The Impact of Synchrotron Radiation in the LHC

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CERN-LHC

Credits

- LHC Vacuum Group and SL/AP Group
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- BINP
  - V.V. Anashin, R. V. Dostovalov, N.V. Fedorov, N.A. Gorbunova, I.A. Koop, A.A. Krasnov, O. B. Malychev, V.P.Naz'mov, V.N. Osipov, V.F. Pindyurin, E.E. Pyata
- LBL (SSC)
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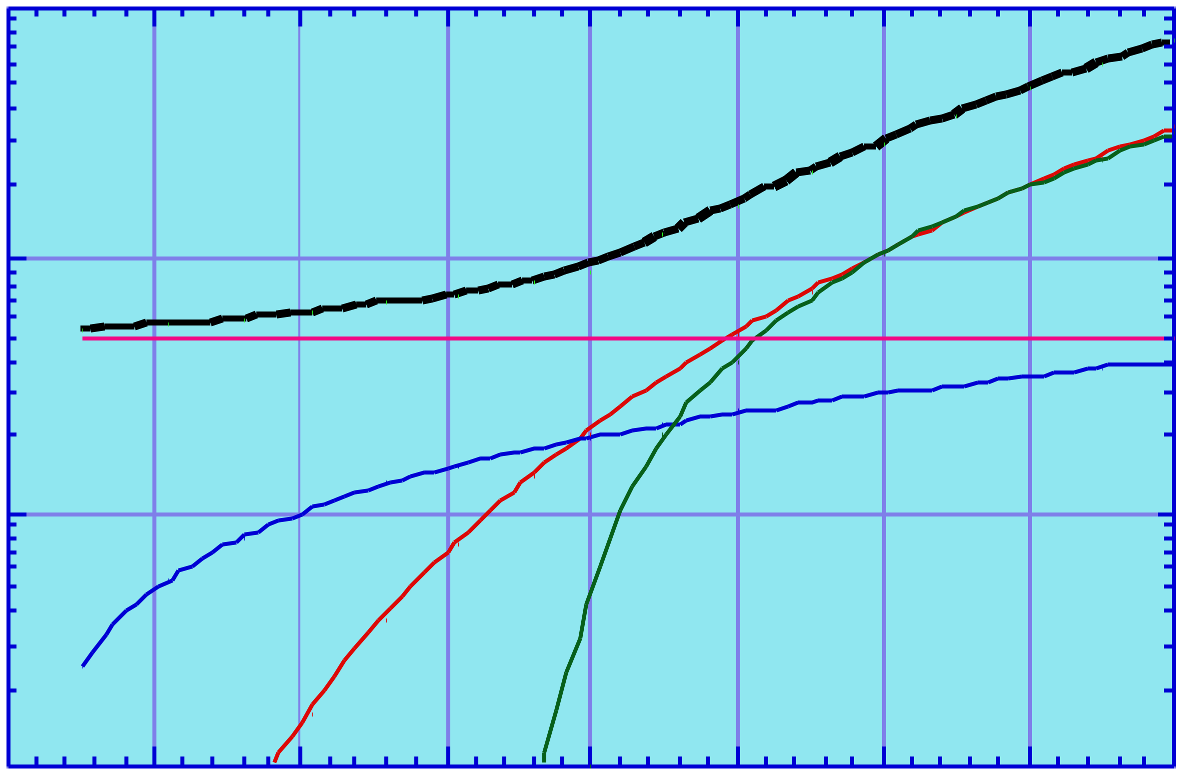
Synchrotron Radiation Effects

- S.R. Power deposition on cryogenic system
- Photon stimulated outgassing -> dynamic pressure increase
- Photoelectron production -> electron cloud effect
  - Power dissipation by bunched beam
  - Beam Induced Multipacting (BIM)
  - Electron stimulated outgassing
- Beneficial effects of S.R. :
  - Cleaning of the vacuum system (beam cleaning effect)
  - Reduction of secondary electron coefficient by photons/electrons
    - (beam scrubbing)
  - For the VLHC : Radiation damping -> Increase of Luminosity

Comparison of S.R. Characteristics

		LEP200	LHC	SSC	HERA	VLHC
Beam particle		e+ e-	p	p	p	p
Circumference	km	26.7	26.7	82.9	6.45	95
Beam energy	TeV	0.1	7	20	0.82	50
Beam current	A	0.006	0.54	0.072	0.05	0.125
Critical energy of SR	eV	$7\ 10^{5}$	44	284	0.34	3000
SR power (total)	kW	$1.7\ 10^{4}$	7.5	8.8	$3\ 10^{-4}$	800
Linear power density	W/m	882	0.22	0.14	$8\ 10^{-5}$	4
Desorbing photons	$s^{-1}\ m^{-1}$	$2.4\ 10^{16}$	$1\ 10^{17}$	$6.6\ 10^{15}$	none	$3\ 10^{16}$

Heat load contributions in the LHC



Beam induced heat loads

1) Resistive losses

$$P \propto r_w I^2 \leq 0.05 (W/m)$$

2) Synchrotron radiation, (s.r.)

$$P(W/m) = 1.24 \cdot 10^3 \frac{E^4(TeV)\ I(A)}{r^2(m)}$$

3) Photoelectrons

s.r. creates an electron cloud ->

Without secondary electrons P ~ N_b^3

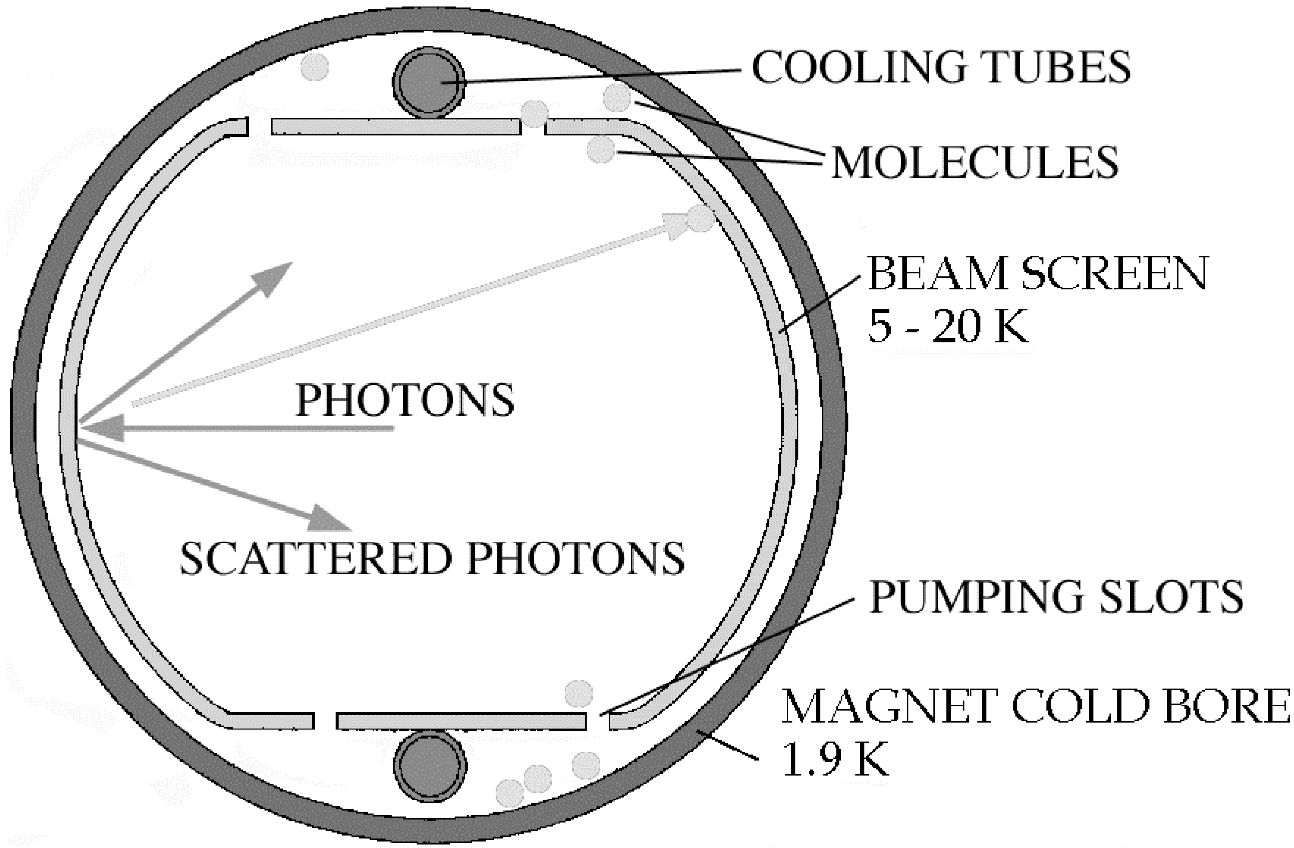
with secondary electrons -> limited by space charge

