Design of large vacuum systems and NEG coatings

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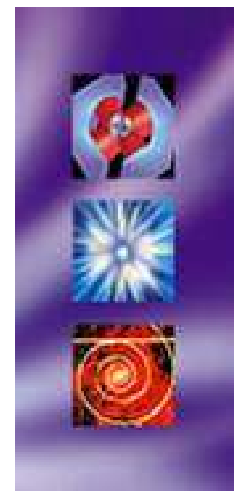


What are usual considerations for vacuum

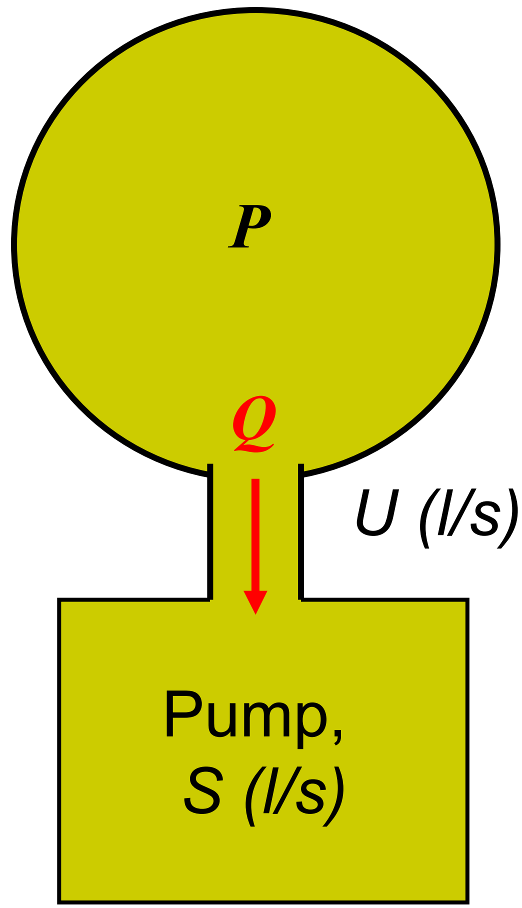
Required pressure P is defined by gas desorption Q in the vessel and effective pumping speed S_{eff}.

In a simple case it is

$$P = \frac{Q}{S_{eff}} = Q\left(\frac{1}{S} + \frac{1}{U}\right)$$

$$Q = qA + \eta_{\gamma}\Gamma + \eta_e \mathrm{I}_e + \eta_{ion}\mathrm{I}_{ion}$$

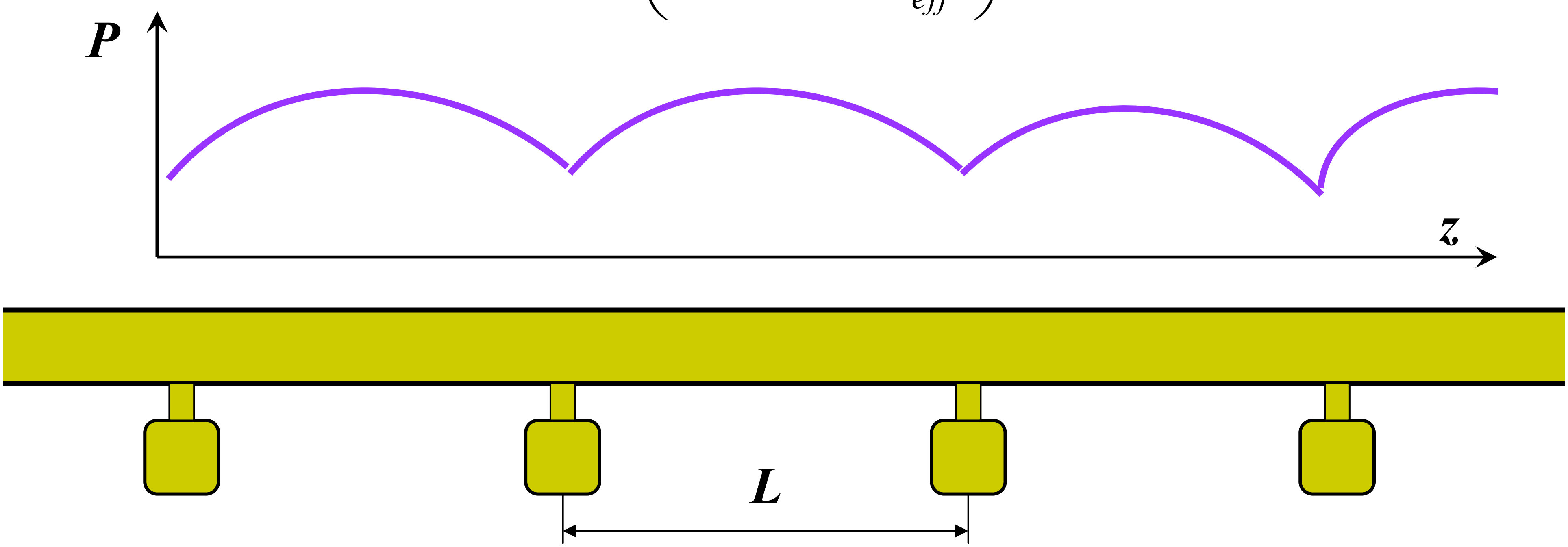
Thermal, photon, electron and ion stimulated desorption



Usual accelerator vacuum chamber

- Average pressure depends on vacuum conductance *u* of the beam vacuum chamber, which depends on the cross section and the length *L*

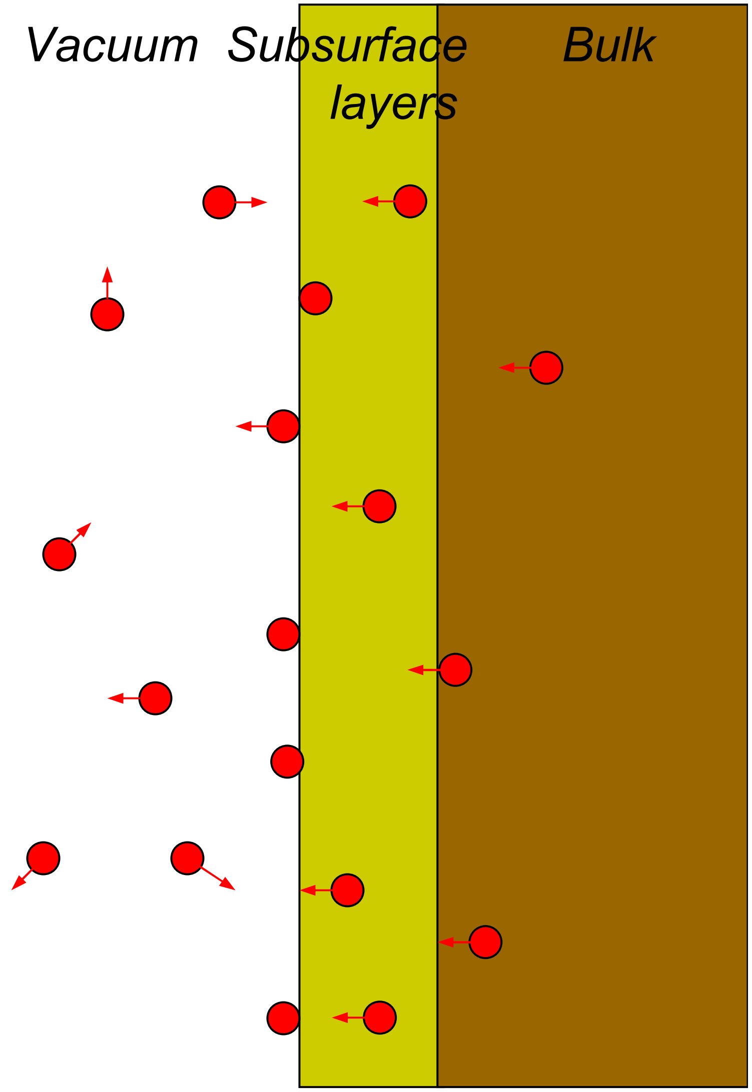
$$\langle P \rangle = qL\left(\frac{L}{12u} + \frac{1}{2S_{eff}}\right)k_B T$$



Source of Gas in a Vacuum System

Thermal, photon, electron or ion stimulated desorption:

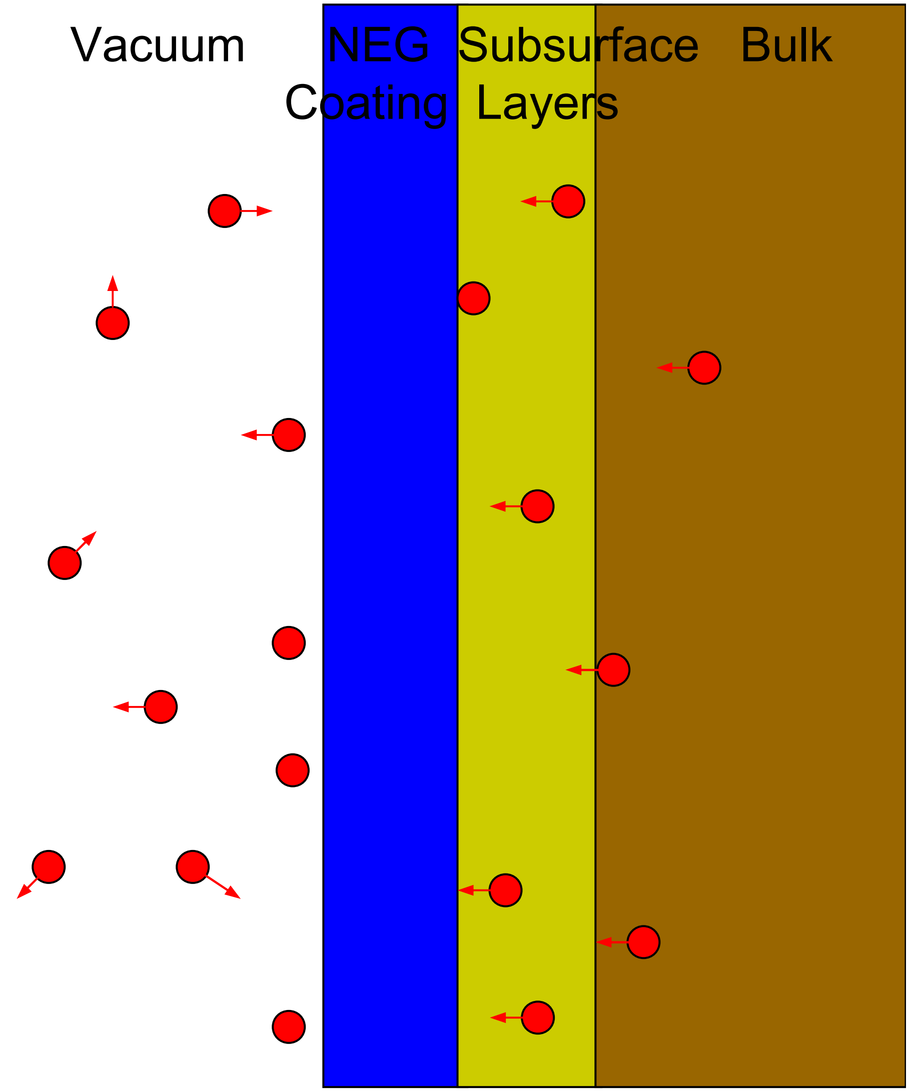
- Molecules diffused through the bulk material (mainly subsurface layers) of the vacuum chamber, entering the surface and desorbing from it
- Molecules adsorbed on the surface (initially or after the air venting) and desorbing when vacuum chamber is pumped



Outgassing rate depends on many factors: choice of material, cleaning procedure, pumping time, bombardment (irradiation) dose, etc...

