Beam induced desorption

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Outline

- Photon simulated desorption

- Electron simulated desorption and BIEM

- Ion simulated desorption and ion induced pressure instability

- NEG coated vacuum chamber

- Cryogenic vacuum chamber: recycling and cracking

Photon stimulated desorption (PSD)

Photon stimulated desorption (PSD) is one of the most important sources of gas *in the presence of SR*.

PSD can be considered as a two-step process:

• first, photons with energy >10 eV cause the photoelectron emission,

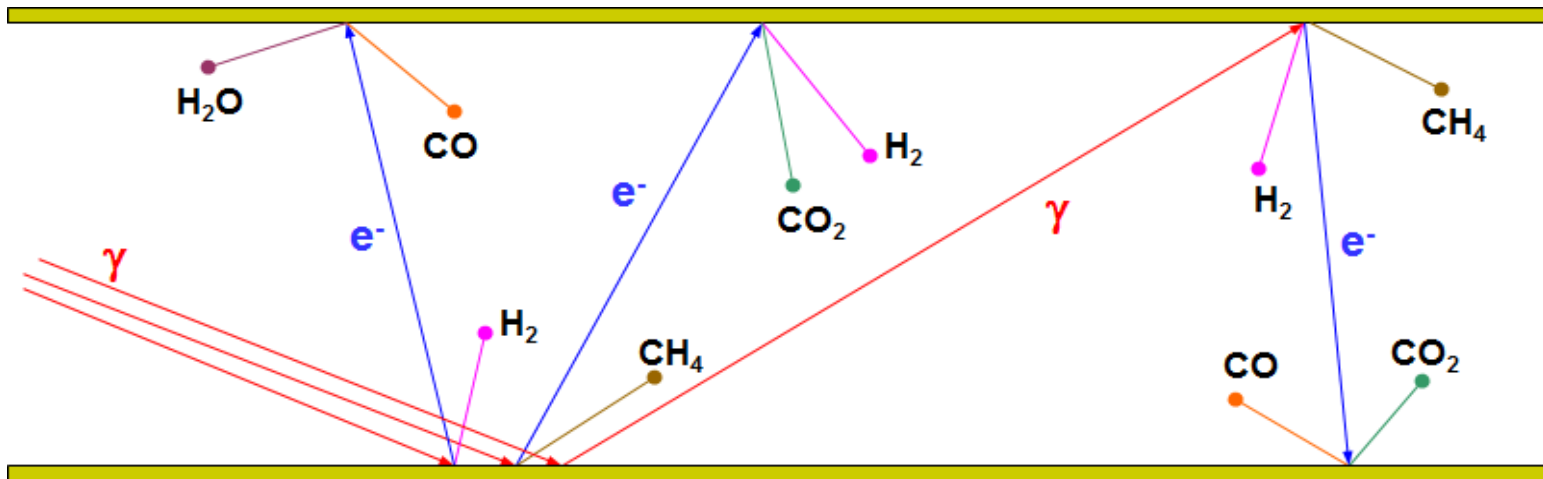• then the photoelectron stimulate gas desorption.
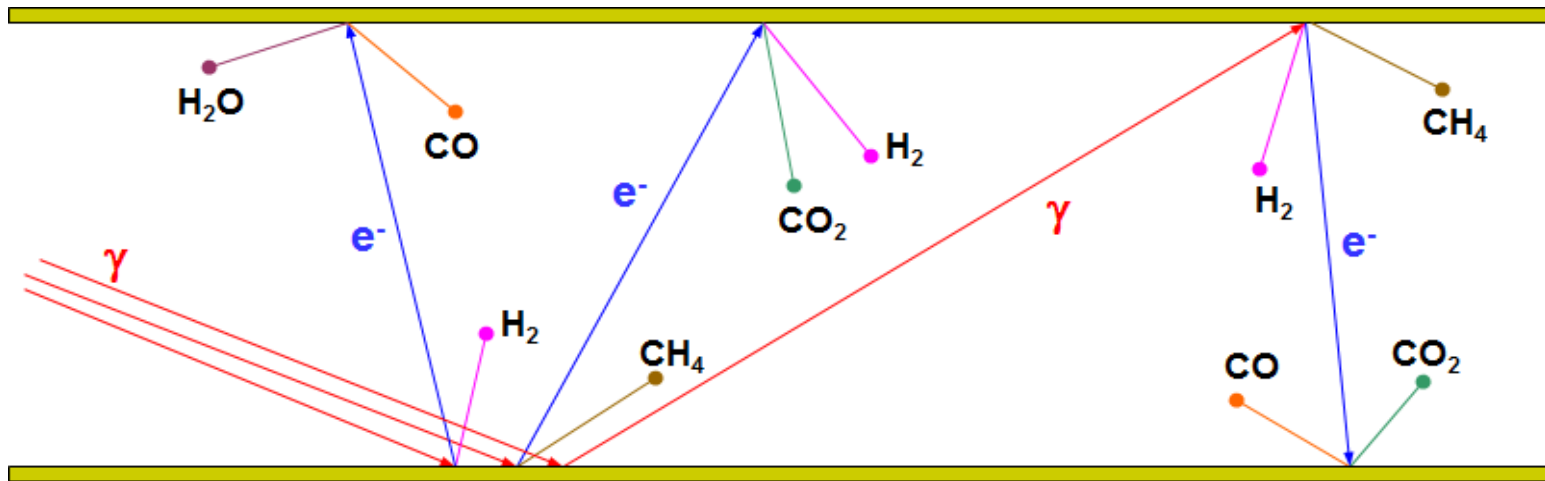
Gas molecules may desorb from a surface when and where *photoelectrons* leave and arrive at a surface

PSD yields are defined as a number of gas molecules desorbed from the surface per incident photon, η_γ [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**

Photodesorption yields, η **(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
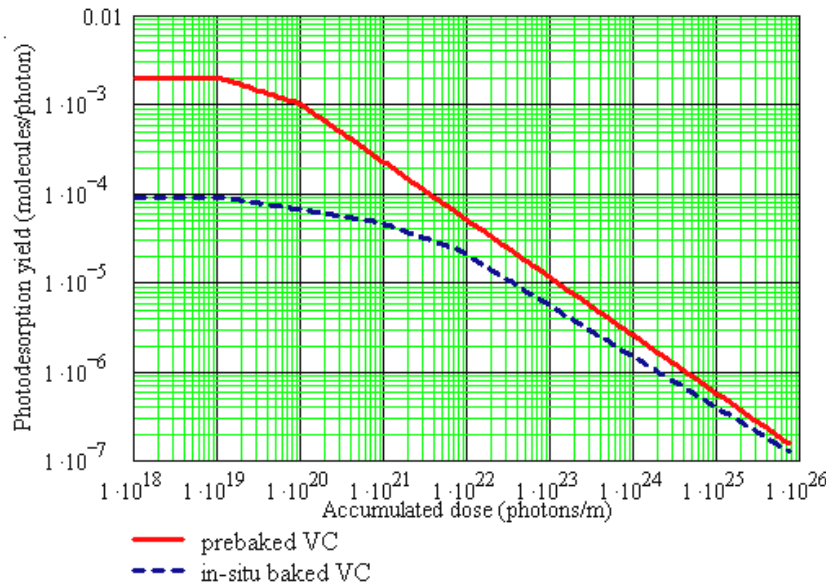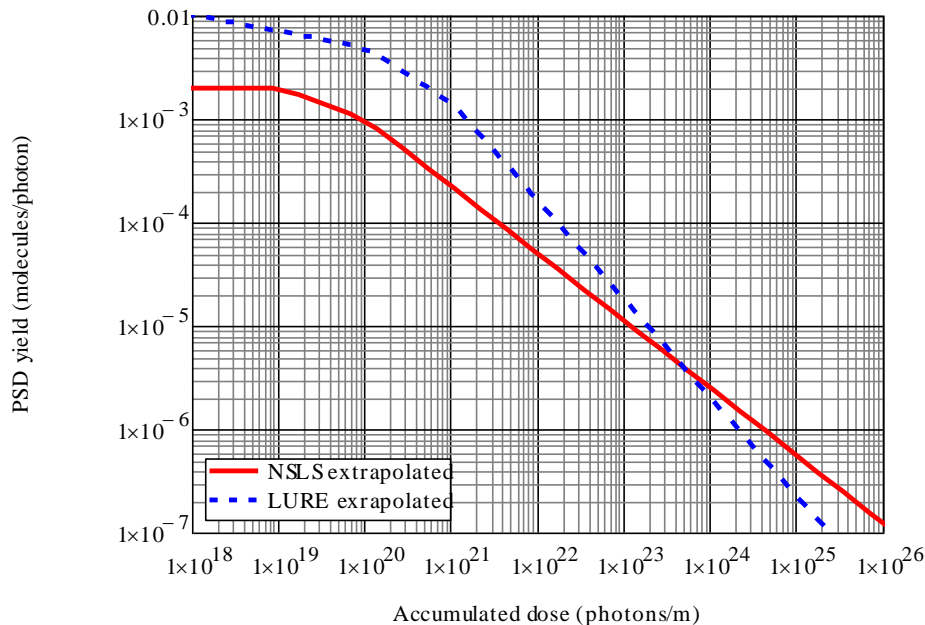

Photodesorption yield as function of accumulated photon dose can be described as:

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

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.

Example of PSD yields for CO for unbaked and baked vacuum chambers as a function of accumulated photon dose D, based on results of experiments at NSLS [J. Vac. Sci. Technol. **A 8**, 2856 (1990)] and LURE [J. Vac. Sci. Technol. **A 17** 635 (1999)]. .

Photodesorption yield as function of accumulated photon dose can be described as:
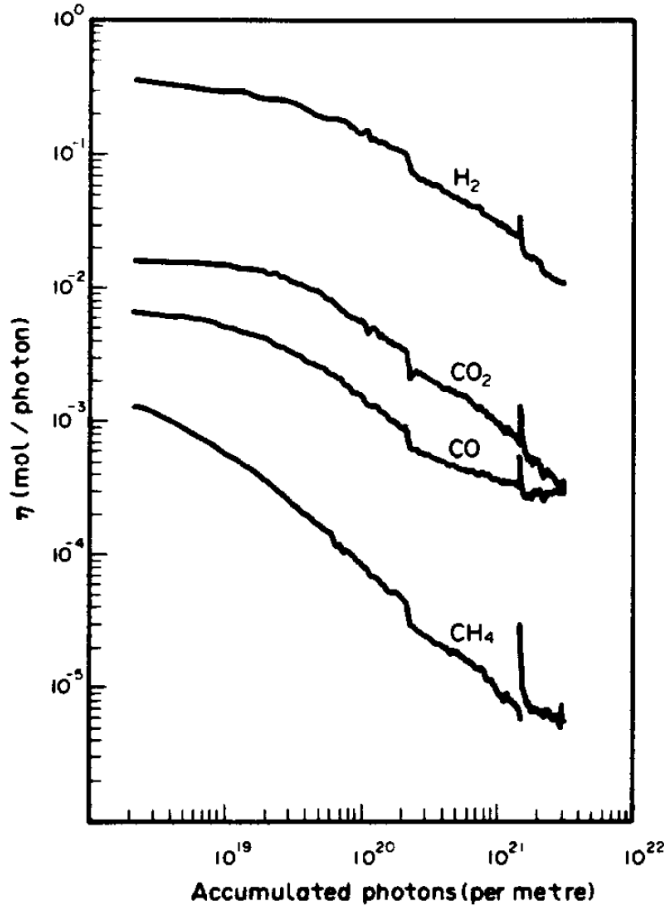
$$\eta = \eta_0 \left(\frac{D_0}{D} \right)^{\alpha},$$

$\alpha = 0.65$ for $\varepsilon_c = 500\ eV$ at NSLS
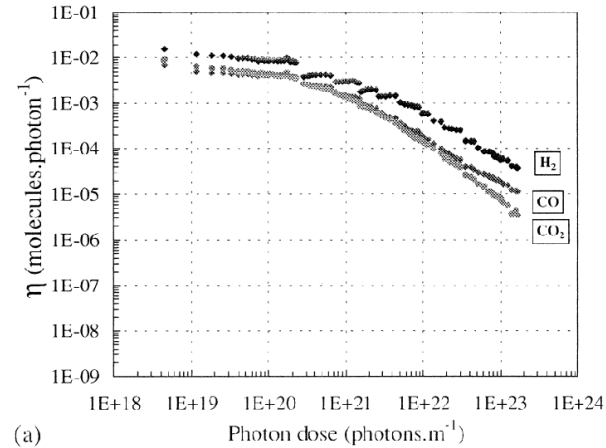
$\alpha = 1$ for $\varepsilon_c = 3.35\ keV$ at LURE

Yields for doses higher then 10^{23} photons/m (1 to 10 Amp·hrs for diamond) are extrapolations.

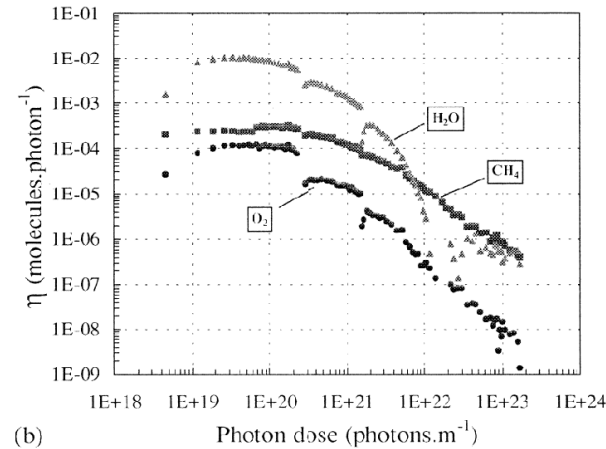Science & Technology Facilities Council
ASTeC

The PSD yield η for various gas species as a function of the accumulated photon dose at ε_c = 3.75 keV at DCI

(a)

(b)

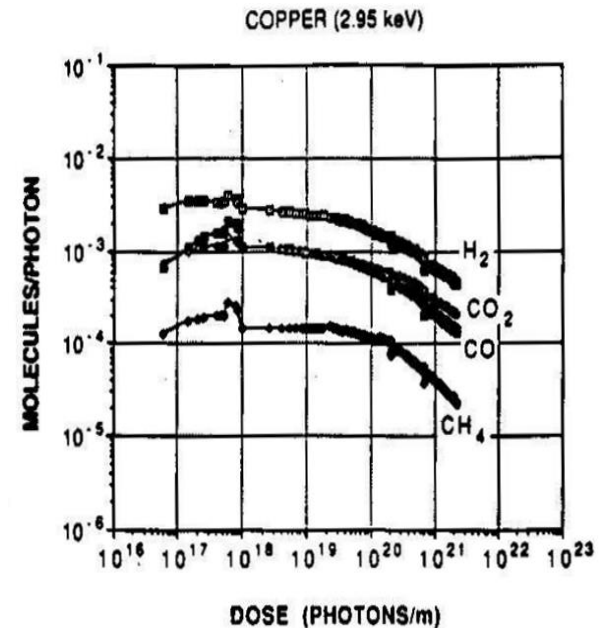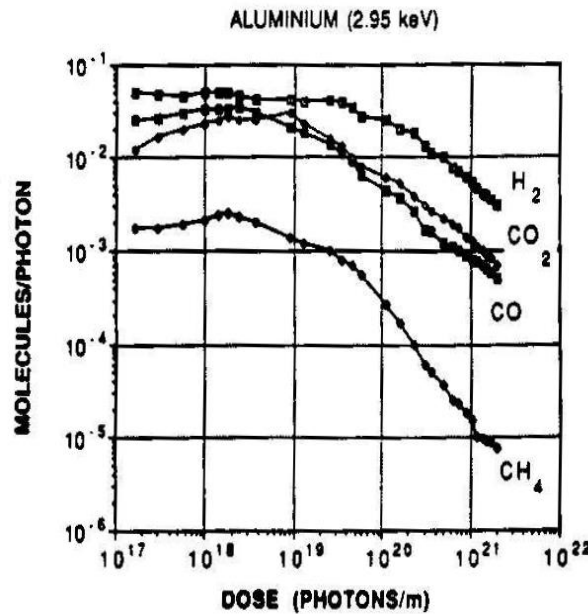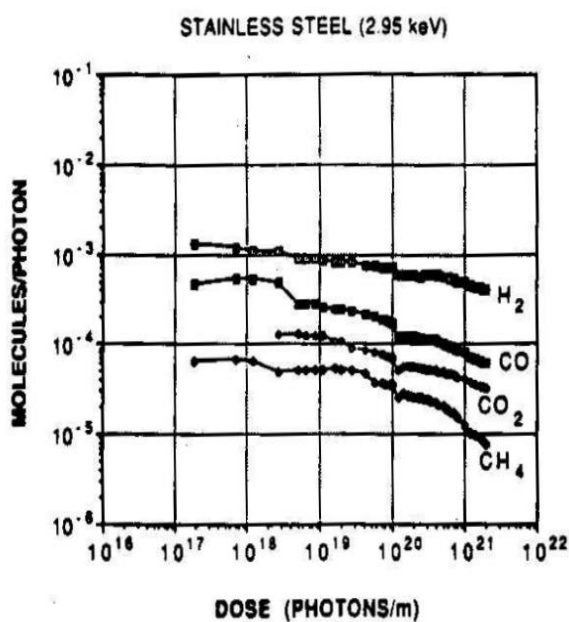aluminium vacuum chamber
(Vacuum 33, 397 (1983))

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

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))
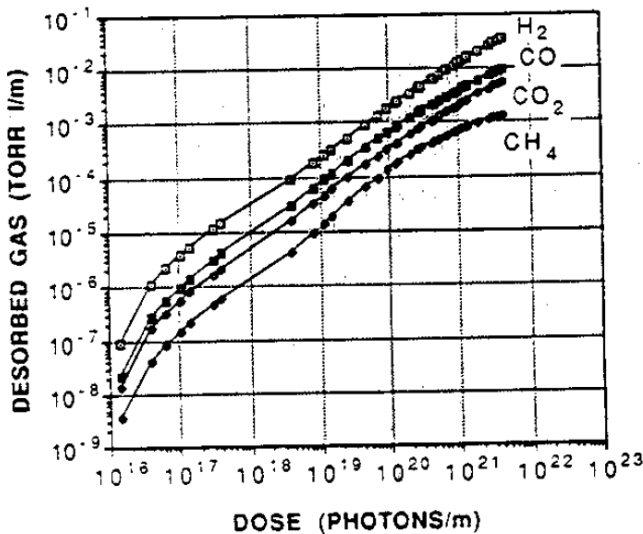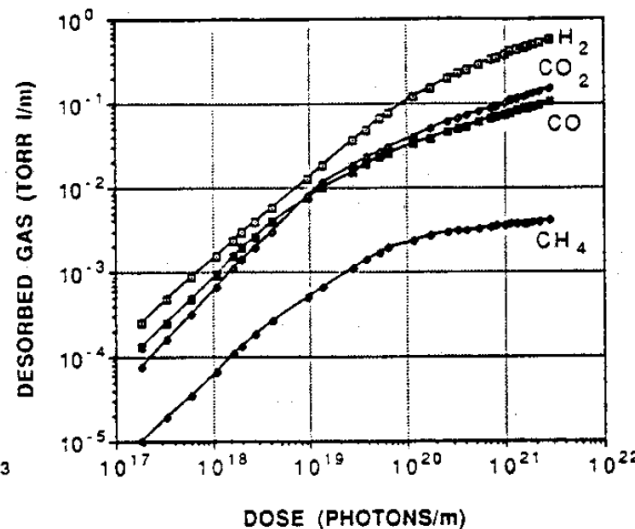
The same data can be analysed differently, amount of desorbed gas :

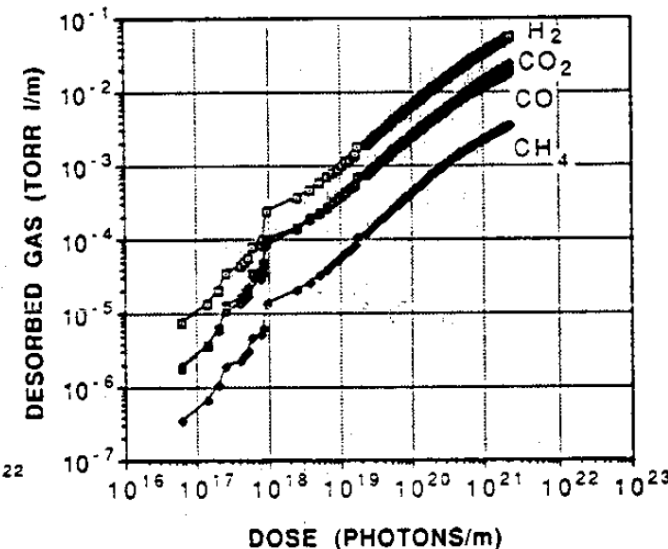$$Q\left[\frac{mbar \cdot l}{s}\right] = \int_0^t \eta(t)\Gamma(t)\,dt = \int_0^D \eta(D)\,dD$$
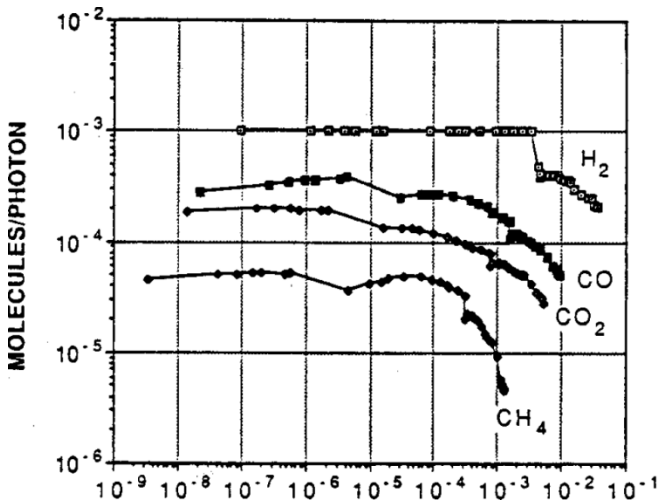
Stainless steel   Aluminium   Copper