4) Nuclear scattering

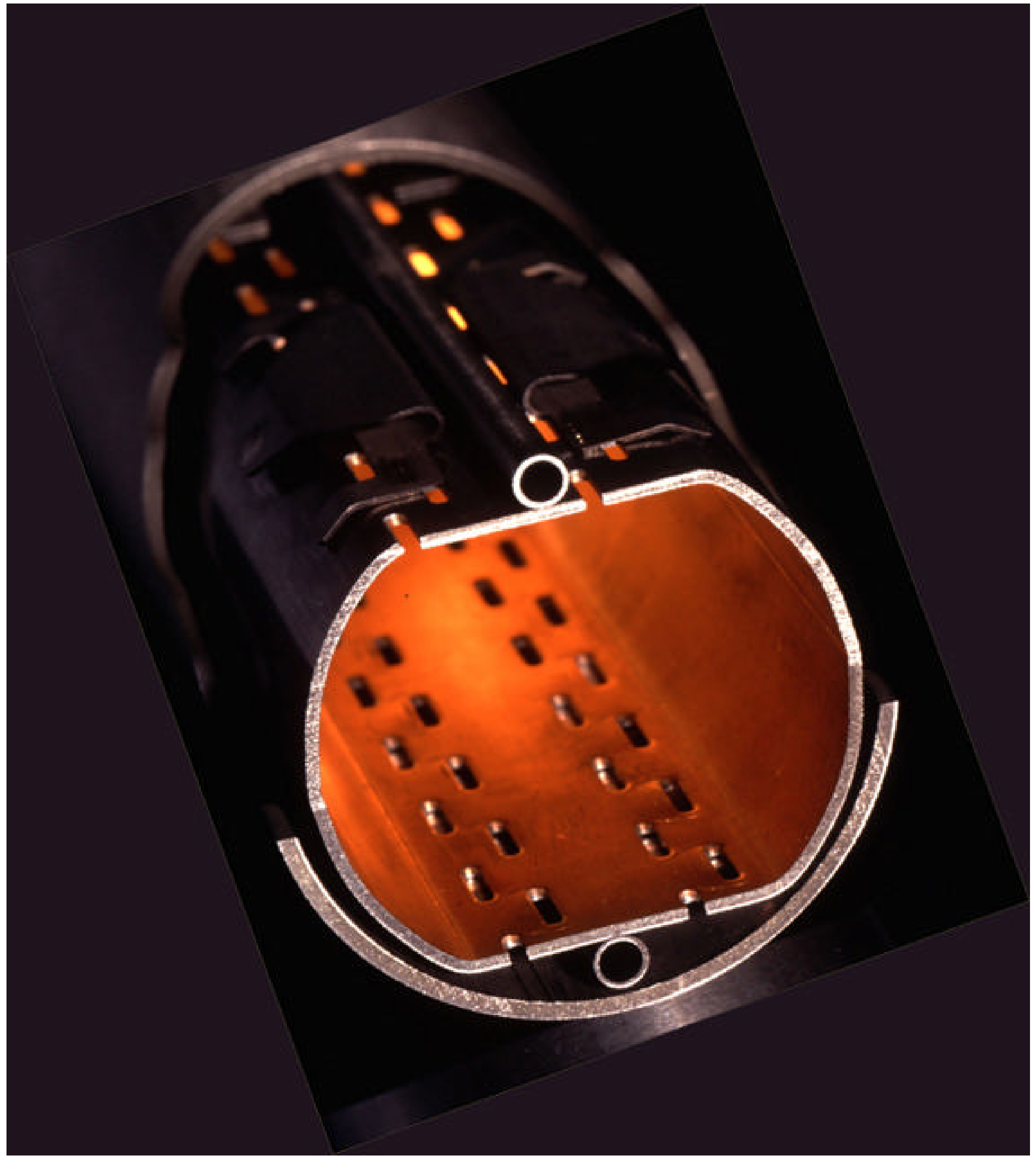
$$P(W/m) = 0.93 \frac{I(A)\ E(TeV)}{t(h)}$$

Beam screen removes #1, #2 and #3 and #4 sets a limit for the beam lifetime

Beam screen inside a Cryo-magnet cold bore



LHC-beam screen with pumping holes and copper coating (0.05 mm).