What NEG coating does

- **A pure metal film ~1-μm thick without contaminants.**
- **A barrier for molecules from the bulk of vacuum chamber.**
- **A sorbing surface on whole vacuum chamber surface**



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 (NEG coated surface)

- 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 160-180°C
- Small pumps for C_xH_y and noble gases

NEG coating pumping properties

$$P = \frac{Q}{S}$$

$$S = \alpha \frac{v}{4} A$$

where α is the sticking probability ($\alpha \leq 1$),
v is the mean molecular velocity and
A is the surface area

NEG coating is a technology for UHV and XHV

The CO capacity of the NEG coating is about **1 monolayer** for CO and CO_2.

$$\frac{1\,ML_{CO}}{s} \quad @ \quad P(CO) = 4.4 \cdot 10^{-7}\, mbar$$

If CO, CO_2, H_2O or N_2 partial pressure during NEG coating activation or after activation is **10^{-9} mbar**, then the amount of molecules hitting the wall is an equivalent of

~250 CO monolayers/day!

NEG coating is a technology for UHV and XHV

1) During NEG activation the pressure of NEG-sorbing gases (CO, CO_2, H_2O, N_2) is limiting the efficiency of activation

if P(CO, CO_2, H_2O, N_2) > ~10^{-10} mbar =>

⇒ the NEG film is continuously poisoning by these gases =>

⇒ **the activation is not full**

2) During operation the pressure of NEG-sorbing gases (CO, CO_2, H_2O , N_2) is limiting operation time: NEG saturates

⇒ at P =10^{-11} mbar in 4 days

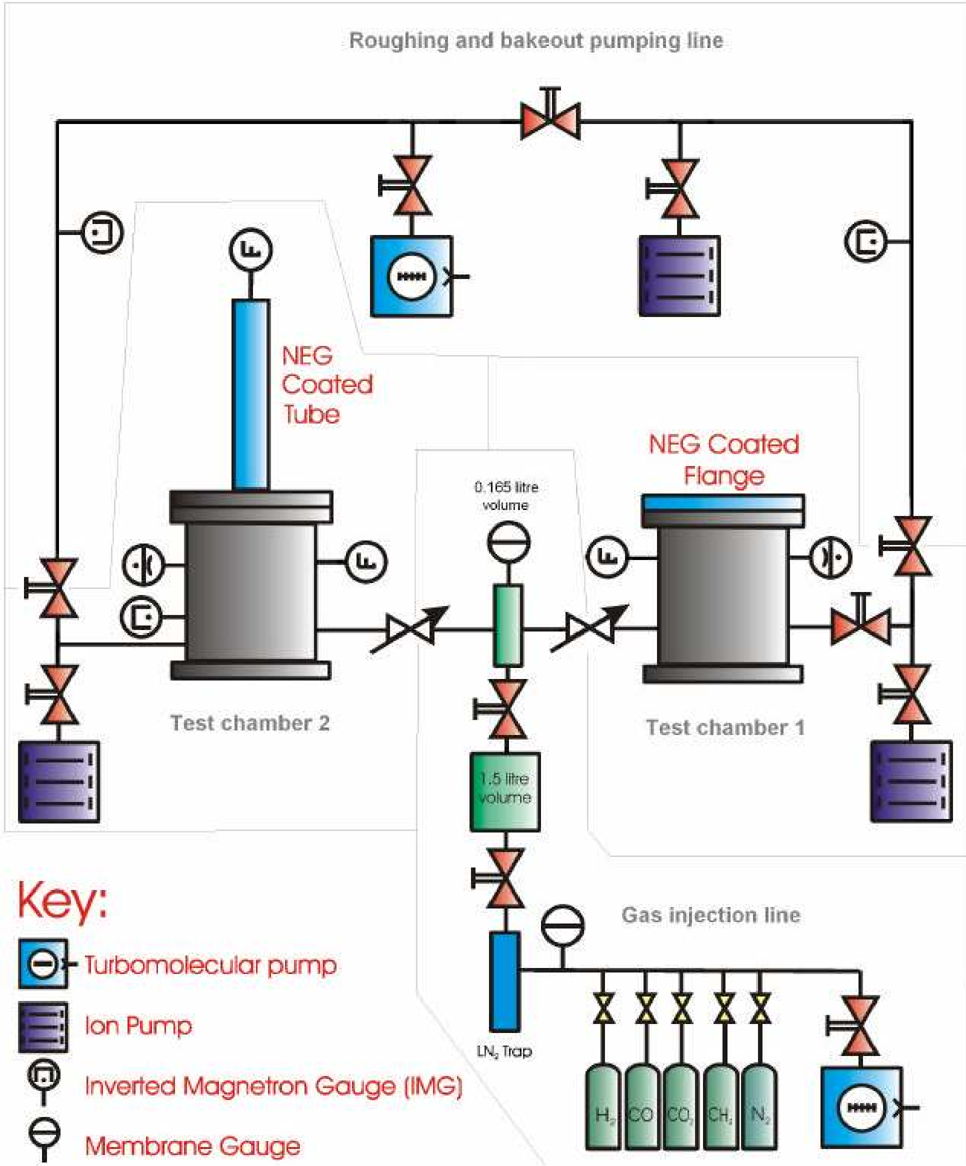
⇒ at P =10^{-12} mbar in 40 days

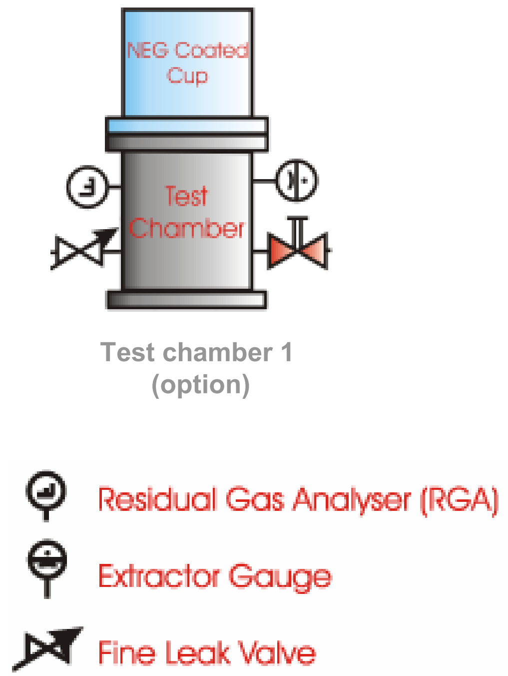
But CO, CO_2, H_2O can be desorbed from non-coated parts only

=> **fully coated vacuum chamber.**

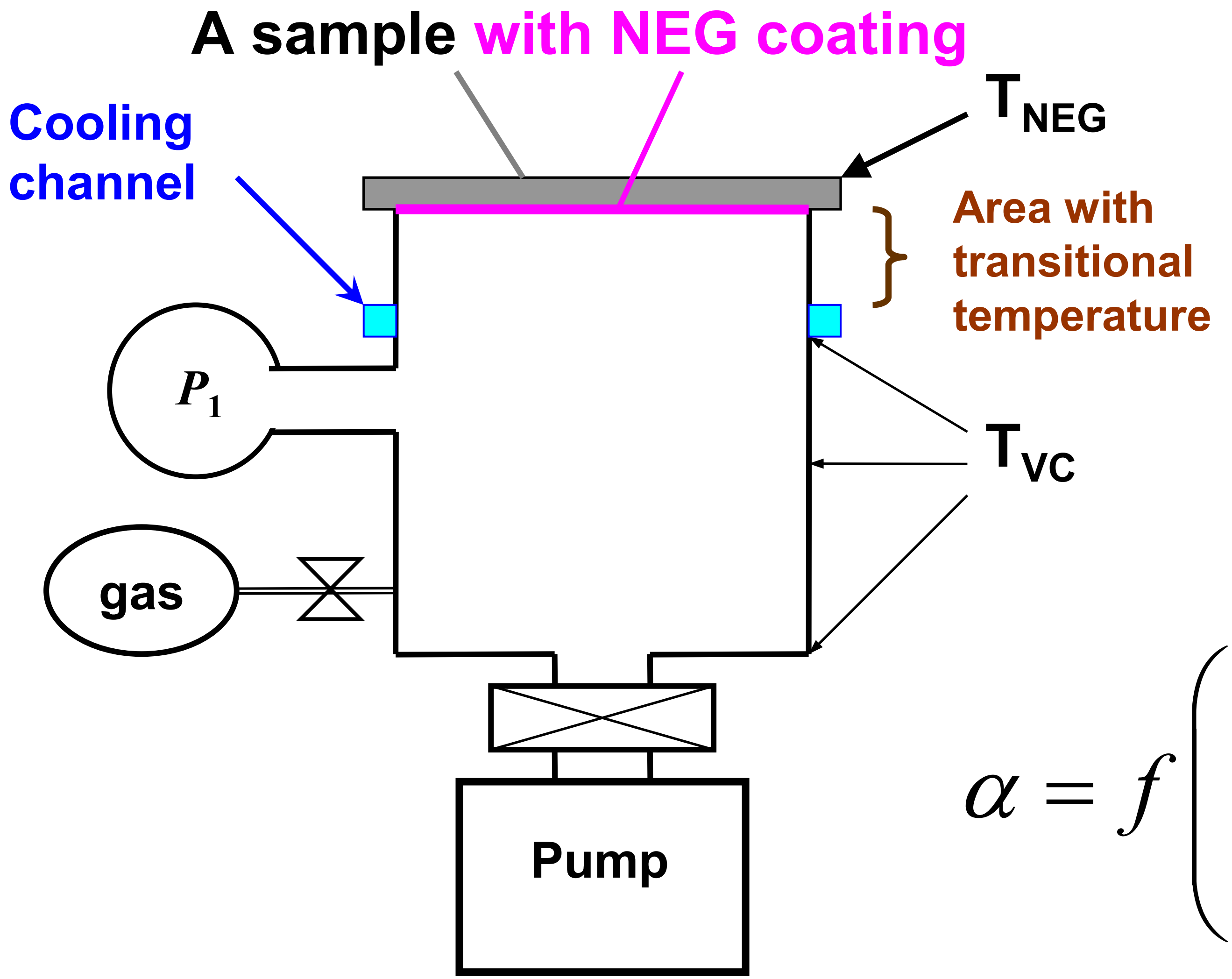
Pumping speed and capacity

Set-up for NEG pumping evaluation in ASTeC VS lab.



