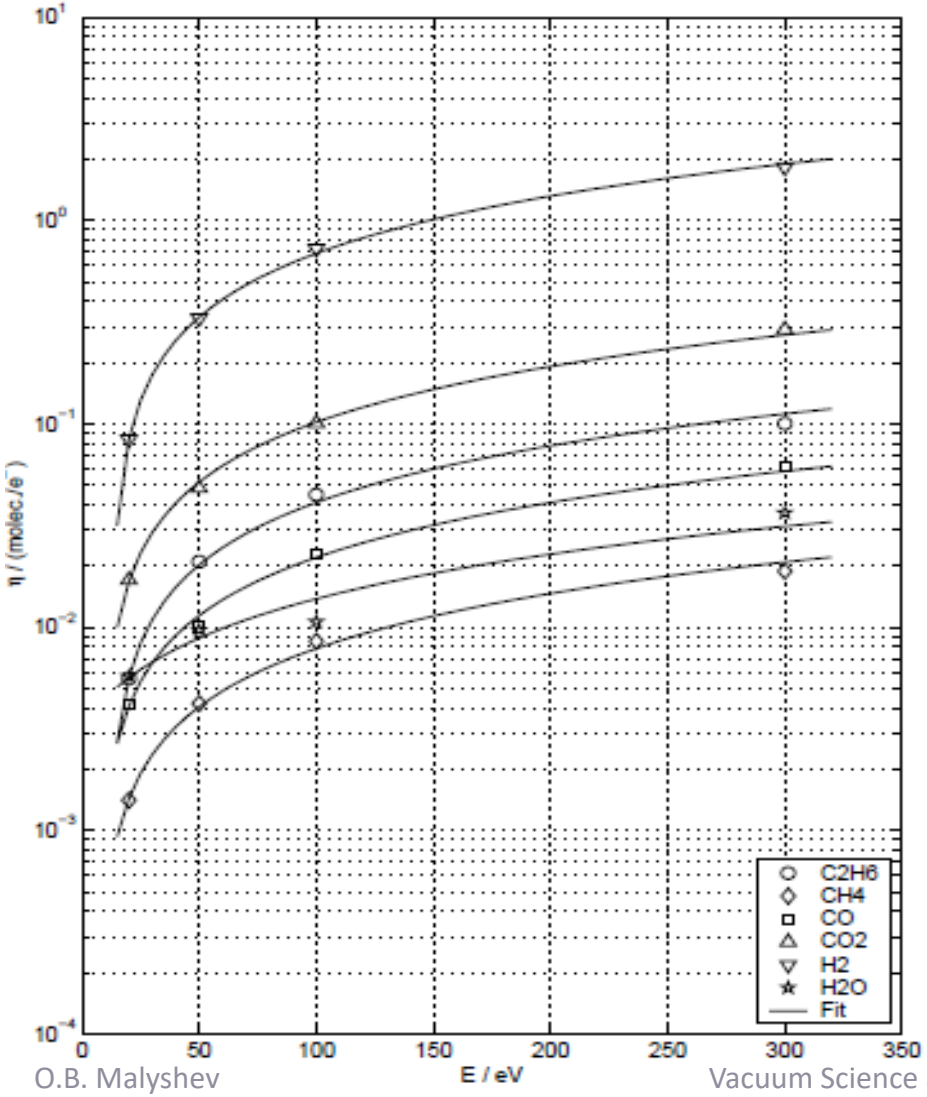

F. Billard *et al*, Some Results on the Electron Induced Desorption Yield of OFHC Copper. Vacuum Technical Note 00-32, December 2000, CERN, Geneva.

O.B. Malyshev *et al*, Vacuum 85 (2011) 1063-1066.

# ESD as a function of electron energy

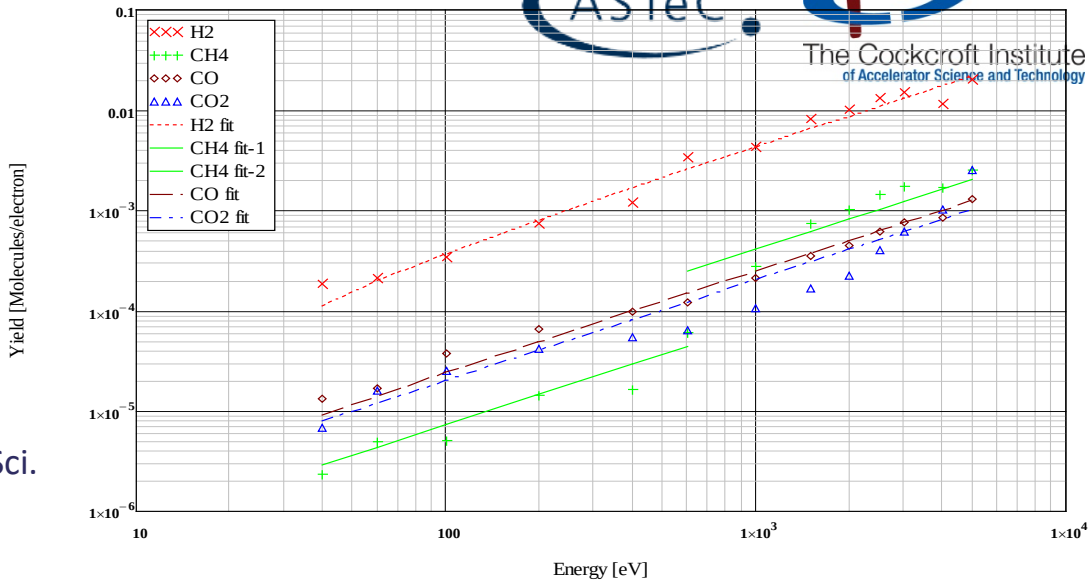
Unbaked OFHC copper at the dose D = 1.4 × $10^{14}$ $e^-/cm^2$

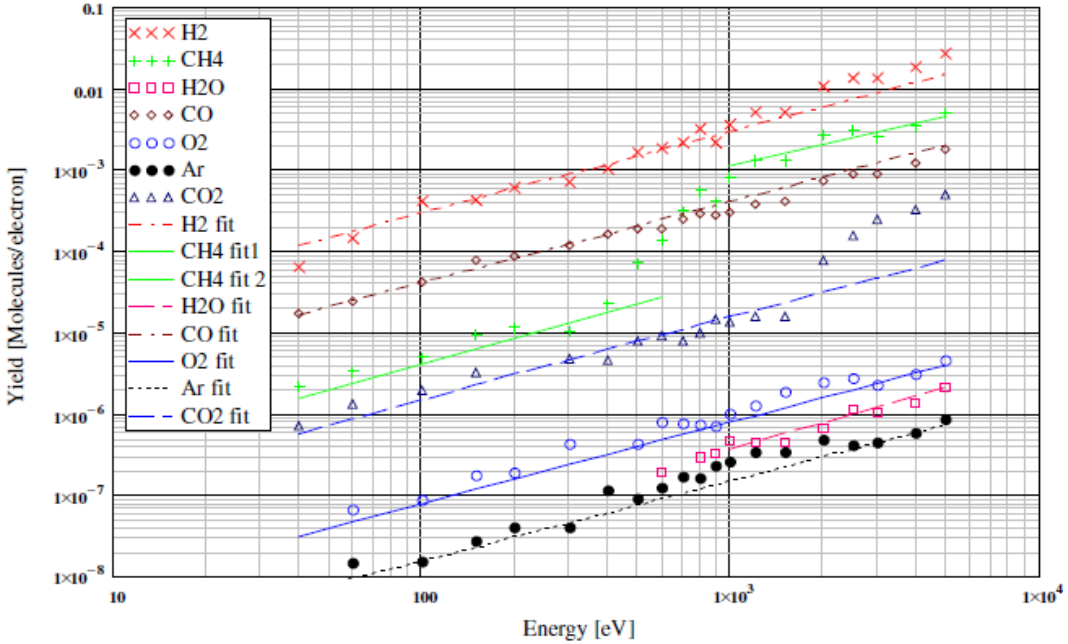
F. Billard *et al*, Vacuum Technical Note 00-32, December 2000, CERN, Geneva.




Stainless steel baked at 250 °C for 24 h at the dose D = 7 × $10^{21}$ $e^-/cm^2$

O.B. Malyshev *et al*, J. Vac. Sci. Technol. **A 28** (2010) 1215.




Aluminium sample baked at 220 °C for 24 h at the dose D = 1.3 × $10^{22}$ $e^-/cm^2$

J. Vac. Sci. Technol. **A12** (1994), 1714.

# Ion stimulated desorption (ISD)

# ISD

**Ion stimulated desorption (ISD)** can be a significant gas source in a vacuum system where the ion beam bombards the surface. There is very little data, most work has been done at CERN.

Similarly to thermal desorption, PSD and ESD, the ISD depends on: choice of material, cleaning procedure, history of material and pumping time.

It is also depends on:

- **Mass, charge and energy of ions impacting the surface**
- **Ion flux to the surface**
- **Integral ion dose**
- **Temperature**

# ISD yields

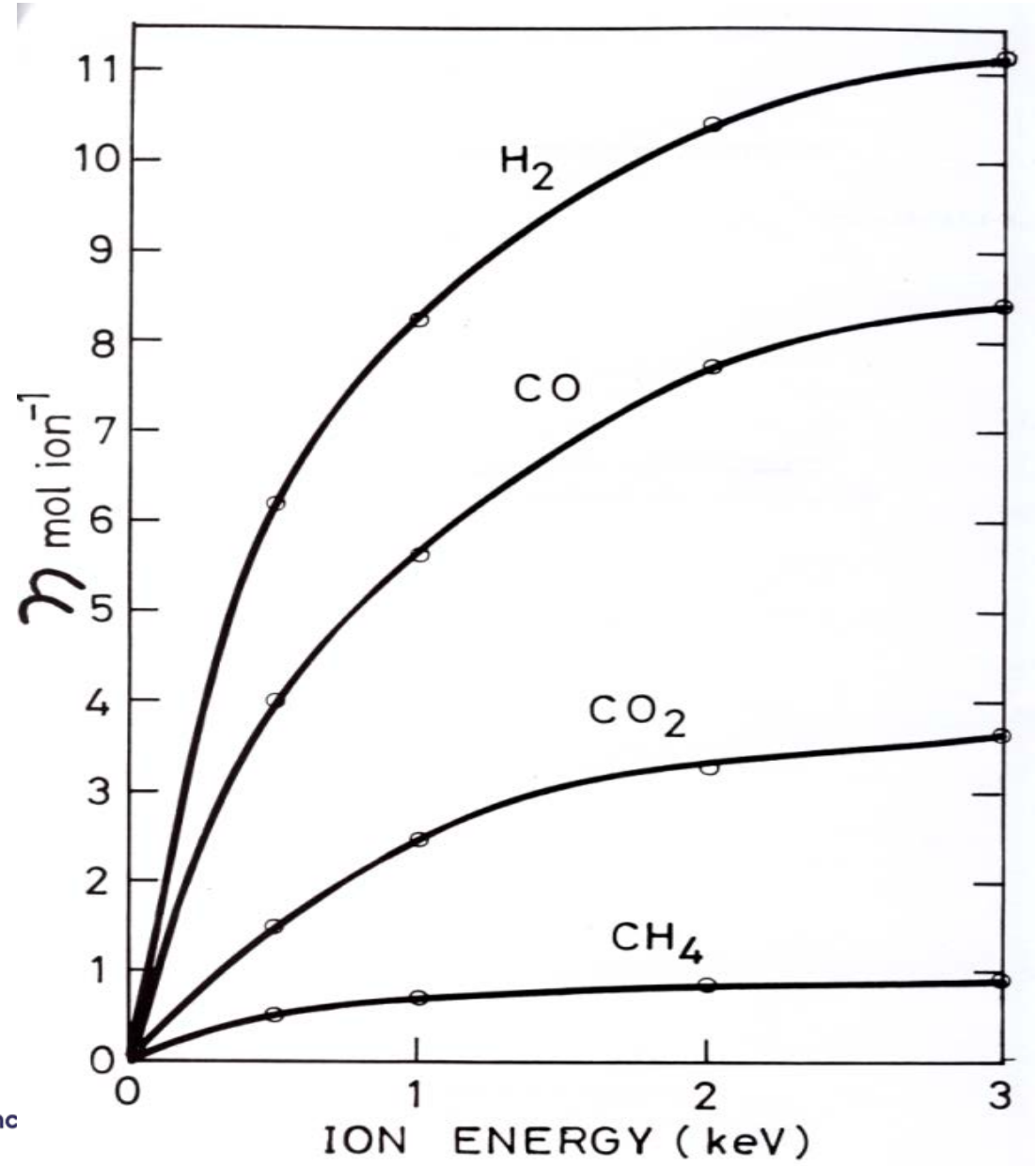
ISD yields, defined as a number of gas molecules desorbed from the surface per incident ion, $\chi$ **(molecules/ion),** :

$$\chi\left[\frac{molecules}{ion}\right] = \frac{N_{molecules}}{N_{ions}} = \frac{Q\left[Pa\cdot m^3/s\right] q_e\left[C\right] n_q}{k_B T\left[K\right] I\left[A\right]},$$

where

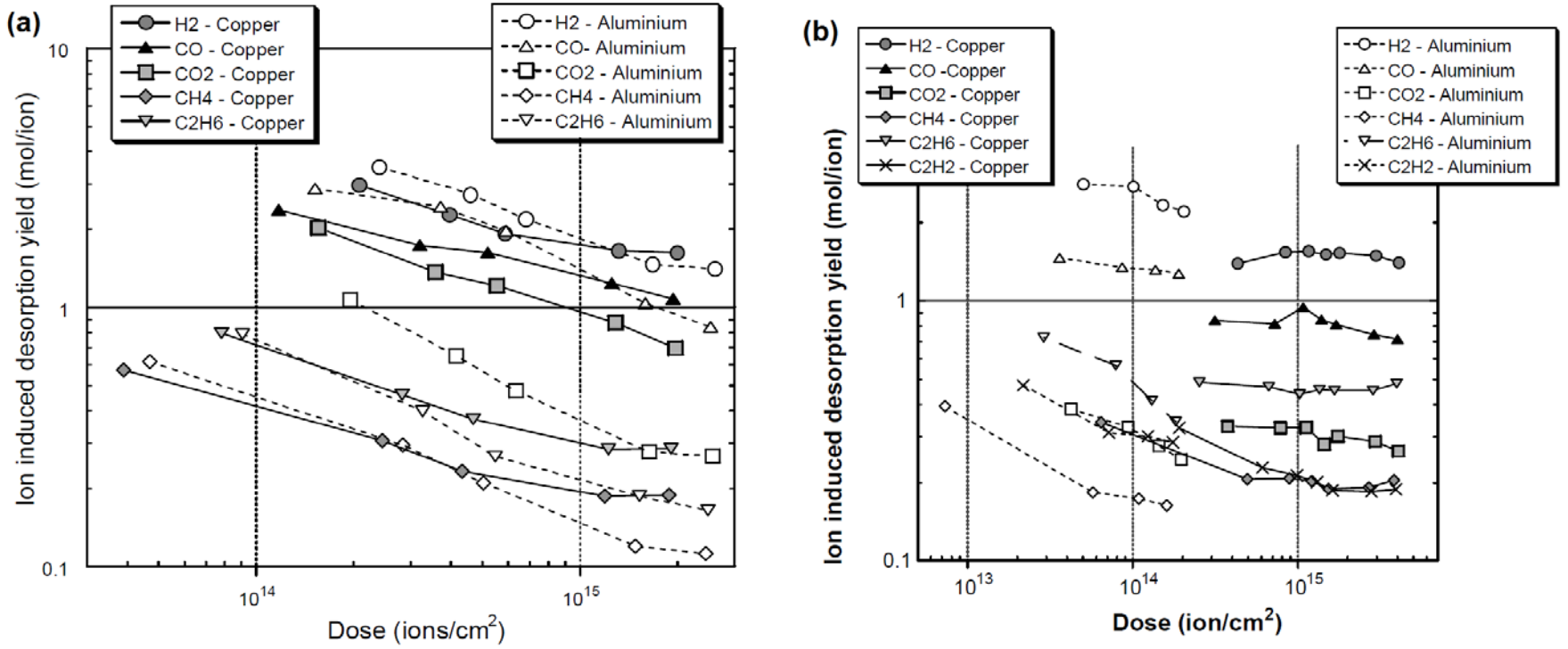
- $Q$ is a flux of molecules desorbed due to ion bombardment,
- $I$ is the ion current,
- $q_e$ is the elementary charge and
- $n_q$ is the ion charge number

# ISD yields as a function of ion energy




A.G. Mathewson. Ion induced desorption coefficients for titanium alloy, pure aluminum and stainless steel. CERN-ISR-VA/76-5 (1976).