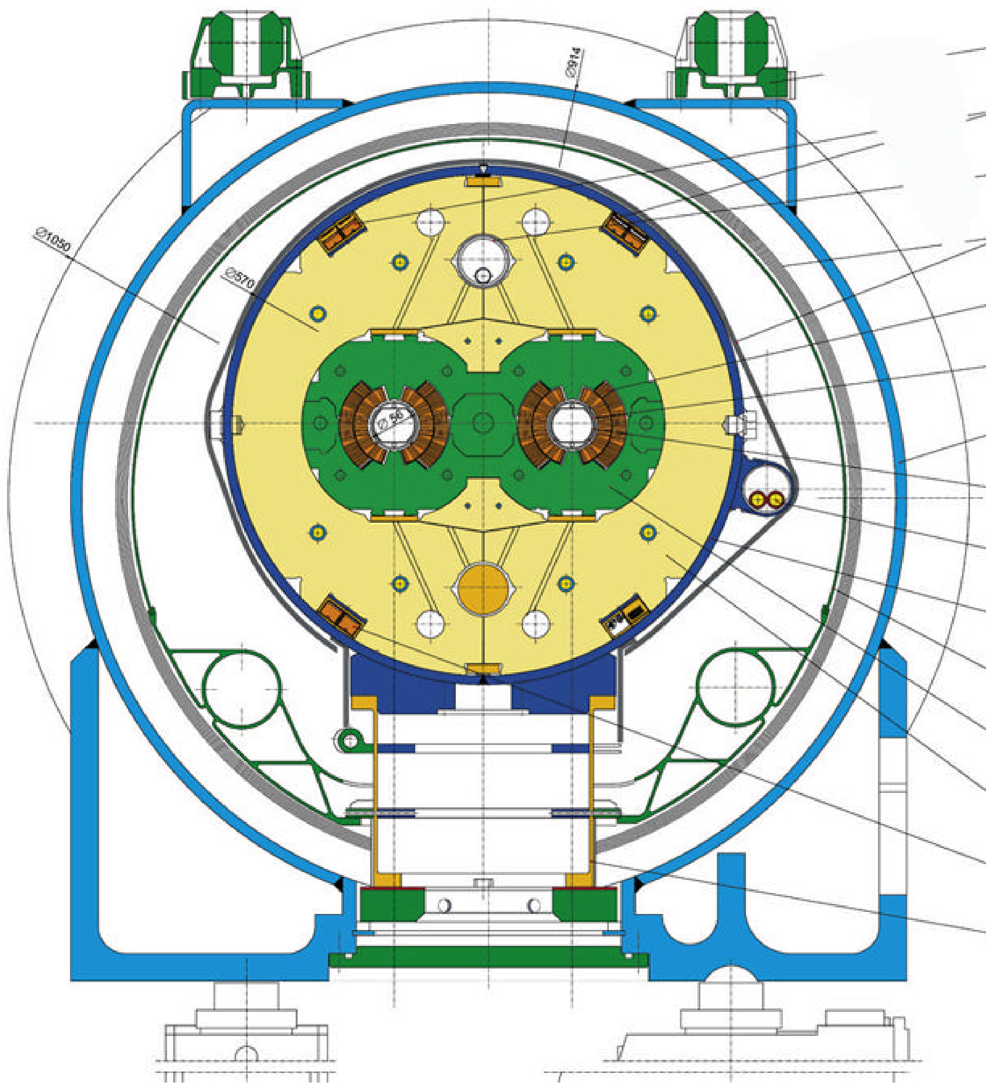
Cooling capillaries are provided to remove beam-induced power:

-> Synchrotron radiation

-> Beam image currents

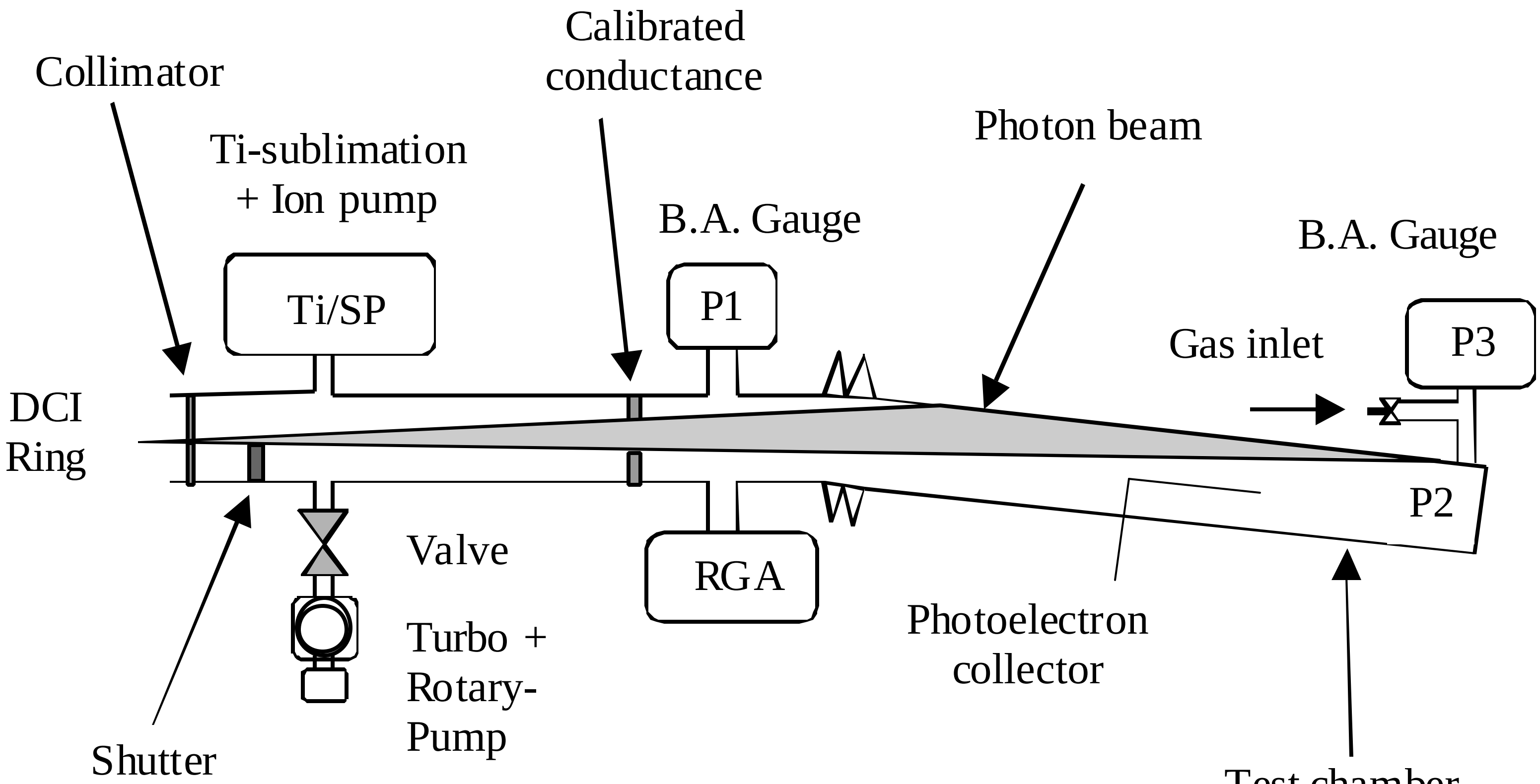
-> Photo-electrons

LHC Twin-aperture cryomagnet