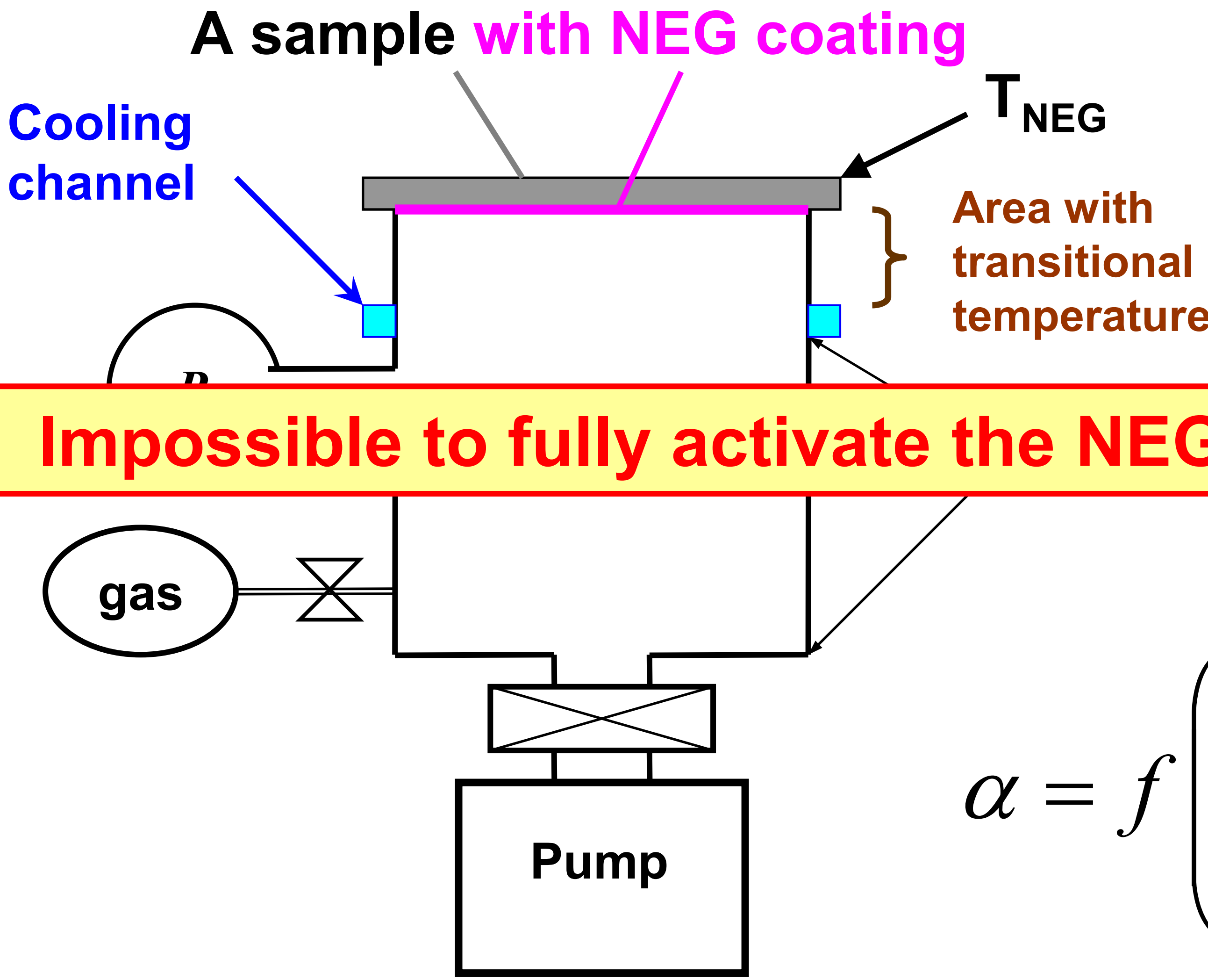


Set-up for flat samples



$$\alpha = f\left(\frac{4Q_{inj}}{\left(P - P_{bg}\right)v}\right)$$

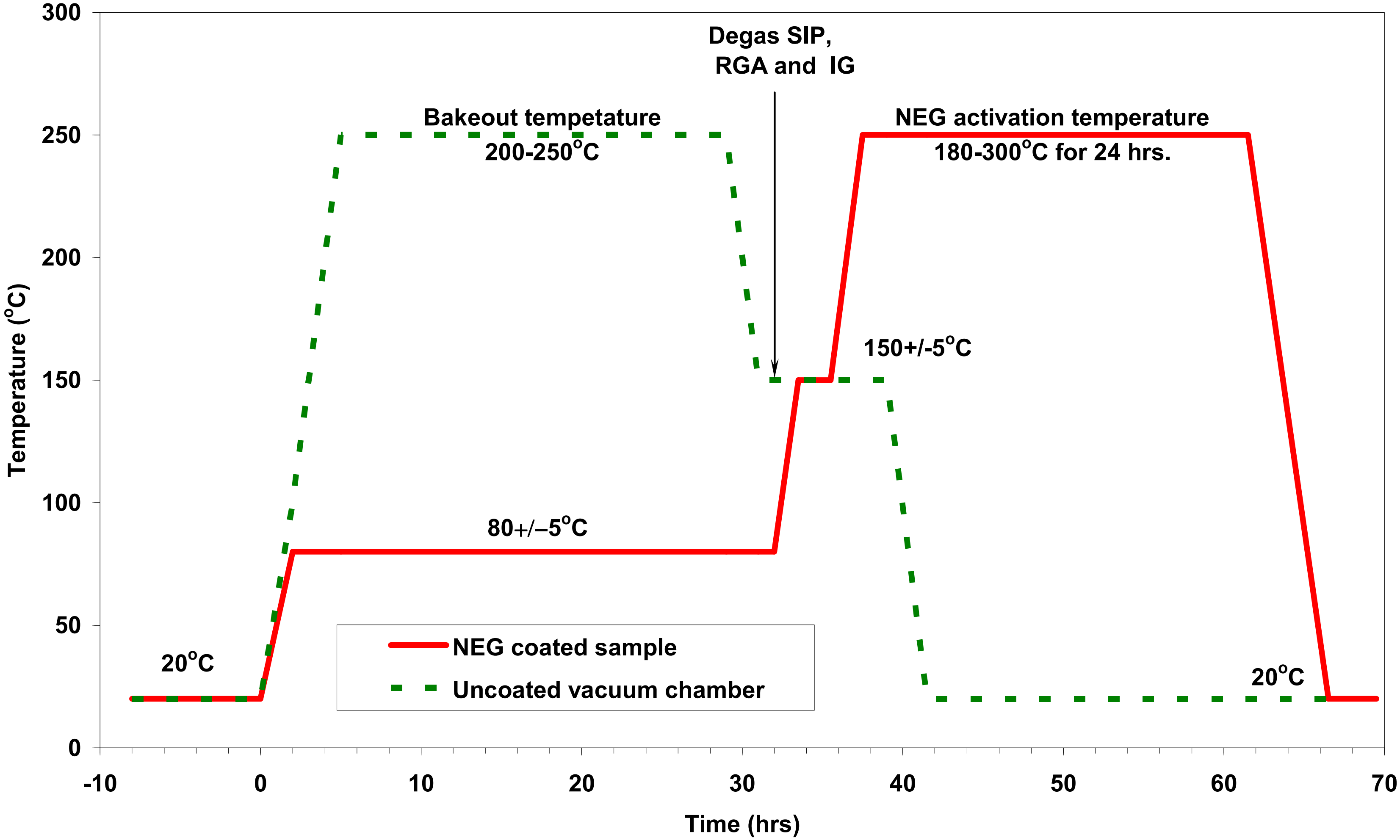
Set-up for flat samples



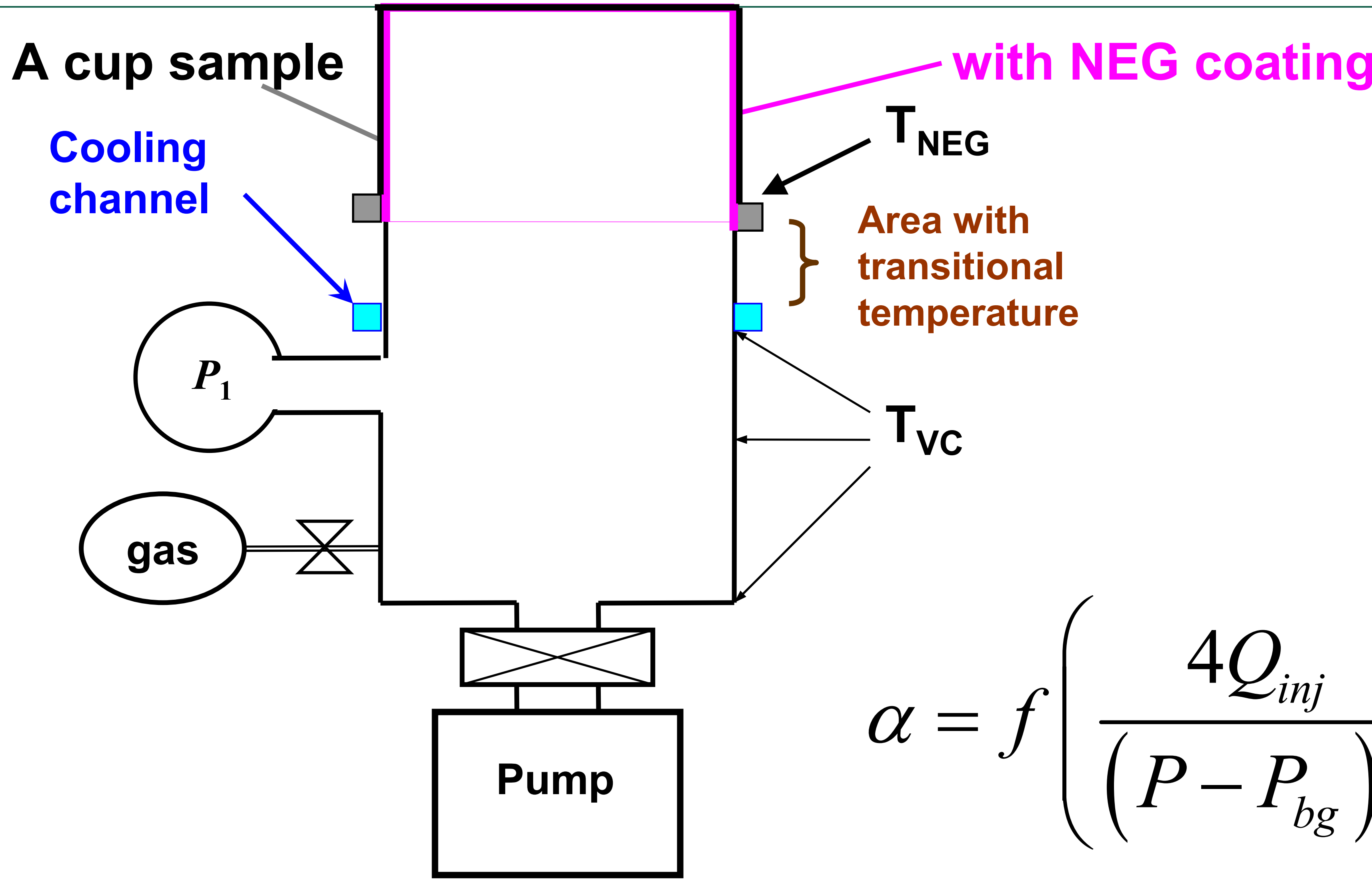
Impossible to fully activate the NEG coating!