# ISD as a function of dose




The ISD yields as a function of accumulated ion dose from (a) as-received and (b) baked aluminium and copper samples bombarded with argon ions at 5 keV.

M.P. Lozano. Ion-induced desorption yield measurements from copper and aluminium. Vacuum **67** (2002) 339.

ISD yield as function of accumulated ion dose can be described as:

$$\chi_i(D) = \chi_i(D^*)\left(\frac{D^*}{D}\right)^{\alpha};$$

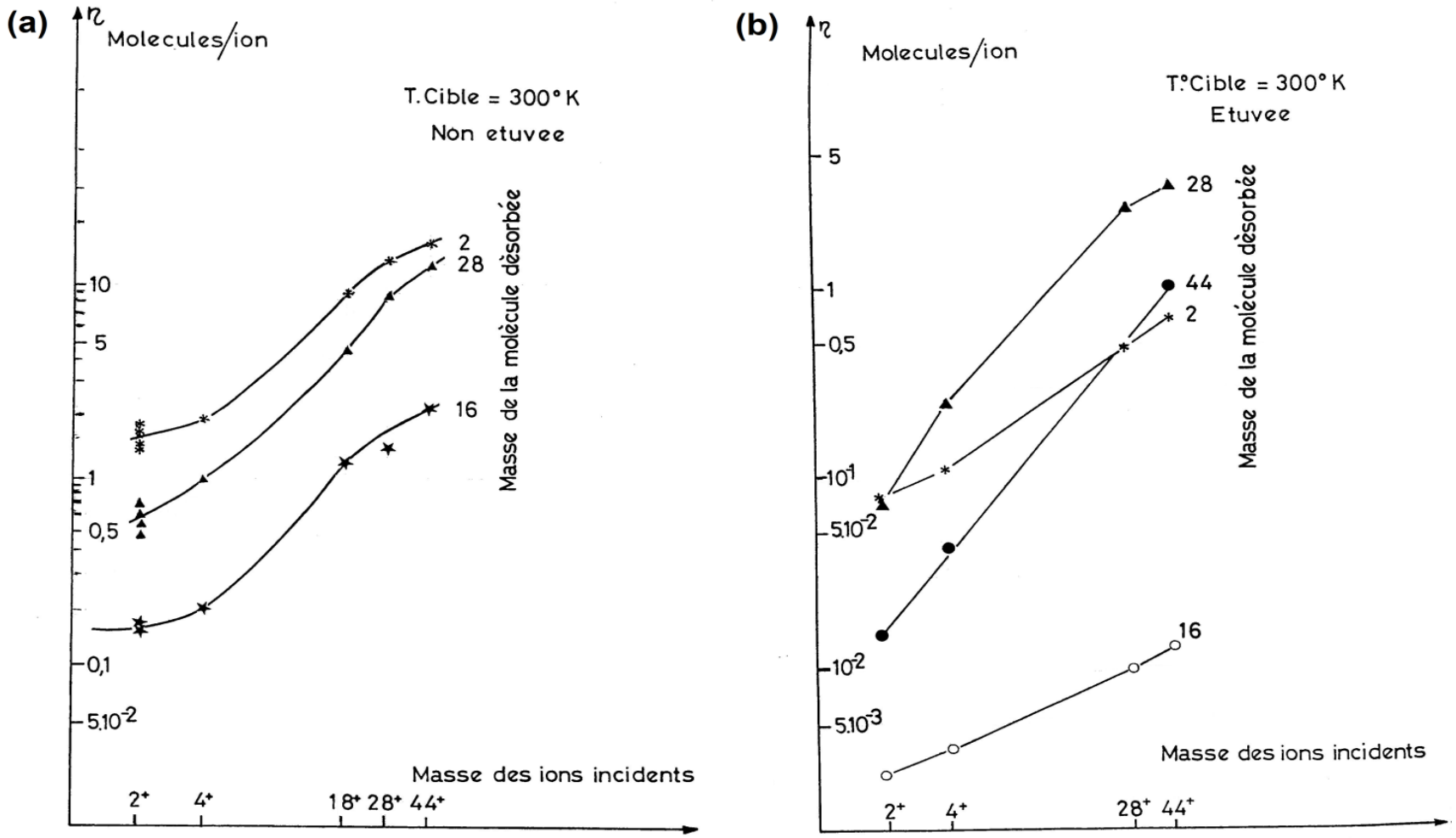
the exponent $\alpha$ lies

between $0.3 \le \alpha \le 0.5$ for as-received samples and

between $0 \le \alpha \le 1/3$ for baked samples

# ISD as a function of ion mass

ISD yield from (a) unbaked and (b) baked stainless steel sample as a function of incident ion mass




N. Hilleret. Influence de la nature des ions incidents sur les taux de desorption par bombardement ionique de molécules adsorbées sur une surface d'acier inoxydable. CERN-ISR-VA/78-10 (1978).

# Two concepts of the ideal vacuum chamber

**Traditional:**

- surface which outgasses as little as possible ('nil' ideally)
- surface which ***does not pump*** otherwise that surface is contaminated over time

**Results in**

- Surface cleaning, conditioning, coatings
- Vacuum firing, *ex-situ* baling
- Baking *in-situ* to up to **300°C**
- Separate pumps

**'New' (C. Benvenuti, CERN, ~1998):**

- surface which outgasses as little as possible ('nil' ideally)
- a surface which ***does pump***, however, will not be contaminated due to a very low outgassing rate

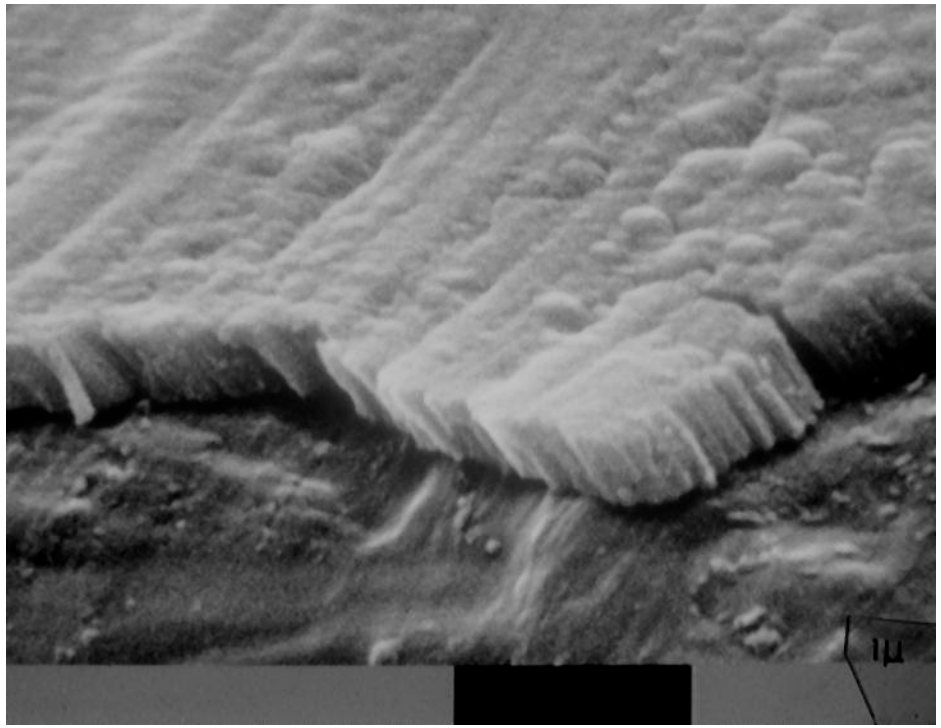
**Results in**

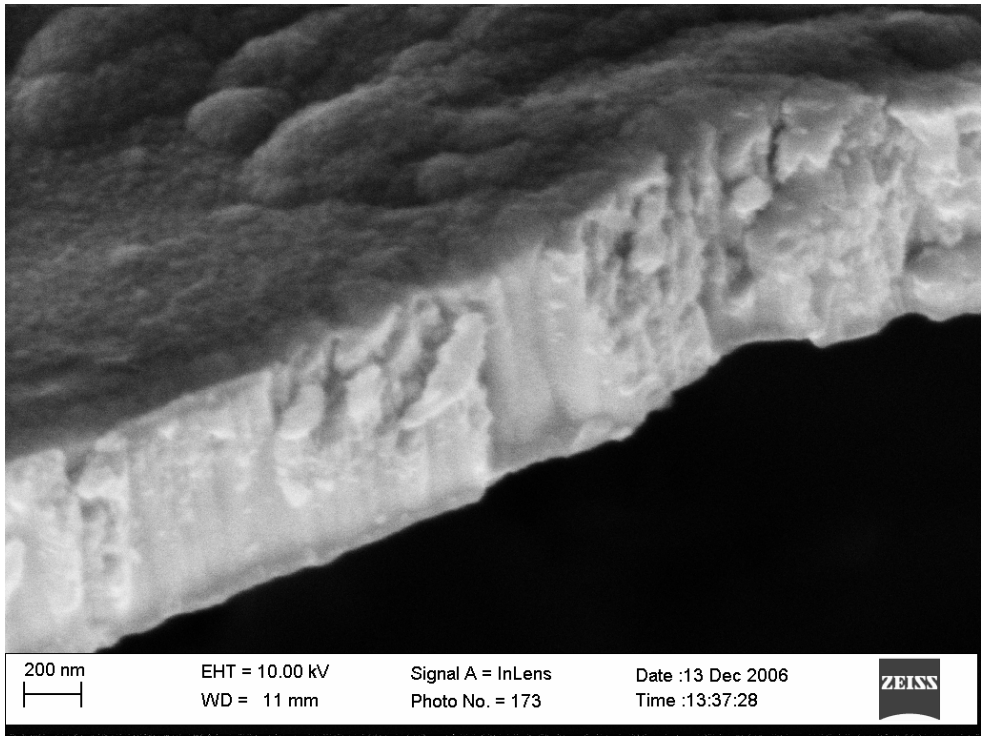
- NEG coated surface
- There should be no un-coated parts
- Activating (baking) *in-situ* at **150-180°C**
- Small pumps for $C_xH_y$ and noble gases

# SEM images of films (film morphology)

columnar

dense




O.B. Malyshev, R. Valizadeh, J.S. Colligon *et al*. J. Vac. Sci. Technol. A 27 (2009), p. 521.

# What NEG coating does

1) Reduces gas desorption:
   - A pure metal (Ti, Zr, V, Hf, etc.) film ~1-μm thick without contaminants.
   - A barrier for molecules from the bulk of vacuum chamber.

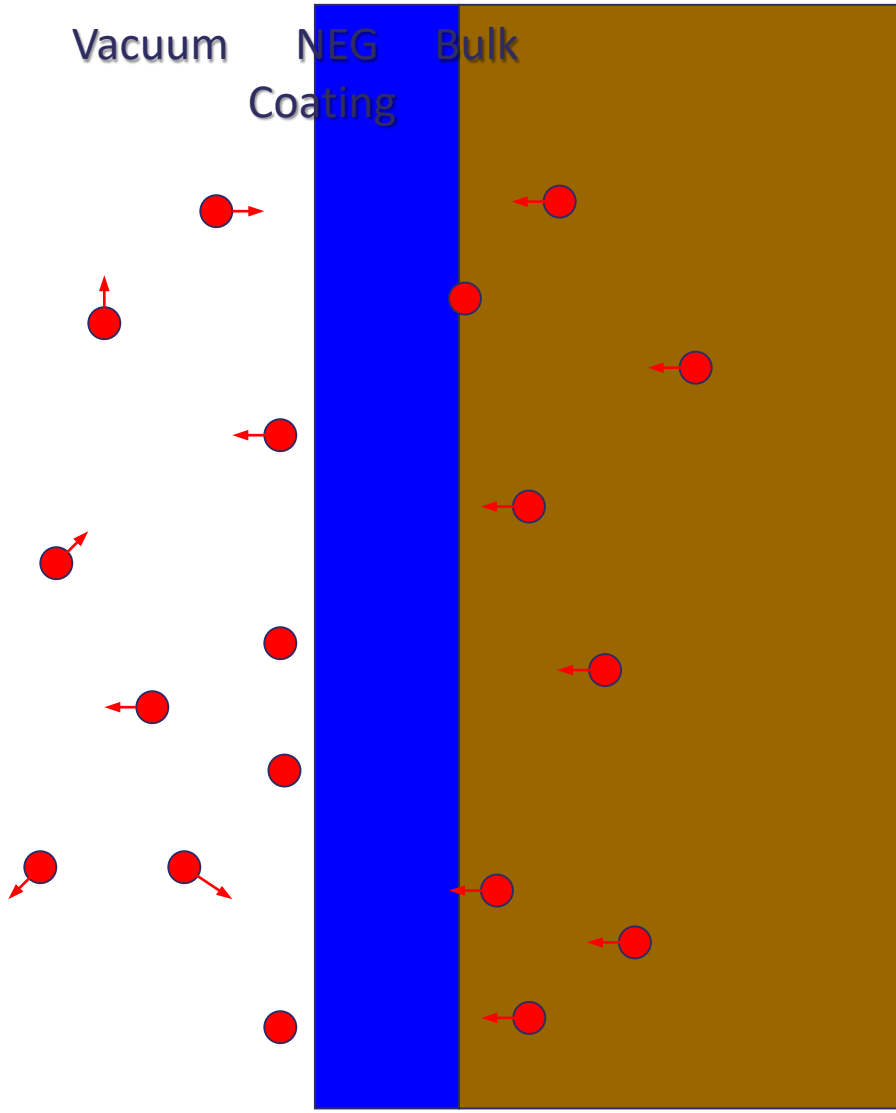
2) Increases distributed pumping speed, *S*:
   - A sorbing surface on whole vacuum chamber surface