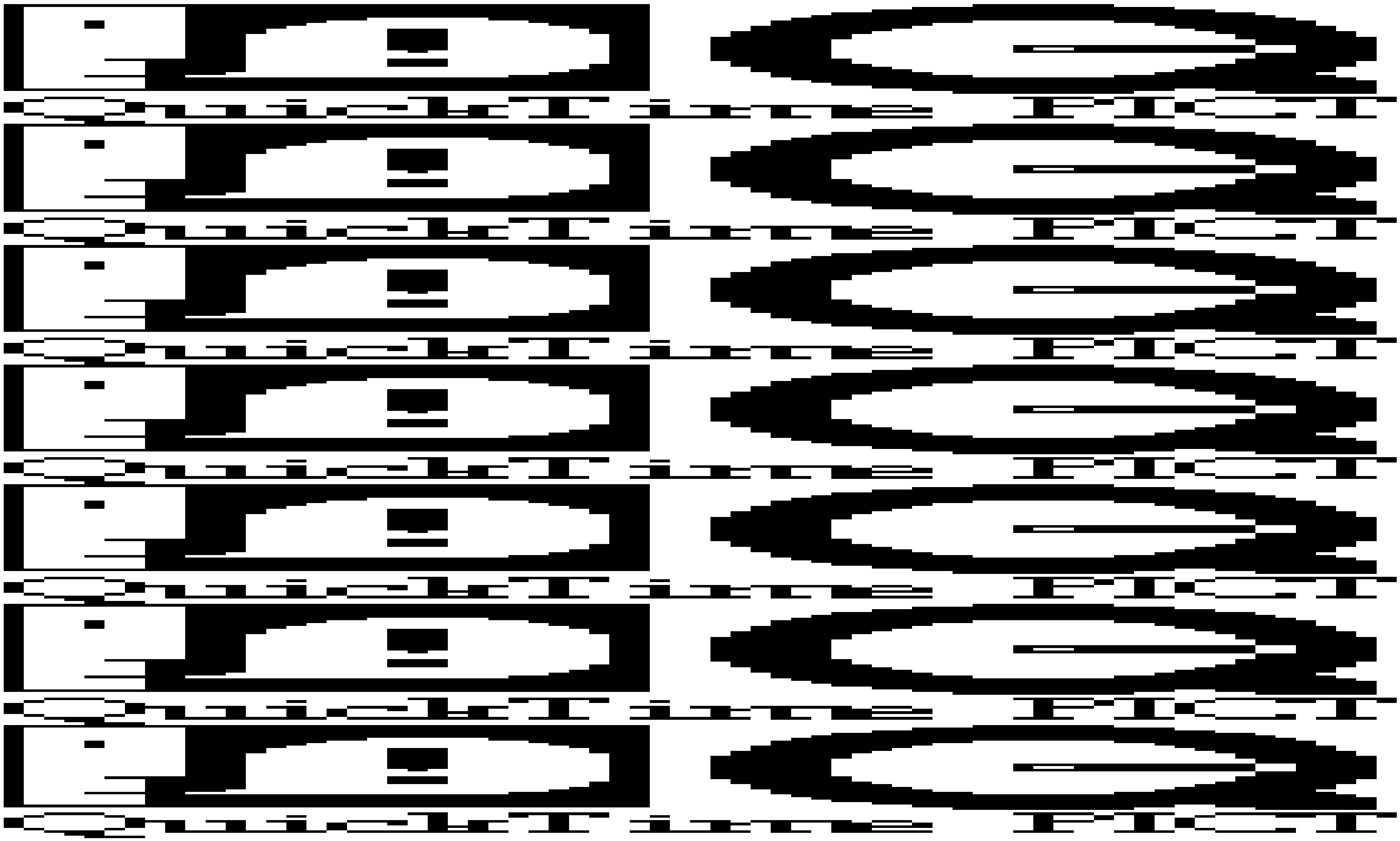


Beam vacuum
Beam screen

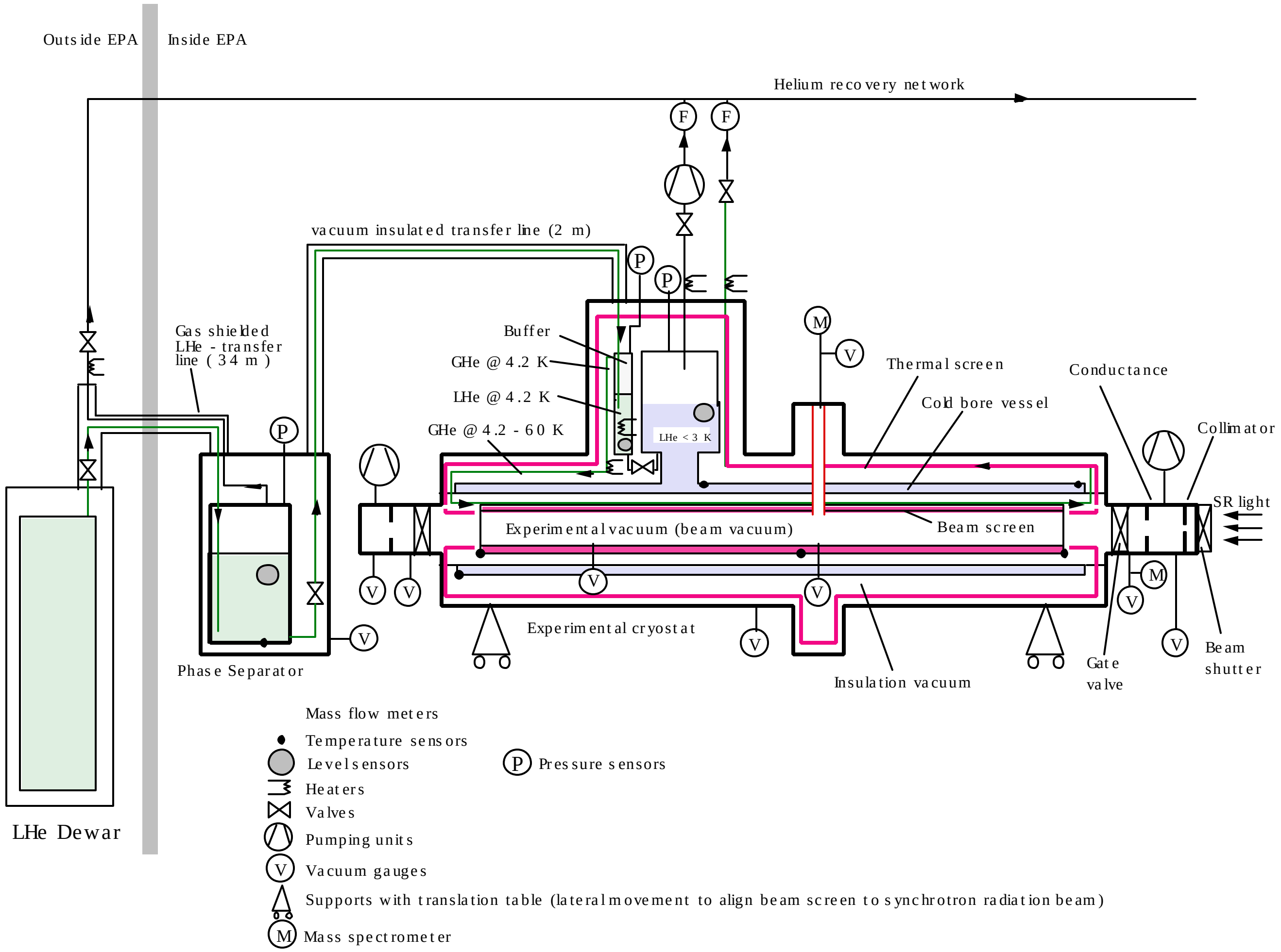
Beam line at DCI and EPA for SR-induced molecular desorption studies