$$\alpha = f\left(\frac{4Q_{inj}}{\left(P - P_{bg}\right)v}\right)$$

ASTeC activation procedure



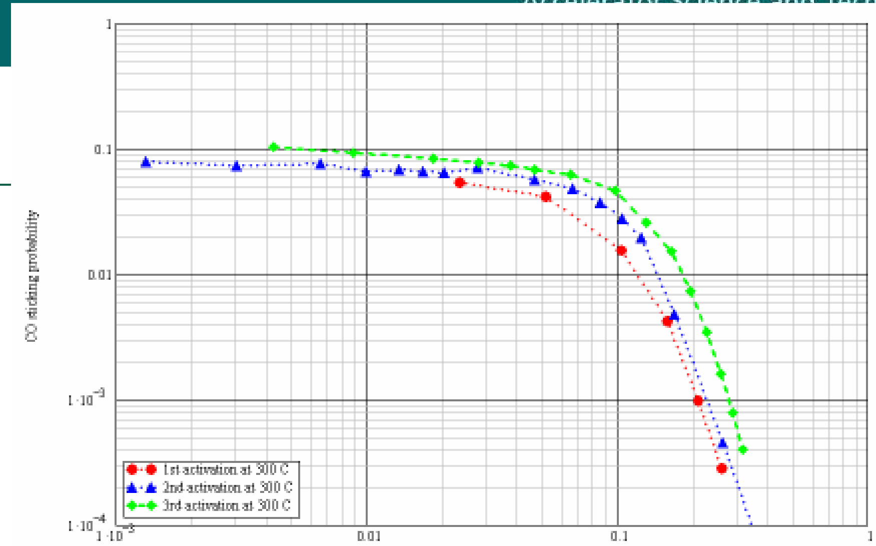
Set-up for flat samples



$$\alpha = f\left(\frac{4Q_{inj}}{\left(P - P_{bg}\right)v}\right)$$

Flat vs. cup sample

Flat sample →

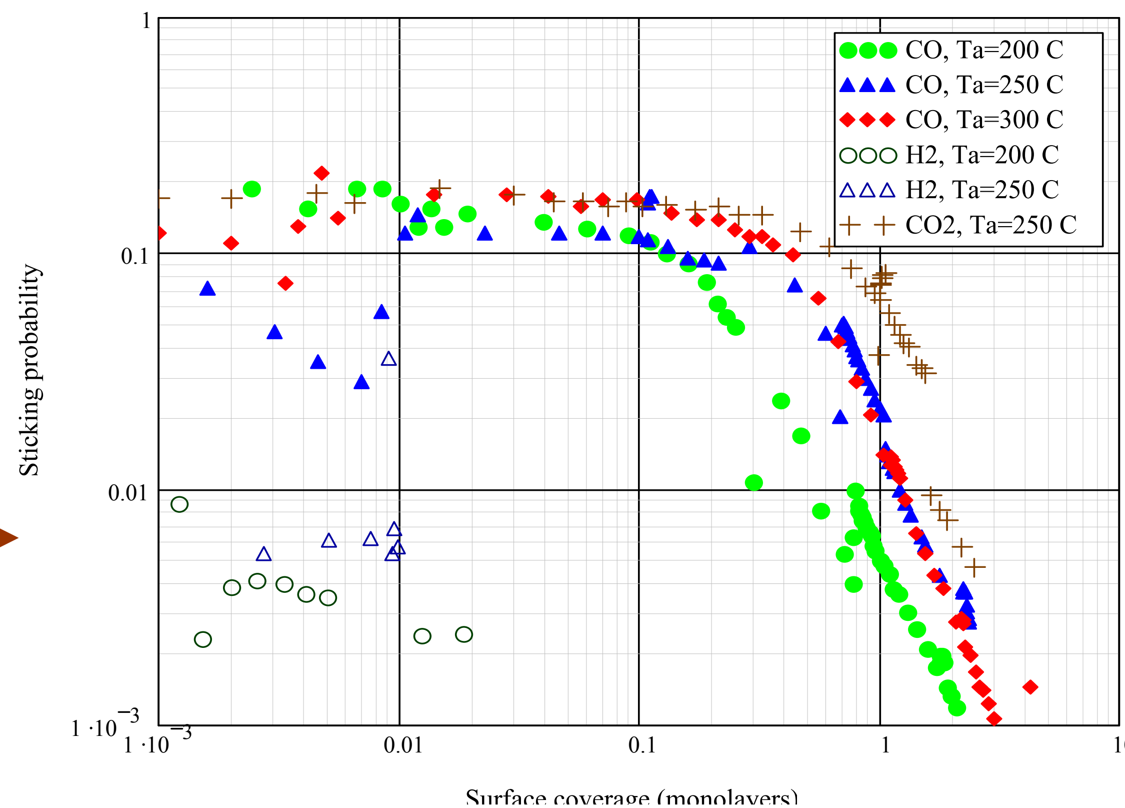


$A_{cup} = 5\ A_{flat}$

$\alpha_{cup} = \sim 2.5\ \alpha_{flat}$

$Q_{cup} = \sim 6\ Q_{flat}$

Cap sample →



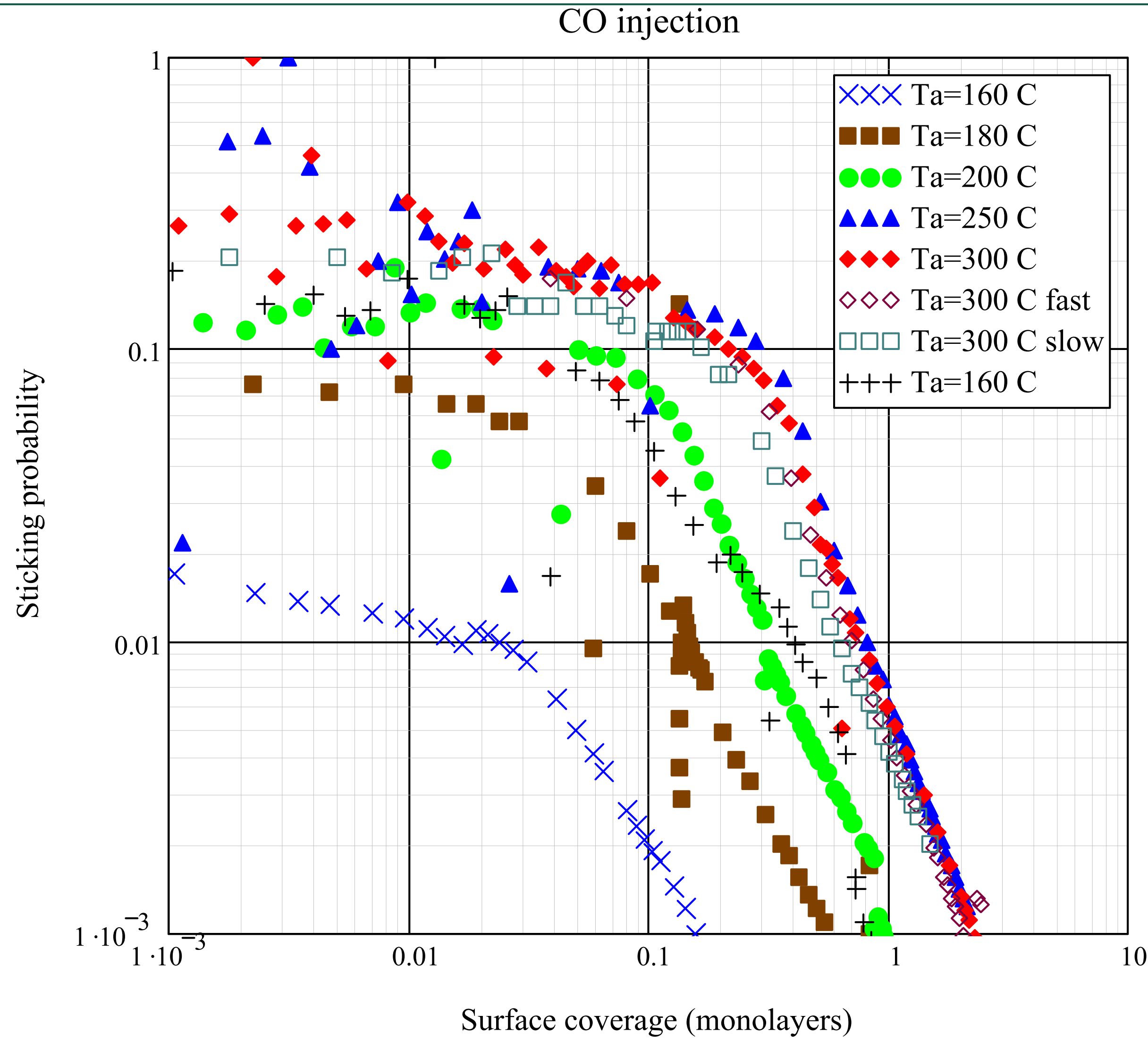
Conditions for NEG film activation

To allow NEG film to be activated and not be poisoned by residual gas molecules for the duration of the experiment (at least 24 hrs).

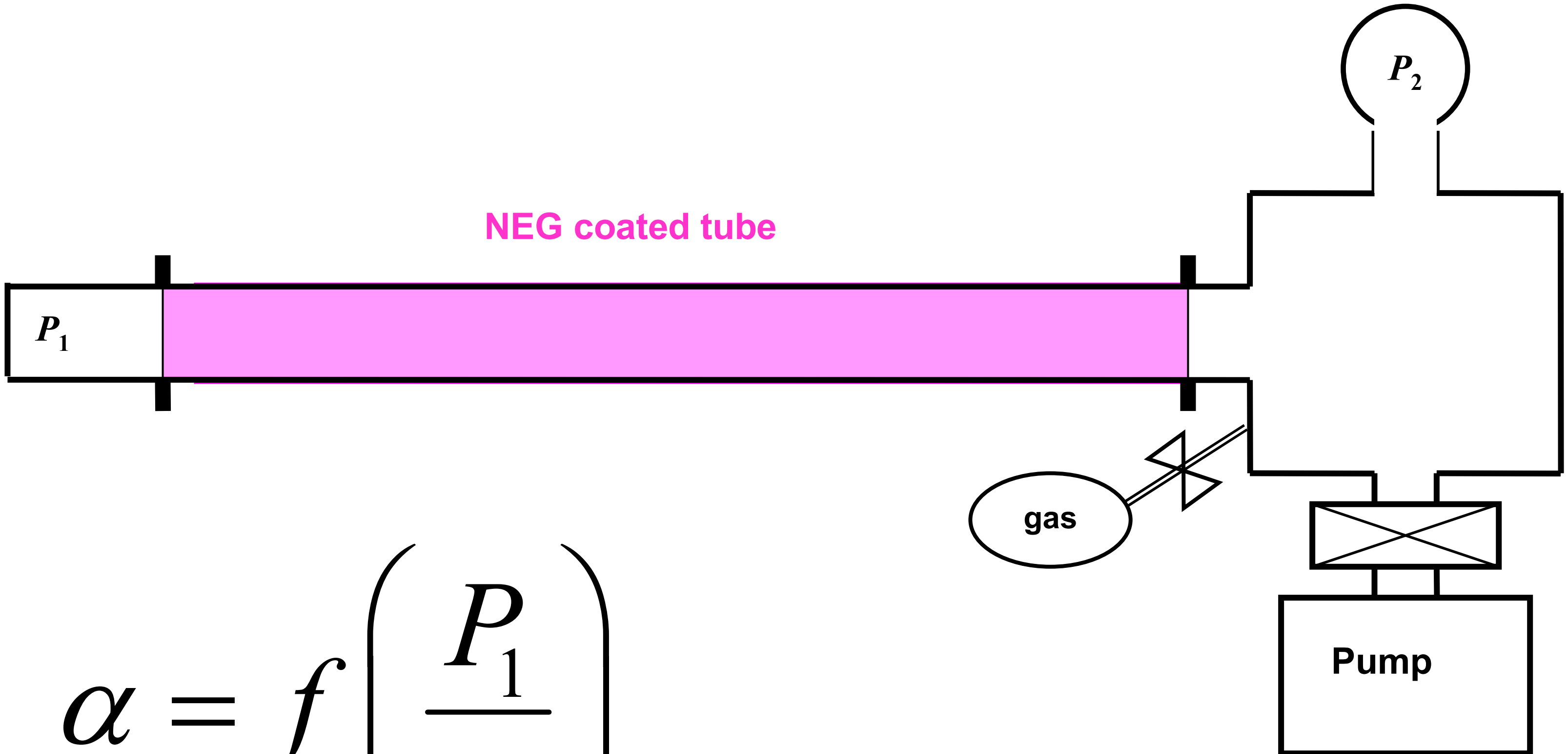
1. The background pressure due to thermal desorption from uncoated part should be better than 10^{-11} mbar for CO, CO_2, H_2O, O_2 and N_2
   - no leaks
   - bakeout and good UHV pumping of the test vacuum chamber (i.e. sufficient pumping speed and ultimate pressure below 10^{-11} mbar) is essential.
2. NEG film activation must be performed only after the bakeout of the uncoated parts of vacuum chamber, when desorption from uncoated parts of the test system is low
   - the temperature of the NEG coated and non-coated parts of vacuum chamber should be maintained independently (separate heaters and air or water cooling).
3. The area NEG coated part inside and of vacuum chamber should be much grater than non-coated area.
   - ideally fully NEG coated.
4. 'Short pressure increase' should be avoided after NEG coating activation.
   - ex.: to switching on the gauge and the RGA, by opening or closing a valve, etc. may cause a pressure increase and saturated neighbouring NEG coating.