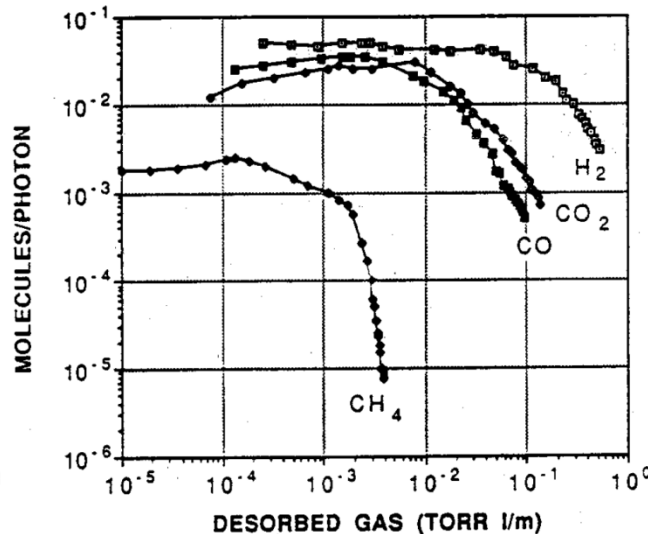This information is important when the sorption pumps are used such as NEG cartridges or cryosorbers

The same data platted differently:

Stainless steel

Aluminium

Copper

ε_c = 10-1000 eV ε_c = 0.1-1.4 MeV

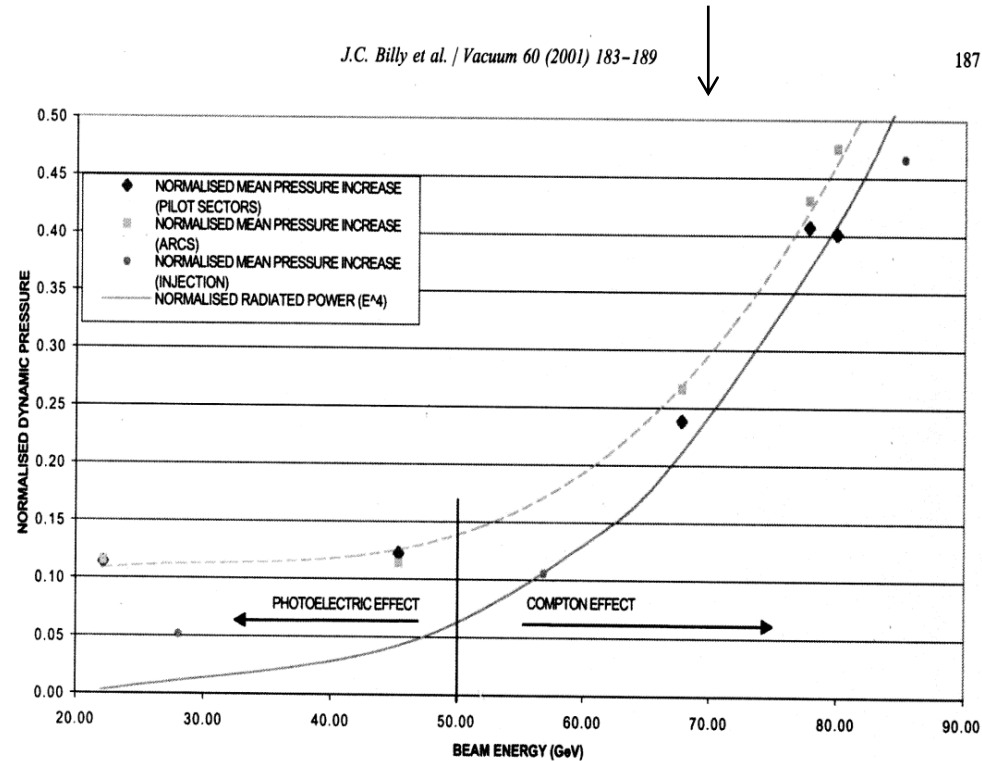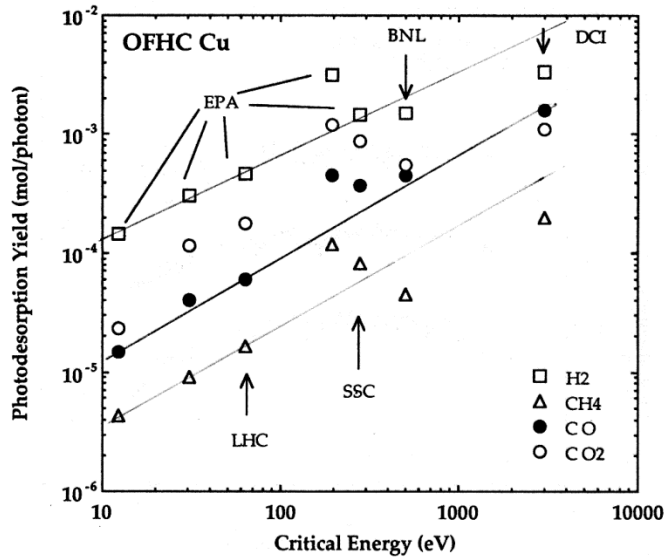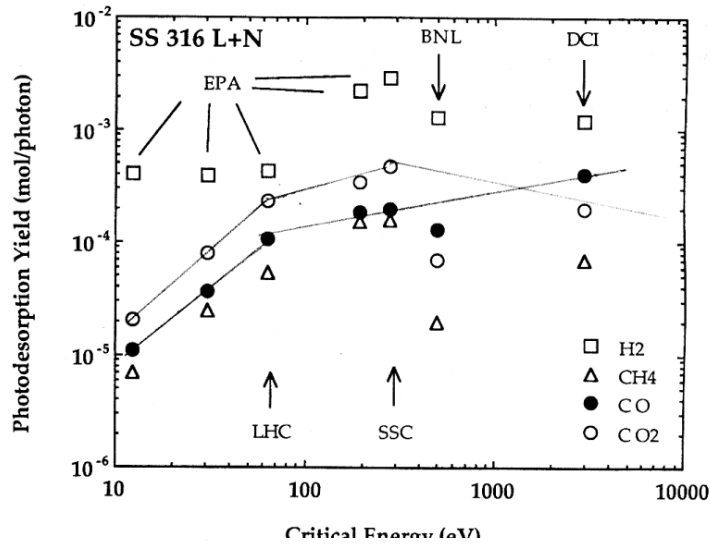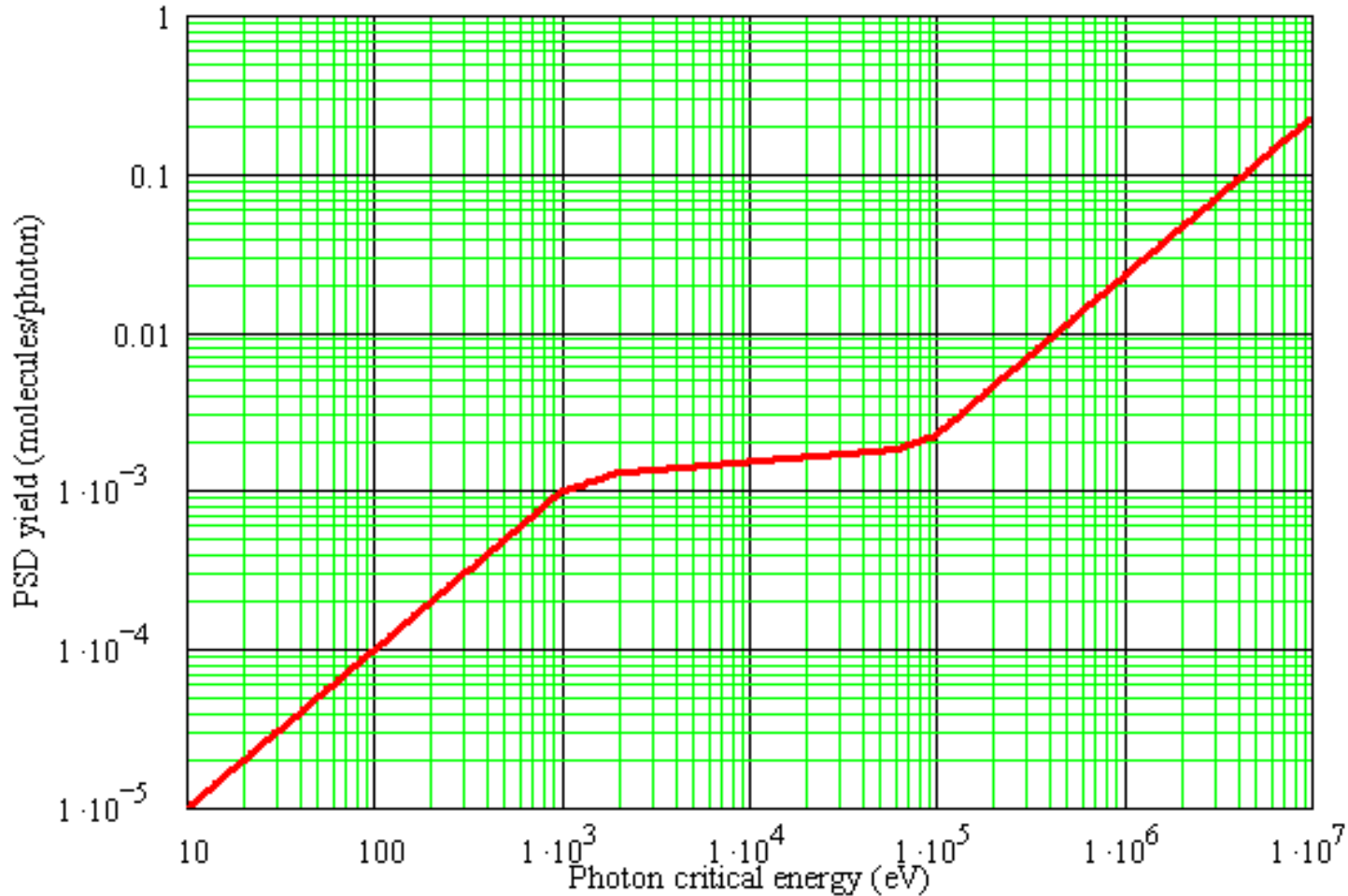J.C. Billy et al. / Vacuum 60 (2001) 183–189   187
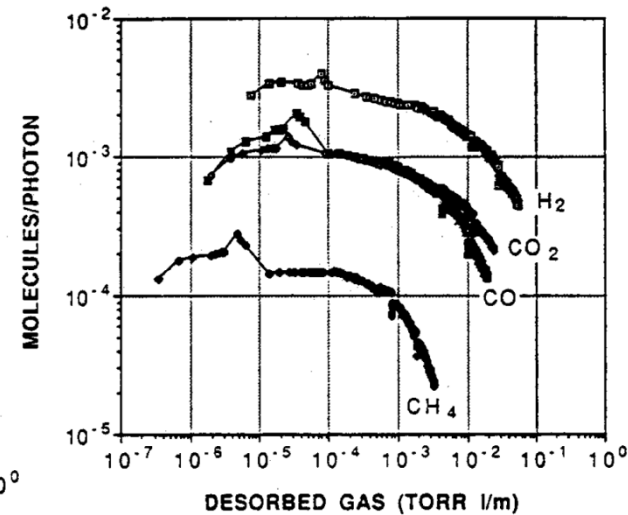
Fig. 5. Normalised pressure increase (low beam energy, measured in LEP arcs, 1999).

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

J. Vac. Sci. Technol. A 25(2007): 791-801
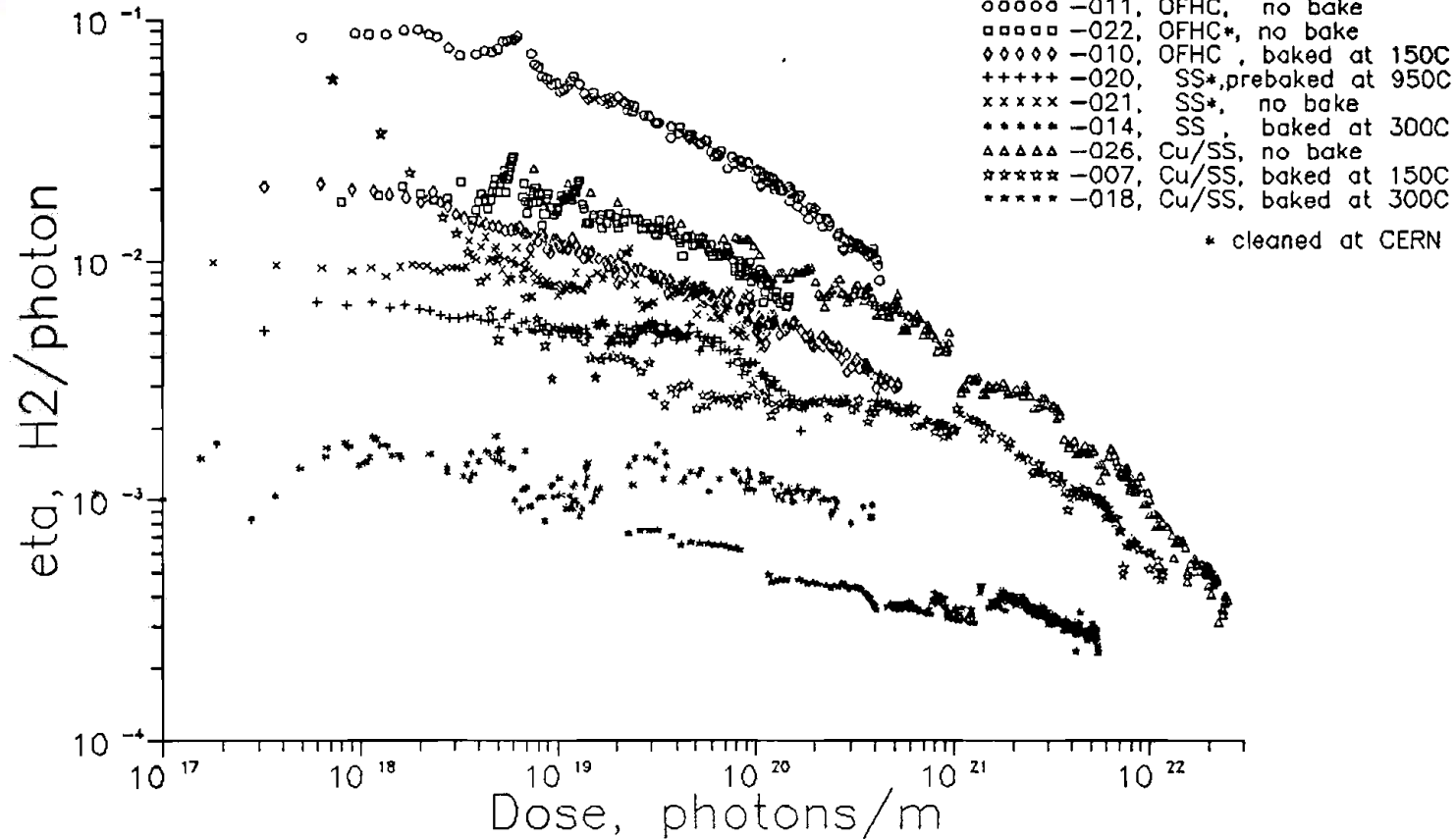
PSD: effect of bakeout

Bakeout	Impact	Comment
In-situ at 150 °C for 24 hrs	reduction of η_{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 η_{H2} by 10-20 times, for other species by 7-15 times	-
Ex-situ at 250-300 °C for 24 hrs	reduction of initial η_{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 η_{H2} by ~1.5-2 times	
In-situ bakeout after vacuum firing	reduction of η_{H2} by ~20-50 times	

The comparison of η_{H2} from OFHC, stainless steel (SS) and copper coated stainless steel samples with and without bakeout
[O.B. Malyshev, PhD Thesis, Budker Institute of Nuclear Physics, Novosibirsk,1995]
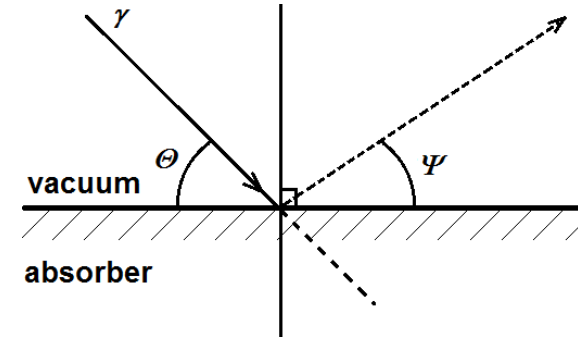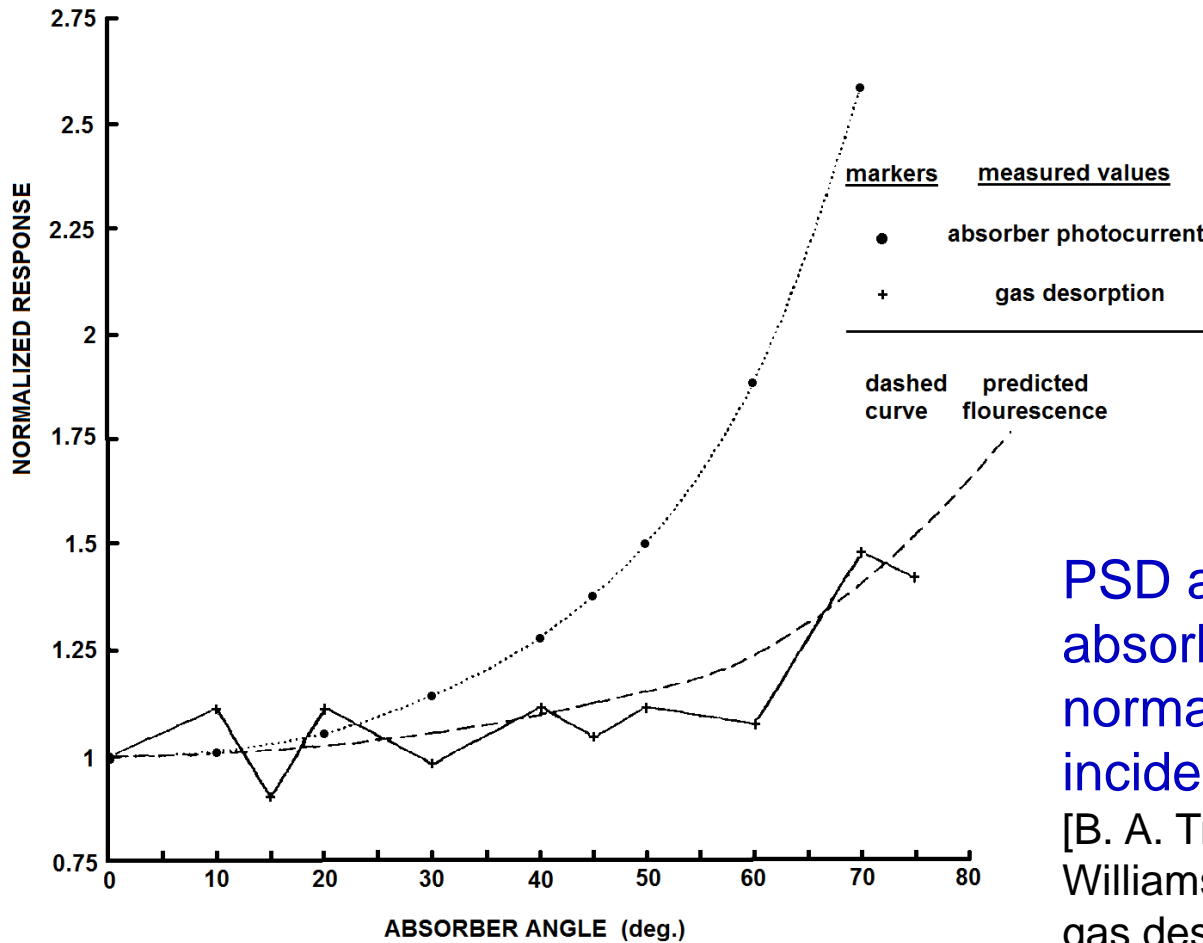
PSD and PEY as a function of absorber angle $(90°{-}\Theta)$ normalised to response at normal incidence for copper surface

[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)

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*.
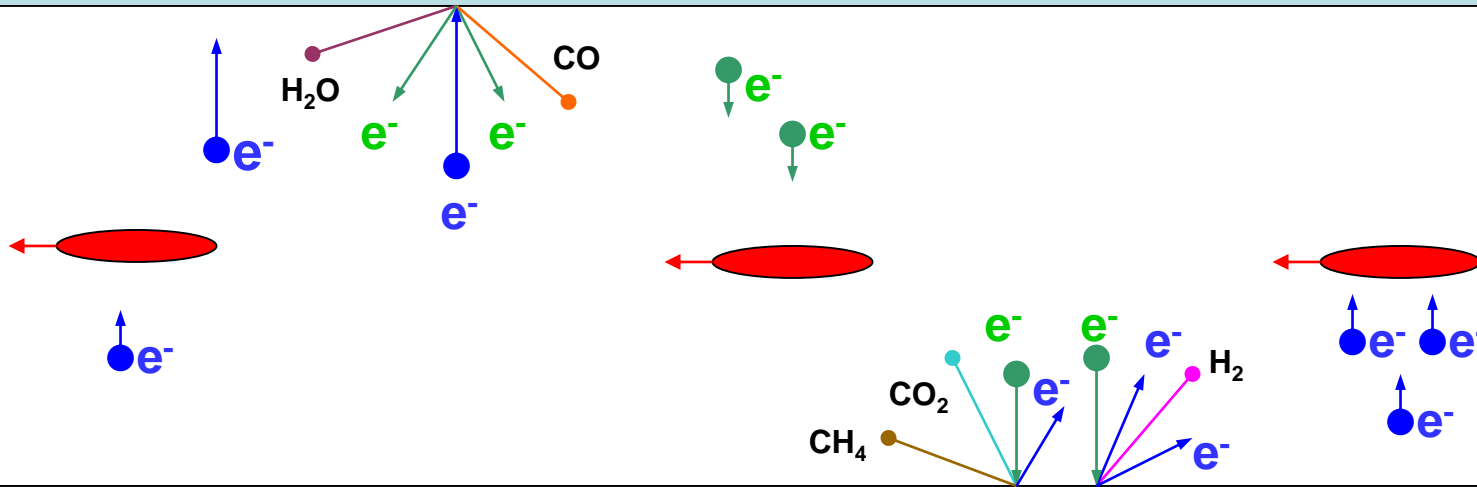
Gas molecules may desorb from a surface when and where *electrons* leave (with low energy) and arrive at a surface (with higher energy)