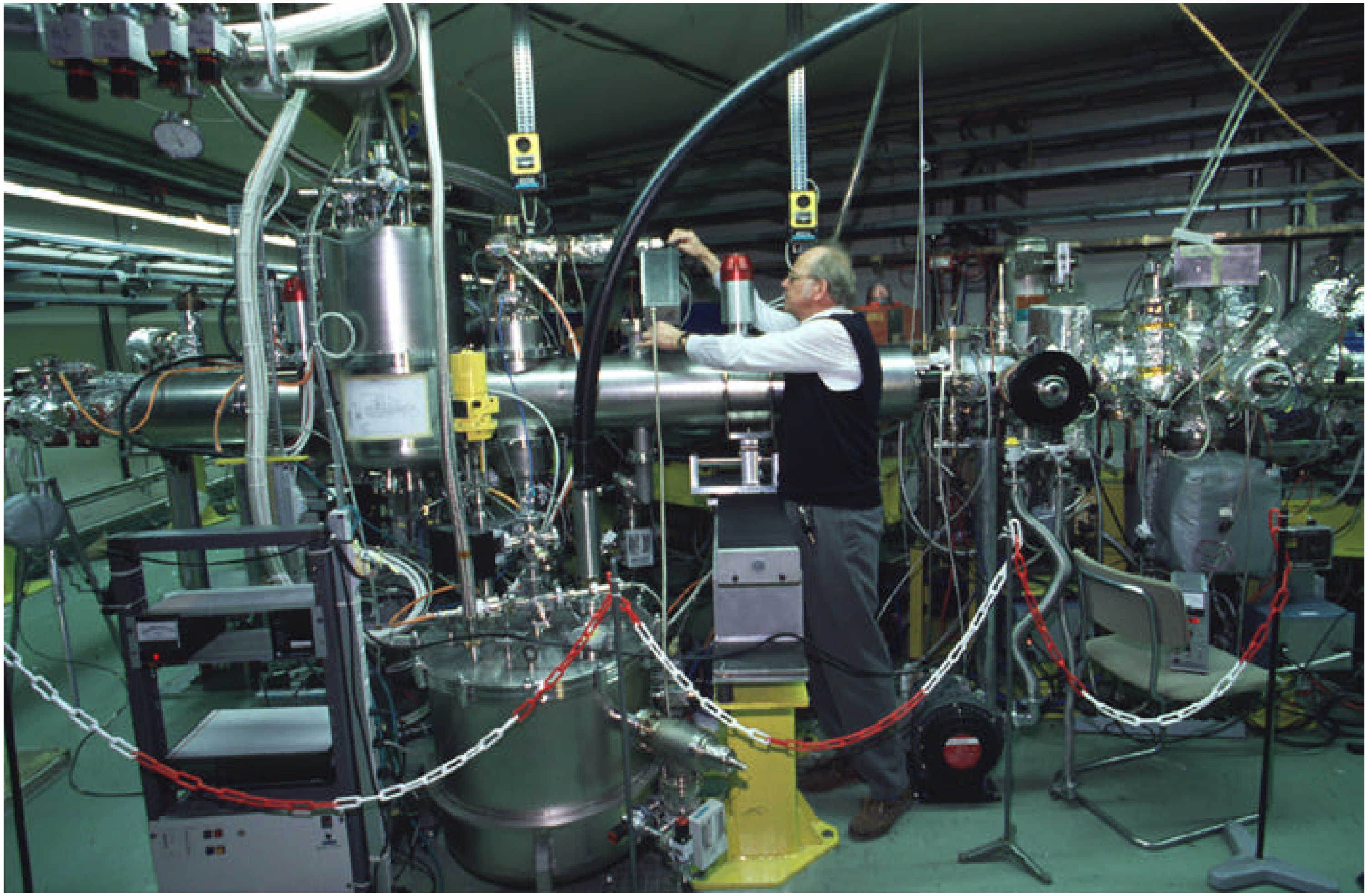
Cryogenic experiment at BINP on VEPP2-M



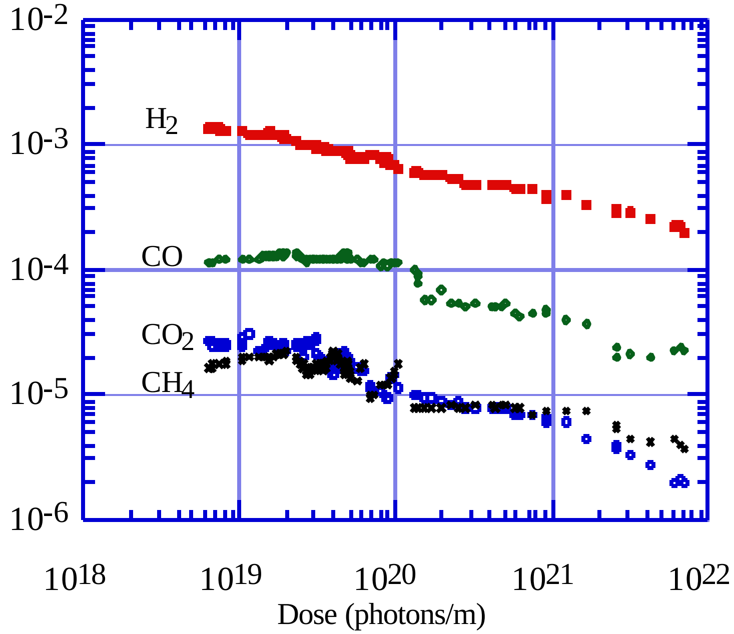
Cold bore experiment (COLDEX) at CERN

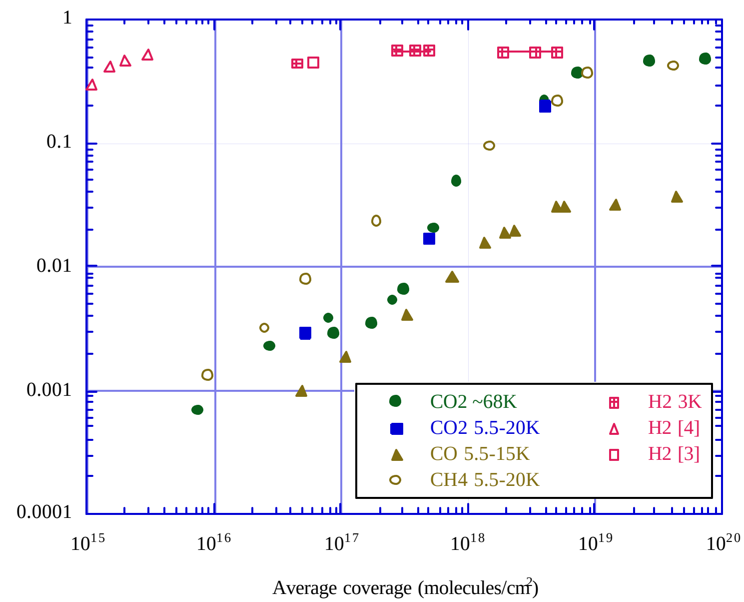


COLDEX in EPA beam line

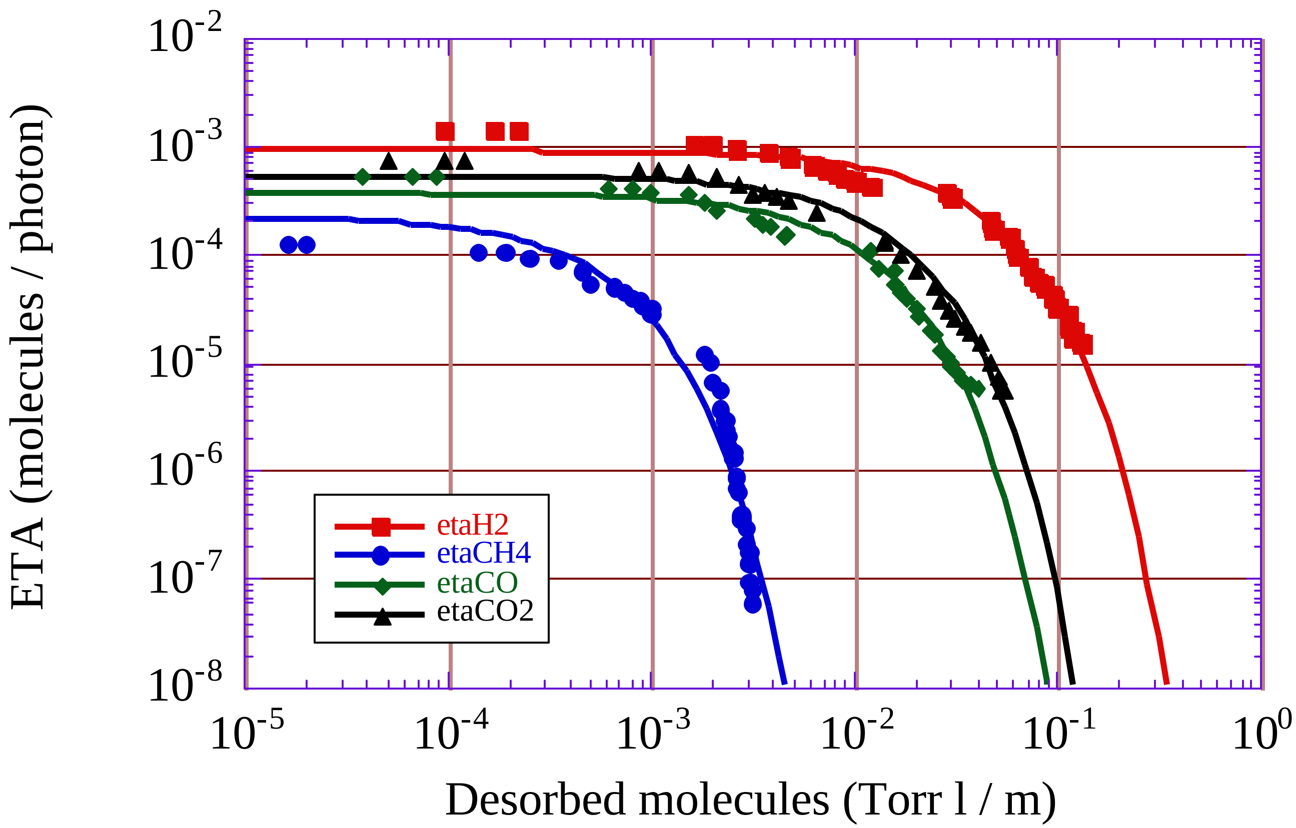


Primary photo-desorption coefficient and re-cycling coefficient of physisorbed gas molecules