Sorption capacity for different activation temperatures

Cup 3

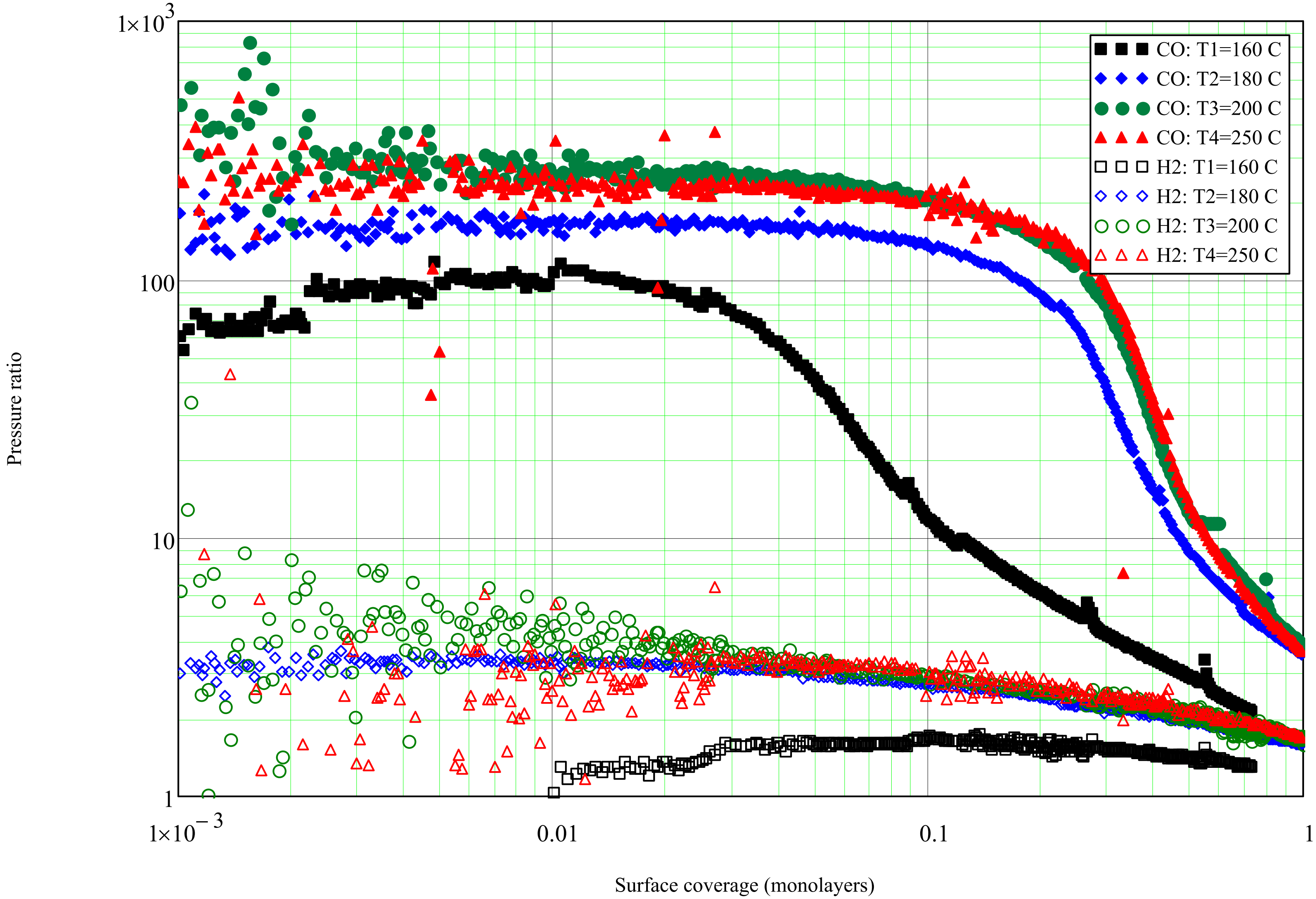


Test chamber with a tubular sample

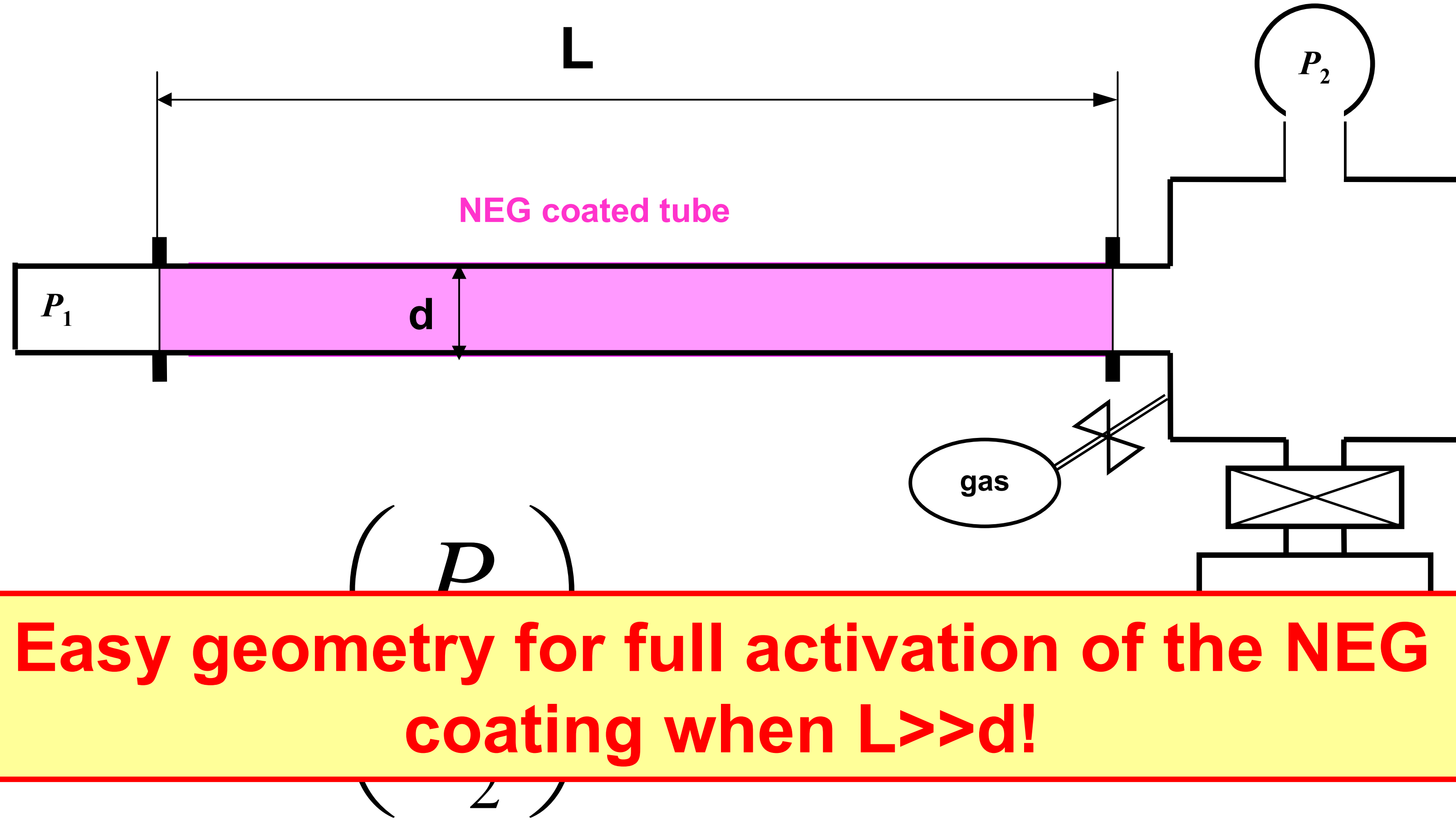


$$\alpha = f\left(\frac{P_1}{P_2}\right)$$

Tubular samples



Test chamber with a tubular sample



Easy geometry for full activation of the NEG coating when L>>d!

Results for pumping speed and capacity tests

- α (H_2) = $5{\cdot}10^{-3}$ – 0.01
- α (CO) = 0.2; capacity – 0.5-2 ML
- α (CO_2) = 0.6; capacity – 1-3 ML

- Results depends on
  - geometry of vessel (narrow tubes or 3D)
  - a ratio and location of coated and non-coated areas
  - bakeout-activation procedure
  - deposition parameters
  - NEG film composition
  - surface roughness

(deposition parameters, NEG film composition, surface roughness:) Details in Dr. R. Valizadeh's talk