$$S = \alpha \cdot A \cdot v/4;$$

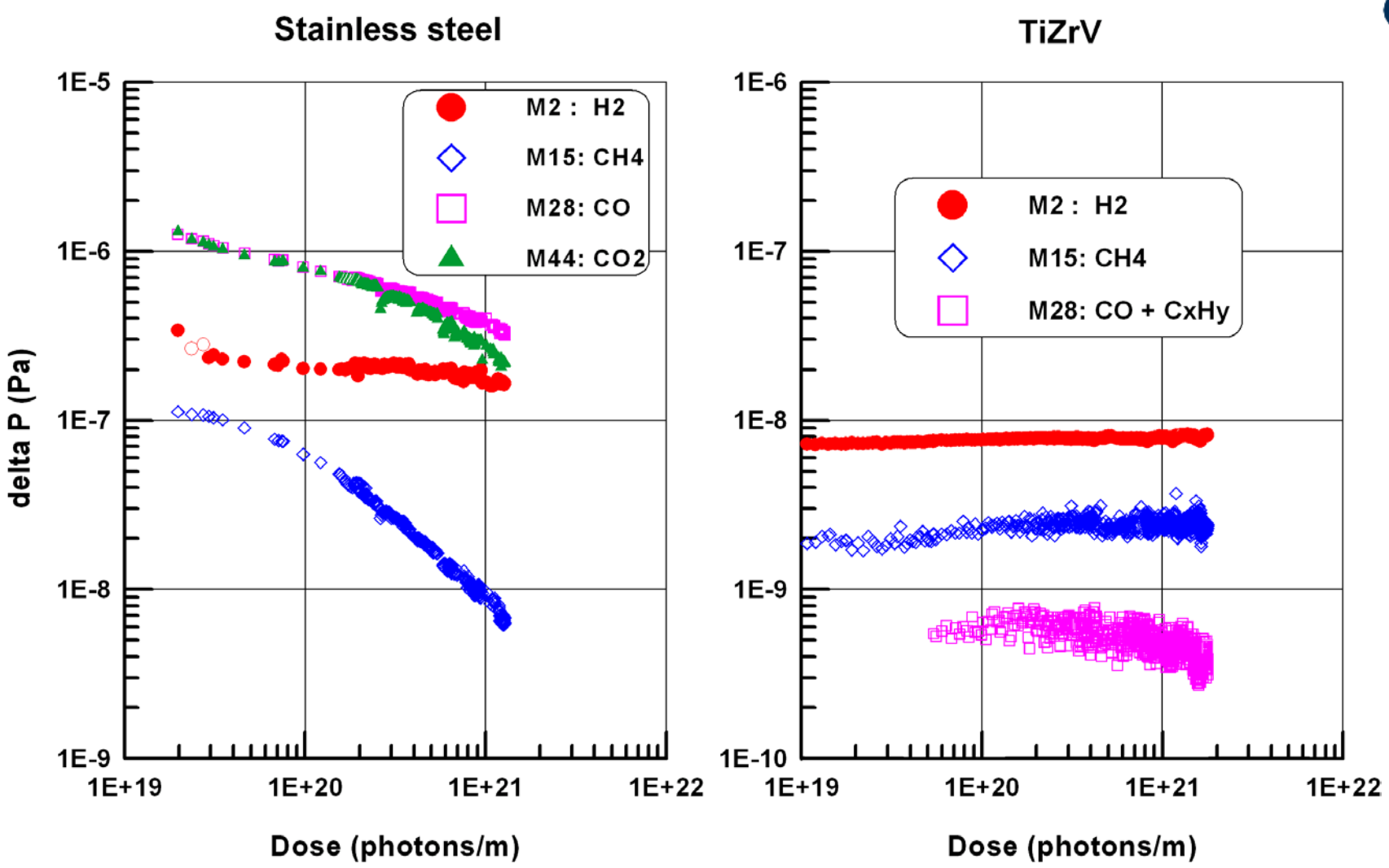
where $\alpha$ – sticking probability,

A – surface area,

v – mean molecular velocity



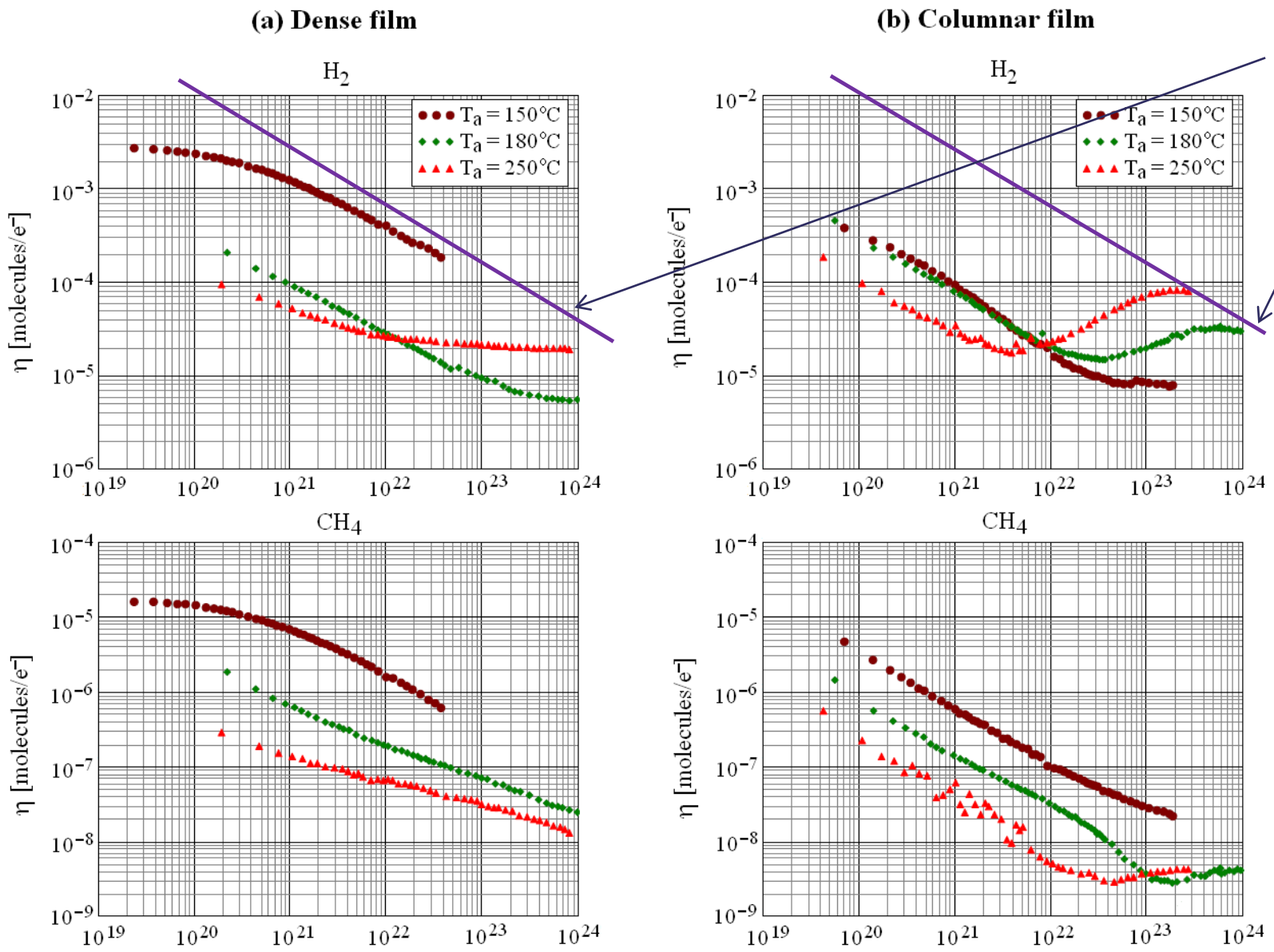
# NEG coated vacuum chamber under SR




Science and Technology Facilities Council

**Dynamic pressure rise for the Stainless Steel (baked at 300°C for 24 hrs) and TiZrV coated vacuum chambers (activated at 190°C for 24 hrs)**

# ESD yield from NEG coated samples



Science and Technology Facilities Council

# Session 6

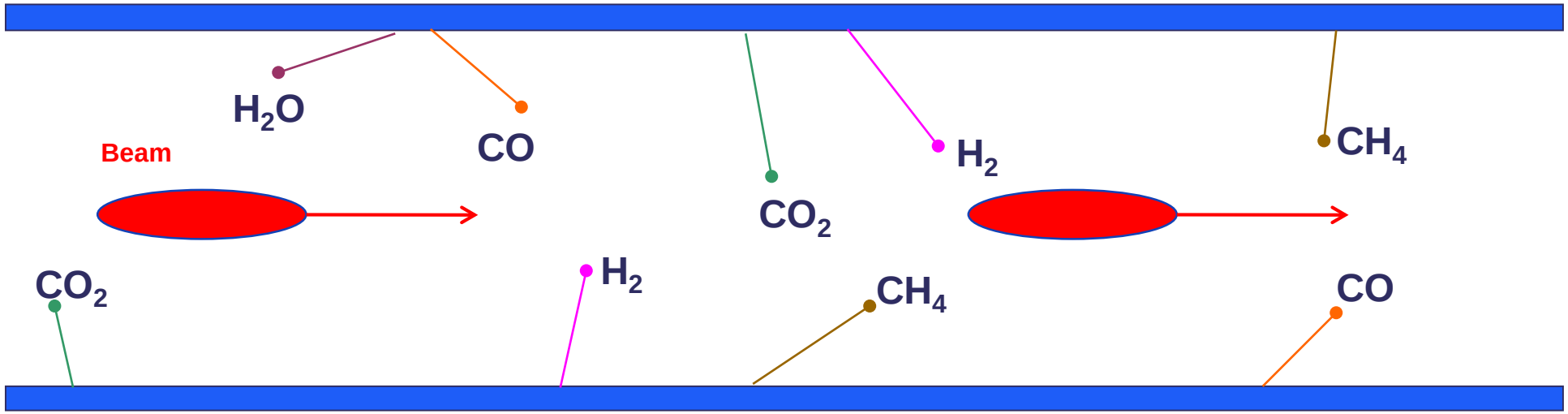
## Part 2:
## Basic vacuum design of accelerators.
## Calculations to support the design

# Aims of Part 2: Basic Principles of Vacuum

- To use some of the concepts and information from earlier lectures as an introduction to the process of delivering a working accelerator from the vacuum system viewpoint
- To present some examples of basic vacuum calculations

# Vacuum required in the particle accelerators

- **High energy particles** collide with residual gas molecules that results in:
  - loss of particles,
  - loss of the beam quality.




- **Examples of vacuum specification for a high energy particle accelerator**:
  - 100 h vacuum life time at I = 560 mA after 100 Ah conditioning (for DLS);
  - $P(N_2\ eqv) = 10^{-8}$ mbar after bakeout and a week of pumping (for a buster);
  - $n(H_2\ eqv) = 10^{15}\ m^{-3}$ after 2 years conditioning (for the LHC); etc...

# Preliminary questions

- What sort of machine is it?
  - Experimental (“Toy”)
    - ex.: VELA, CLARA
  - Data collector
    - ex.: colliders (LHC, RIHC, DAΦNE)
  - User Facility
    - ex.: SR sources, medical and industrial accelerators
- Implications
  - Reliability
  - Serviceability
  - Access
    - Physical
    - Duty cycle

# Vacuum specifications are affected by

- Lattice design
  - Location and required space for key components:
    - Magnets, collimators,
    - Detectors,
    - SR absorbers
    - Beamlines
  - Choice of materials and coatings
    - Electric and magnetic properties
    - Surface resistance,
    - Surface roughness,
    - Reflectance or transparency
  - Beam size (close orbit) =>
    - Apertures (lower limit)
  - Magnet design =>
    - Apertures (upper limit)
  - Preliminary mechanical layout
- Specific components
  - E-gun,
  - gas target,
  - detectors,
  - Wigglers and undulators,
  - SR or particle beamlines
  - etc.
- Specific problems
  - Electron cloud; ion instability, ion induced pressure instability
  - High power loss, high radiation damage, etc.
  - Health and safety

# Vacuum design

- Defining all sources of residual gas in vacuum chamber
  - with and without a beam
- Calculating required pumping
  - type of pumps, locations
- Defining the means of pressure measurements
  - their types and locations
- Defining the necessary procedures for
  - material selection,
  - cleaning,
  - treatments (polishing, coating, firing baking, etc.)
- Providing the results of modelling for the gas density (or pressure) profile
  - along the beam path and at any specific location

# Initial Rough Design

- Guess (or estimate) internal surface area
  - $A$ [m$^2$]
- Assume an achievable outgassing rate
  - $q_{th}$ [mbar·l/(s·m$^2$)]
- Determine total required pumping speed, $S$ [l/s] to reach the base pressure, $P_b$

$$S = \frac{Aq_{th}}{P_b} = \frac{Q_{th}}{P_b}$$

- *Since conductance was not considered here, this a **lower limit** estimate of a total required pumping speed.*

# Initial Rough Design

- Work out the significance of any stimulated desorption
  - Location
    - Direct
    - Scattered
  - Intensity
  - Desorption coefficients
- This will result in a dynamic gas load, $Q_d$ (integrated along the machine)
- If $Q_d << Q_{th}$, it may be ignored and dynamic pressure $P_d \sim P_b$.
- Otherwise, the minimum (but not necessary sufficient!) total required pumping speed, $S_{d,}$ calculated from