ESD yields

ESD yields are defined as a number of gas molecules desorbed from the surface per incident electron, η_e [molecules/e⁻]:

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

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

Similarly to PSD and thermal desorption, ESD depends on:

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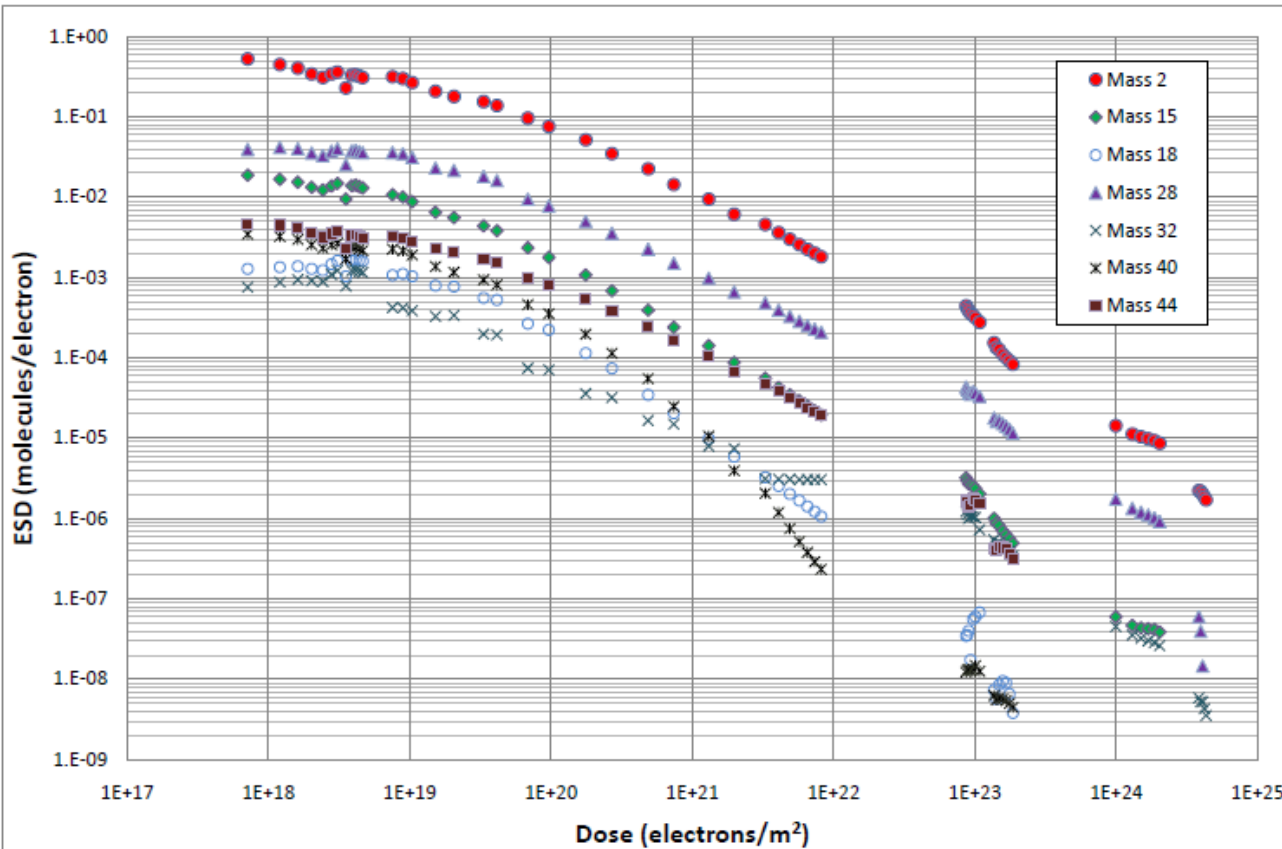- Pumping time

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 α lies between $0.5 \leq a \leq 1$
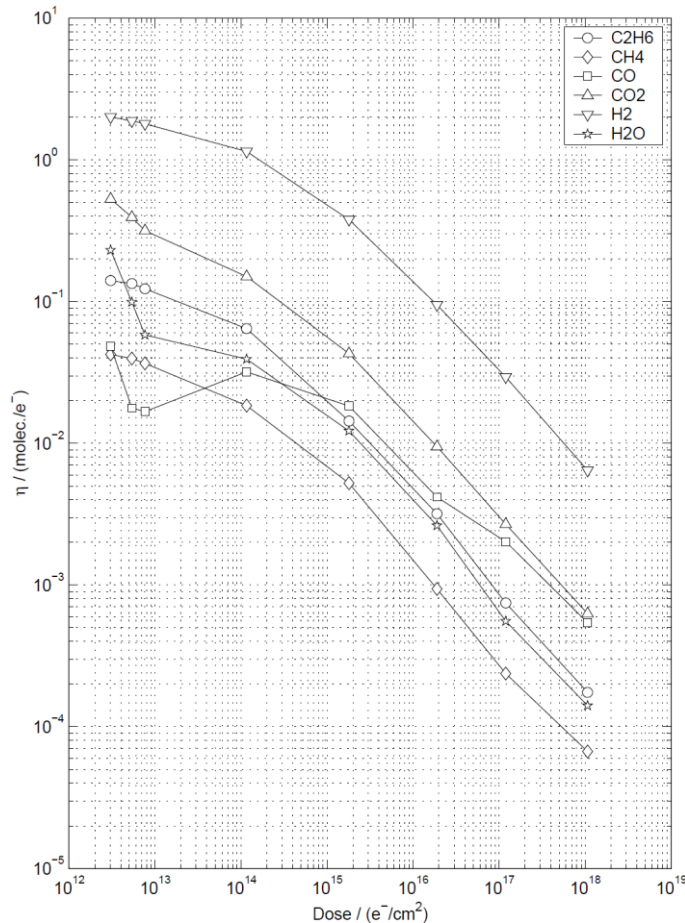
ESD yields of 316 LN stainless steel baked to 250 ºC for 24 hours as a function of electron dose at electron energy Ee = 500 eV.
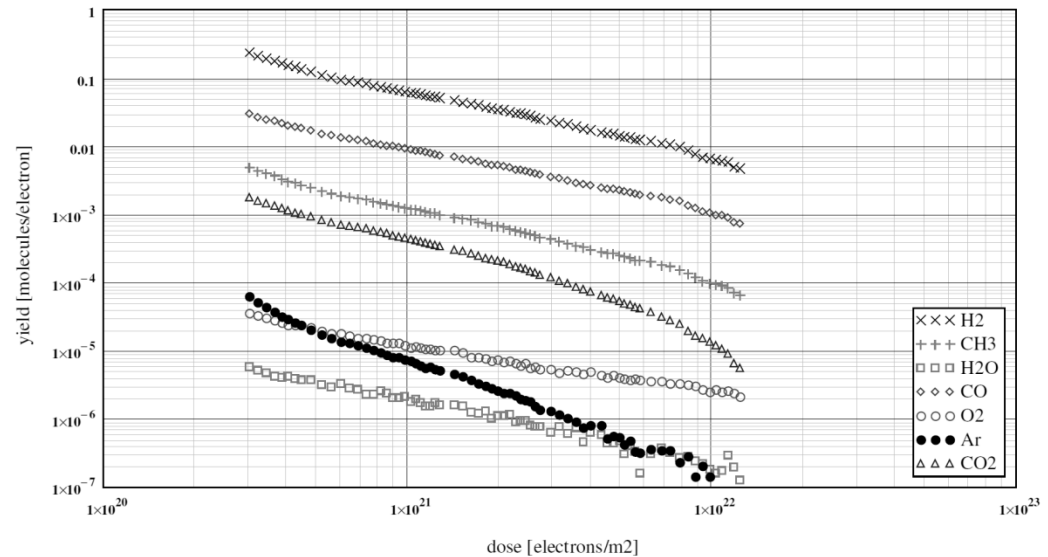
O.B. Malyshev and C. Naran. Vacuum **86** (2012), 1363-1366.

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
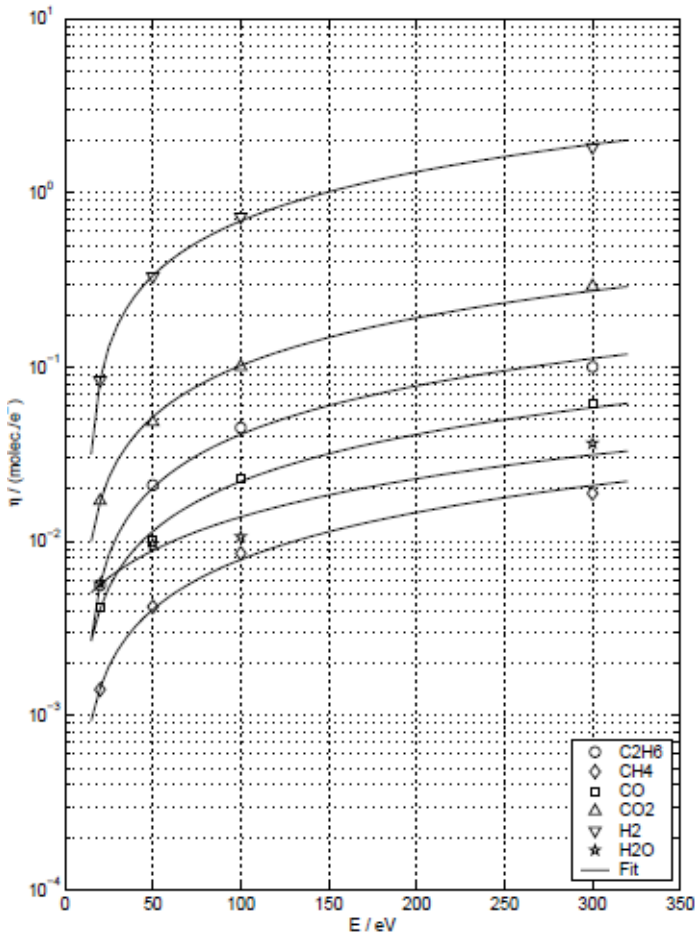

F. Billard *et al*, Some Results on the Electron Induced Desorption Yield of OFHC Copper. Vacuum Technical Note 00-32, December 2000, CERN, Geneva.

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

Unbaked OFHC copper at the dose D = 1.4 $\times 10^{14}$ e⁻/cm²

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⁻/cm²
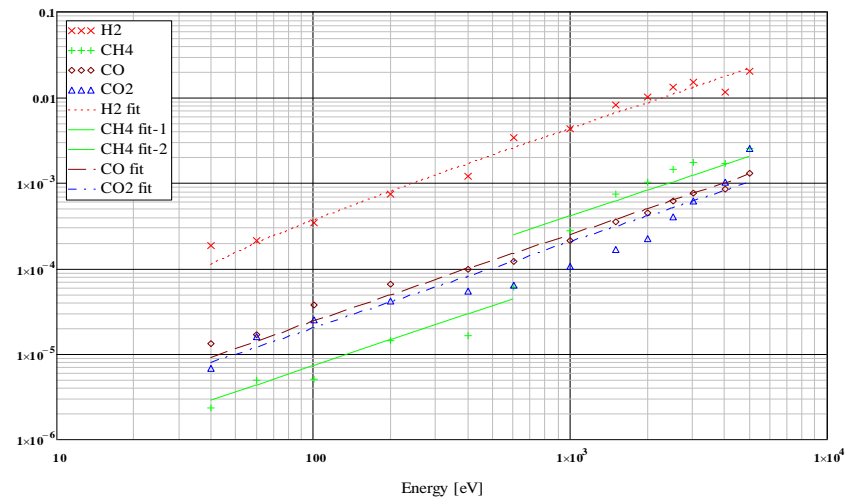
O.B. Malyshev *et al*, J. Vac. Sci. Technol. **A 28** (2010) 1215.
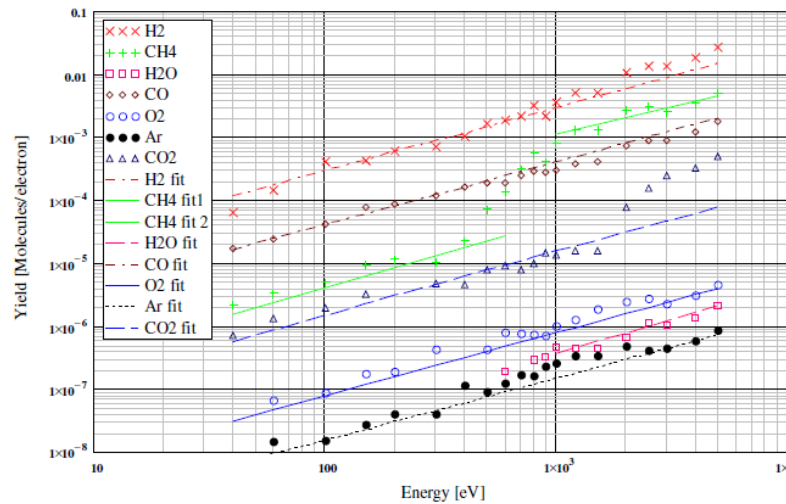
Aluminium sample baked at 220 °C for 24 h at the dose D = 1.3×10^{22} e⁻/cm²

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

O.B. Malyshev

316LN stainless steel baked at 250 °C for 24 h   O.B. Malyshev *et al*, J. Vac. Sci. Technol. **A 31** (2013) 031601.
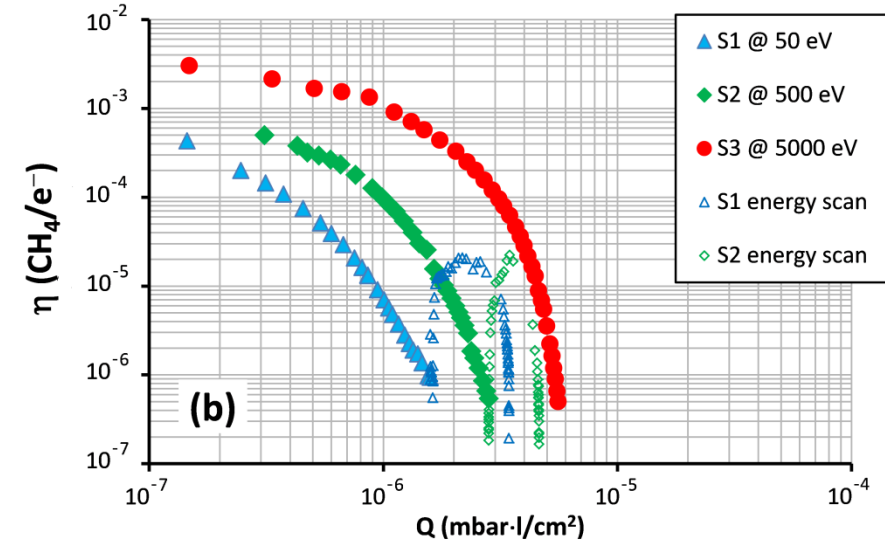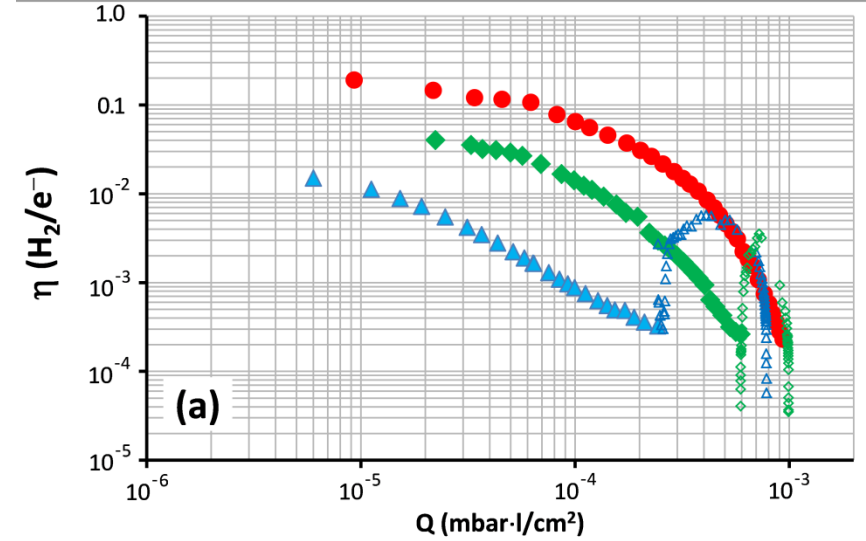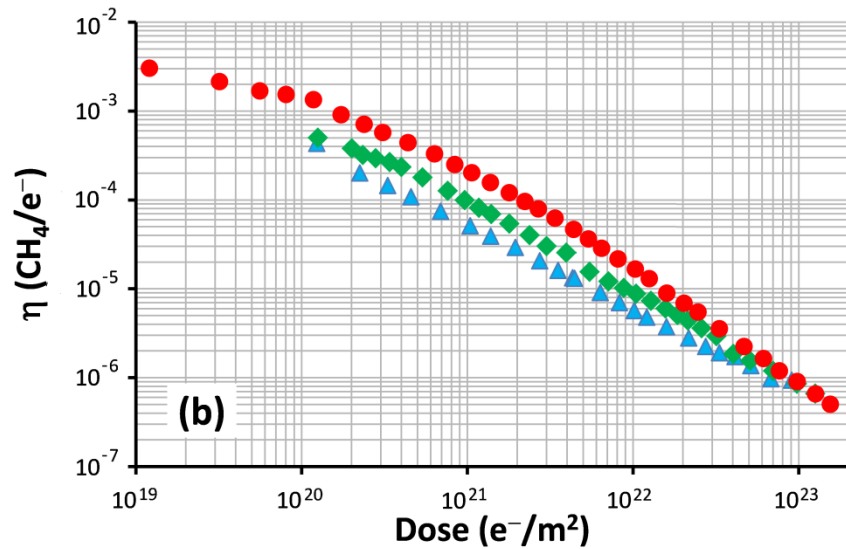
ESD from polished and vacuum fired tubes

316LN stainless steel baked at 250 °C for 24 h

O.B. Malyshev *et al*, J. Vac. Sci. Technol. **A 32** (2014) 051601.