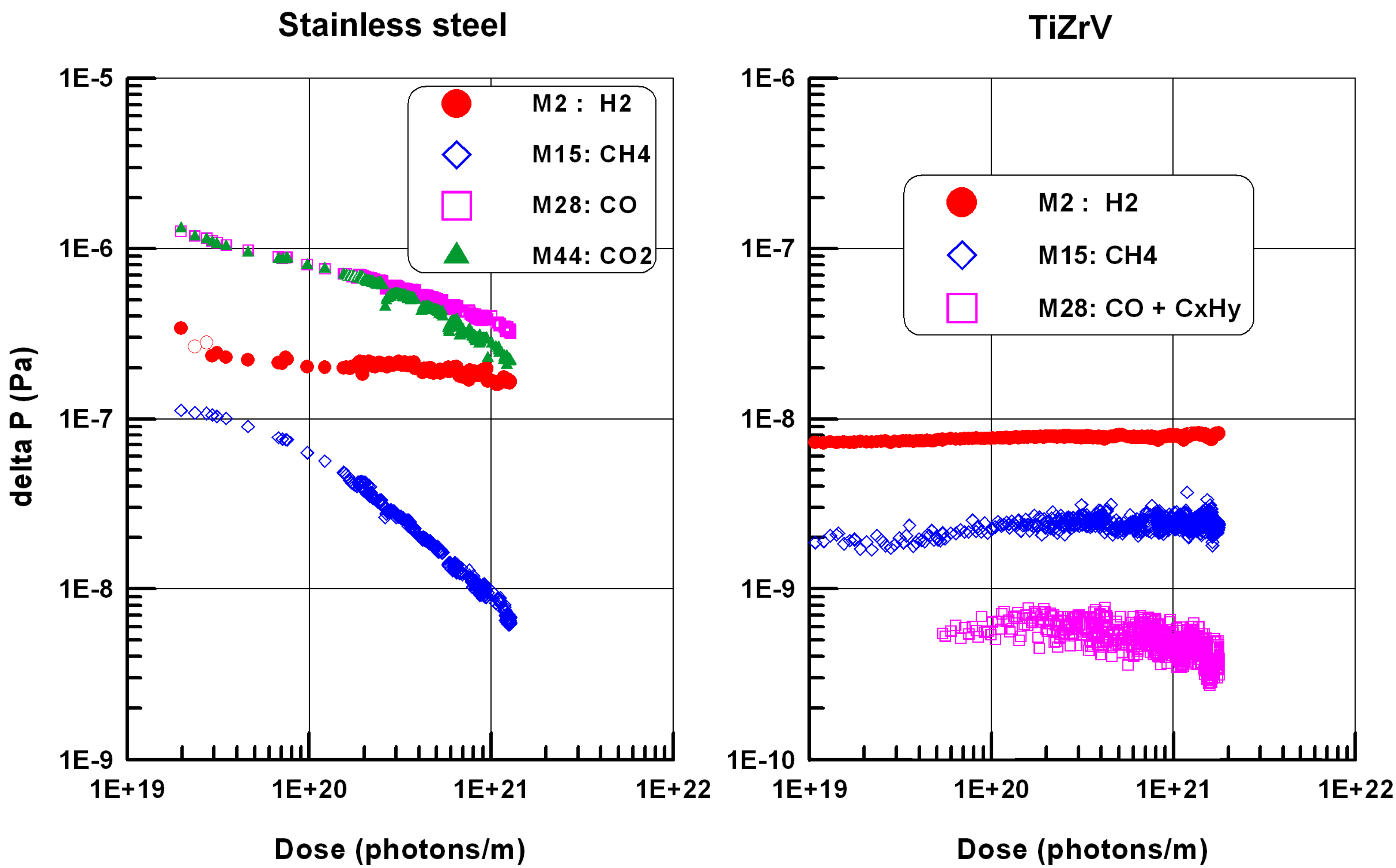
Desorption from the NEG coatings

$$P = \frac{Q}{S}$$

$$Q = qA + \eta_{\gamma}\Gamma + \eta_{e}\mathrm{I}_{e} + \eta_{ion}\mathrm{I}_{ion}$$

Thermal, photon, electron and ion stimulated desorption

Stainless steel vs NEG coated vacuum chamber under SR

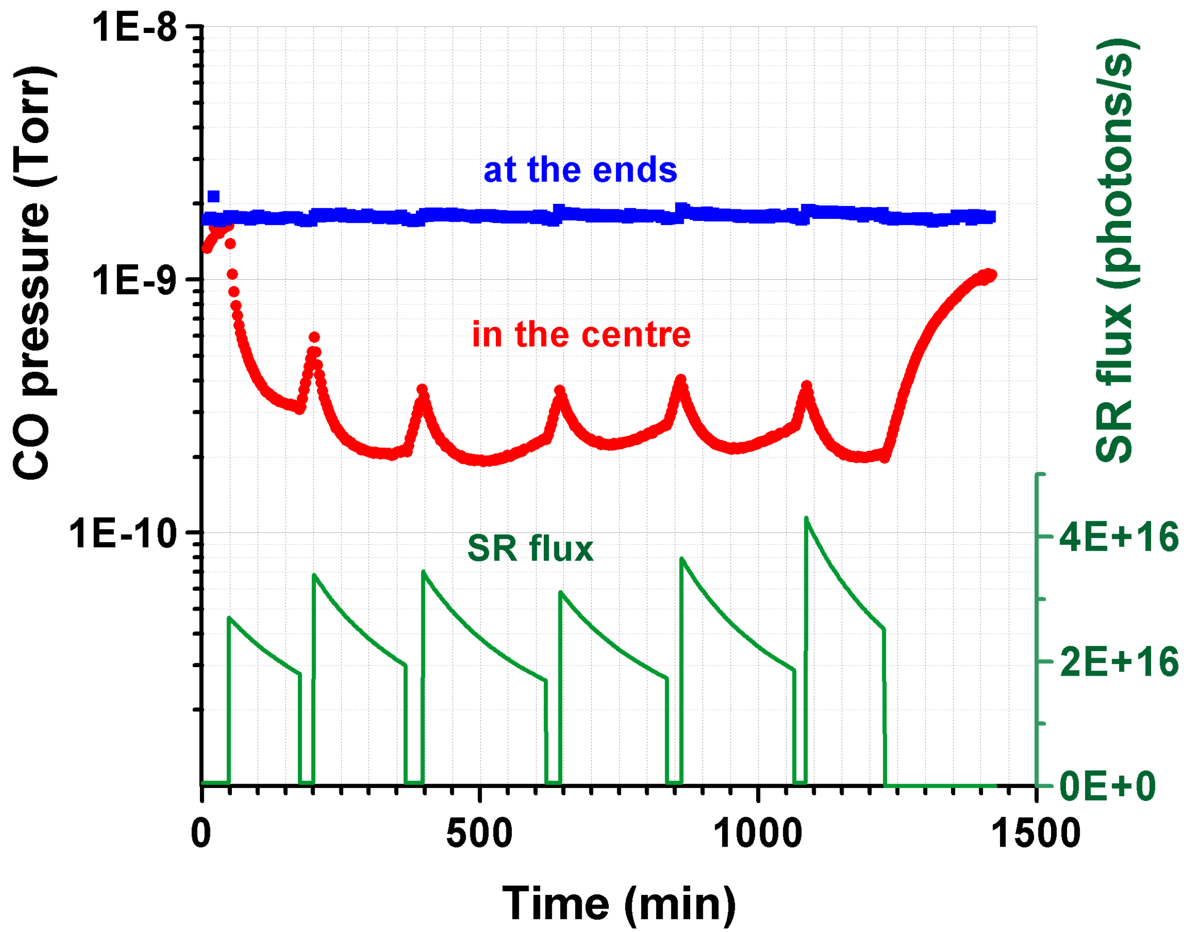


NEG Coated Vacuum Chamber: Main Parameters

Gas	α	ΔP, [Torr]	η, [molecules/ photon]	α	ΔP, [Torr]	η, [molecules/ photon]
	NEG TiZrV coated vacuum chamber					
	Before activation			After activation at 190°C for 24 hrs		
H_2	0	$4 \cdot 10^{-8}$	$1 \cdot 10^{-3}$	0.007	$5 \cdot 10^{-11}$	$1.5 \cdot 10^{-5}$
CH_4	0	$2.5 \cdot 10^{-8}$	$2.5 \cdot 10^{-4}$	0	$1.5 \cdot 10^{-11}$	$2 \cdot 10^{-7}$
C_xH_y(28)	–	–	–	0	$<4 \cdot 10^{-12}$	$<3 \cdot 10^{-8}$
CO (28)	0	$6 \cdot 10^{-8}$	$5 \cdot 10^{-4}$	0.5	$<2 \cdot 10^{-12}$	$<1 \cdot 10^{-5}$
CO_2	0	$5 \cdot 10^{-8}$	$3 \cdot 10^{-4}$	0.5	$<5 \cdot 10^{-13}$	$<2 \cdot 10^{-6}$
	Stainless steel vacuum chamber baked at 300°C for 24 hrs					
	Initially			After $1 \cdot 10^{21}$ photons/m		
H_2	–	$3 \cdot 10^{-9}$	$8 \cdot 10^{-5}$	–	$1.5 \cdot 10^{-9}$	$4 \cdot 10^{-5}$
CH_4	–	$8 \cdot 10^{-10}$	$1 \cdot 10^{-5}$	–	$6.5 \cdot 10^{-11}$	$8 \cdot 10^{-7}$
CO	–	$1 \cdot 10^{-8}$	$8 \cdot 10^{-5}$	–	$3 \cdot 10^{-9}$	$2.5 \cdot 10^{-5}$
CO_2	–	$1 \cdot 10^{-8}$	$7 \cdot 10^{-5}$	–	$2 \cdot 10^{-9}$	$1.5 \cdot 10^{-5}$

NEG Coated Vacuum Chamber: SR Induced Pumping

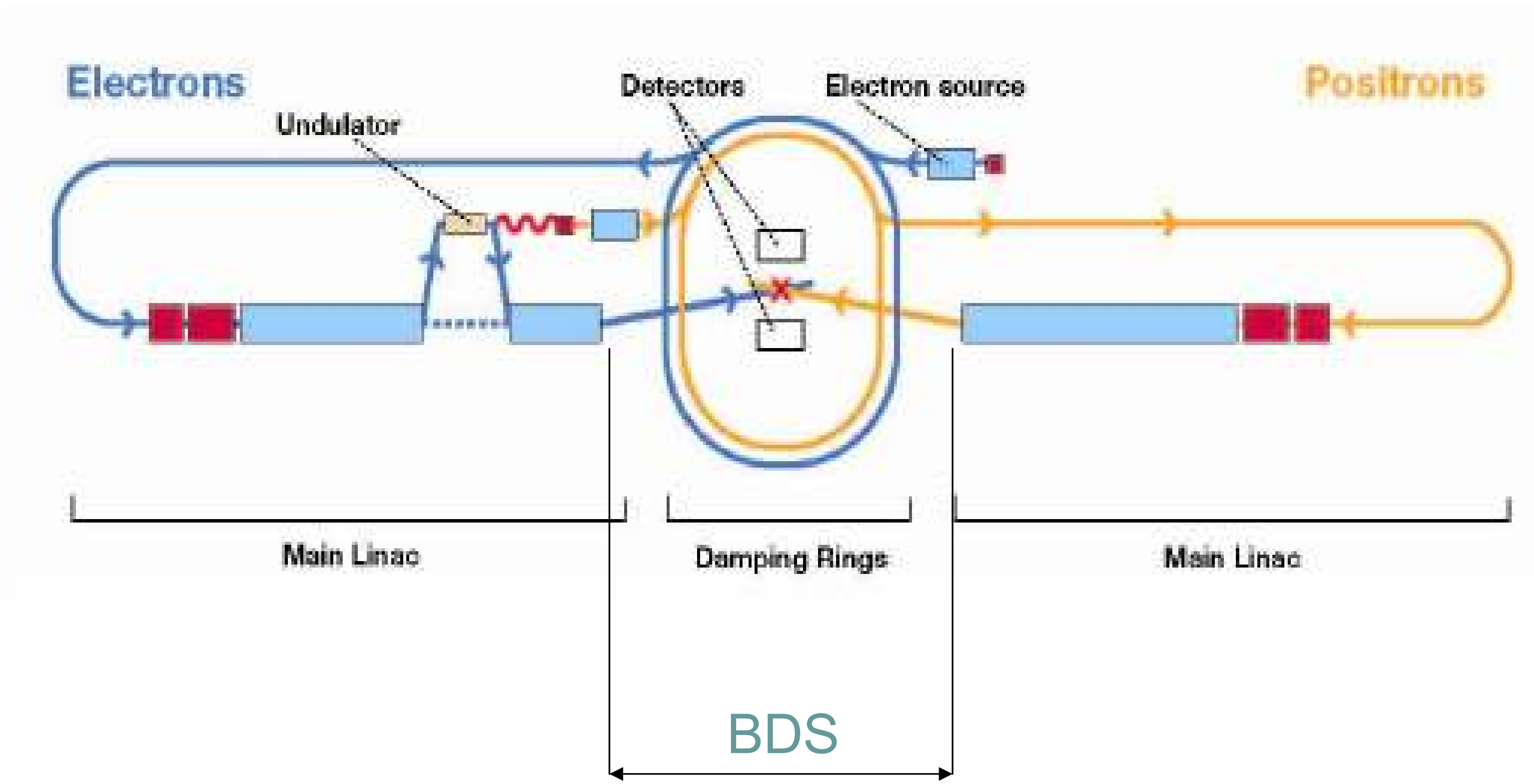
NEG TiZrV coated surface saturated with CO (i.e. no pumping speed) exposed to SR