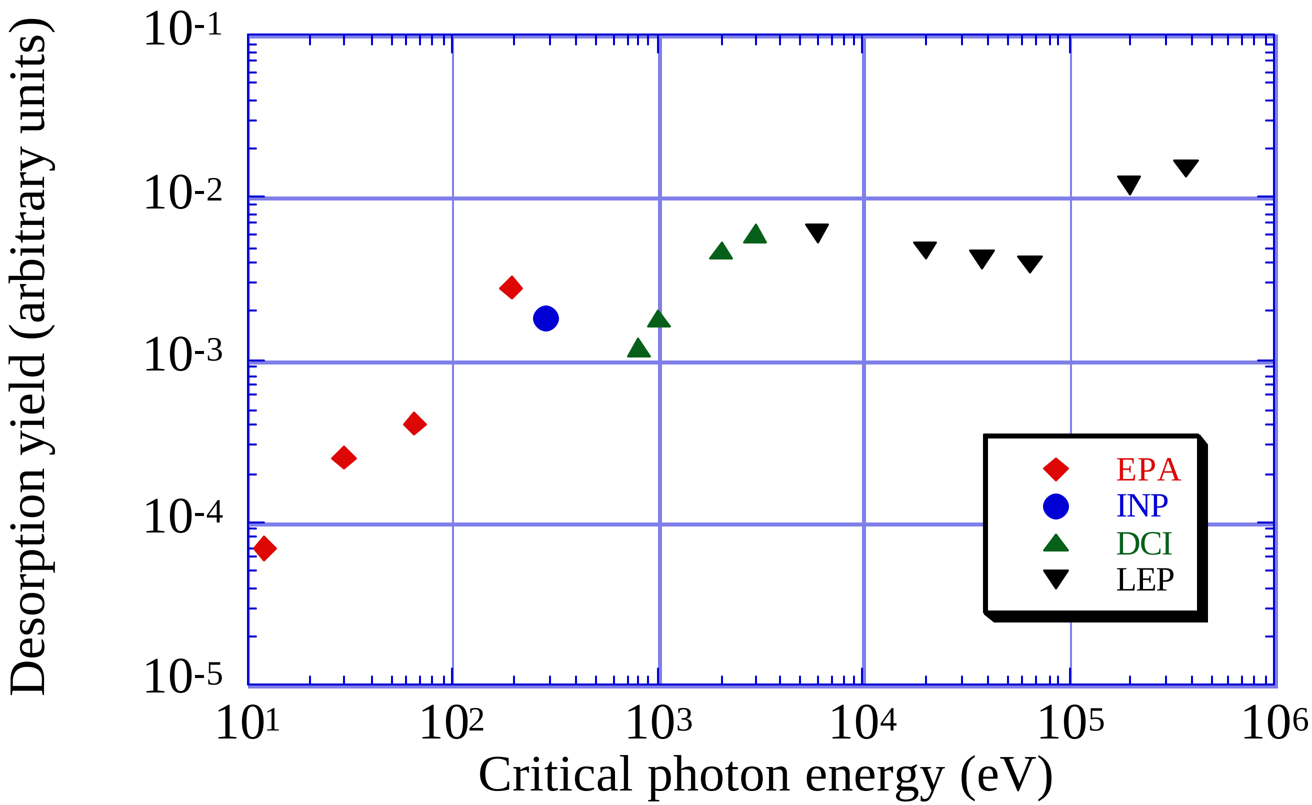


Molecular desorption yield vrs desorbed gas load



OFHC copper, baked. With 3.75 keV critical energy synchrotron radiation

Variation of the desorption yield with critical photon energy

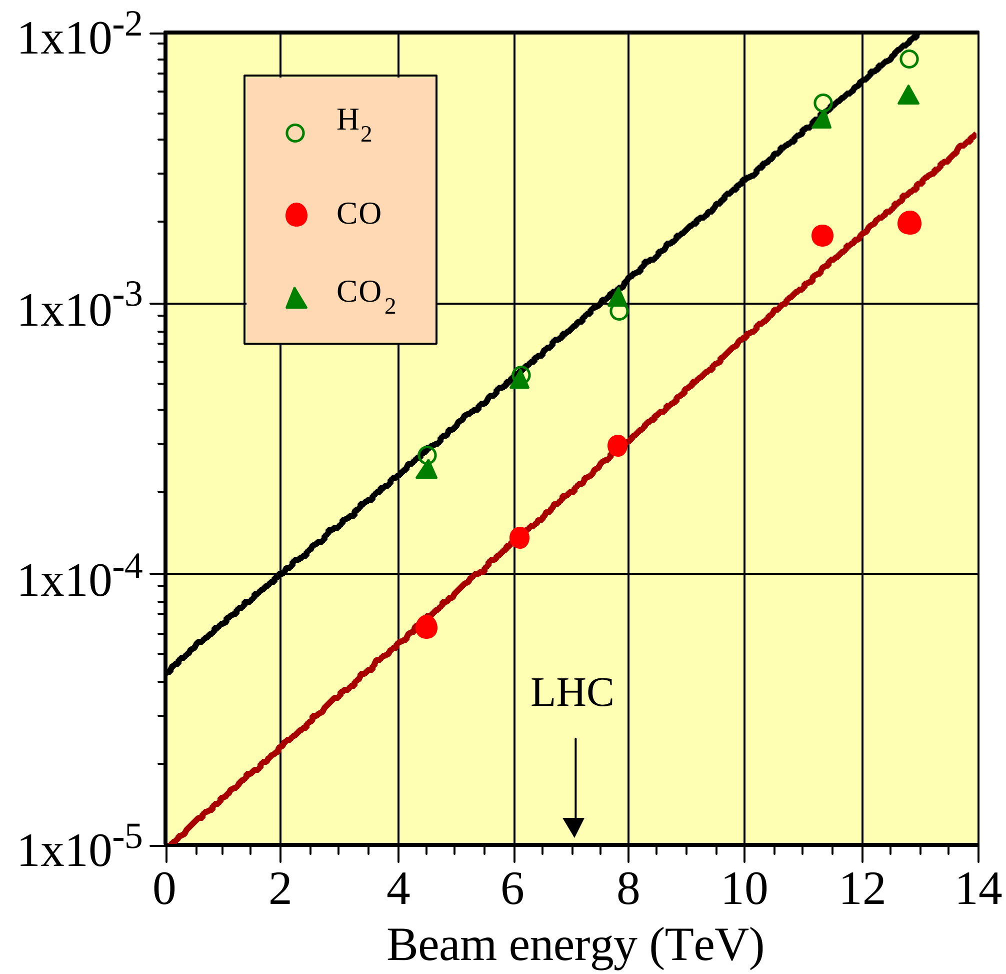


Data compiled for different materials (Al, OFHC copper and stainless steel) and for different machines

Molecular desorption yield

Photon induced molecular desorption yield as a function of the LHC beam energy.

Data obtained with unbaked, electroplated copper on stainless steel. Measured at room temperature in the photon beam line at EPA in CERN

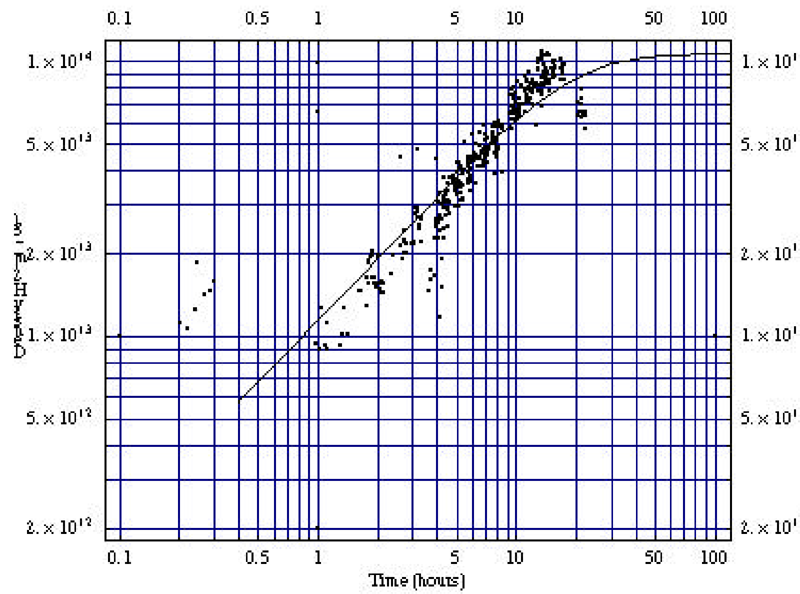


EVC 95, Uppsala

Dynamic Vacuum model for the LHC

q photon induced desorption rate
a pumping by the wall and by the pumping holes
b physisorbed molecules desorb thermally and by photons
c adsorption rate proportional to sticking probability, s

$$V\,\frac{dn}{dt} = q - a\,n + b\,q \quad \text{and} \quad F\,\frac{dq}{dt} = c\,n - b\,q$$



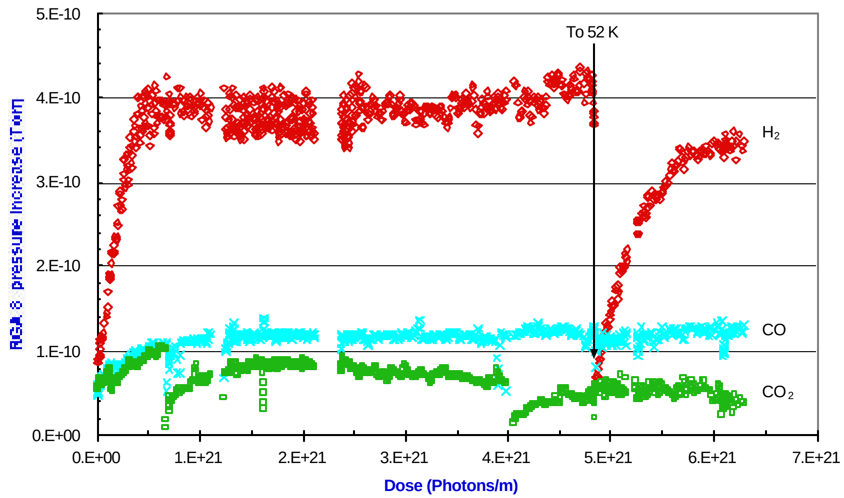
$$a = \frac{1}{4}\,\bar{v}\,F\,(s + f)$$