S1 – non-polished S3VF – non-polished and vacuum fired

S3 – polished S3VF – polished and vacuum fired

O.E
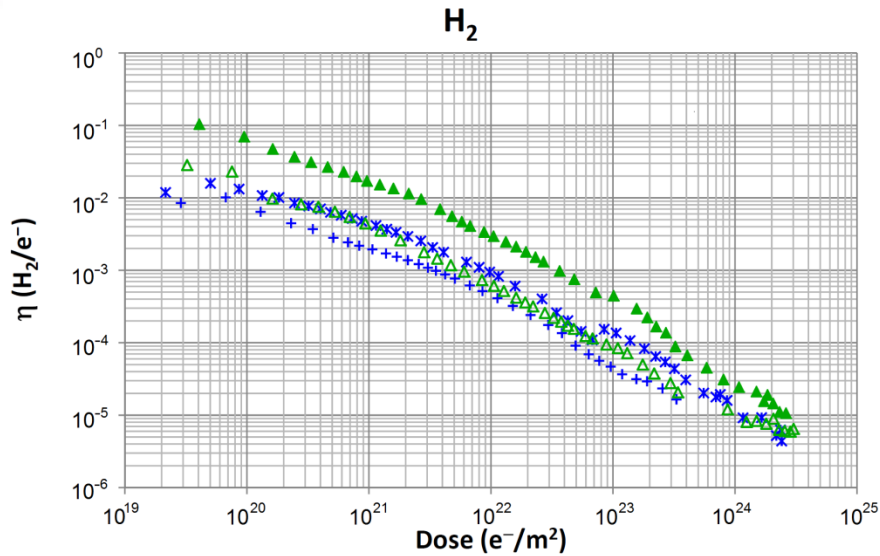
ESD as a function of amount of desorbed gas

316LN stainless steel baked at 250 °C for 24 h

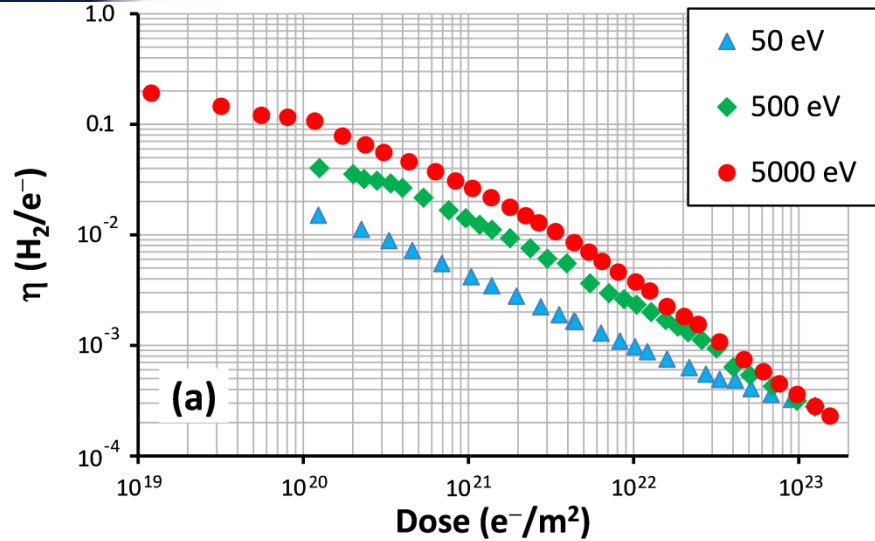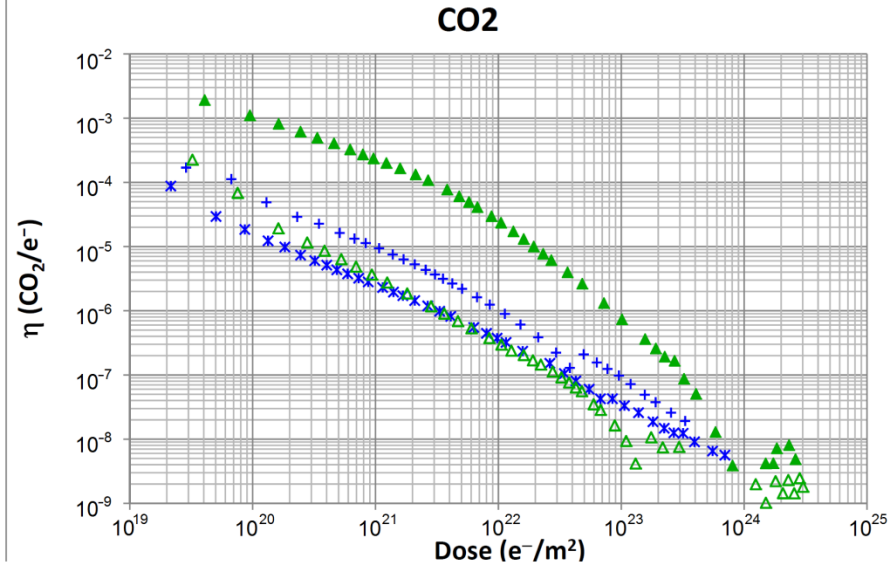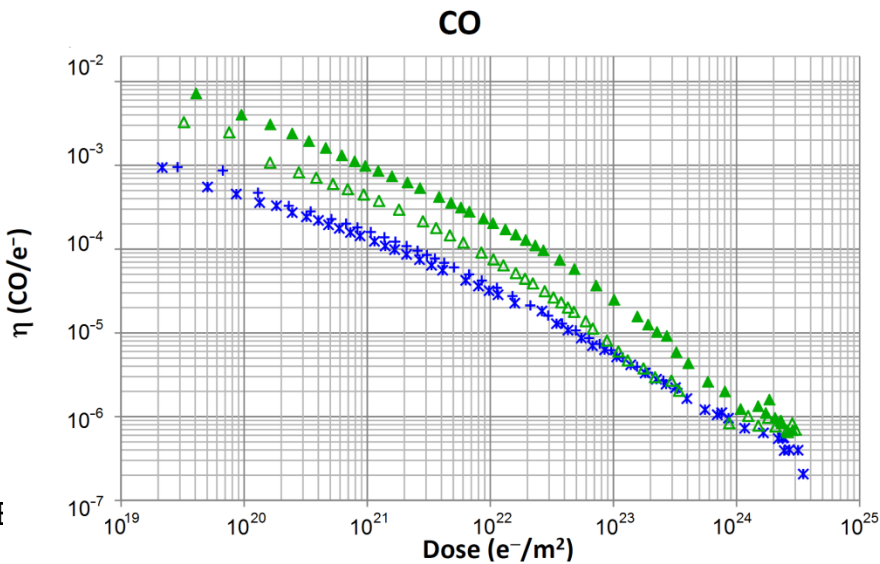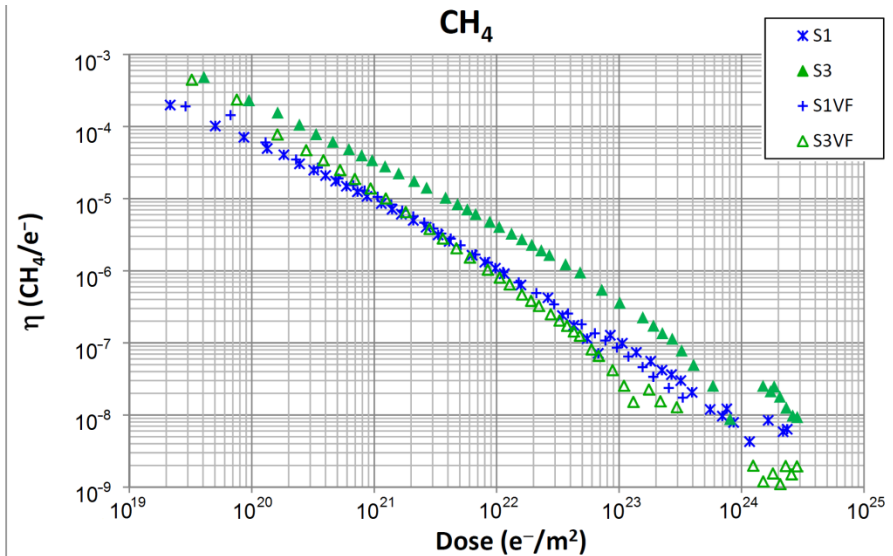O.B. Malyshev *et al*, J. Vac. Sci. Technol. **A 32** (2014) 051601.

S1 – non-polished   S3VF – non-polished and vacuum fired

S3 – polished   S3VF – polished and vacuum fired
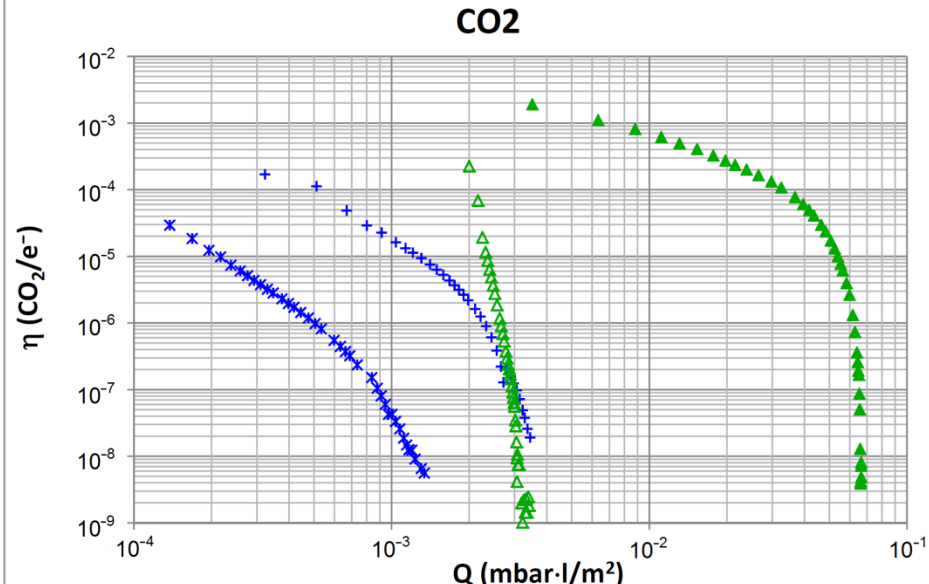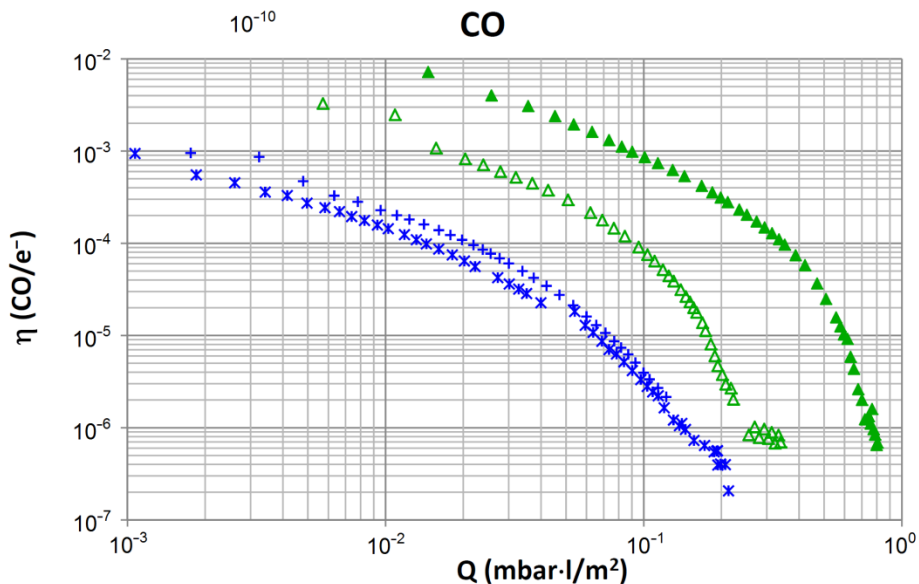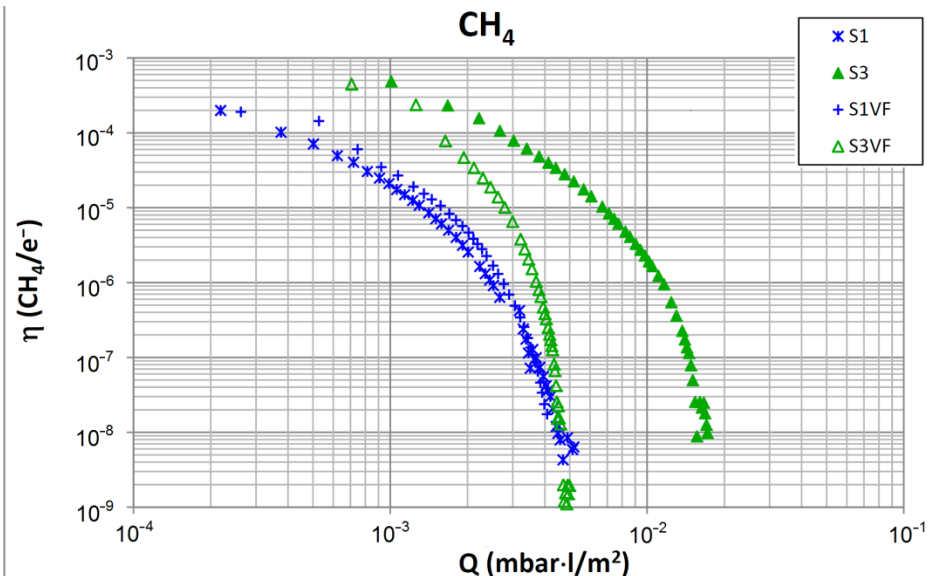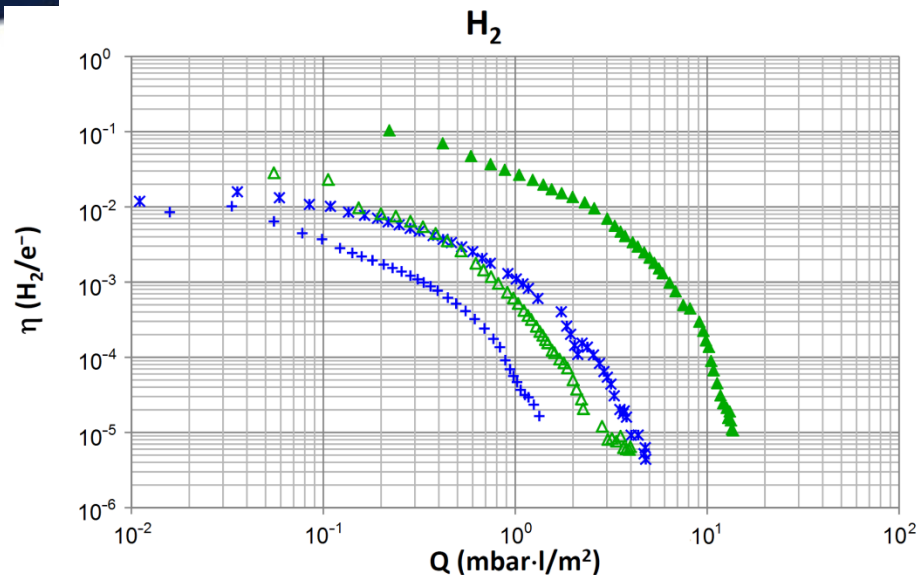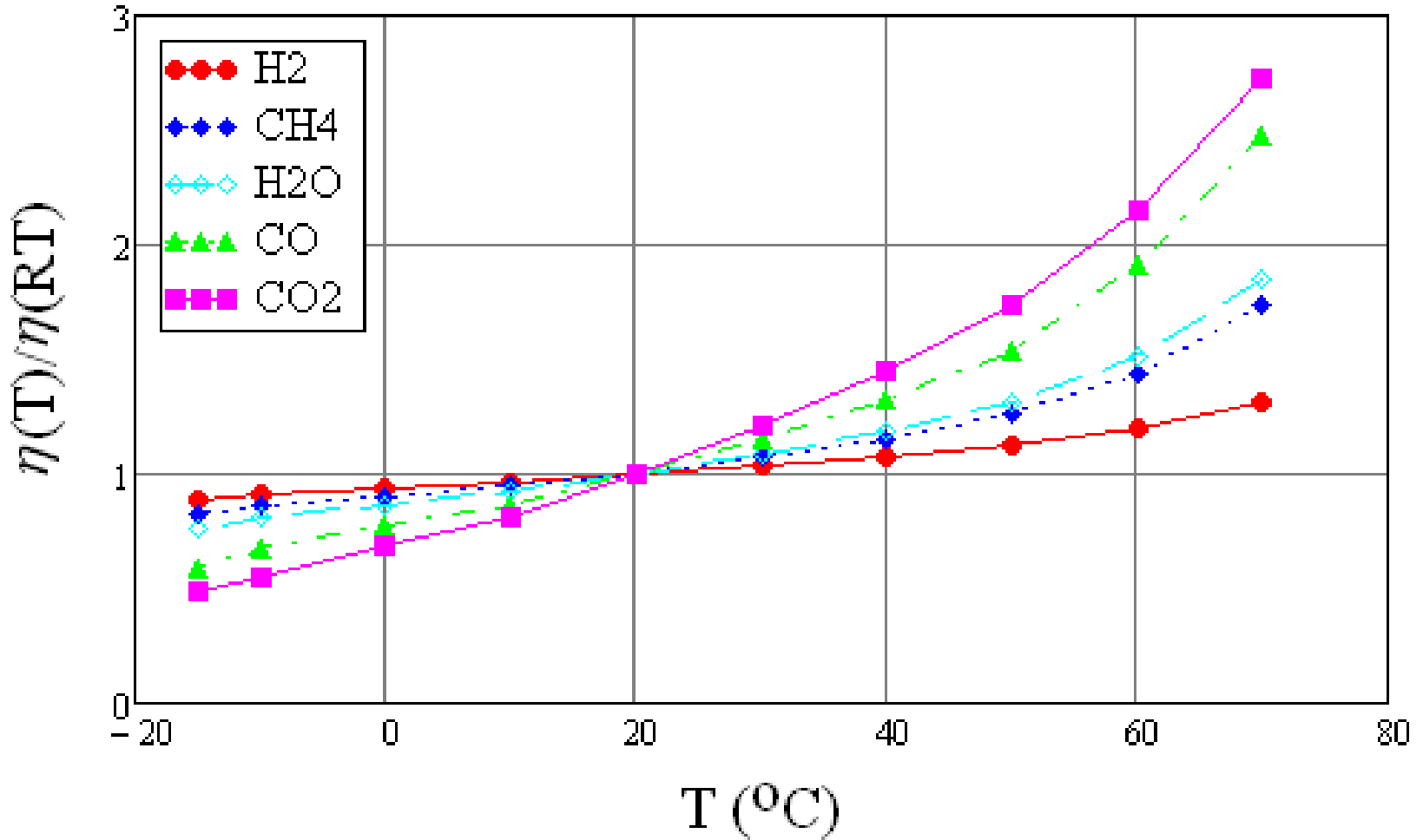
O.B. Malyshev, C Naran. Vacuum 86 (2012) 1363.

Ion stimulated desorption (ISD)

When the **positive charged beam particles** colliding with residual gas molecules ionise them, these ions are accelerated towards the vacuum chamber wall. This causes ion induced gas desorption, the pressure rises and more molecules will be ionised, accelerated and bombard the wall…

$$n = \frac{Q}{S_{eff} - \chi \frac{\sigma I}{e}} = \frac{Q}{\chi \frac{\sigma}{e}(I_c - I)} \qquad I_c = \frac{S_{eff}\, e}{\chi \sigma}$$

where

Q = gas desorption,
S_{eff} = effective pumping speed,
χ = ion induced desorption yield
σ = ionisation cross section,
I = beam current.
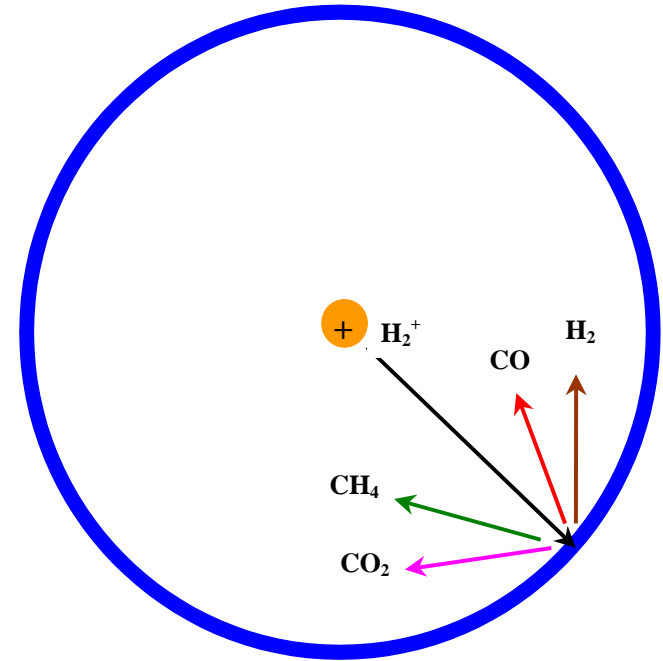
When $I \to I_c$ (or $S_{eff} \le \chi \dfrac{\sigma I}{e}$)

then gas density (pressure) increases dramatically!

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, χ **(molecules/ion),** :

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

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

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

(a)

(b)

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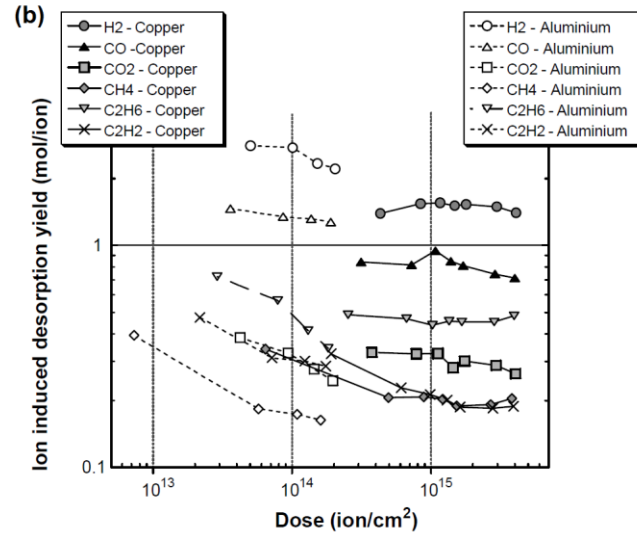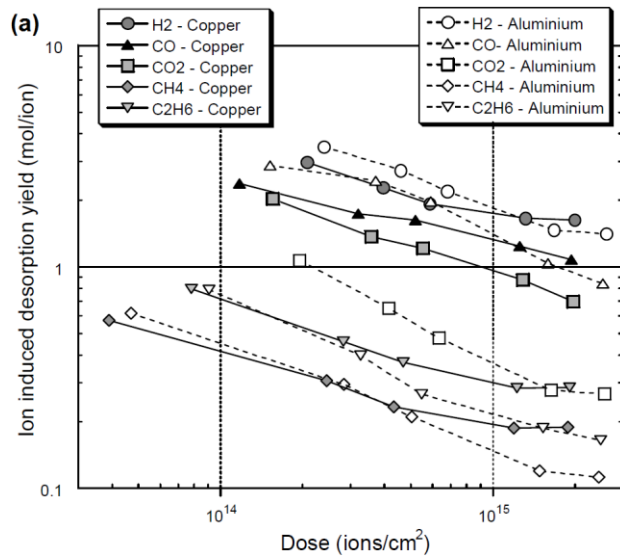
ISD yield as function of accumulated ion dose can be described as:

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

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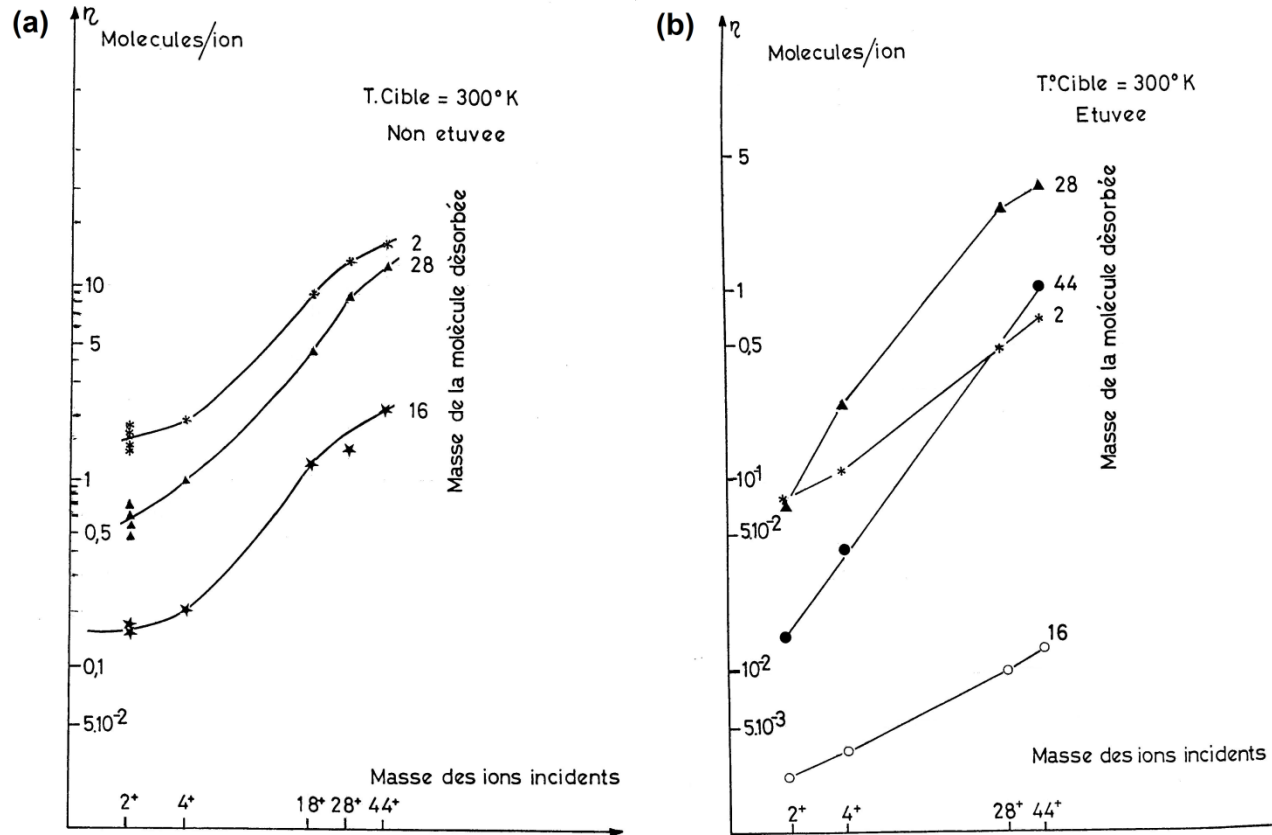
N. Hilleret. Influence de la nature des ions incidents sur les taux de desorption par bombardement ionique de molécules adsorbées sur une surface d'acier inoxydable. CERN-ISR-VA/78-10 (1978).