NEG coating used in existing particle accelerators

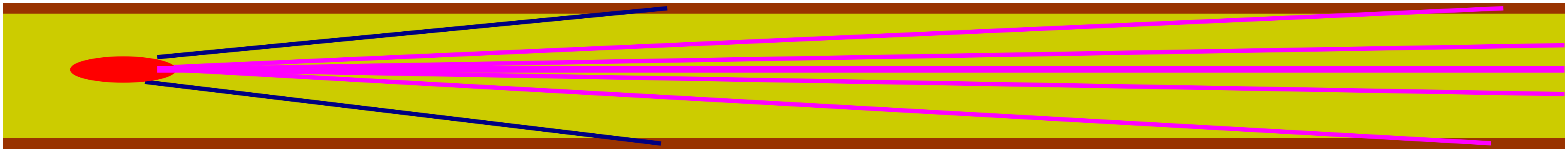
- Insertion device vessel at the ESRF, ELETTRA, Diamond LS, others…
  - Narrow and long vacuum chamber – much easier and quicker to provide the required vacuum
- Fully coated machine: Soleil
  - To shorten commissioning time at the start up
- Elements of vacuum chambers at, LHC, KEK-B, SIS-18, etc.
  - To reach and guarantee required vacuum
  - To suppress e-cloud
  - To avoid beam induced vacuum instabilities

International Linear Collider

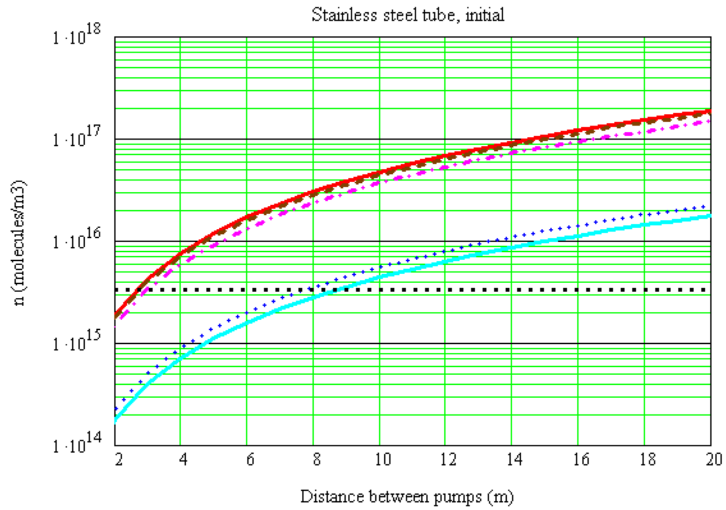


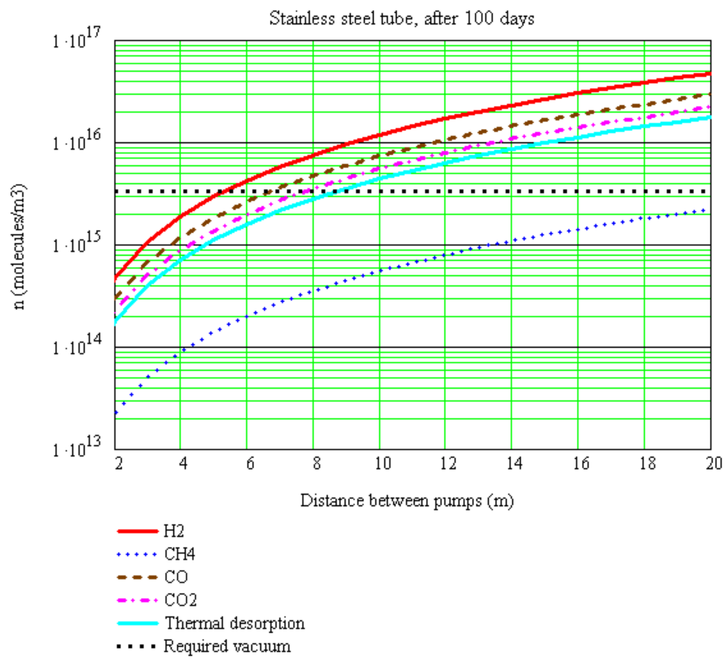
Vacuum for helical undulator

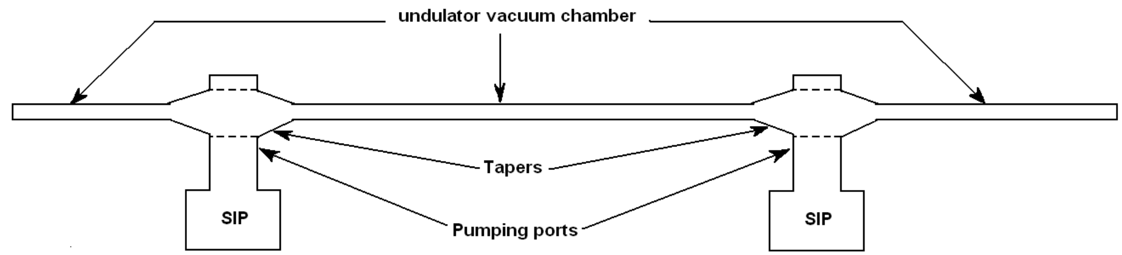
- Narrow vacuum chamber: d = 4-6 mm and L = 200 m
- Unlike undulator in SR sources **some SR from the undulator strikes its vacuum chamber walls and must be considered in vacuum design**

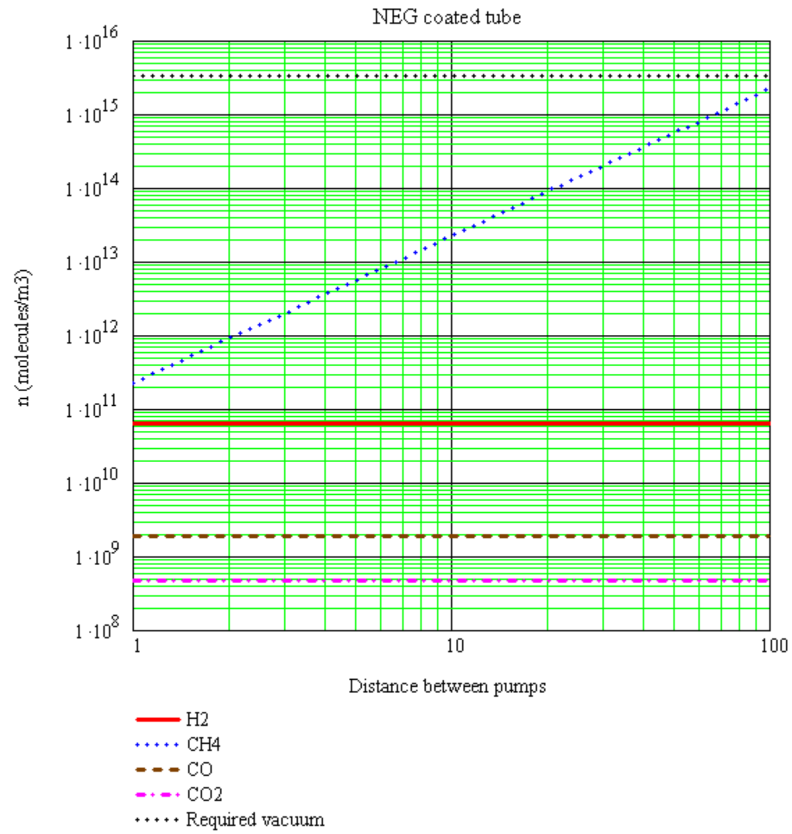


Gas density at room temperature at z = 100 m

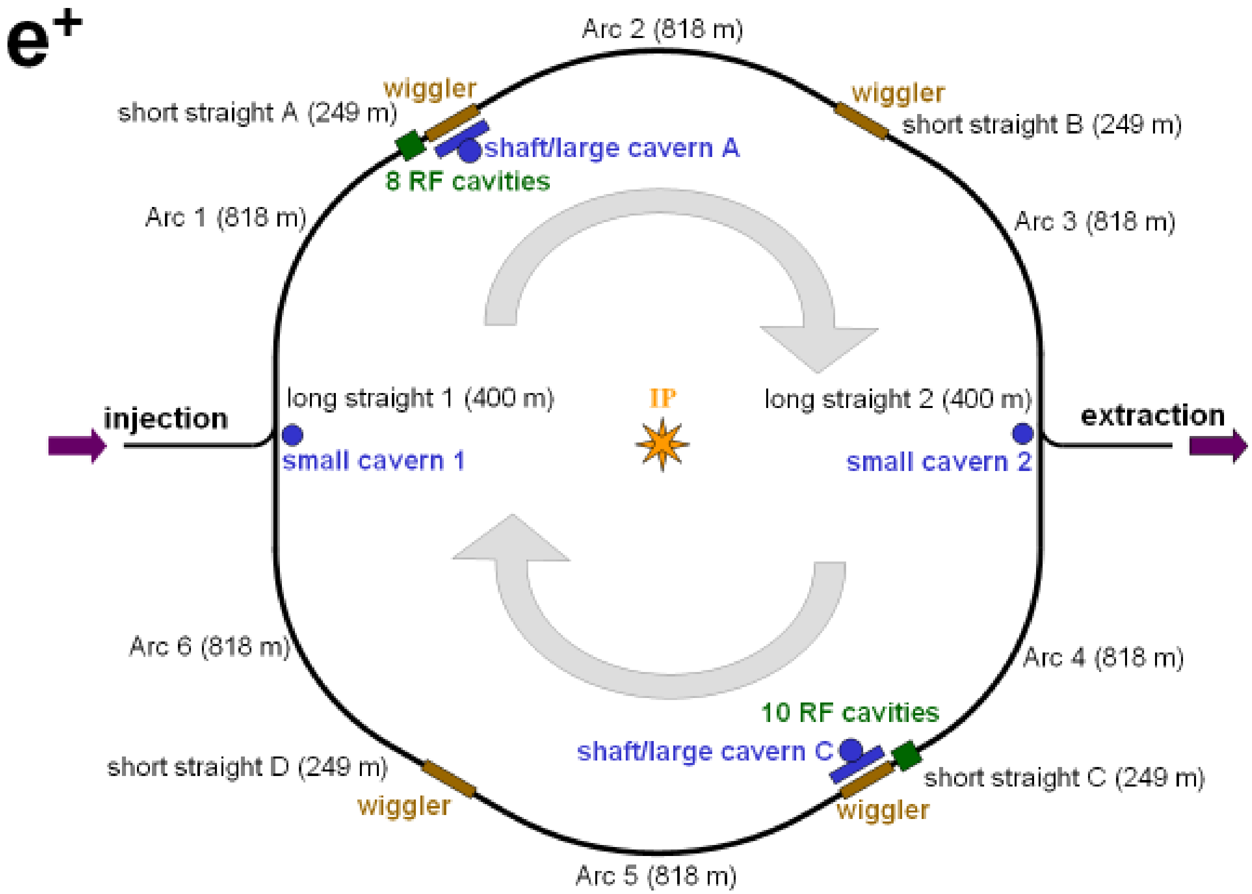








Damping rings

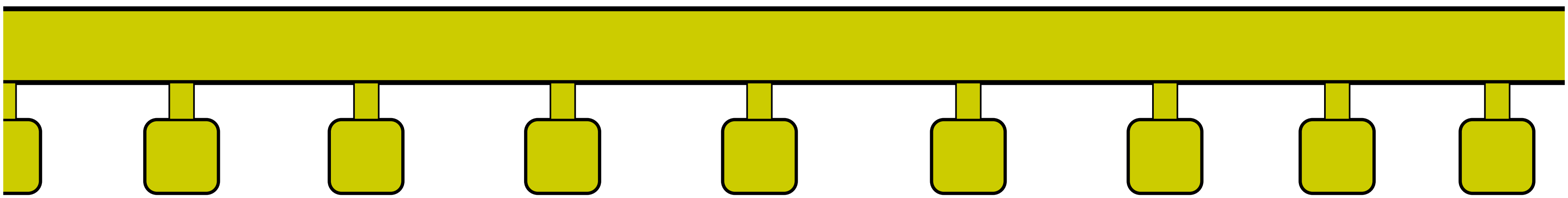


- E = 5 GeV
  I = 0.4 A
  Required residual gas pressure (after 100 Ahr)
  - Electron ring (to avoid fast ion instability)
    - 0.5 nTorr in arc
    - 2 nTorr in wiggler
    - 0.1 nTorr in straights
  - Positron ring (defined by SR and e-cloud)
    - ~1 nTorr