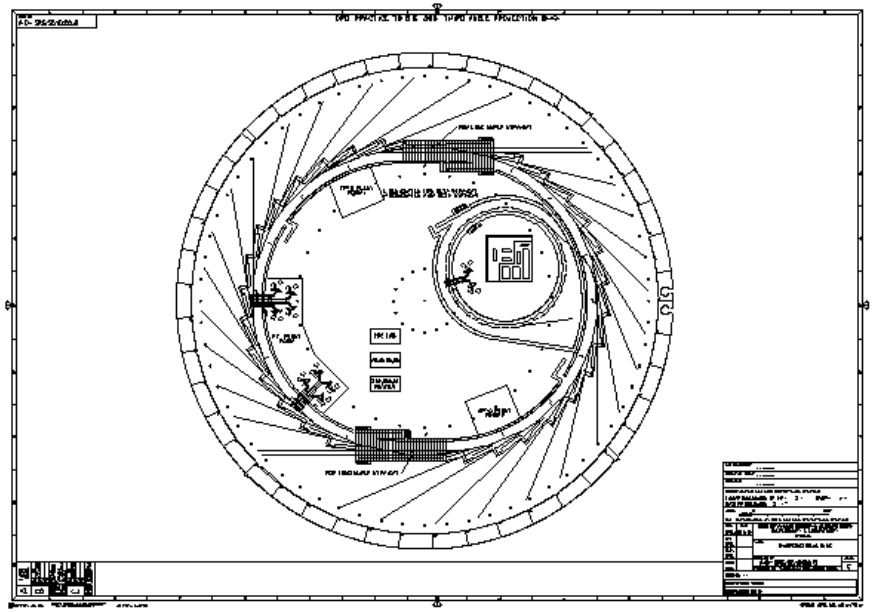
$$S_d = \frac{Q_d + Q_{th}}{P_d}$$

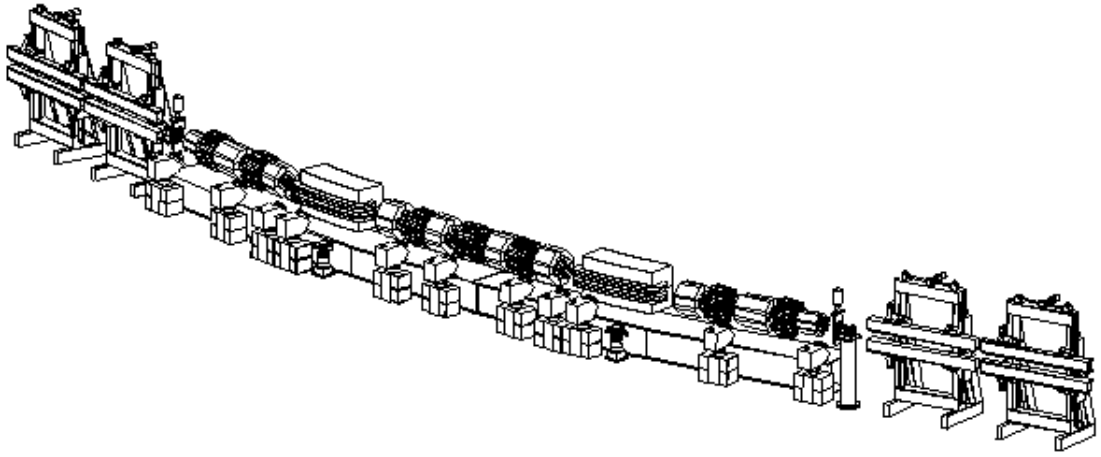
# Initial Rough Design

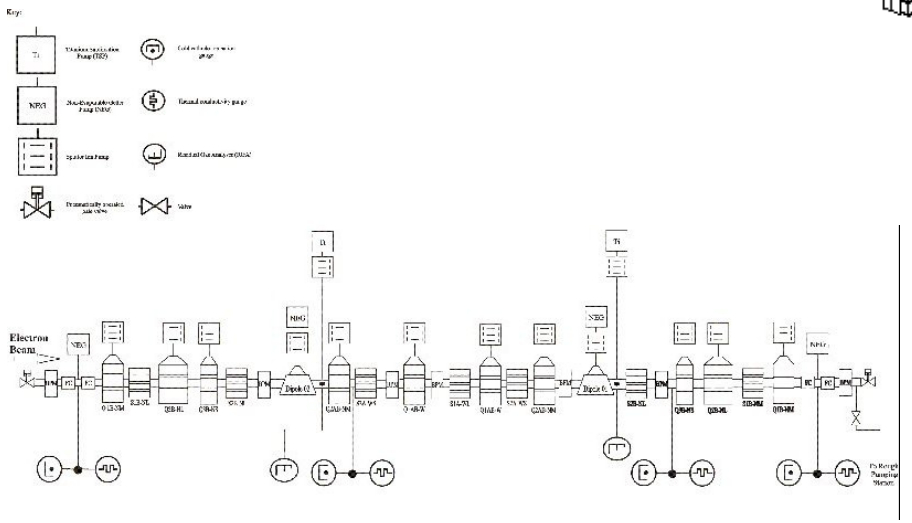
- Determine type of pumps to use
  - Sputter Ion pump (SIP)
    - Lumped
    - Distributed
  - TSP
  - NEG
    - Lumped
    - Distributed
    - Coatings
  - Turbo-molecular pump (TMP)
  - Cryo-pumping
    - Lumped
    - Distributed

# Initial Rough Design

- From a knowledge of what is available, with an eye on economics, and a dash of know-how, work out how many pumps of each type will be required overall.
- Then, using the preliminary mechanical layout, draw up a rough vacuum design layout.







# Towards the final design

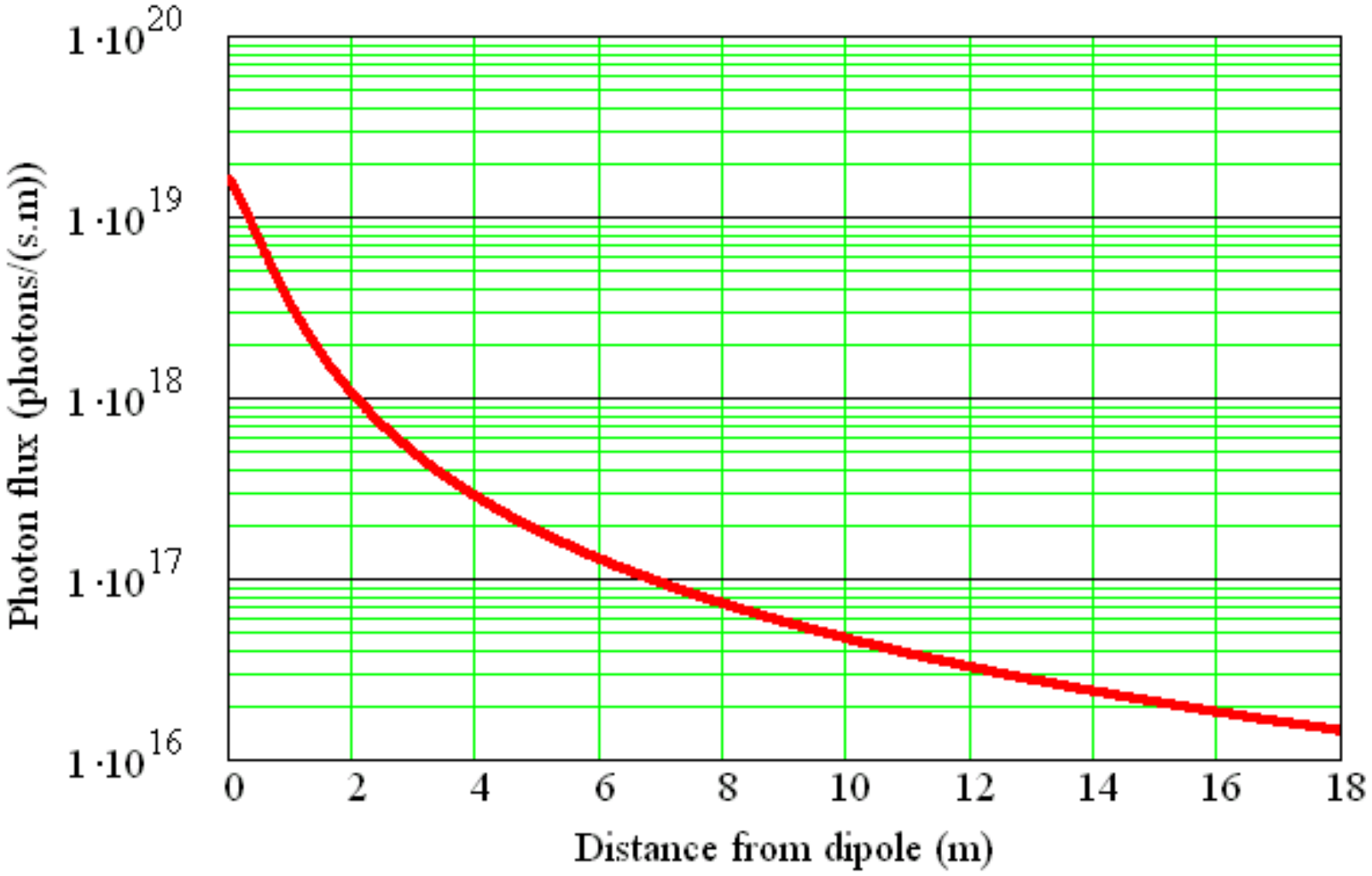
- Using the preliminary layout, carry out a full pressure distribution calculation.
  - This will use a more detailed mechanical layout which takes into account all the vacuum conductances which the preliminary layout has ignored.
- Refine the design (position, size and type of pump) to achieve the basic specification.
- Overlay the vacuum diagnostics needed to obtain the required information.

- Add in valves and other necessary bits and pieces, such as roughing pump positions.
- Vacuum instrumentation (pumps, valves and gauges require space along the beam chamber.
- This all may well involve multiple re-iteration of the mechanical design
  - Changes in the lattice design may require reconsidering both vacuum and mechanical design

# Towards the final design

- If stimulated desorption is important, then calculate the beam conditioning behaviour of the machine.
- Determine the processing and conditioning required to achieve the necessary values of outgassing and desorption.
  - Polishing
  - Coating
  - Cleaning and passivation processes
  - Bakeout, pre-installation and *in situ*

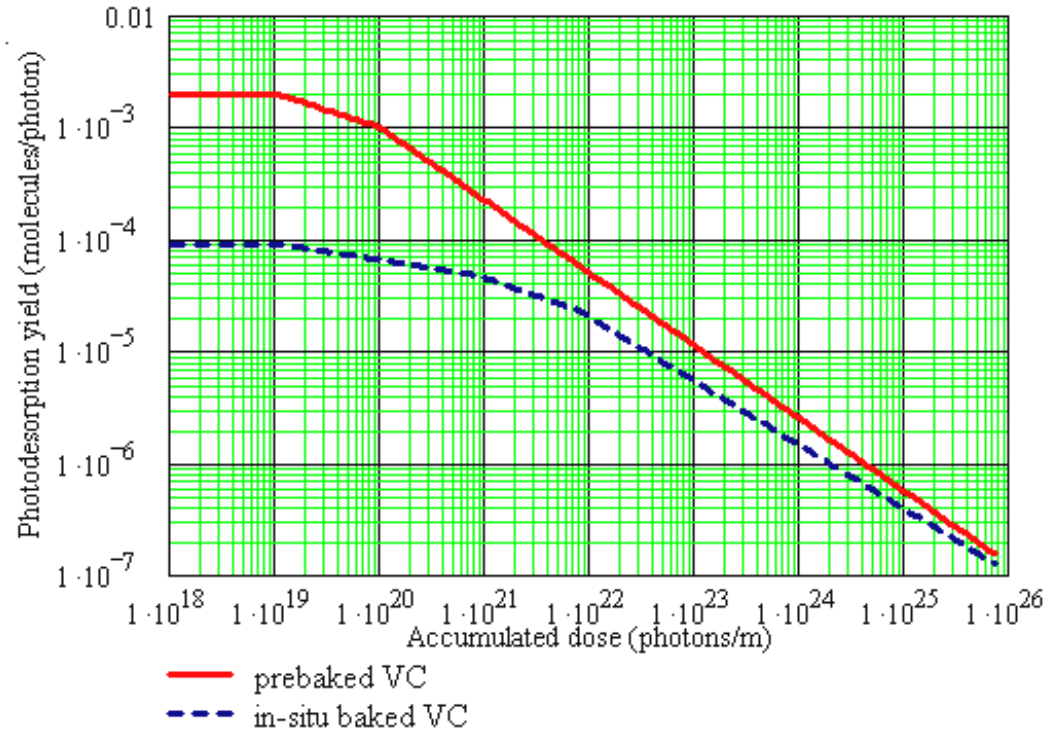
# SR from a dipole magnet




=> This is for an ideal orbit and is very sensitive to the real beam position

# Example: photon stimulated desorption (PSD)

PSD yields, $\eta$ **(molecules/photon),** as a function of accumulated photon dose, ***D***, for different materials measured up to certain doses, these results are extrapolated for use in the design of new machines



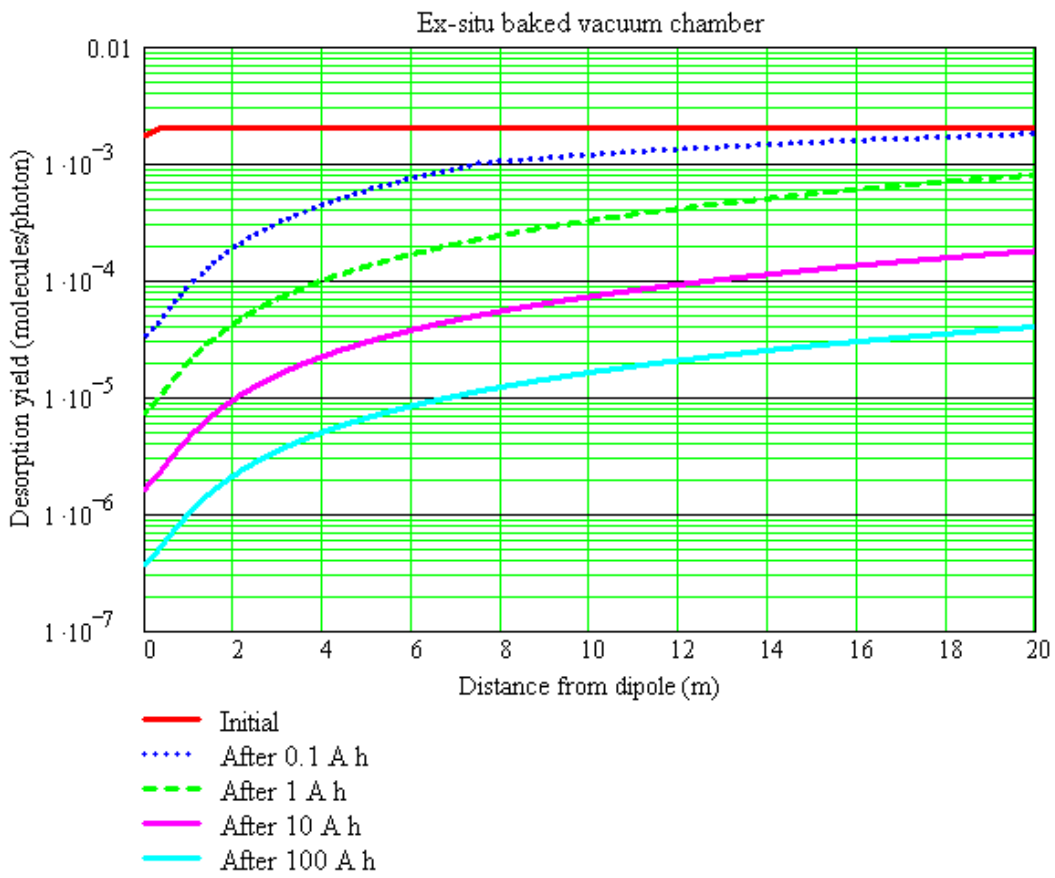

PSD yield at room temperature as function of accumulated photon dose can be described as:

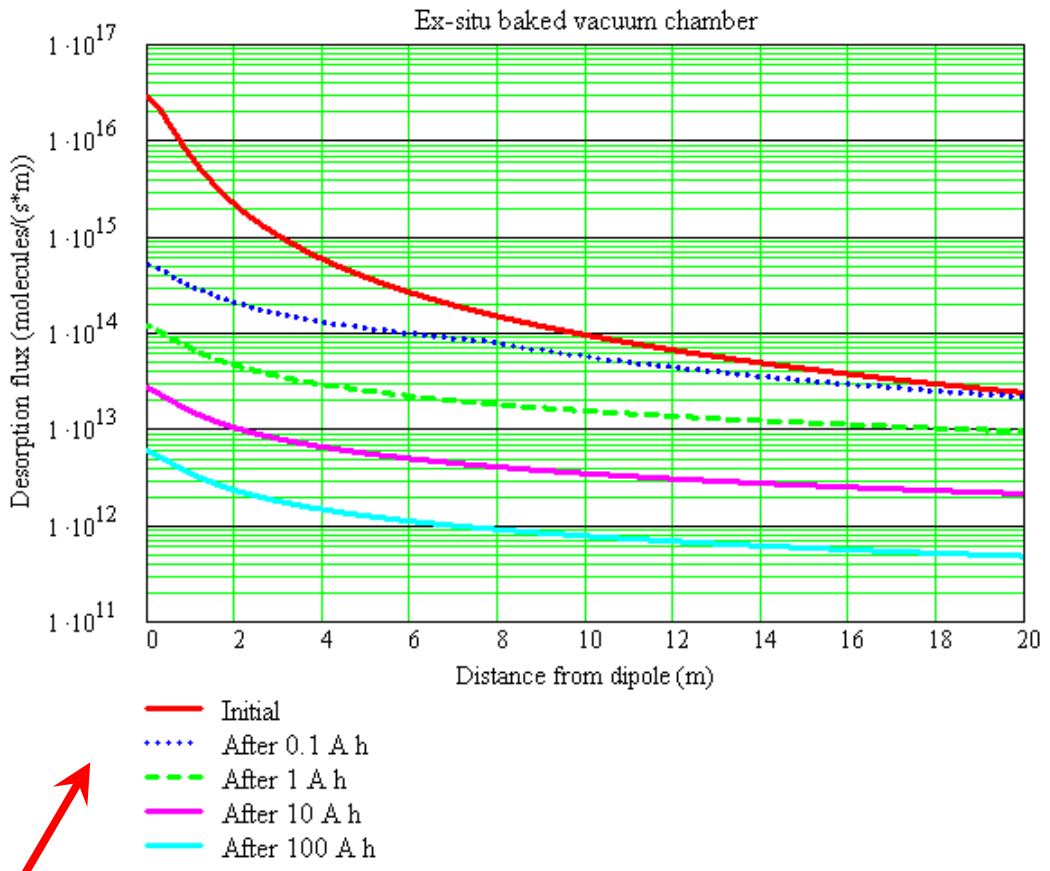
$$\eta = \eta_0 \left( \frac{D_0}{D} \right)^{\alpha}, \quad 0.65 < \alpha < 1$$

PSD yield for CO for prebaked and *in-situ* baked stainless steel vacuum chambers.
Yields for doses higher then $10^{23}$ photons/m (1 to 10 Amp·hrs for Diamond LS) are extrapolations.

**=> Input data for a gas dynamic model are very approximate**

# PSD yield and flux as a function of distance from a dipole magnet




**=> These data for each gas can be used in the gas dynamics model.**
**=> Uncertainty in desorption flux is less than in photon flux and desorption yield**

# Models used in the molecular gas flow regime

- Analytical 1D diffusion model (Knudsen-Clausing)
- Monte-Carlo simulations (2D and 3D)
- Method of angular coefficient (2D and 3D)

# Diffusion model

- Diffusion model is **analytical one-dimensional** approach
- It uses global and averaged parameters: pressure, pumping speed, uniform molecular velocity speed, etc.
- In many cases accuracy is within 0.1 to 10%
- In some cases (ex.: vacuum chamber with sorbing walls, molecular beaming effect) the error  may be times or even orders of magnitude

# A model of dynamic desorption processes in a beam vacuum chamber (1)

**The equations of gas dynamic balance inside a vacuum chamber:**

$$V\frac{dn}{dt} = q - cn + u\frac{d^2n}{dz^2}$$

where

*n* is the gas volume density;

*q* is the gas desorption flux;

*z* is the longitudinal axis of the vacuum chamber;

*V* is the vacuum chamber volume;

*c* is the distributed pumping speed

**Gas desorption *q* consists of two main sources: thermal and photon stimulated desorption:**

$$q = \eta_t F + \eta_\gamma \Gamma$$

where

$\eta_t$ is the thermal desorption yield,

$\eta_\gamma$ is the photon stimulated desorption yield,

$F$ is the vacuum chamber surface area,

$\Gamma$ is the synchrotron radiation photon flux

# A model of dynamic desorption processes in a beam vacuum chamber (2)

In the **quasi-equilibrium state** when the condition $V\frac{dn}{dt} \approx 0$ is satisfied then:

$$u\frac{d^2n}{dz^2} - cn + q = 0$$

This second order differential equation for the function *n(z)* has two solutions:

$$n(z) = -\frac{q}{2u}z^2 + C_{1a}z + C_{2a} \qquad for \quad c = 0$$

$$n(z) = \frac{q}{c} + C_{1b}e^{\sqrt{\frac{c}{u}}z} + C_{2b}e^{-\sqrt{\frac{c}{u}}z} \qquad for \quad c > 0$$

where the constants $C_1$ and $C_2$ depend on the boundary conditions.

# A model of dynamic desorption processes in a beam vacuum chamber (3)

All vacuum chamber along the beam can be fragmented on $N$ elements with $c = 0$ and $c > 0$.

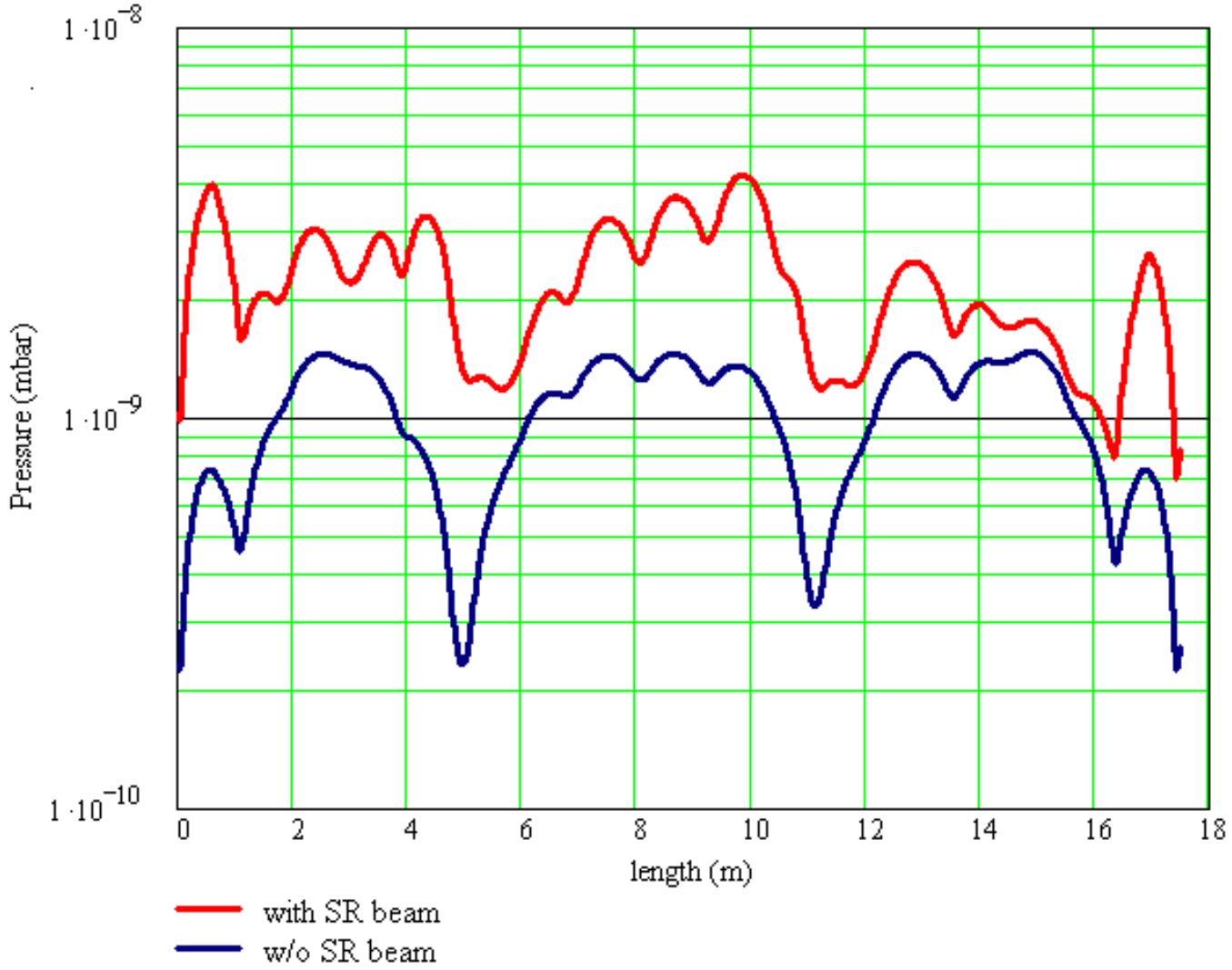
Every $i$-th element lying between longitudinal co-ordinates $z_{i-1}$ and $z_i$ will be described by above equations with two unknowns $C_{1i}$ and $C_{2i}$. The boundary conditions are

$$n_i(z_i) = n_{i+1}(z_i) \quad \text{and} \quad \partial n_i(z_i)/\partial z = \partial n_{i+1}(z_i)/\partial z$$

A system of $N–2$ equations with $2N–2$ unknowns which can be easily solved. Then the pressure along the vacuum chamber can be described analytically:

$$\begin{cases} n_i(z) = -\dfrac{q_i}{2u_i} z^2 + C_{1i} z + C_{2i} & for \;\; c_i = 0 \\ n_i(z) = \dfrac{q_i}{c_i} + C_{1i} e^{\sqrt{\frac{c_i}{u_i}} z} + C_{2i} e^{-\sqrt{\frac{c_i}{u_i}} z} & for \;\; c_i > 0 \end{cases}$$

# Pressure profile along the arc after 100 A·h beam conditioning




**Average pressure**

without a beam:

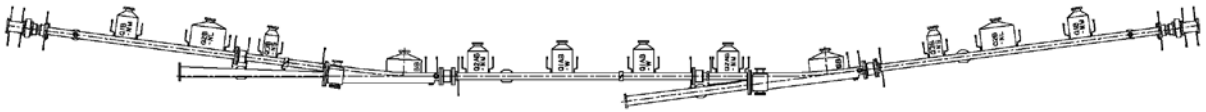
$\langle P_t \rangle = 1 \cdot 10^{-9}$ mbar

due to SR photons only:

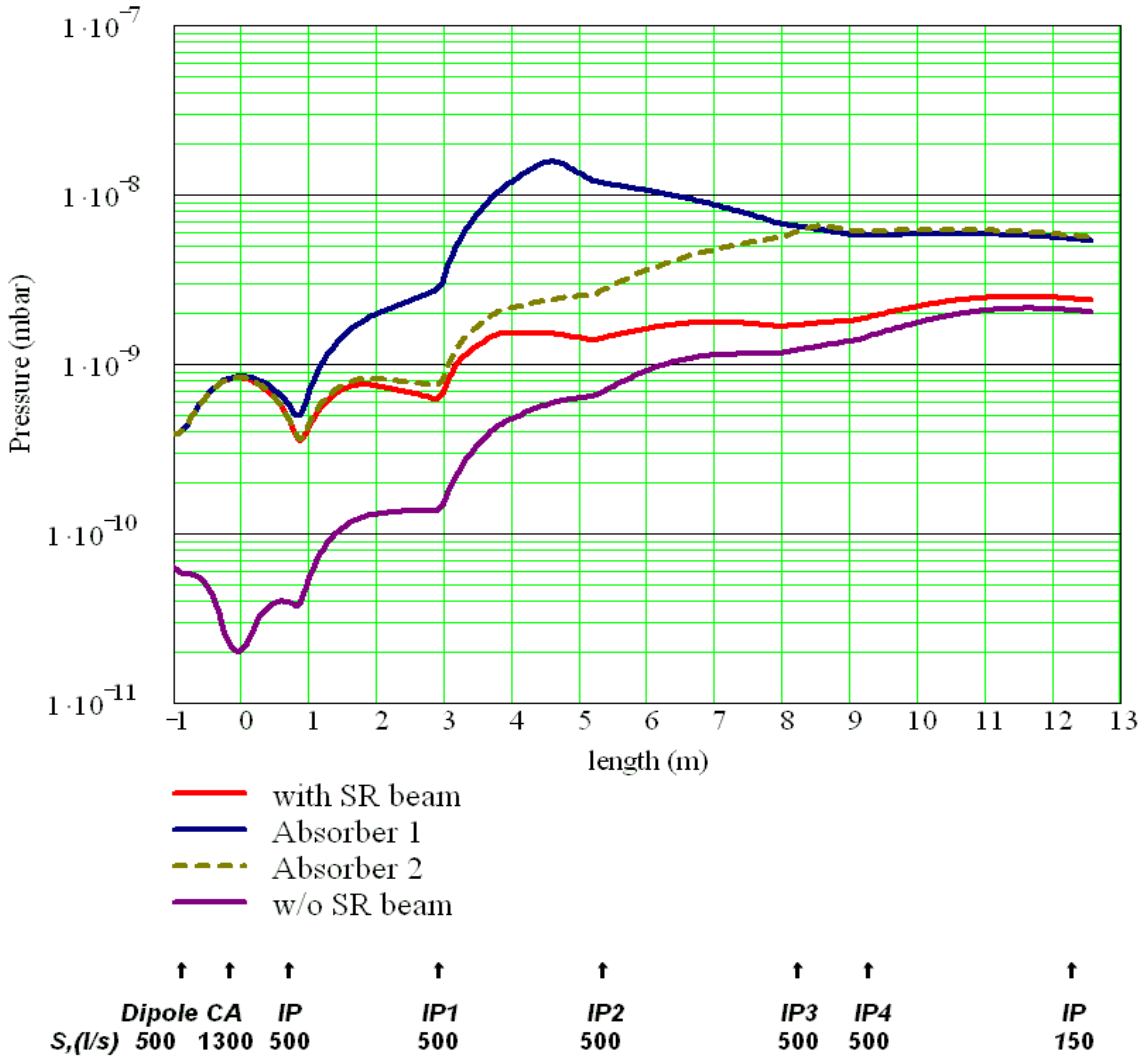
$\langle P_\gamma \rangle = 1 \cdot 10^{-9}$ mbar

Sum (i.e. with a beam):

$\langle P_{din} \rangle = \langle P_t \rangle + \langle P_\gamma \rangle = = 2 \cdot 10^{-9}$ mbar



# Pressure profile along the front ends after 30 A·h beam conditioning




Analytical solution allows simple and quick analysis of various operation scenarios for accelerator vacuum system:

- moving absorbers
- faulty pumps,
- changing outgassing rates
- closing valves
- etc.