Heavy ion stimulated desorption (HISD)

Heavy Ion Induced Pressure Instability

The ***heavy ion beam particles*** colliding with residual gas molecules may lose or trap an electron and be ***lost*** in 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…

|<-Dipole-> | < -------------------- --- Straight   --------------------------- >

HISD
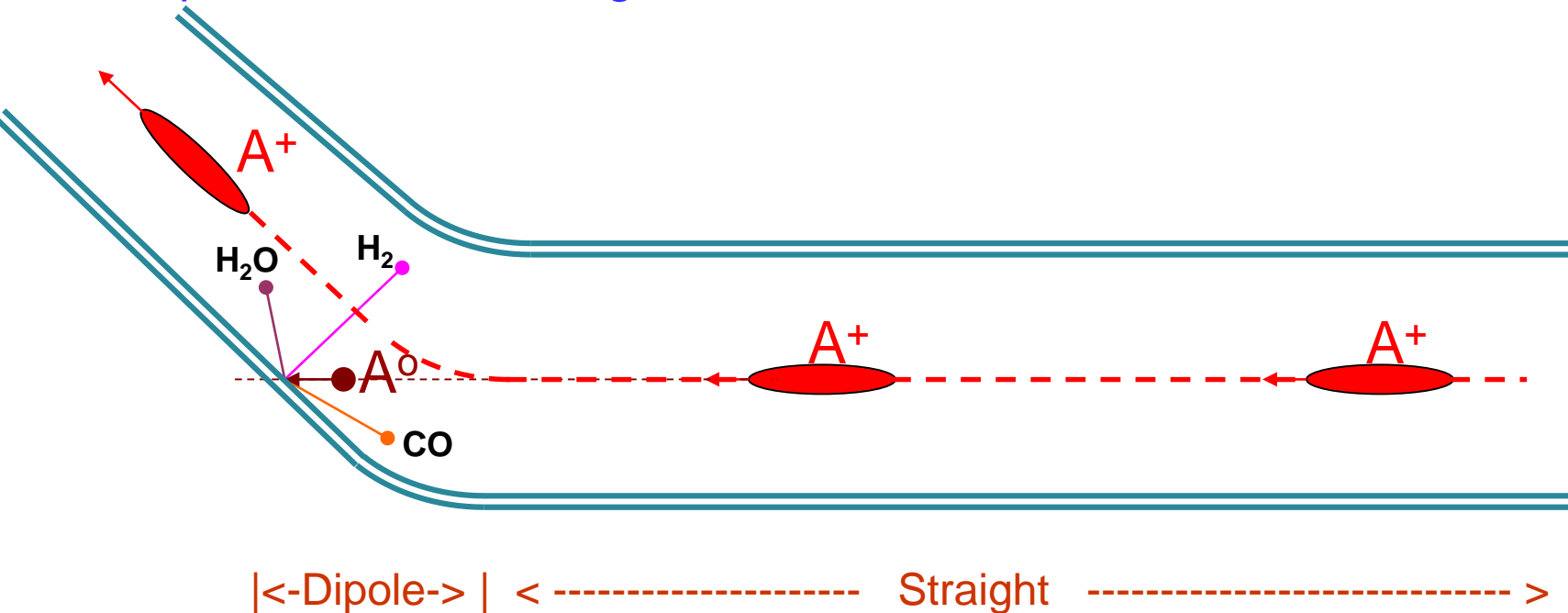
Heavy ion stimulated desorption (ISD) is a key parameter to model pressure instability in high intensity ion machines like FAIR at GSI, LURE at CERN, RHIC at BNL. It can be a significant source of gas in a vacuum system where the ion beam bombards the surface.

There is very little data, most work has been done at GSI and CERN.

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

It is also depends on:

- **Mass, charge and energy of heavy ions impacting the surface**
- **Ion flux to the surface**
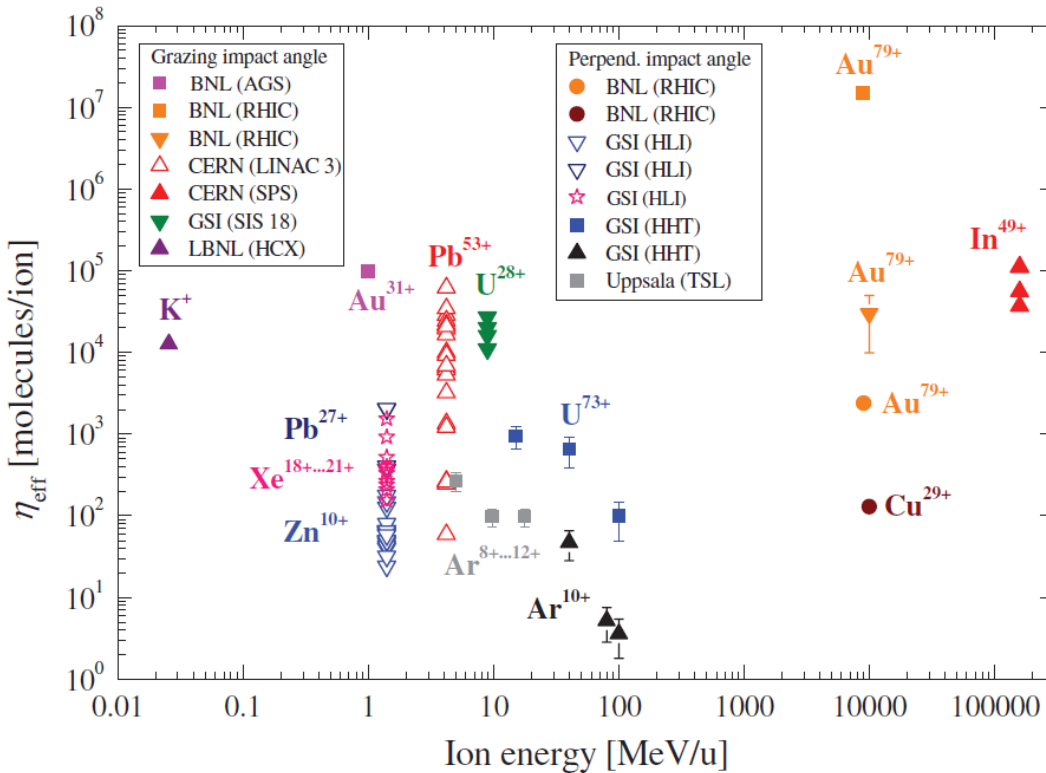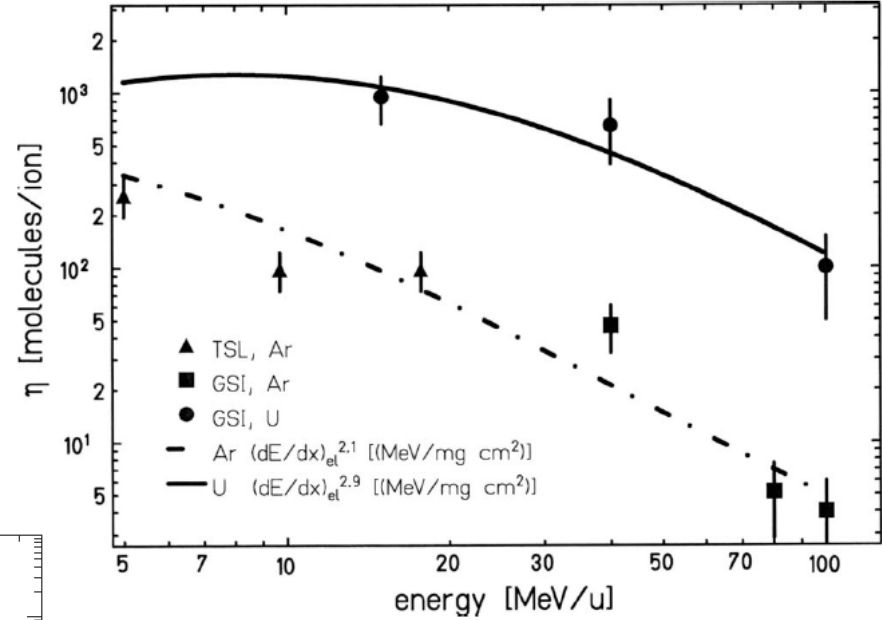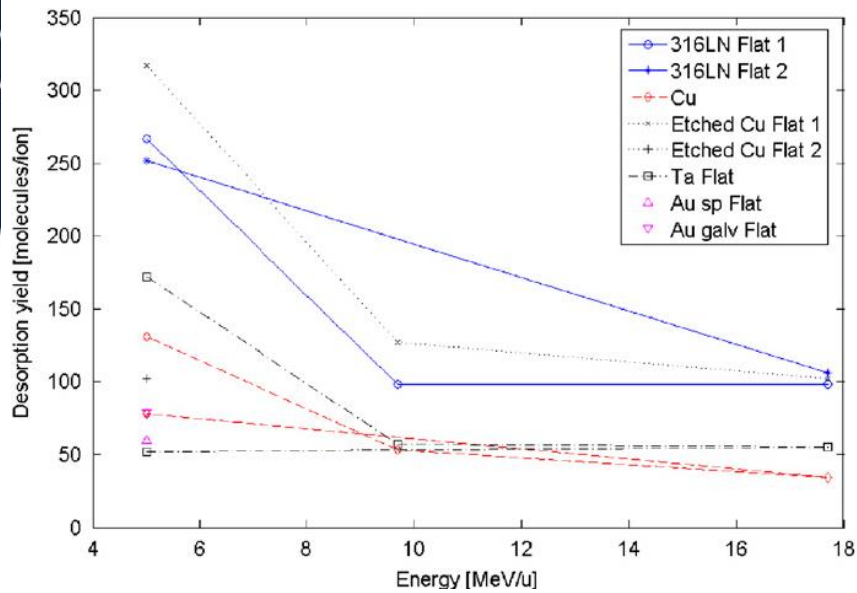
- E. Hedlund et al. NIM A 599 (2009) 1–8.
- H. Kollmus, et al., J. Vac. Sci. Technol. A 27 (2009) 245-247.
- E. Mahner. Phys. Rev. ST Accel. Beams 11, 104801 (2008)

NEG coated vacuum chamber

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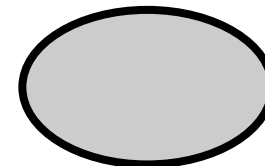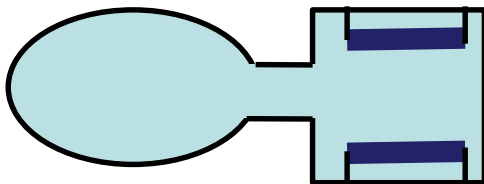
'New' (C. Benvenuti, CERN, ~1998):

- 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

columnar
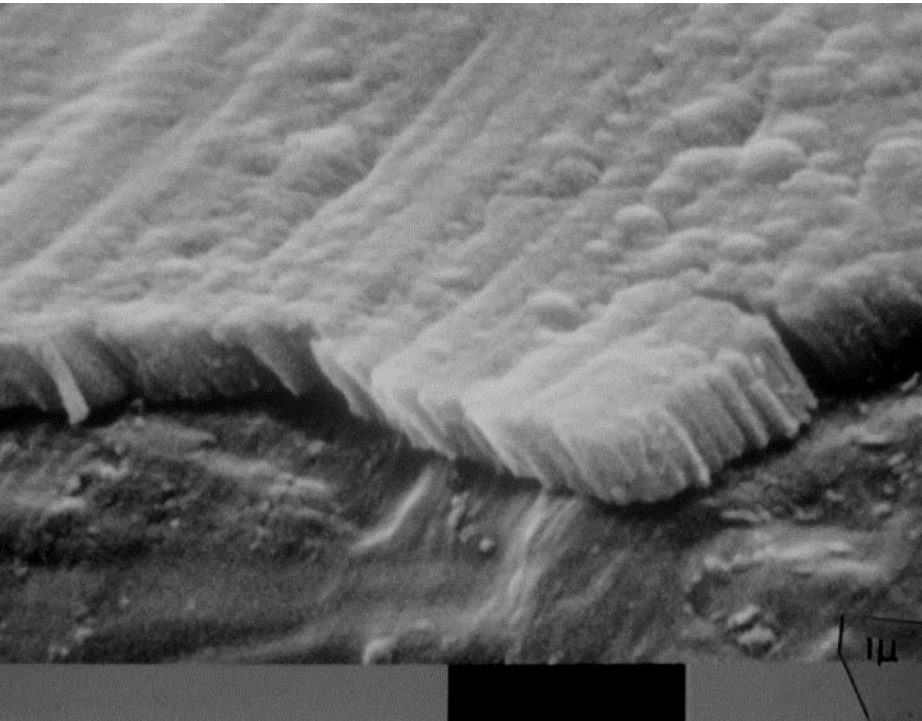
dense
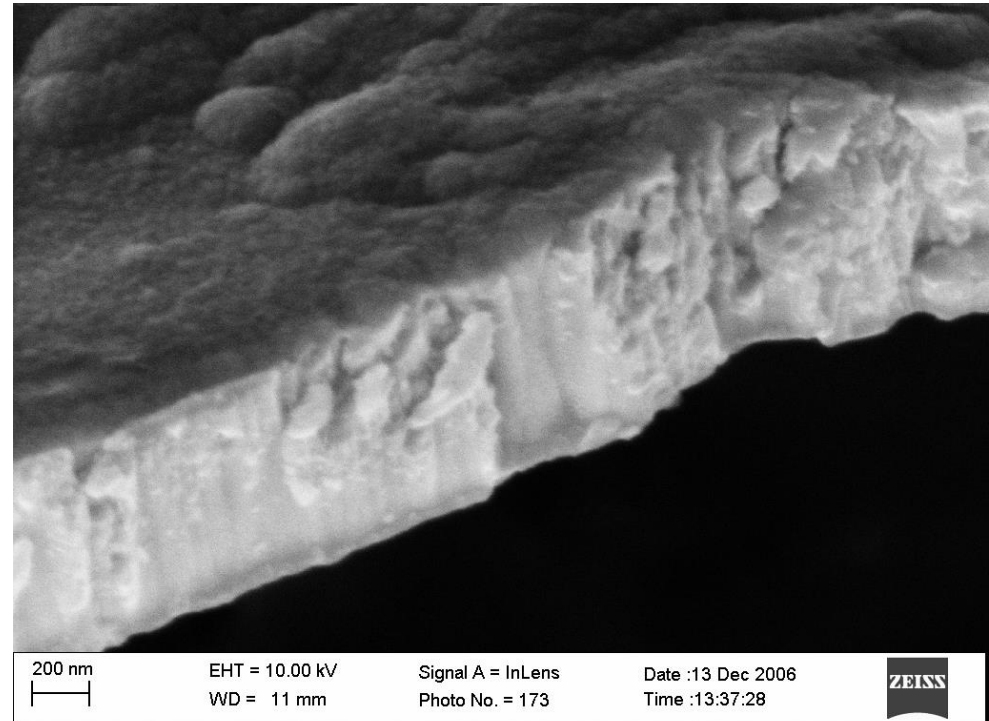
O.B. Malyshev, R. Valizadeh, J.S. Colligon _et al_. J. Vac. Sci. Technol. A 27 (2009), p. 521.

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   **α – sticking probability,**

        A – surface area,

        v – mean molecular velocity

Vacuum   NEG Coating   Bulk
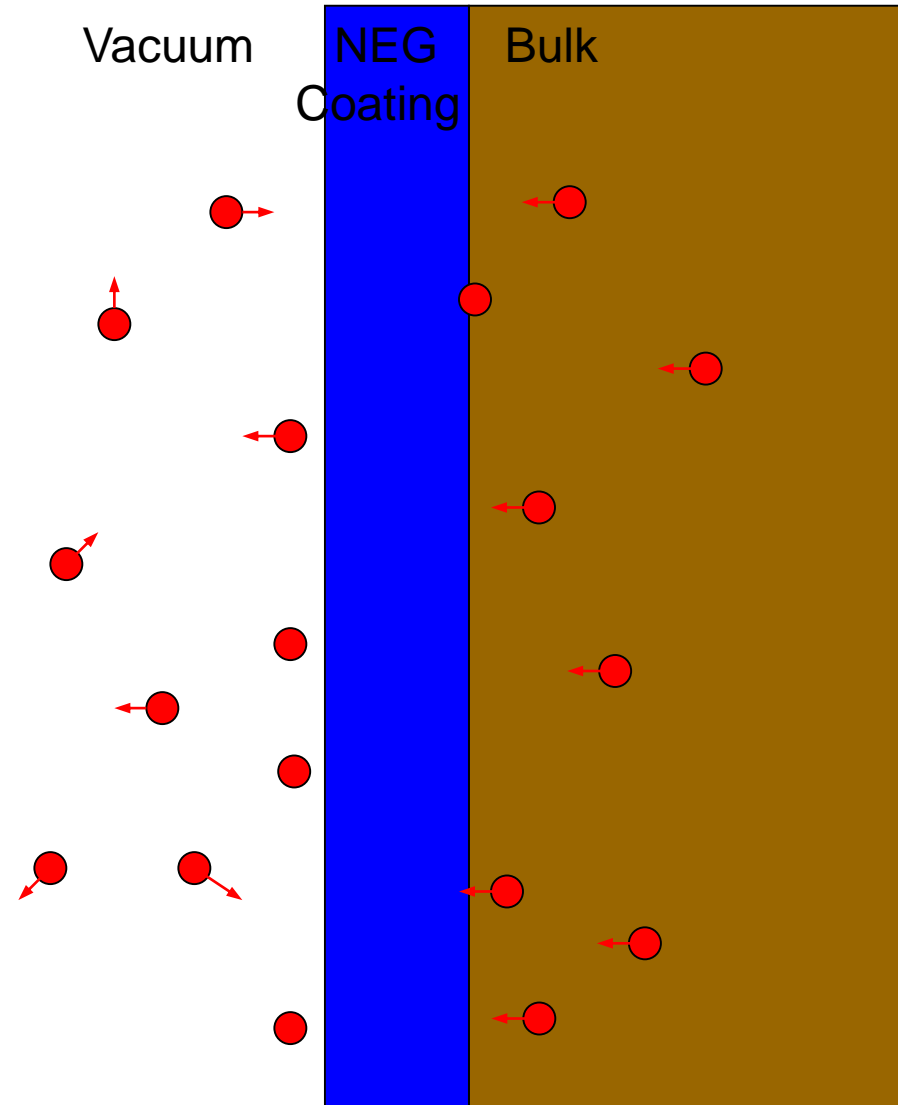
First experiments with NEG coating: Conductance method

- Samples coated with Ti-Zr-V at CERN (Switzerland)
- Experiments on a SR beamline at ESRF (France)