Pumping scheme along the ILC DR arc

An aluminium tube after bakeout at 220°C for 24 hrs and 100 Ahr beam conditioning:

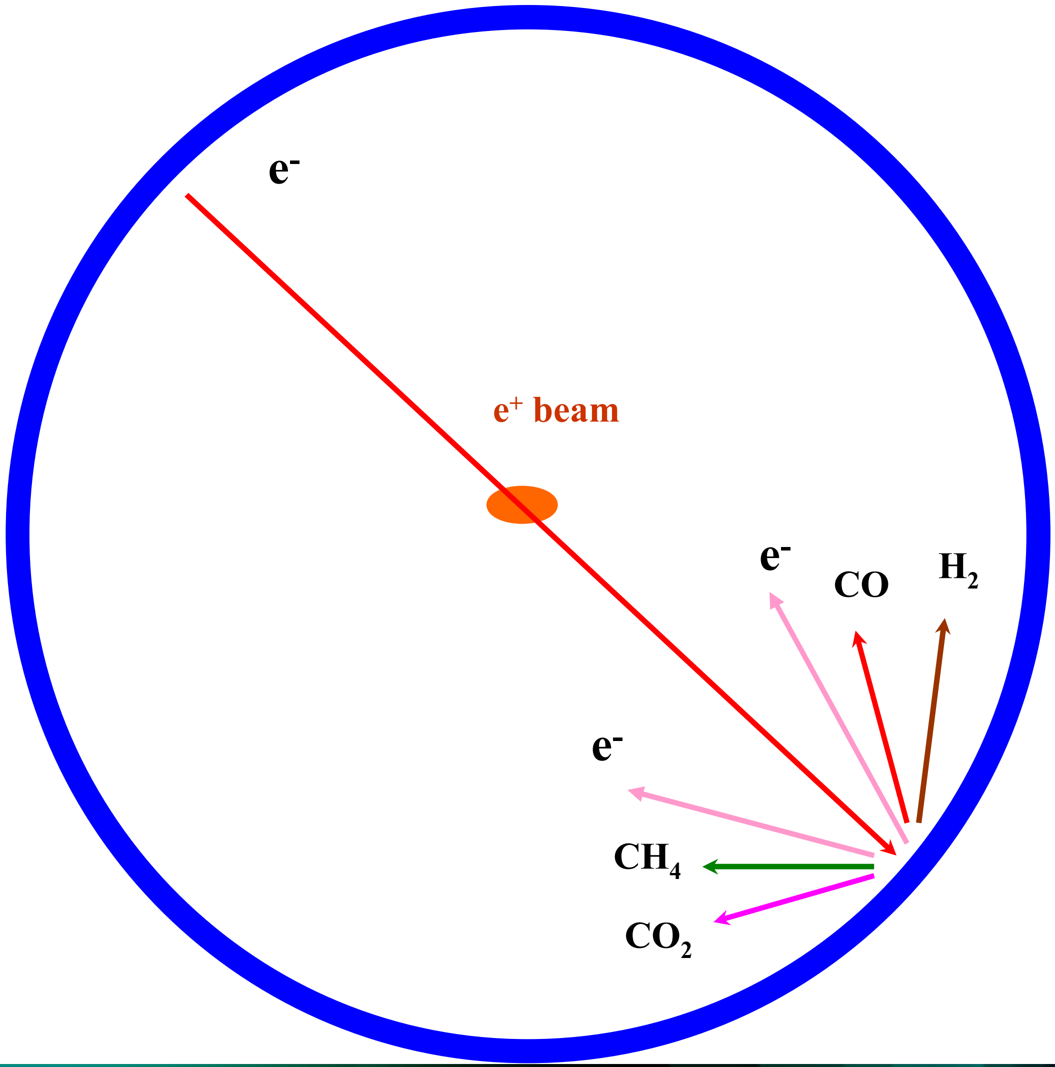
- a pump with **S_{eff} = 200 l/s every 5 m**
- H_2, CO and CO_2



Inside a NEG coated tube after activation at 160°C for 24 hrs and 100 Ahr beam conditioning:

- a pump with **S_{eff} = 20 l/s every 30 m**
- A H_2 and CH_4

Electron cloud in a vacuum chamber



1. Electrons appear in vacuum chamber due to photoemission and electron from beam induced gas ionisation

2. They accelerated by a beam charge

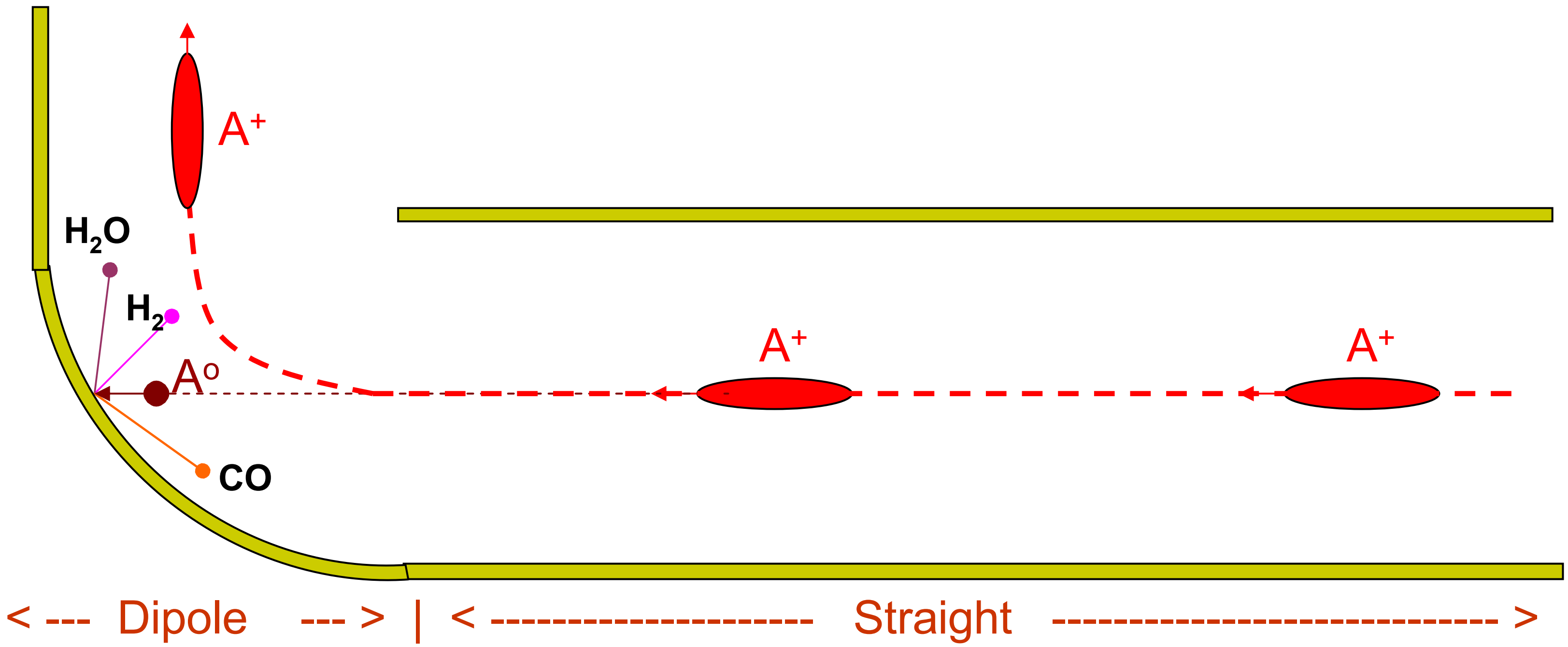
3. These electrons may strike the vacuum chamber wall causing
   - Secondary electrons
   - Electron stimulated gas desorption

The sources of electrons

- Photo-electrons
  - Geometrical: antechamber or other means of reduction or localisation of direct and reflected photons
  - Surface treatment, conditioning, coating (ex.: **TiZrV**)
- Secondary electrons
  - **TiZrV or TiN coating**
  - Other low SEY coatings
  - Biased electrodes
- Gas ionisation
  - Surface treatment and conditioning
  - Low outgassing coating (ex.: **TiZrV**)
  - Better pumping (ex.:**TiZrV**)
- A complex solution required:
  - Good solution against Photo-electro ns or Secondary electrons might lead to higher gas density and higher gas ionisation, and vice versa.
  - NEG coating is the best choice for UHV systems

Ion Induced Pressure Instability in Heavy Ion Accelerators

The ***heavy ion beam particles*** colliding with residual gas molecules may lose or trap an electron and be ***lost*** in or after the bending magnet. These very high energy ions or neutrals bombard the vacuum chamber wall which results in a very high desorption yield (*up to a few thousands molecules per ion*). This causes further gas desorption, resulting in a pressure rise and more lost beam particles bombarding the wall…



Ion Induced Pressure Instability in Heavy Ion Accelerators

- NEG coated vacuum chamber is the easiest and cheapest solution
  - to reduce ion induced desorption and
  - to provide distributed pumping speed

Summary

- NEG film coating of whole surface of vacuum chamber allows operating **UHV/XHV systems** of particle accelerators at lower cost or could be event the only solution in some cases.
- NEG coating has **large pumping speed to** provide UHV/XHV.
- NEG coating activated at 160-180°C provides **low photon, electron and ion induced desorption**, lower than from baked 316LN, aluminium or copper.
- **Photon stimulated NEG film activation** increases the NEG capacity or allows to avoid the NEG coating re-activation.
- **Low photon and secondary electron yield** is an important characteristic which is very useful for particle accelerators.

Summary (cont.)

However, design and operation of vacuum system with NEG coating is delicate.

- Although NEG coating provides **large pumping speed**, it should not be used as a usual pump because a low pumping capacity.
- To achieve maximum benefit the NEG film should coat whole area of vacuum chamber and *in-vacua* components
  - Beam chamber and antechamber
  - Pumping ducks and pump bodies.
- Three-step bakeout-activation procedure (~70 hrs)
  - Bakeout of non-coated part with NEG coated parts at 80°C
  - Transitional period when all parts are at 150°C
  - The NEG coating activation at 160-180°C with non-coated part at RT.