# Diffusion model

- **Advantages of this method**
  - Easily variable parameters $q_i$, $u_i$ and $c_i$
  - Possibility in include functional description of each parameter
  - Possibility to compare instantly various options of design
  - It is good for initial optimisation of vacuum system
    - Locations of pumps and their pumping speed
    - Modelling the beam conditioning
- **Disadvantages of this method**
  - Sharp change in vacuum chamber shape is not included
  - Difficulty of calculating $u_i$ for non-standard shapes of beam vacuum chamber
  - Difficulty of calculating $c_i$ for complicated shapes of pumping ports
  - Not accurate if molecular beaming is strong

# Test Particles Monte-Carlo method (TPMC)

- 3D model
- Mechanical analogy to particle movement in free molecular flow regime
- Random statistical generation of initial position, velocity direction, reflection from walls, sorption probability.
- Accuracy is proportional to number of generated particles

***Input parameters:***

- *gas load q*
  - *(desorbing surfaces and angular distribution),*
- *pumping speed S*
  - *(pumping surfaces sticking probability or capture coefficient)*
- *geometry of vacuum system.*

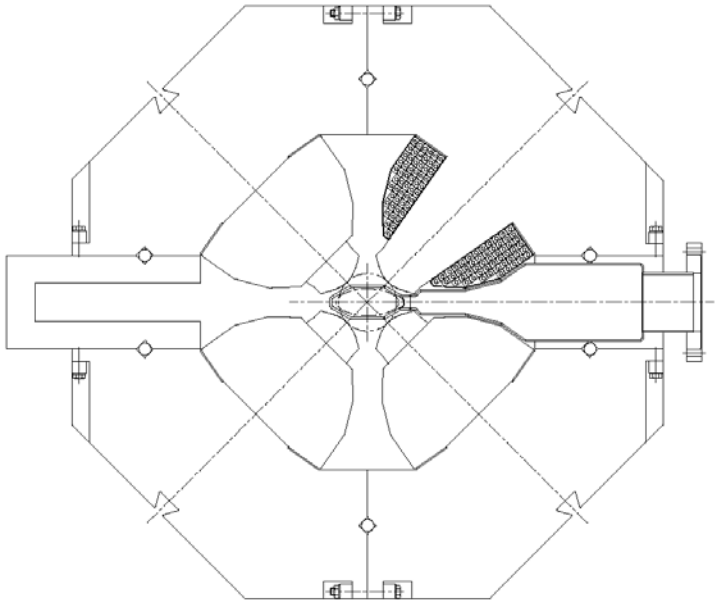
# Relations between TPMC parameters and measured values

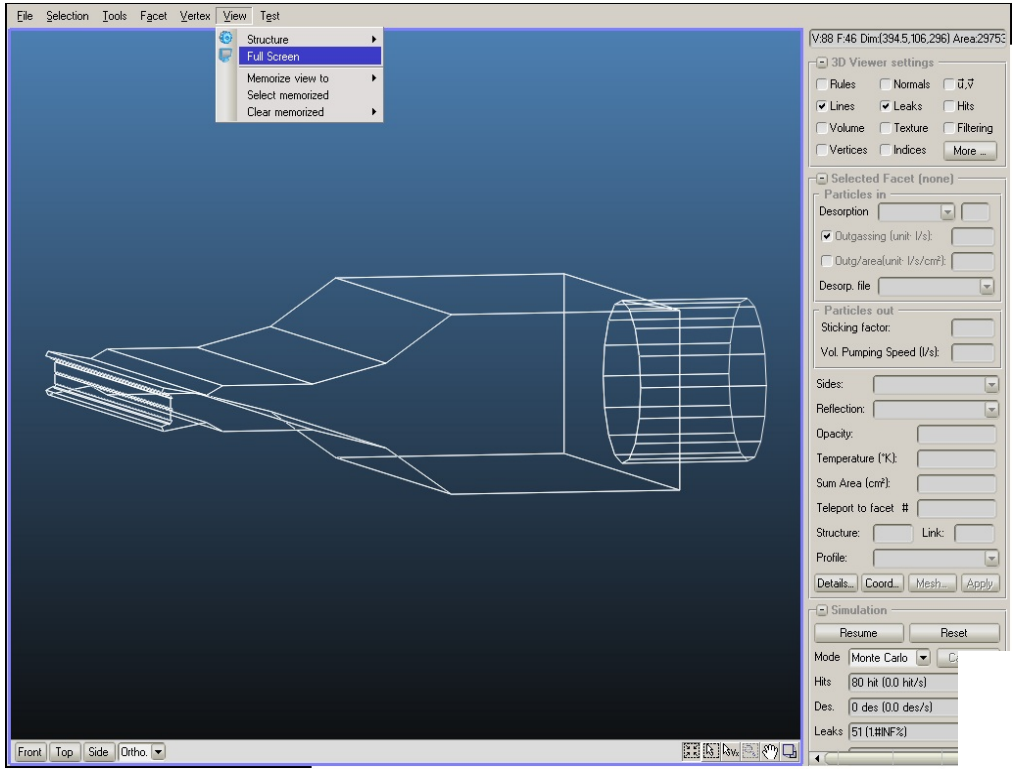
| Measured parameter | Symbol and dimensions | Model parameter | Symbol | Relation |
|---|---|---|---|---|
| Gas flux | $Q_n$ [molecules/s]<br>$Q_p$ [Pa·m$^3$/s] | A number of generated molecules | $N$ | See eq. below |
| Gas density and pressure | $n$ [molecules/m$^3$]<br>$P$ [Pa] | A number if hits to the facet $i$ | $Mhit_i$ | See eq. below |
| Pumping speed | $S$ [m$^3$/s] | Sticking probability | $\alpha$ | |
| Ideal pumping speed | $S_{ideal}$ [m$^3$/s] = $A\,v/4$ | Maximum sticking probability | $\alpha = 1$ | |
| Pumped gas flow | $Q_{pump}$ [molecules/s] | A number particles pumped at the facet $i$ | $Mpump_i$ | |
| Vacuum conductance | $U$ [m$^3$/s]= $w\,A\,v/4$ | Transmission probability of tube | $w$ | |

$$\frac{N\left[particles\right]}{Mhit_i\left[particles\right]} = \frac{Q\left[molecules/s\right]}{n\left[\frac{molecules}{m^3}\right] A_i\left[m^2\right] \frac{v\left[m/s\right]}{4}} \Rightarrow n = 4\frac{Q\,Mhit_i}{N\,A_i\,v} \Rightarrow P = nk_BT = 4\frac{Q\,Mhit_i}{N\,A_i\,v}k_BT$$

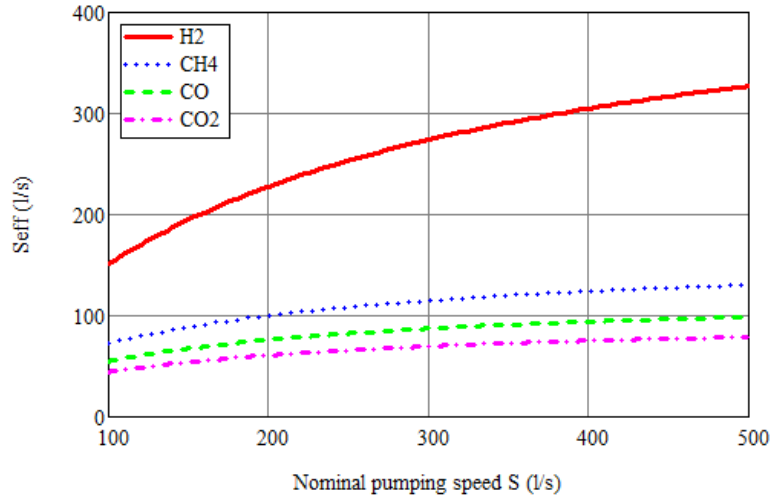
# Modelling a DLS pumping port with TPMC

A drawing of a quadrupole with a beam vacuum chamber and a pumping port





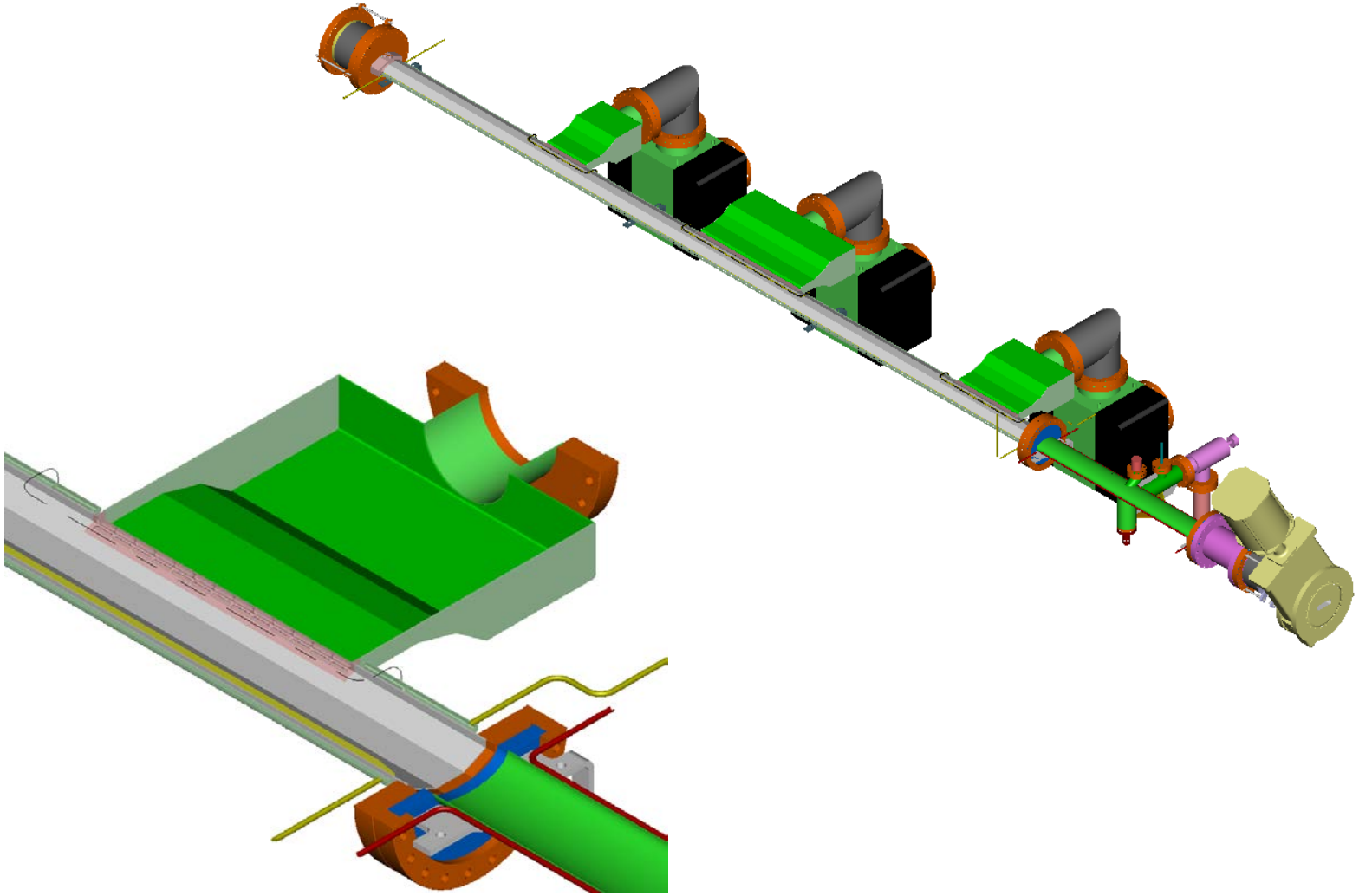

A transmission probability of the pumping port were obtained with a **Molflow** code based on TPMC (written by R. Kersevan, CERN)