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)
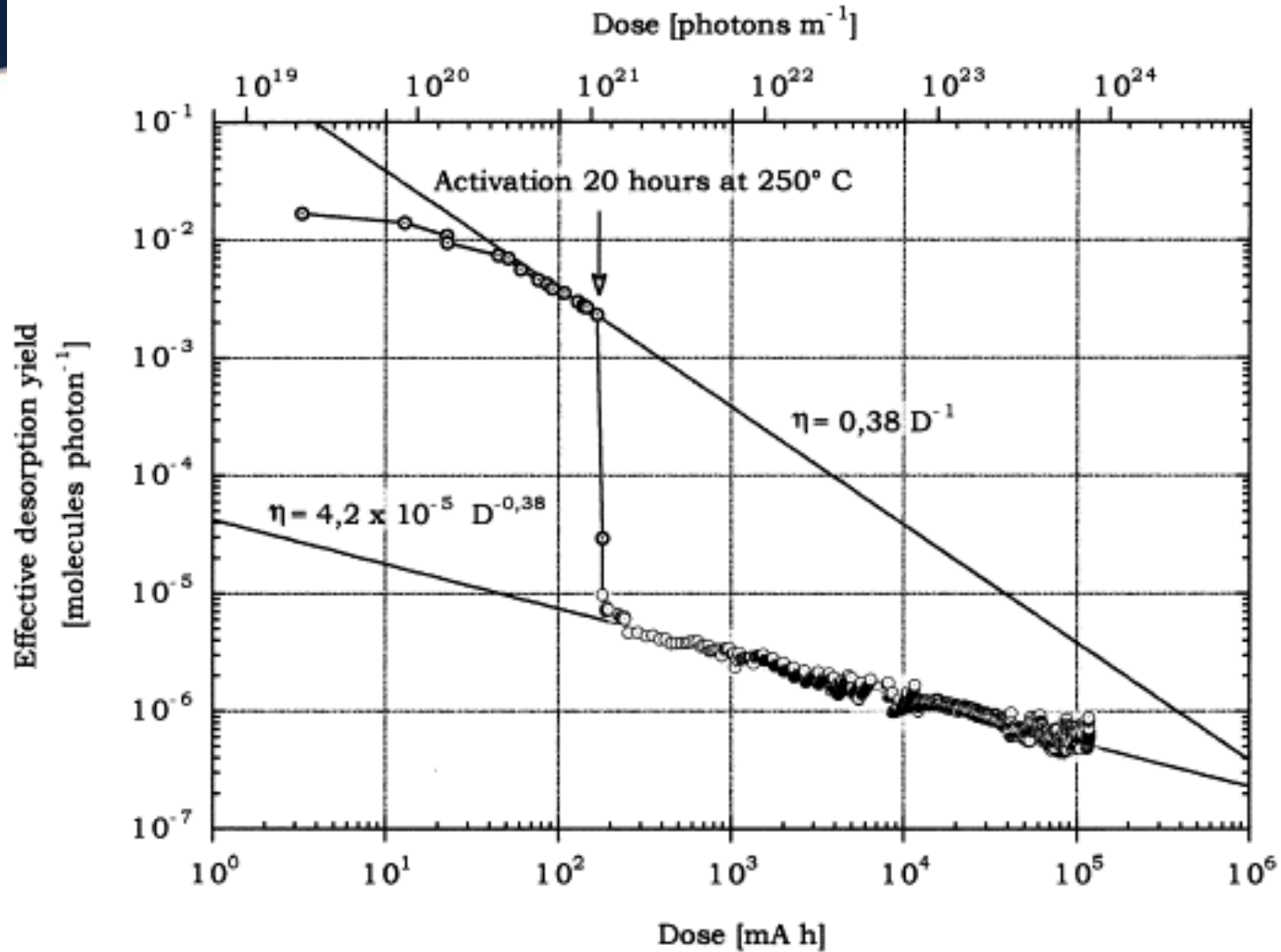
P. Chiggiato, R. Kersevan, Vacuum 60 (2001) 67.
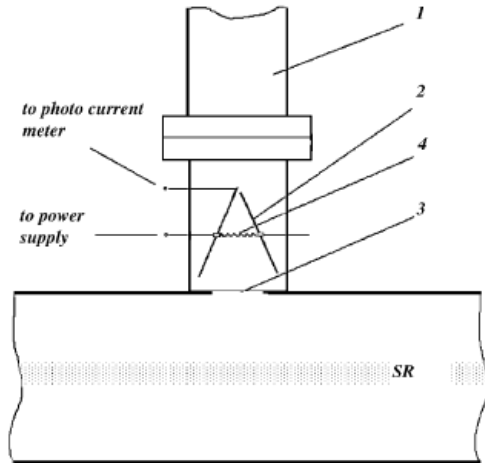
Fig. 2. The cone baffle inside the central RGA port.

- Samples coated with Ti-Zr-V at CERN (Switzerland)

- Experiments on a SR beamline at BINP (Russia)

O.B. Malyshev

Stainless steel and **TiZrV** plots of delta P (Pa) versus Dose (photons/m)

Legend (Stainless steel):
- M2 : H2
- M15: CH4
- M28: CO
- M44: CO2

Legend (TiZrV):
- M2 : H2
- M15: CH4
- M28: CO + CxHy

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)
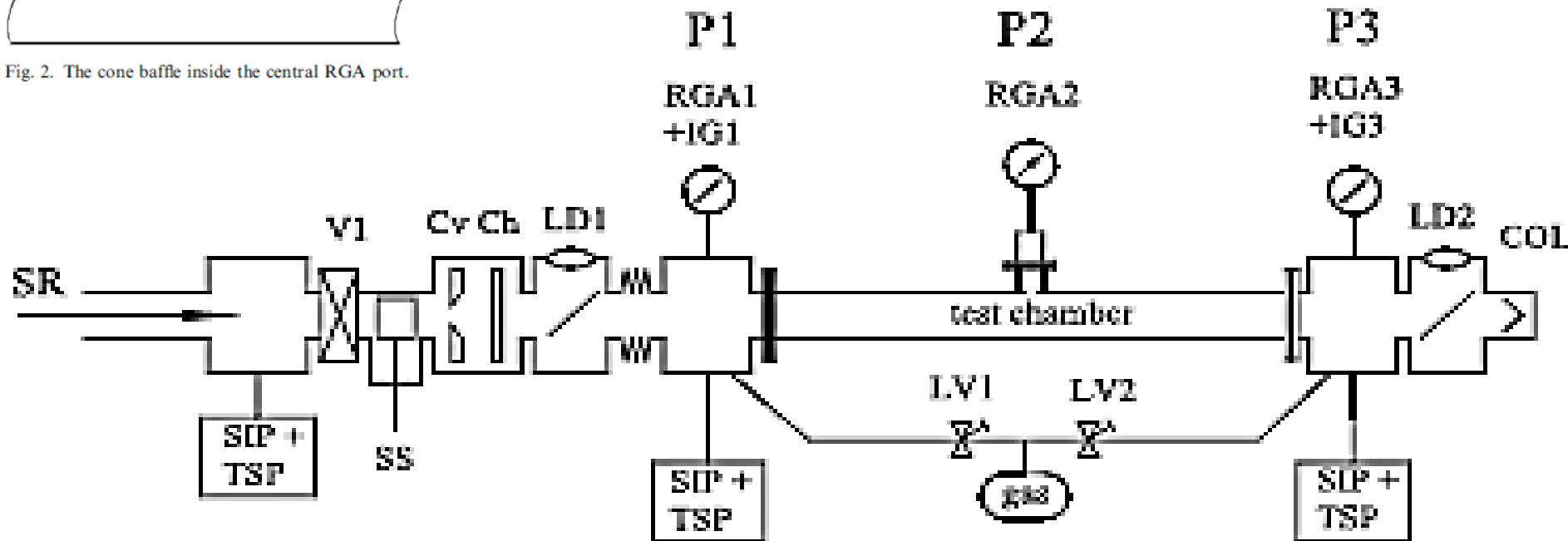
Comparison of PSD from 316LN and NEG coated vacuum chamber under SR

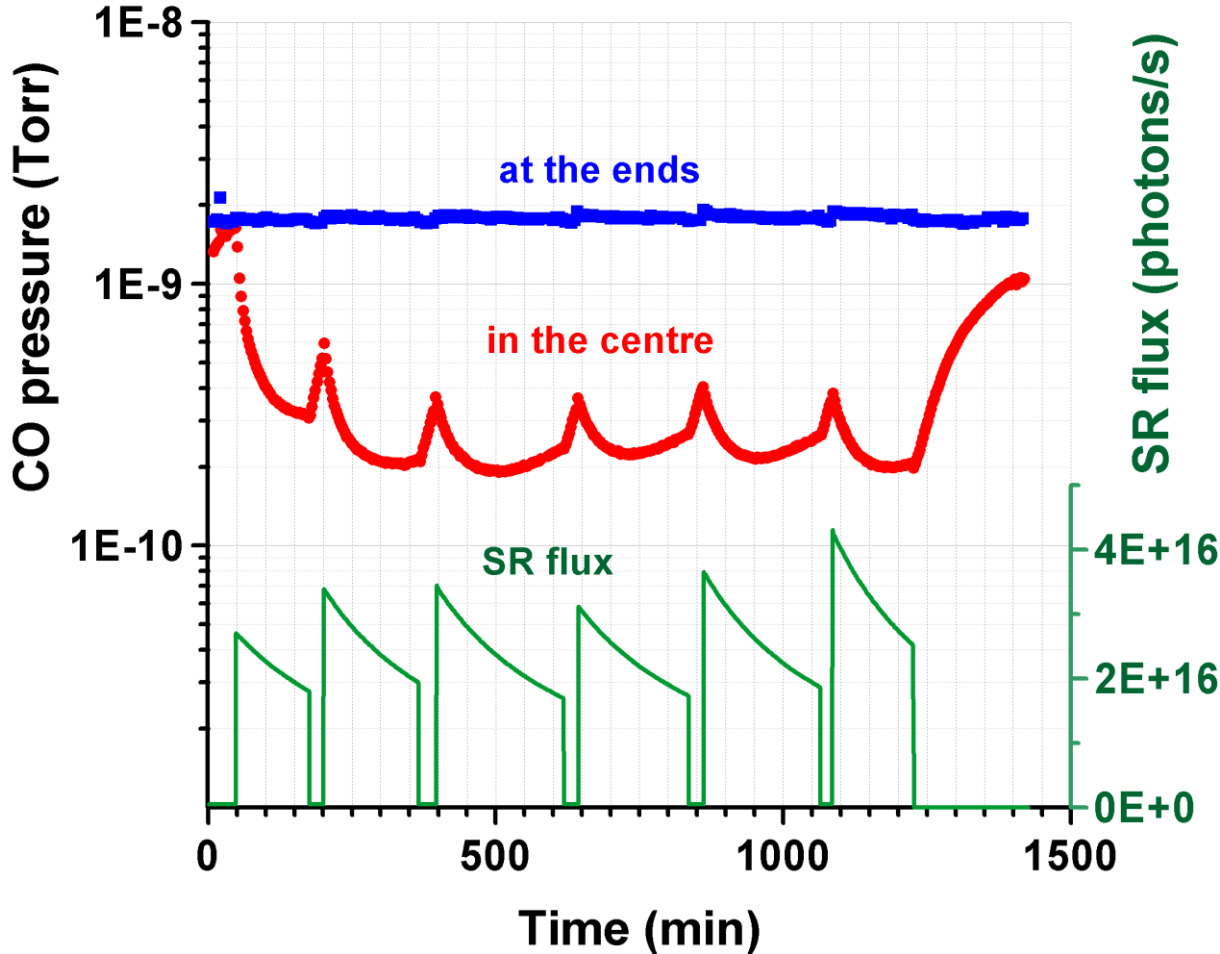| Gas	α	ΔP, [Torr]	η, [molecules/photon]	α	ΔP, [Torr]	η, [molecules/photon]
	NEG TiZrV coated vacuum chamber					
	Before activation			After activation at 190°C for 24 hrs		
H_2	0	$4 \cdot 10^{-8}$	$1 \cdot 10^{-3}$	0.007	$5 \cdot 10^{-11}$	$1.5 \cdot 10^{-5}$
CH_4	0	$2.5 \cdot 10^{-8}$	$2.5 \cdot 10^{-4}$	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	–	$1 \cdot 10^{-8}$	$7 \cdot 10^{-5}$	–	$2 \cdot 10^{-9}$	$1.5 \cdot 10^{-5}$

V.V. Anashin et al. Vacuum 75 (2004), p. 155.

CAS on Vacuum for Particle Accelerators 2017
6-16 June, 2017, Glumslöv, Sweden

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

The photon stimulated NEG activation efficiency estimated as

$\sigma_\gamma = 2 \times 10^{-5}$ [CO/γ]

V.V. Anashin et al. Vacuum 75 (2004), p. 155.

NEG coating in accelerators

- First used in the ESRF (France);
- ELETTRA (Italy);
- Diamond LS (UK);
- Soleil (France) – first fully NEG coated;
- LHC (Switzerland) – longest NEG coated vacuum chamber;
- SIS-18 (Germany); MAX-IV (Sweden)
- and many others.

Meanwhile:

- NEG film capacity for CO and CO_2 is ~1 ML:
  - If P = 10^{-9} mbar then 1 ML can be sorbed just in ~10^3 s;
  - Lab measurements of different NEG coatings often don't repeat CERN's data on sticking probability and capacity;
  - **However, NEG coated parts of accelerators work well.**

What is required:

- Input data for accelerator design:
  - $\eta(D,E,T_a)$, $\alpha(M,T_a)$, pumping capacity;
- Better understanding:
  - what and why;
  - practical 'do's and 'don't's;
- Further development of this coating:
  - lower η, T_a, SEY;
  - higher $\alpha(M)$, pumping capacity;
  - optimising for an application.

NEG coating activation procedure
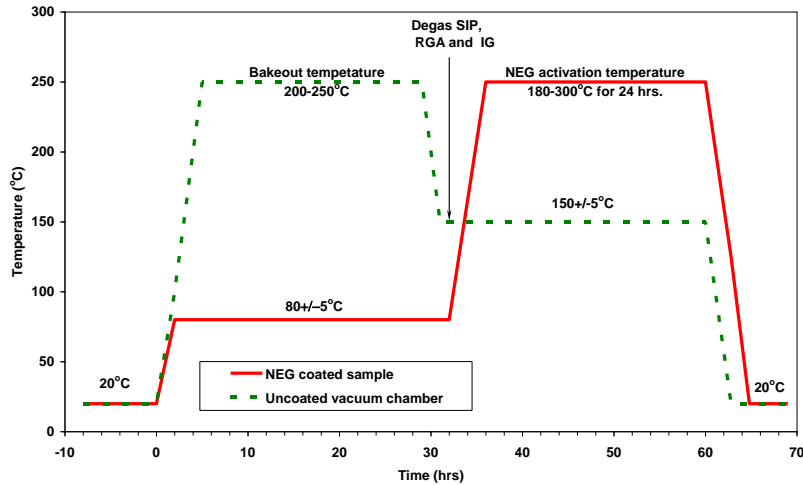
Original procedure

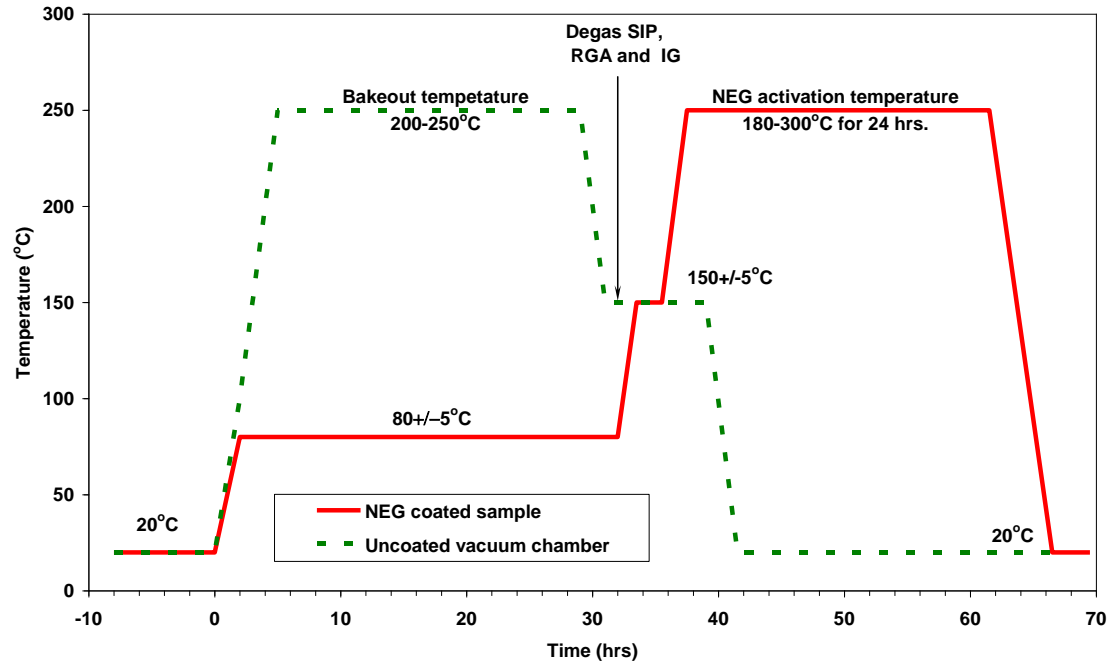ASTeC procedure

O.B. Malyshev et al,
J. Vac. Sci. Technol. 27
(2009) 321-327.

ASTeC's NEG coating activation procedure results in a better NEG activation (higher α and pumping capacity) because less gas from uncoated parts is poisoning NEG during the activation

Reducing activation temperature: Twisted wires vs. alloy target
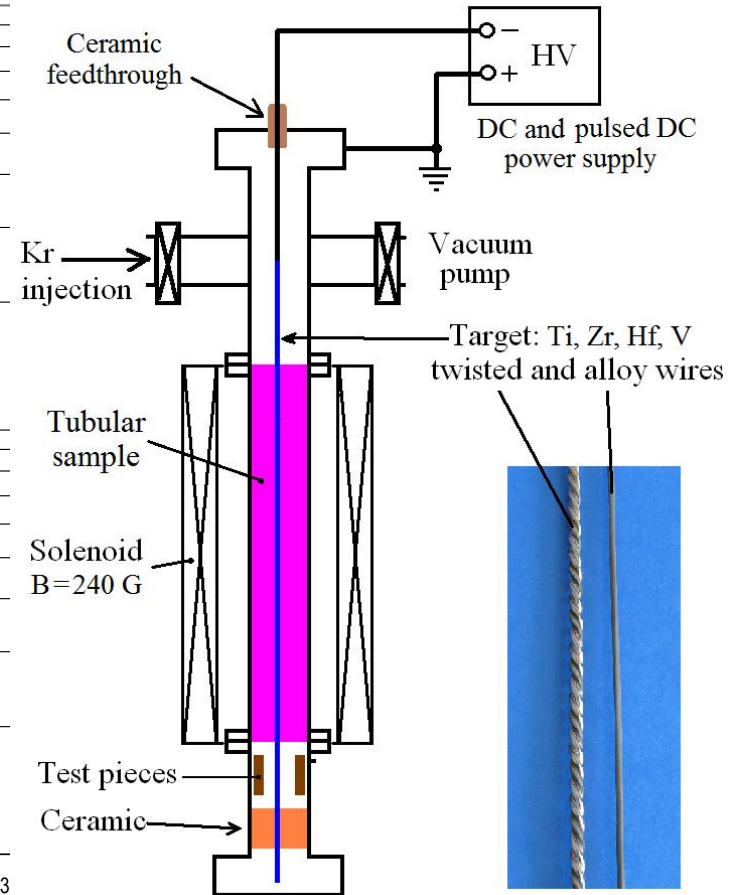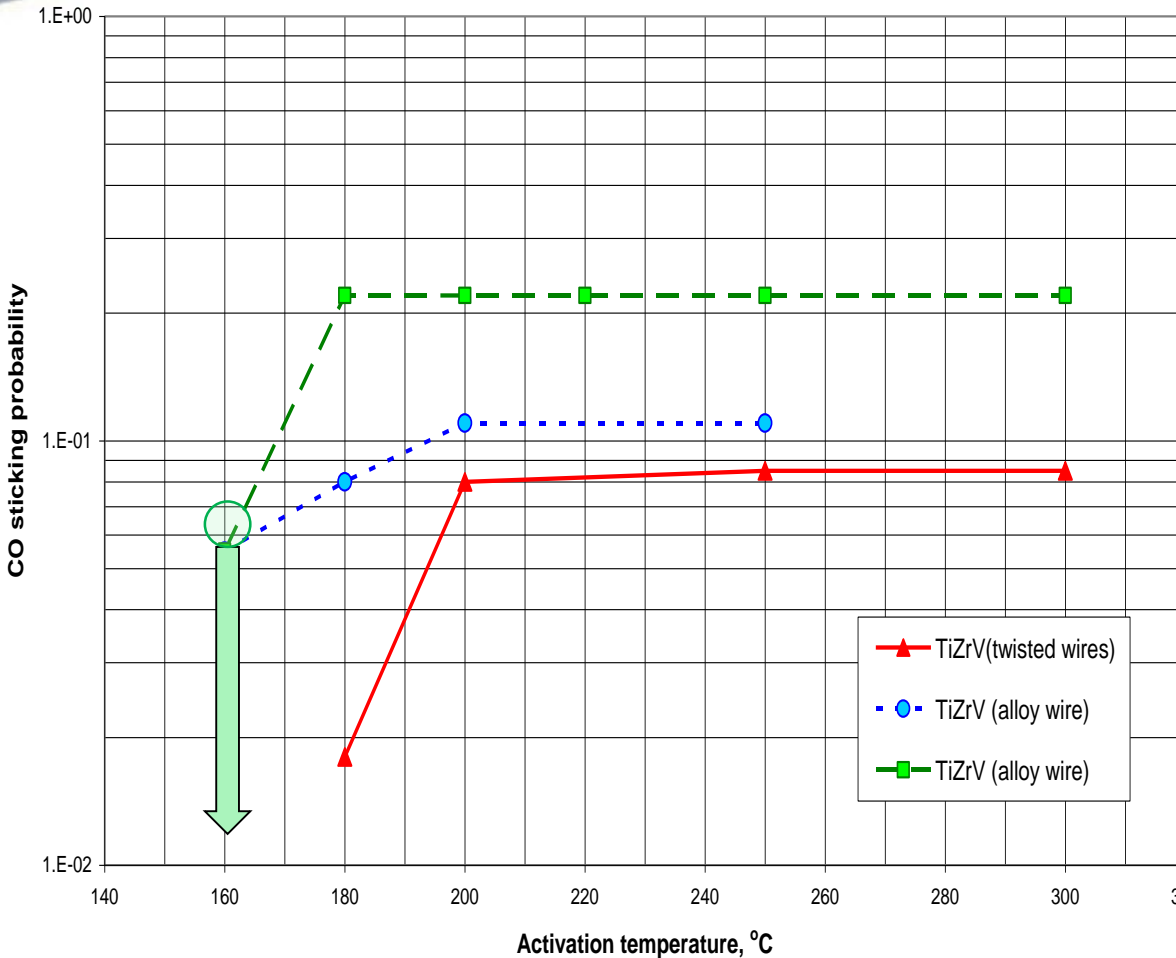
R. Valizadeh et al, J. Vac. Sci. Technol. 28 (2010) 1404-1412.