Effective pumping speed $S_{eff}$: can be calculated for various gases and various pumps using only the *w* value:

$$C = w\frac{A\bar{v}}{4};\ S_{eff} = \frac{S \cdot C}{S+C}$$

# Combining of TPMC results and diffusion model

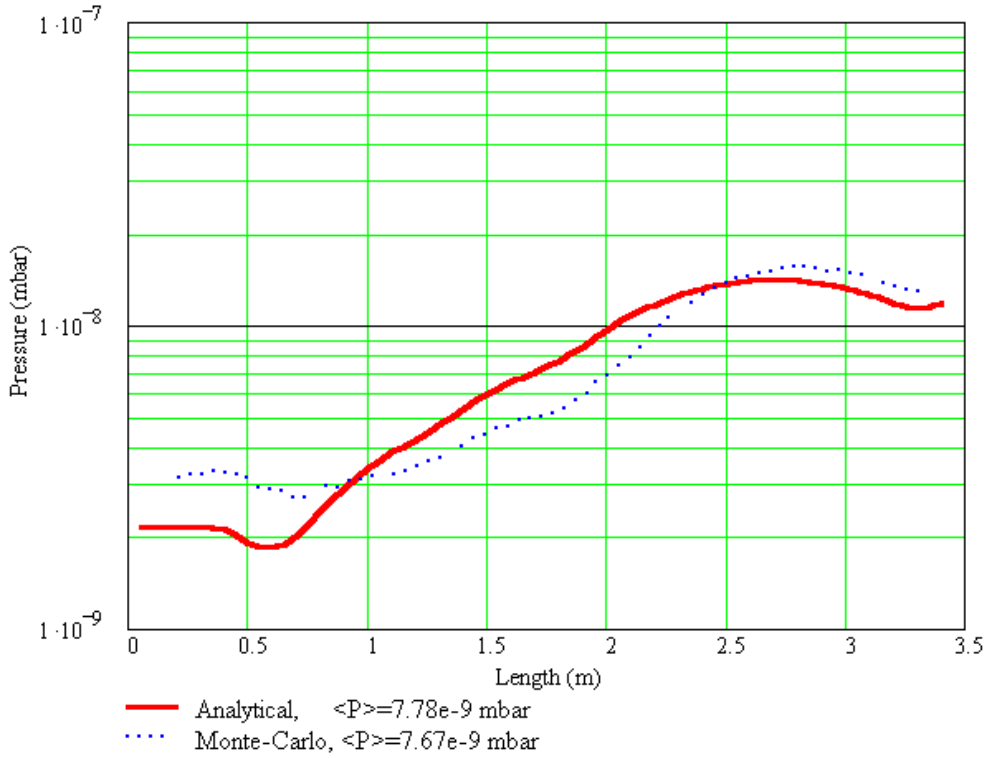


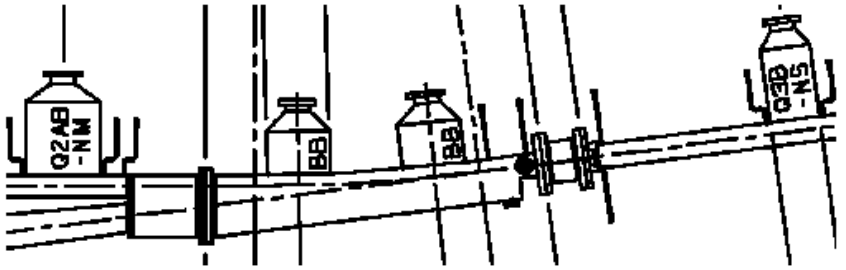
- Complex shape vacuum chamber components can be modelled with TPMC
  - Transmission probability of pumping ports $w$ will be converted to
    - Vacuum conductance
    - Distributed pumping speed:
- Analytical 1D optimisation can include these results as parameters or variables.

# Pressure profile along the DLS arc

Comparison between
a **1D analytical results** and
a **3D TSMC (MOLFLOW)** simulation results for some elements of the Diamond LS vacuum chamber:

- Local difference is up to 50% - acceptable in this application
- Average difference is less than **1.5%** - insignificant



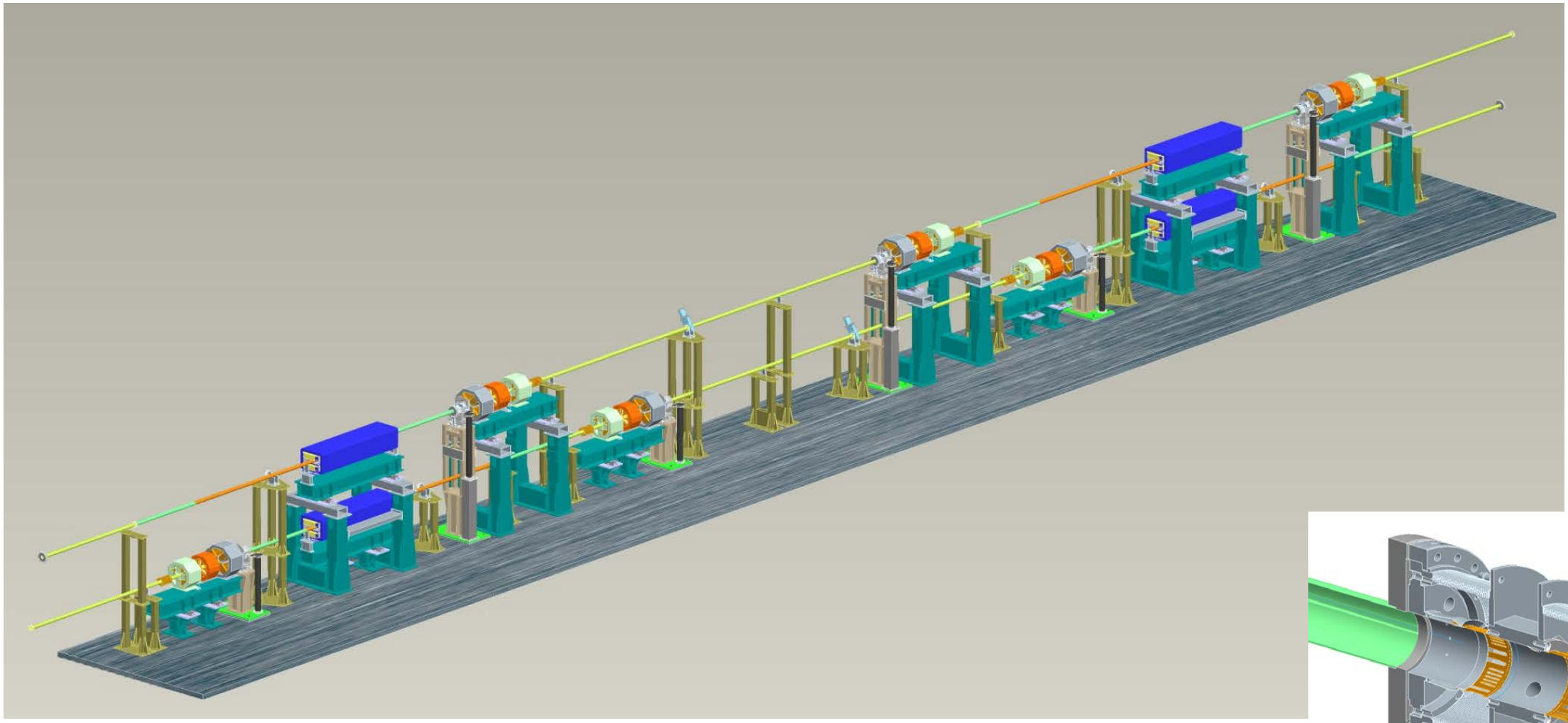
# Comparison between models

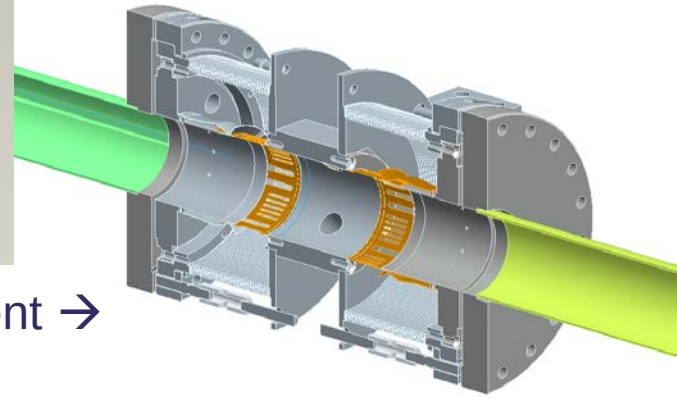
| Model | Diffusion | Test Particle Monte-Carlo |
|---|---|---|
| Accuracy | 1D simplified model<br>Global parameters:<br>P, u, S, etc. | 3D accurate model<br>Local parameters:<br>n, w, α, etc. |
| Complicate shape | Not accurate | Accurate |
| Long structures | Short time calculations | Very long calculations |
| Vacuum system optimisation | Easy to change and calculate | Time consuming modelling and calculations |
| Molecular beaming | Does not consider | Accurate |
| Including e-cloud induced desorption | Easy, just by adding another term on q(z,t) | Possible. |
| Including ion induced pressure instability | Quite easy, modifying equation and new finding another solution. | Requires another algorithm of modelling and a new code |
| Use | Good knowledge of gas dynamic is essential | |

# Towards the final design

- Proceed with the mechanical engineers to produce design and manufacturing specifications and drawings for vessels and components
  - Build to print
  - Design and manufacture
- Liaise with accelerator physicists over vessel impedances
  - Transitions
  - Tapers
  - Spring fingers
- Dealing with specific problems
  - SR power
  - E-cloud
  - Etc.

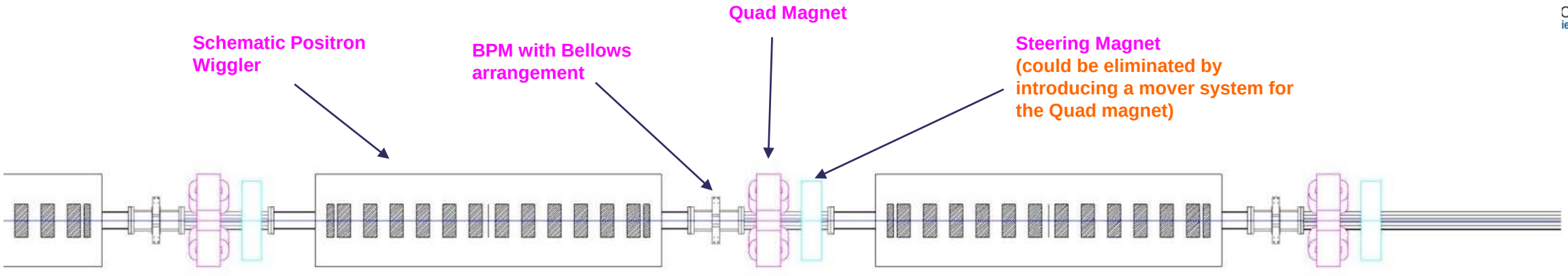
# Example: ILC DR arc cell components





BPM bellow arrangement →

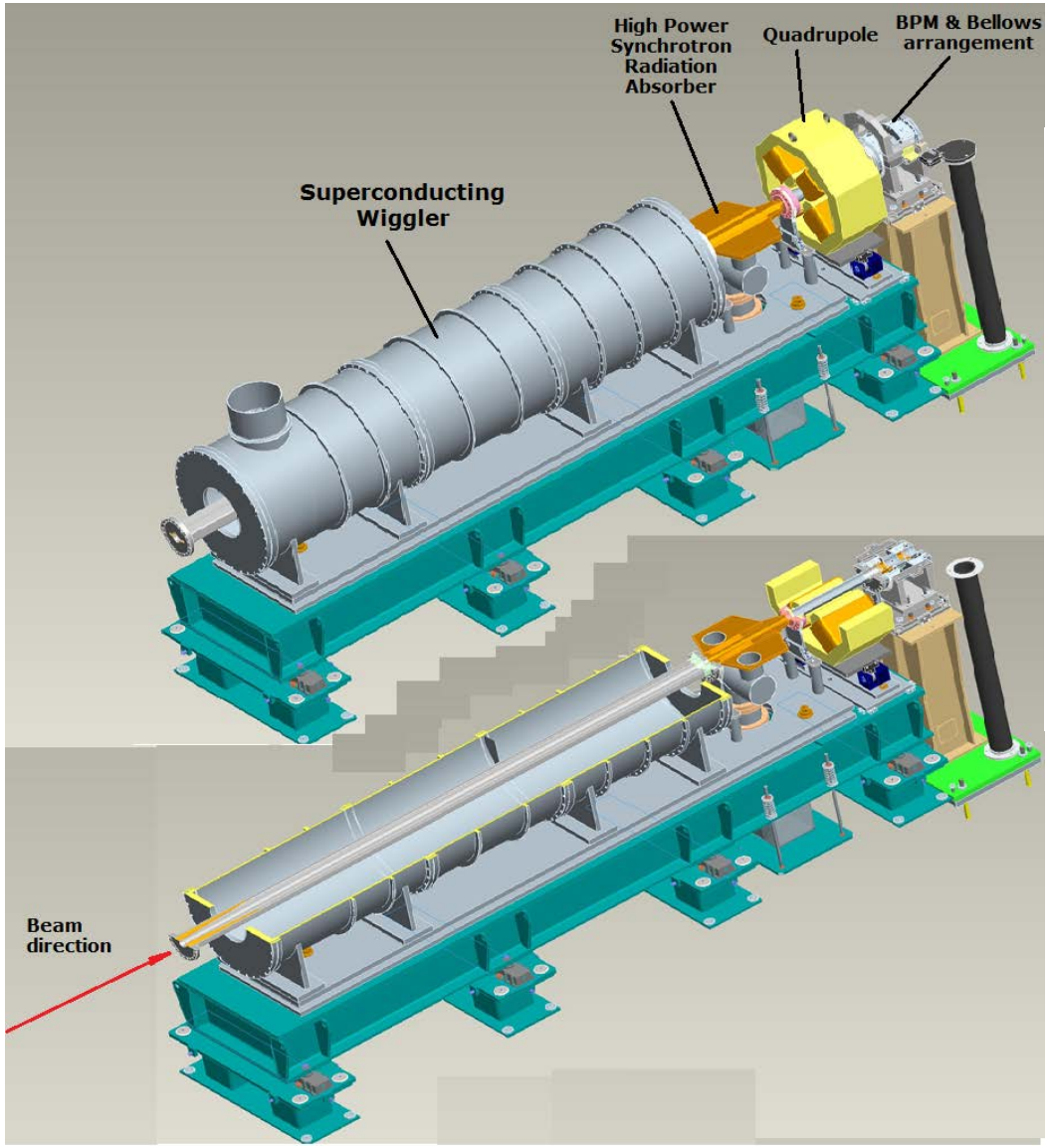
# Example: ILC DR wiggler section

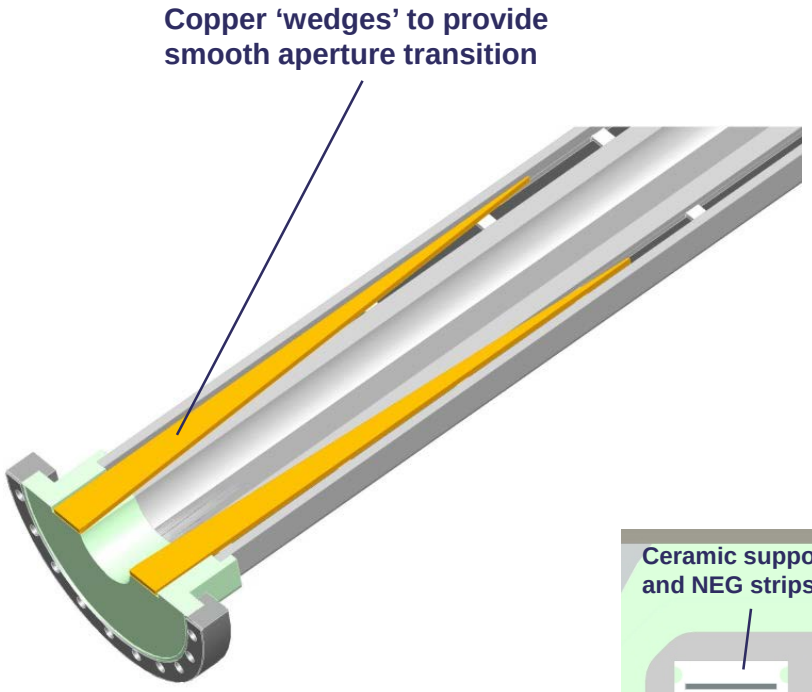


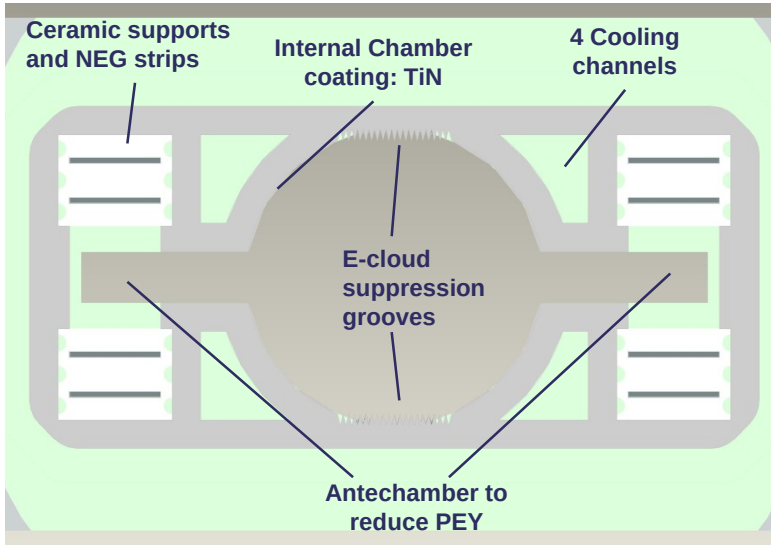

Challenges in a wiggler section design:

- SR power absorption – up to ~40 kW per wiggler
- Minimising a number of SR photons hitting beam chamber inside a wiggler to provide low PEY
  - Antechamber and shadow
- Grooved top and bottom and TiN coating to provide low SEY
- Sufficient pimping (NEG strips + SIPs)
- Impedance calculation

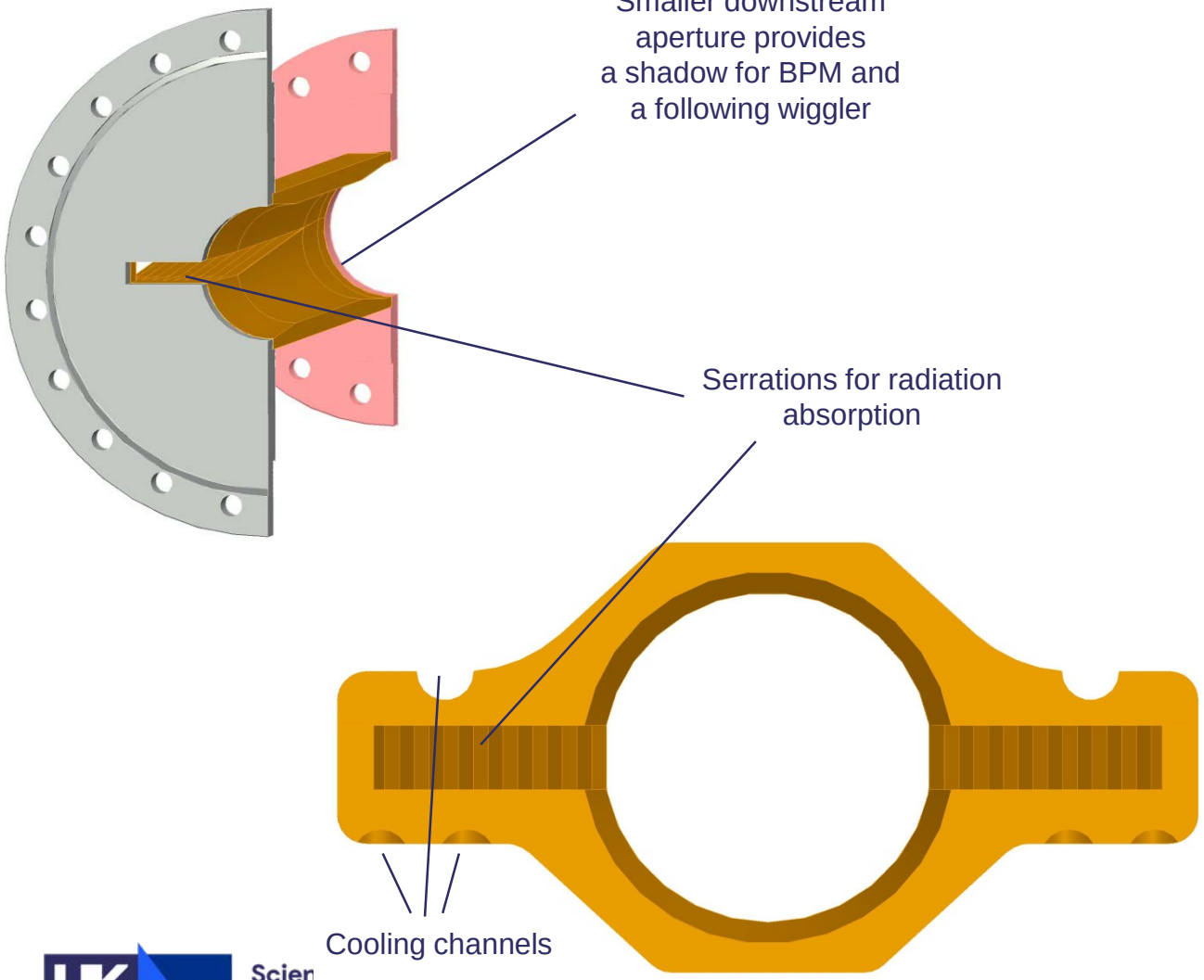
# ILC DR wiggler section (88 Section repetitions)

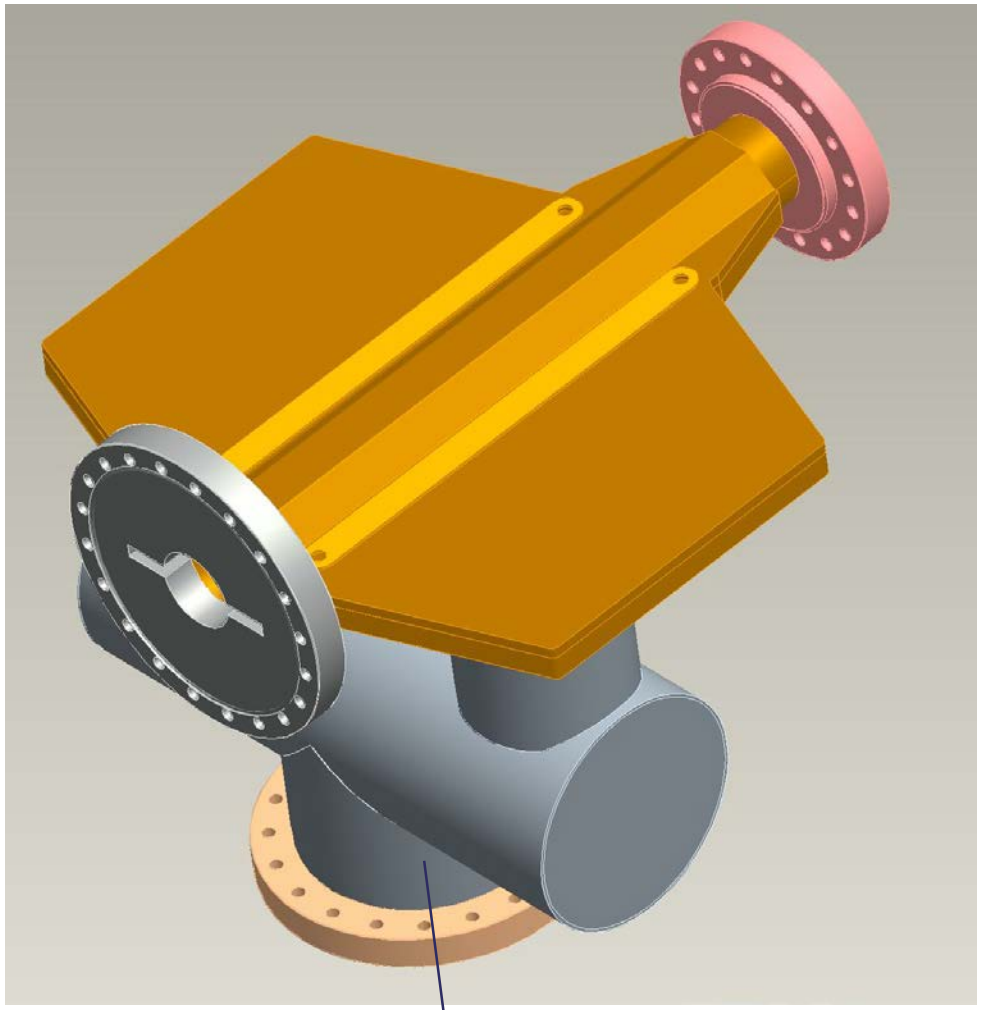


# SR power absorber



# Vacuum Diagnostics

- Total and Partial Pressure measurement
  - Matched to requirements
  - Inherent accuracy
- Location
  - Representative readings
  - Gauge interactions
  - External influences
    - Magnetic fields
    - Radiation

# Towards the final design

- Draw up test and acceptance specifications and schedules.
  - Leak testing
  - Cleanliness
  - Factory and Goods Inward
- Draw up installation procedures.

# Some common pitfalls

## Basic Design

- Underestimating internal surface areas and “gassy” items.
- Forgetting about conductance limitations.
- Forgetting about pumping speeds being pressure, species and history dependent.
- Failing to appreciate the extent and implications of dynamic processes.

## Manufacturing Design

- Failure to check vessel and component manufacturing drawings for:
  - Materials used
  - Trapped volumes (solvent traps)
  - Cleanability
  - Temperature limitations
  - Impedance problems
  - Handling

# Some common pitfalls

## Process

- Over specifying
- Under specifying

## Manufacturing

- Assuming manufacturers know what they are doing (management and shop floor).
- Failing to think through the implications of concessions and design changes.
- Failing to specify (or agree) a rigorous enough test programme, including methods.
- Incorrect sequencing of inspection and test procedures.
- Insufficient documentation.

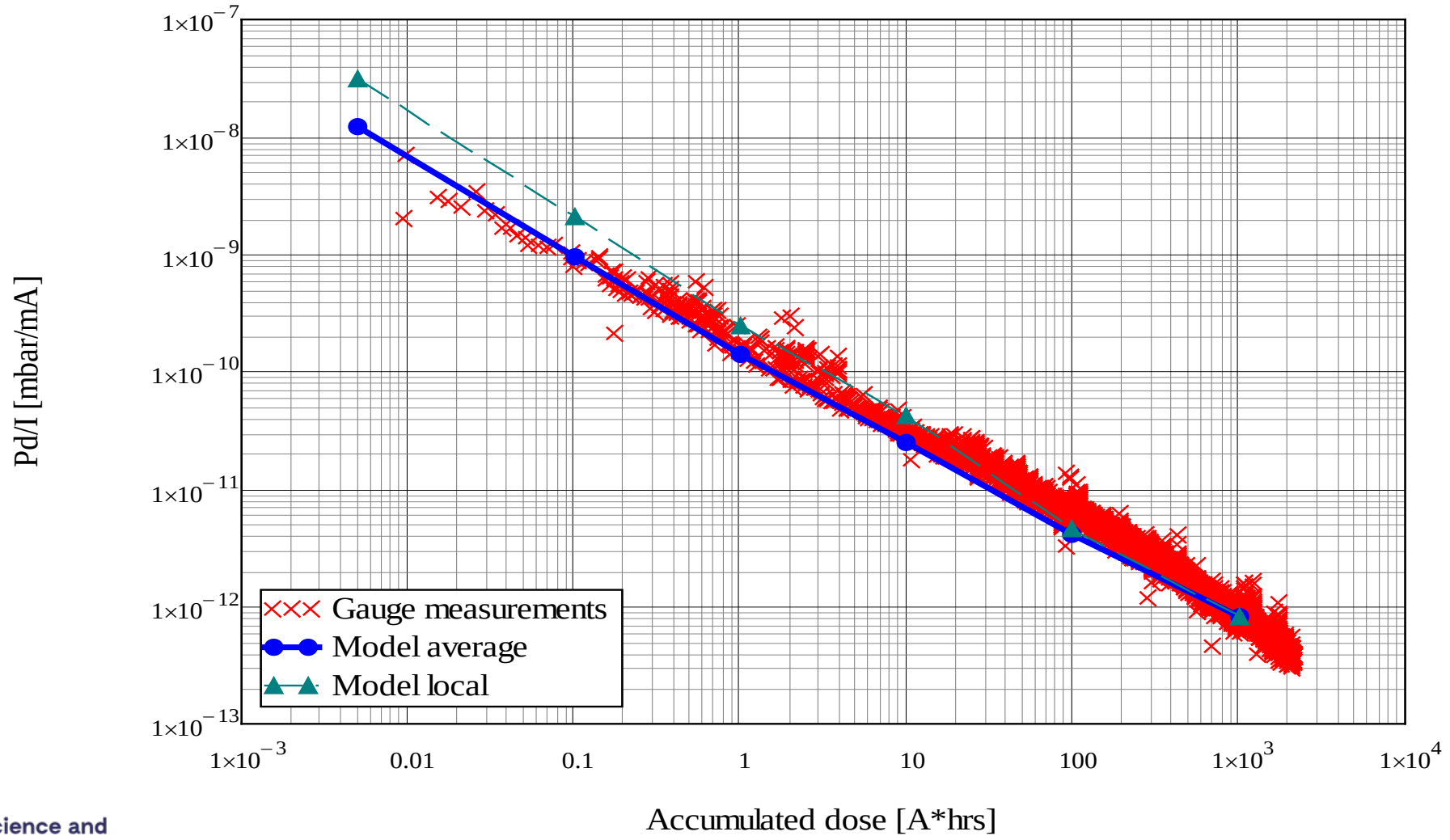
# … and finally

- A good design is one which
  - meets its specification
  - allows for later improvements
  - is economical
  - is reliable
  - is maintainable

# How good is a vacuum design?

- If everything considered correctly in modelling and vacuum and mechanical design:
  - Input data
  - Parameters
  - Specification
- If everything done correctly
  - At manufacturer's sites
  - Storage, installation and operation
- If there is no unexpected changes in start-up and operation scenario
  - Then the vacuum design can be made to meet the vacuum specifications

# Modelling vs measured data for the Diamond LS



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# Questions?