Reducing activation temperature: ternary vs quaternary target
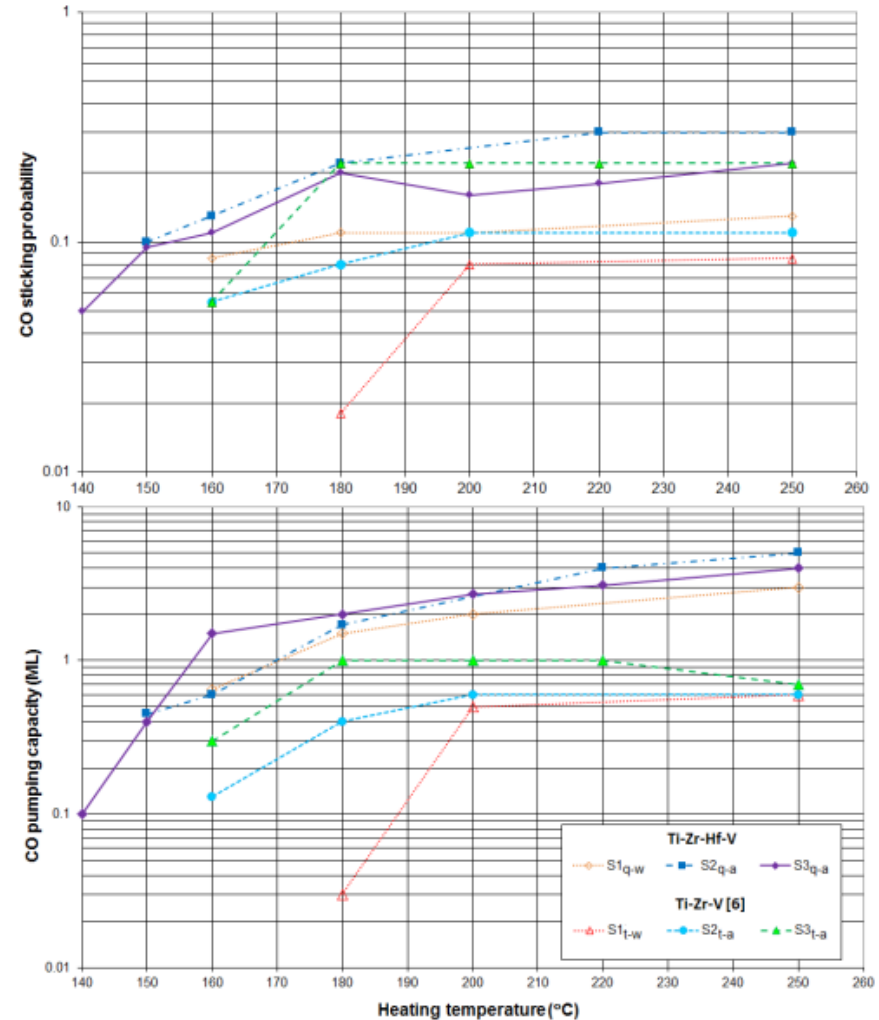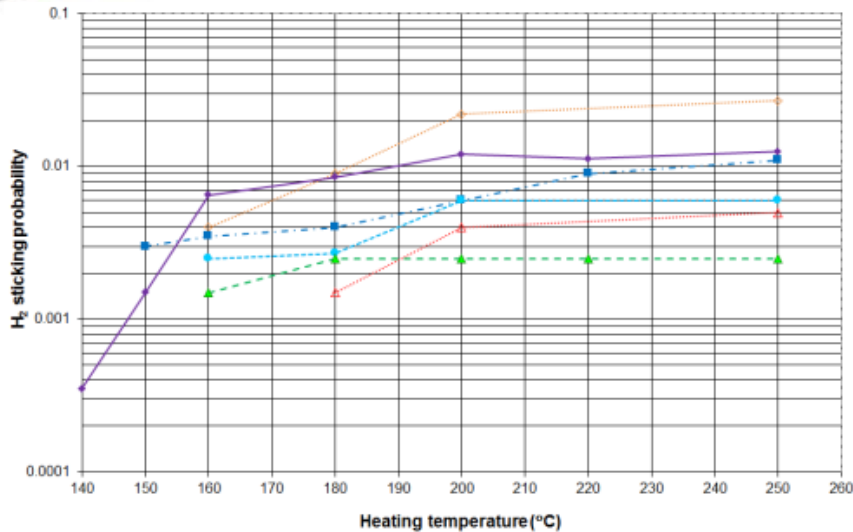
O.B. Malyshev et al, Vacuum 100 (2010) 26-28.

Pressure in the accelerator vacuum chamber

$$P \propto \frac{\eta}{\alpha}$$

where

η - desorption yield

α - sticking probability

- Improving pumping properties is limited:

$$\alpha \le 1$$

$$0.005 < \alpha_{H2} < 0.01$$
$$0.1 < \alpha_{CO} < 0.5$$
$$0.4 < \alpha_{CO2} < 0.6$$

- Reducing the desorption yields η <u>in orders of magnitude</u> is a realistic task

ESD yield from NEG coated samples
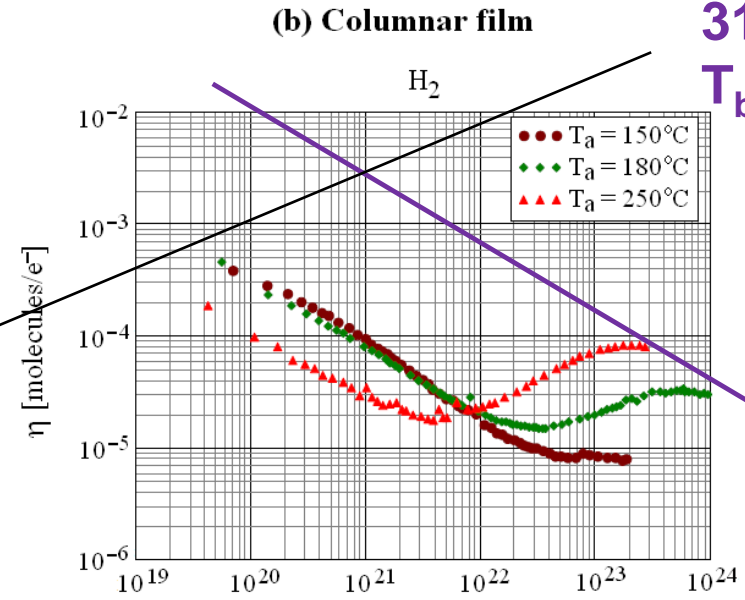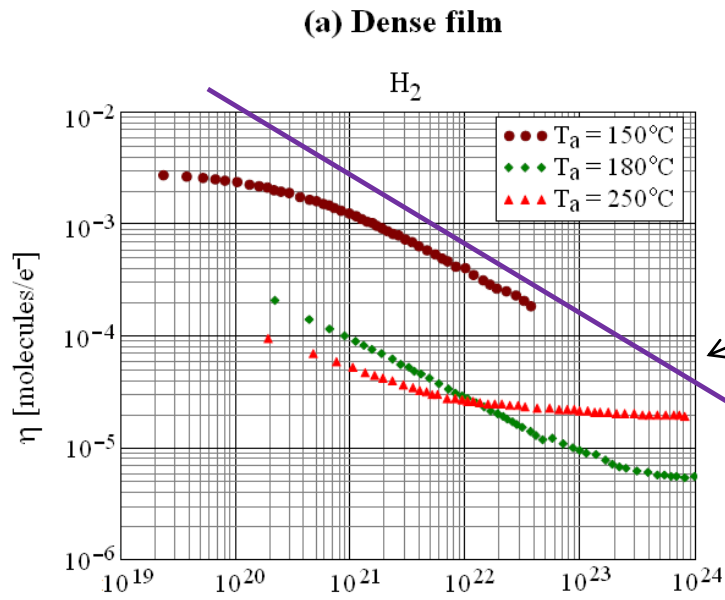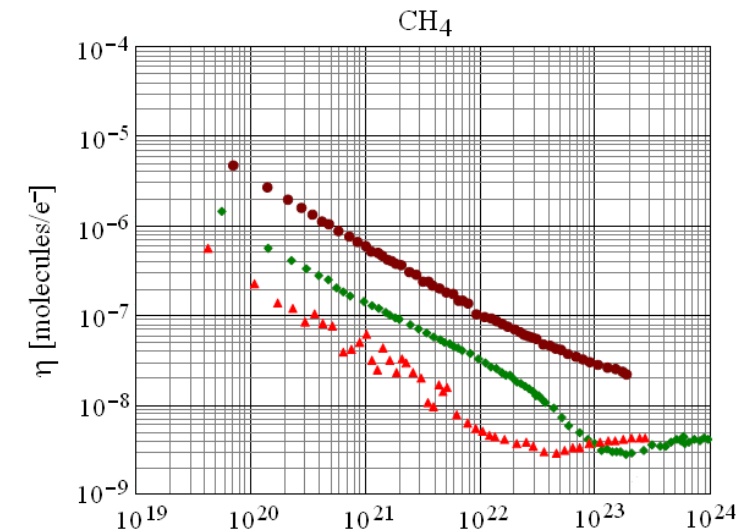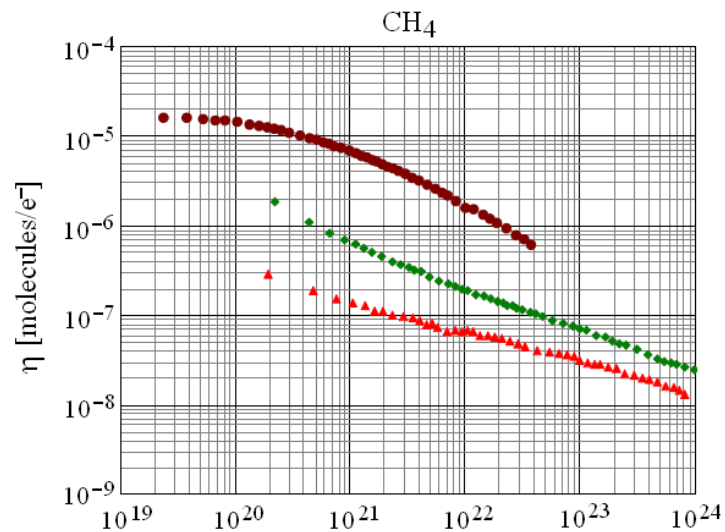
H2 ESD from NEG coated vacuum fired 316LN

(a) Columnar film

(b) Dense film

Vacuum fired
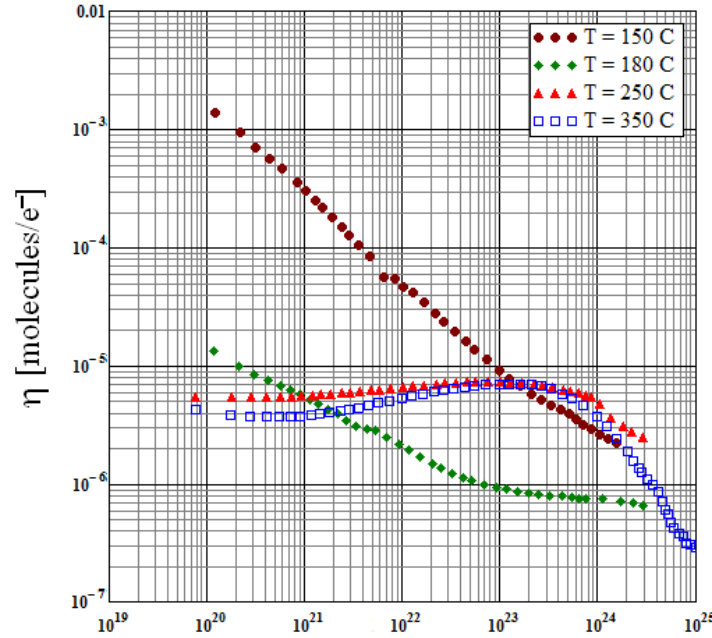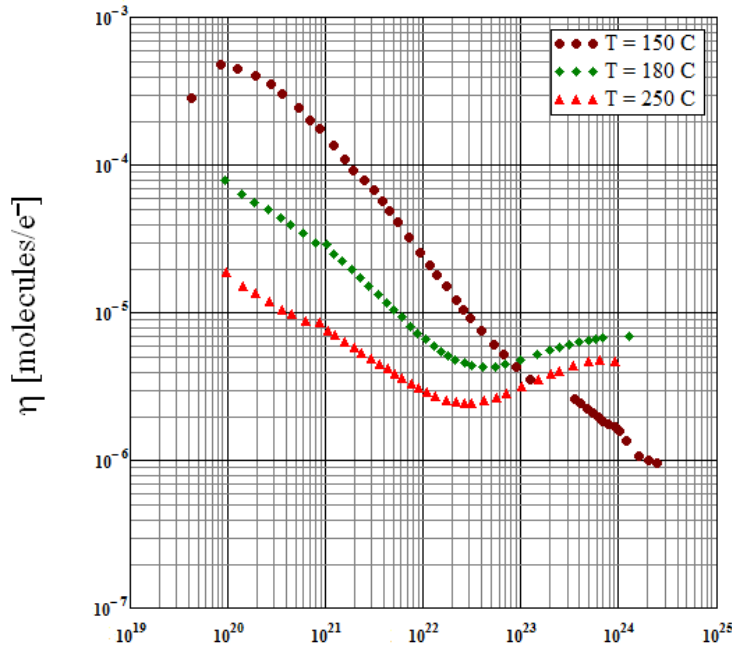
No vacuum firing

O.B. Malyshev et al,
J. Vac. Sci. Technol. **32**
(2014) 061601.
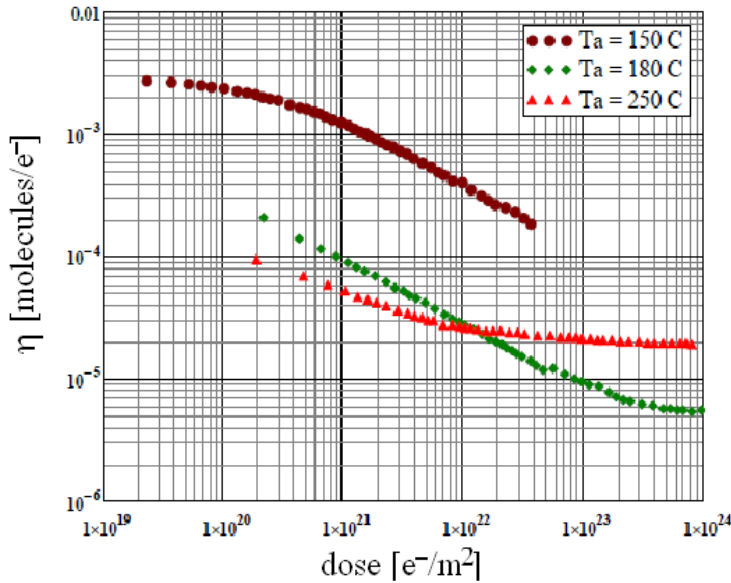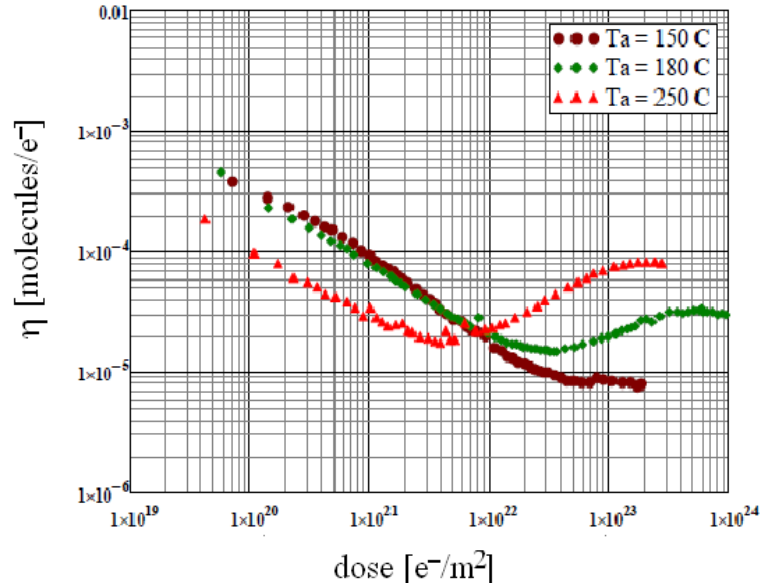
O.B. Malyshev et al,
Vacuum **86** (2012)
2039-2039.

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$\eta(E_{e-})$ for different gases for NEG coating
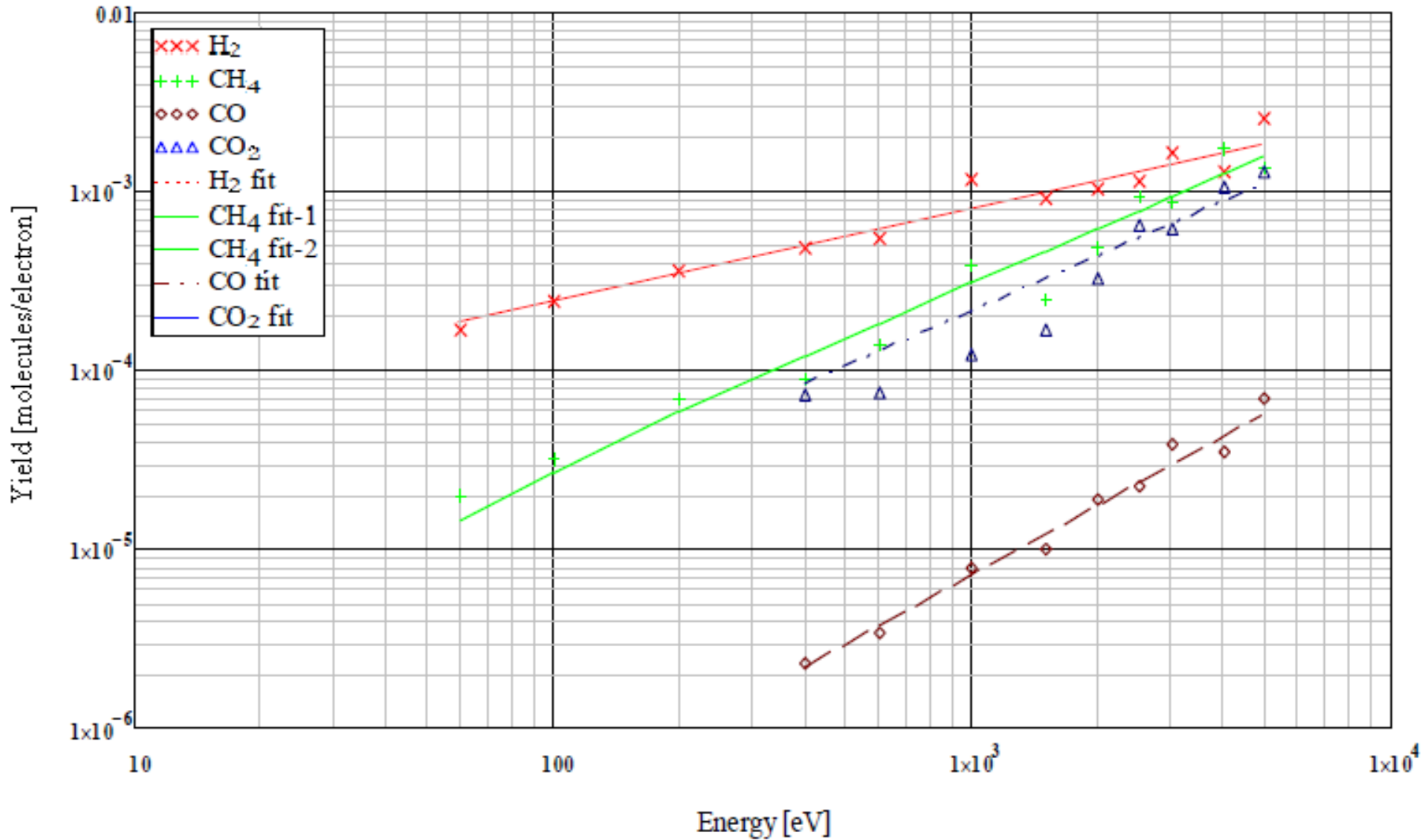
Cryogenic beam vacuum chamber

A and B are vacuum chamber without a liser

SR

SR
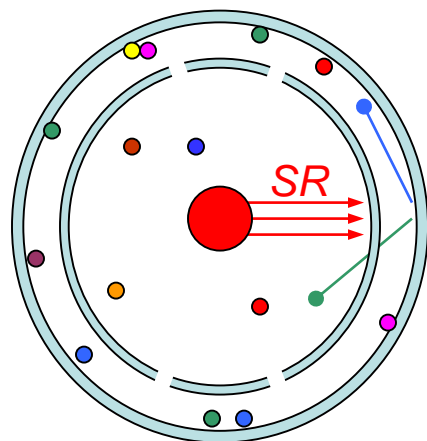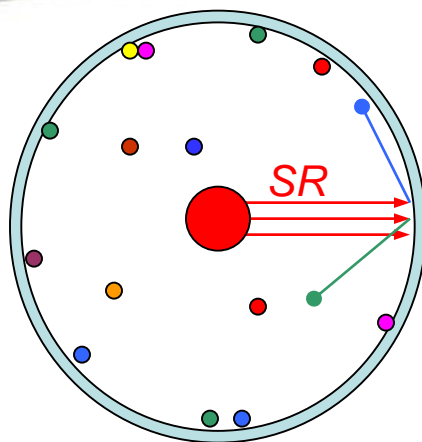
- C and D are experiments with a liner with pumping holes

- E is the beam lifetime limit
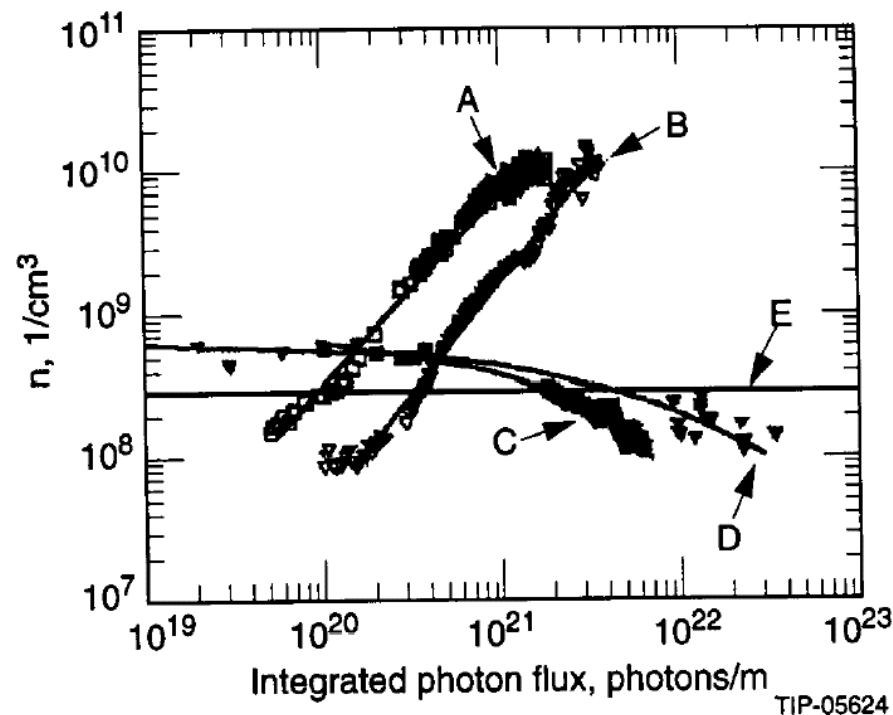
Figure 2. Dynamic H_2 density measured at the center of the beam tube with and without liner. The density is normalized to $1 \cdot 10^{16}$ photons/m/s.

V. Anashin et al. SSCL-Preprint-517 Rev.2, Apr 1994.
V. Anashin et al. JVST A12 (1994), p. 2917.

☞ *Low temperature does not necessary provides good vacuum in a vacuum chamber!*

Primary photodesorption

Secondary photodesorption: recycling and cracking

Photodesorption yield at 77 K as a function of photon dose
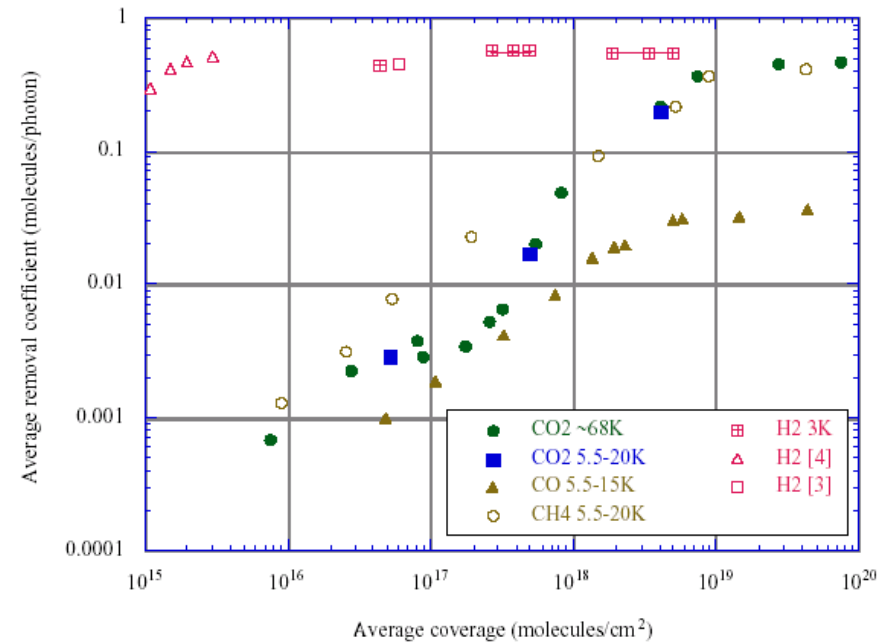
Average removal coefficient as a function of surface coating

Cracking of cryosorbed CO_2 molecules by SR

Fig. 3. The dynamic pressure dependance on the photon dose for CO, O_2 and CO_2 in the experiment with an average coverage of $8.2 \cdot 10^{17}$ molecules/cm².
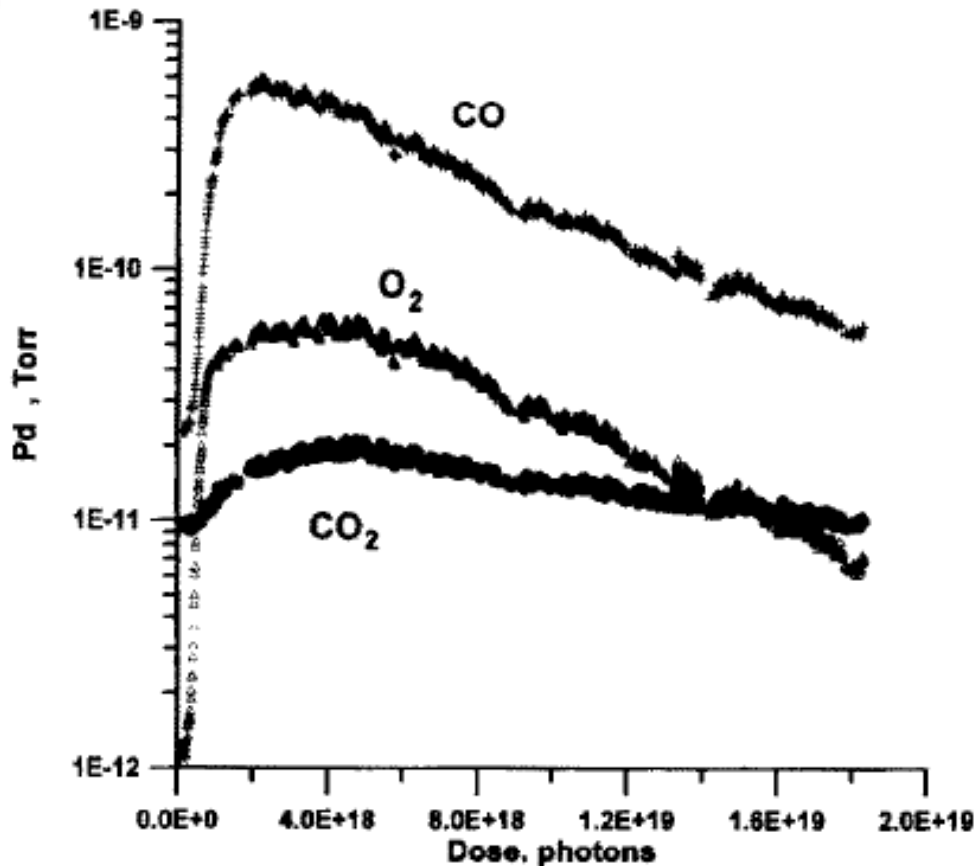
- About 10^3 monolayers of CO_2 were condensed
- CO is the main gas during SR
- O_2 is ~10 times lower
- CO_2 is ~30 times lower

$$2CO_2 + \tilde{\gamma} \rightarrow 2CO + O_2$$
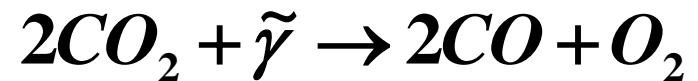
V. Anashin et al, NIM A (1998), p. 258.

Vacuum Chamber at Low Temperature: Molecular Cracking

There are four main photodesorbed gases in a cryogenic vacuum chamber: H_2, CH_4, CO and CO_2, and two of them (CH_4 and CO_2) can be cracked by photons, $\tilde{\gamma}$:

$$CH_4 + \tilde{\gamma} \rightarrow C + 2H_2 \qquad \text{and} \qquad 2CO_2 + \tilde{\gamma} \rightarrow 2CO + O_2$$

The additional amount of H_2, CO and O_2 appears in a vacuum chamber due to photo-cracking of CH_4 and CO_2.

The efficiency of photo-cracking of CH_4 and CO_2 is about 10 times higher then CH_4 and CO_2 desorption from their cryosorbant!

How to use the experimental data in accelerator design

SR from a dipole magnet
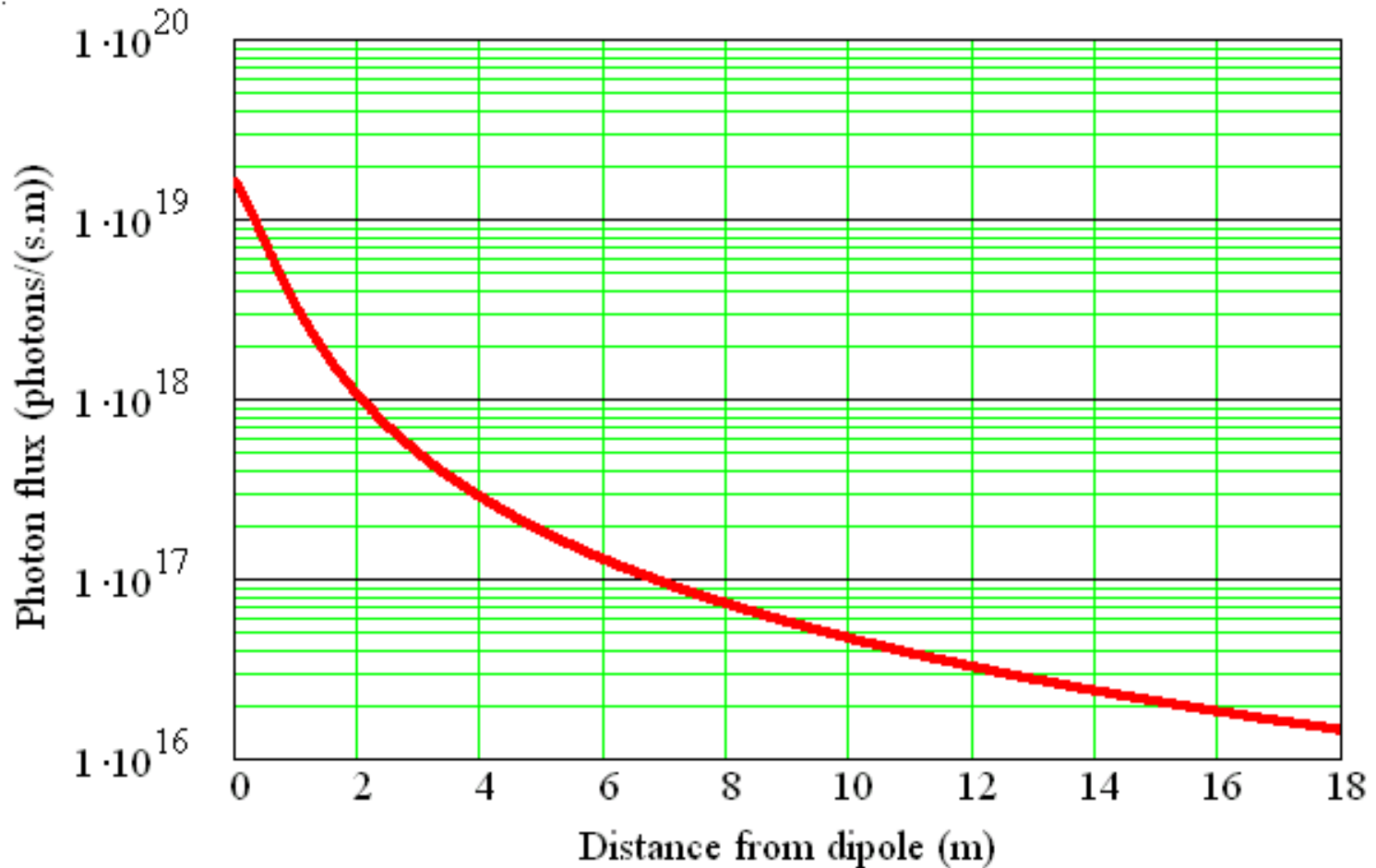
=> This is for an ideal orbit and is very sensitive to the real beam position

Legend:
- prebaked VC (red solid line)
- in-situ baked VC (blue dashed line)
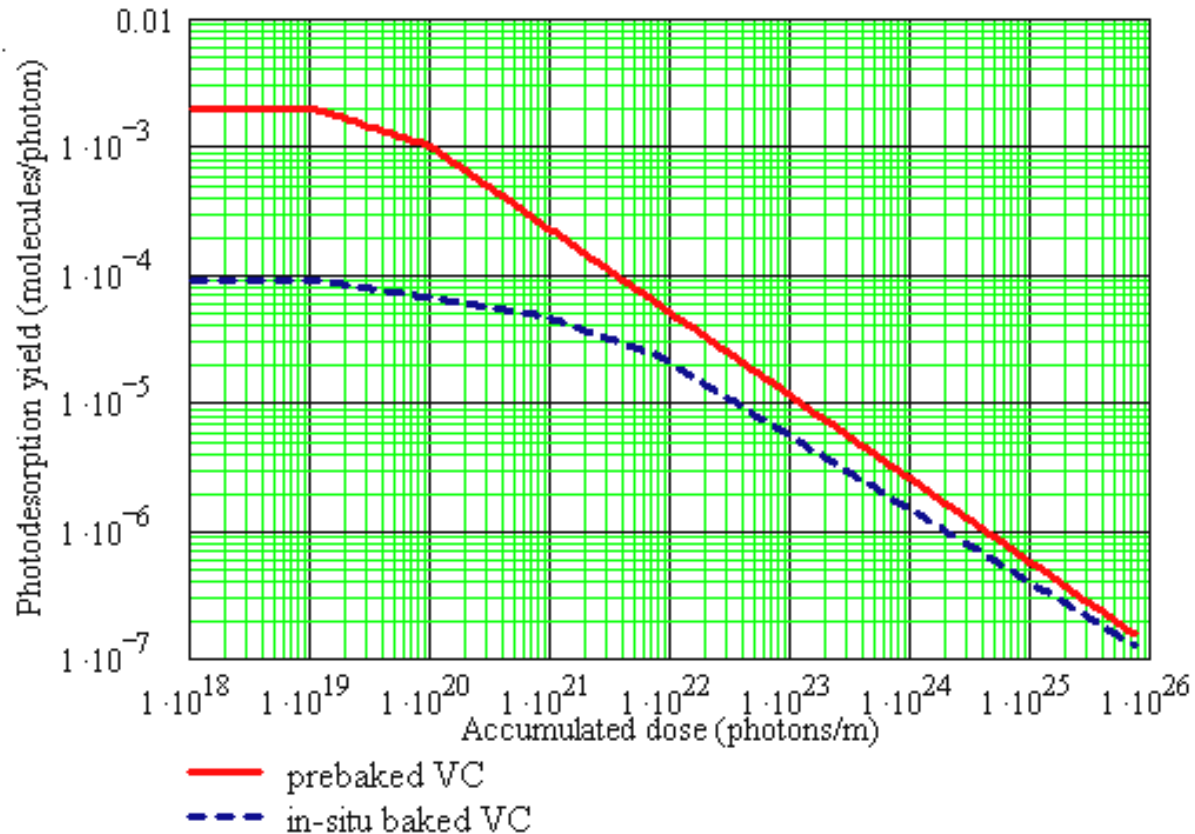
$$\eta = \eta_0 \left(\frac{D_0}{D} \right)^{\alpha}, \quad 0.65 < \alpha < 1$$

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

Ex-situ baked vacuum chamber

Legend:
- Initial
- After 0.1 A h
- After 1 A h
- After 10 A h
- After 100 A h
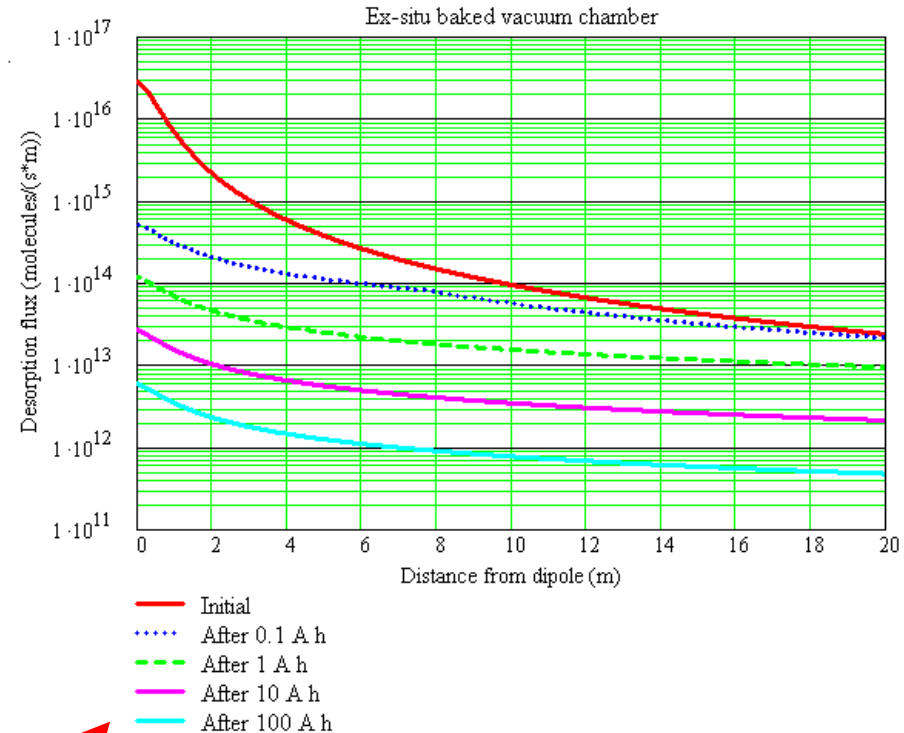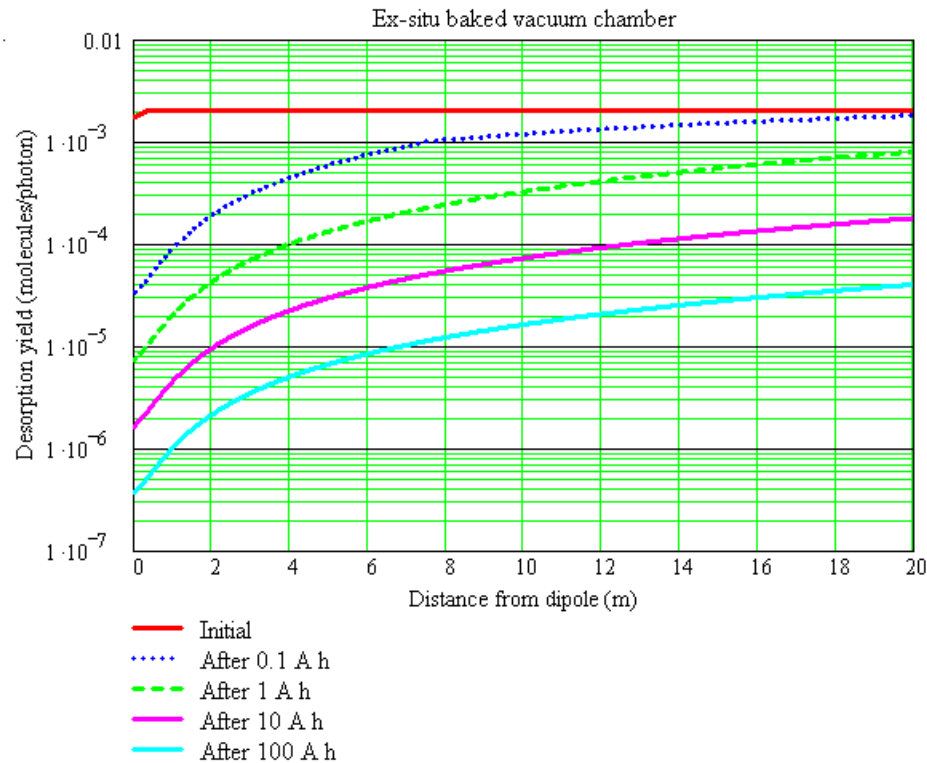
=> **These data for each gas can be used in the gas dynamics model.**
=> **Uncertainty in desorption flux is less than in photon flux and desorption yield**

Final remarks:
Vacuum is not an exact science

- **There are a number of uncertainties in desorption yields:**

- Desorption yields may differ (by factor 2 or even more) for vacuum components made of the same material after exactly the same cleaning procedure and treatments

- Results of Experiments:

    - 10-20% accuracy for all gauges at UHV

    - RGA calibration procedure can lead to an error: up to a factor 5 with a Faraday cap or a factor 10 with SEM

    - Modelling error (from 0.5% to a factor 2 or even more)

- Approximations: extending of experimental results on a few order of magnitude, - it is just a reasonable guess!

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