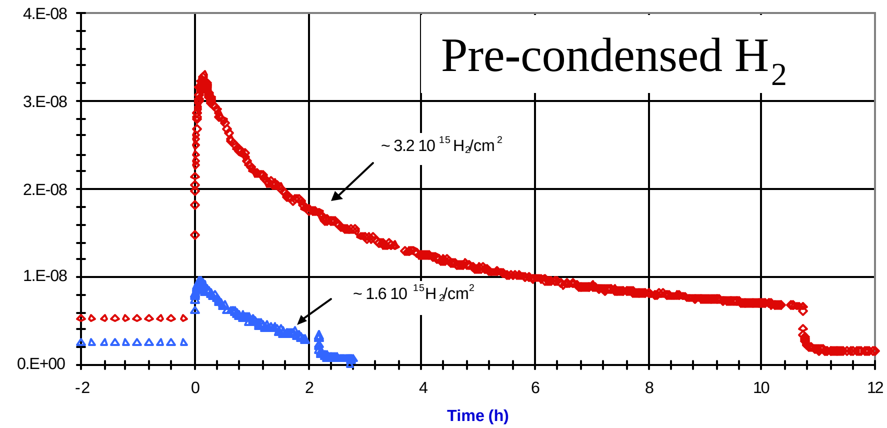
$$b = F\;n_o\,e^{-\frac{E}{kT}} + k\;\text{ÎÝ}$$

$$c = \frac{1}{4}\,\bar{v}\;s\;F$$

$$q = \frac{c}{b}\,n = \frac{\frac{1}{4}\,\bar{v}\,s\;F}{F n_o\,e^{-E/kT} + k\;\text{ÎÝ}}\;n$$

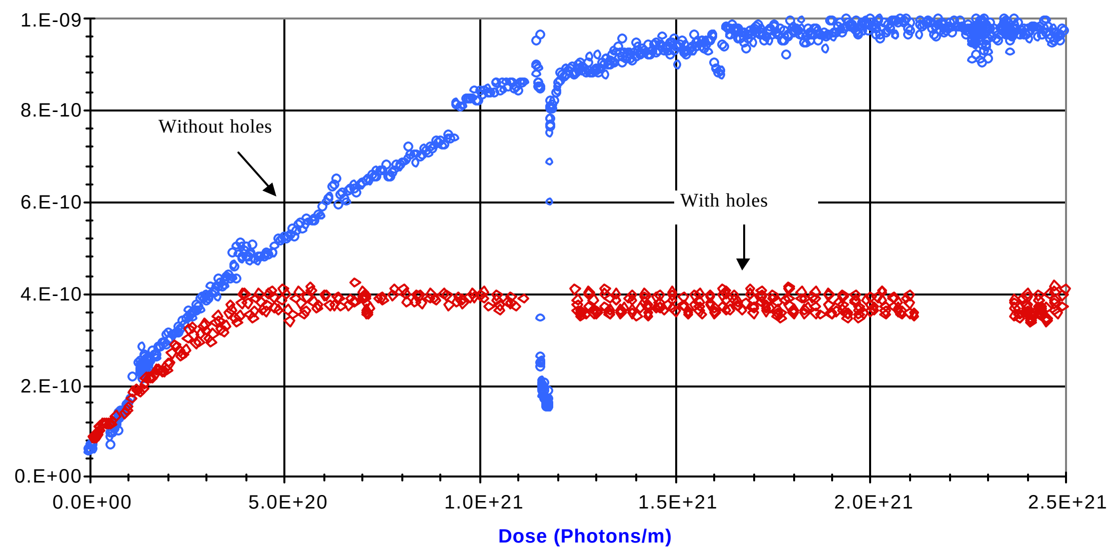
COLDEX-Results at EPA between 3K to 20 K



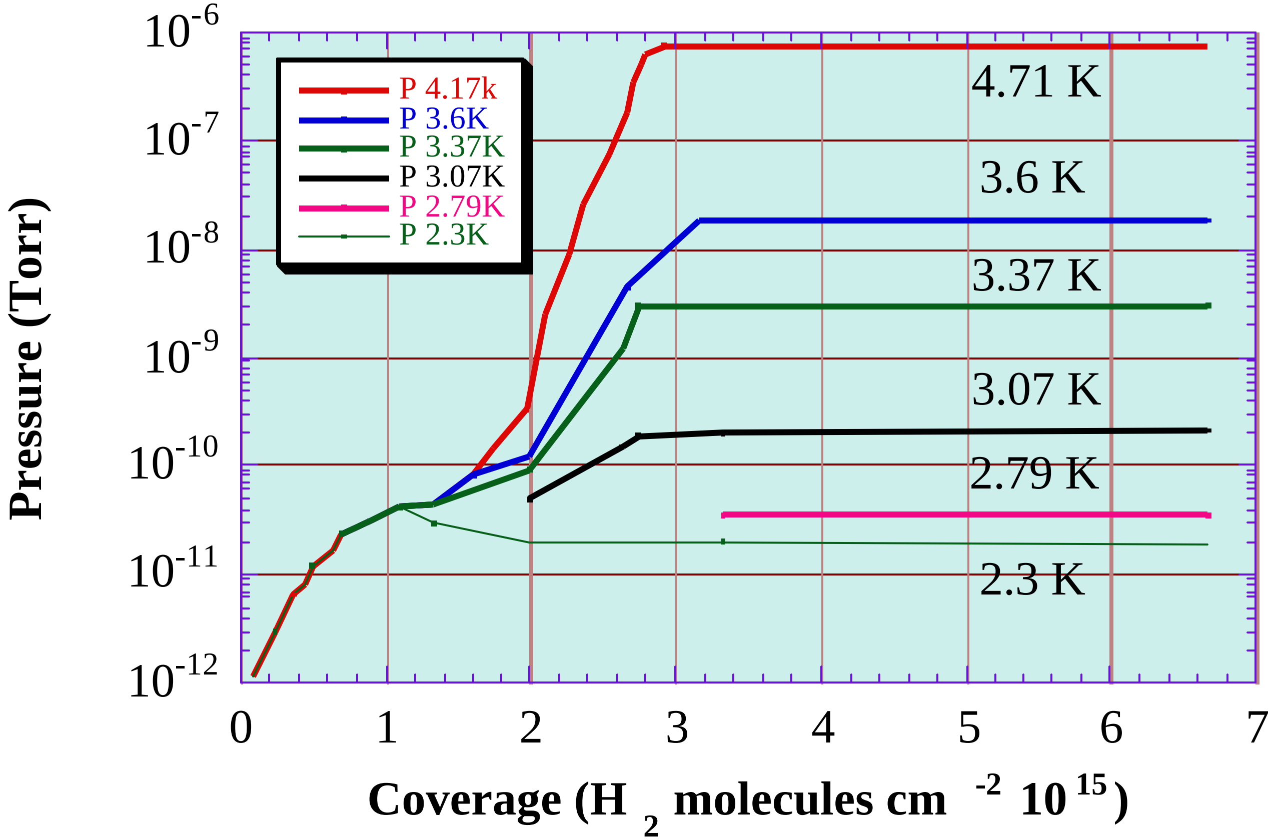


With pumping holes

without pumping holes

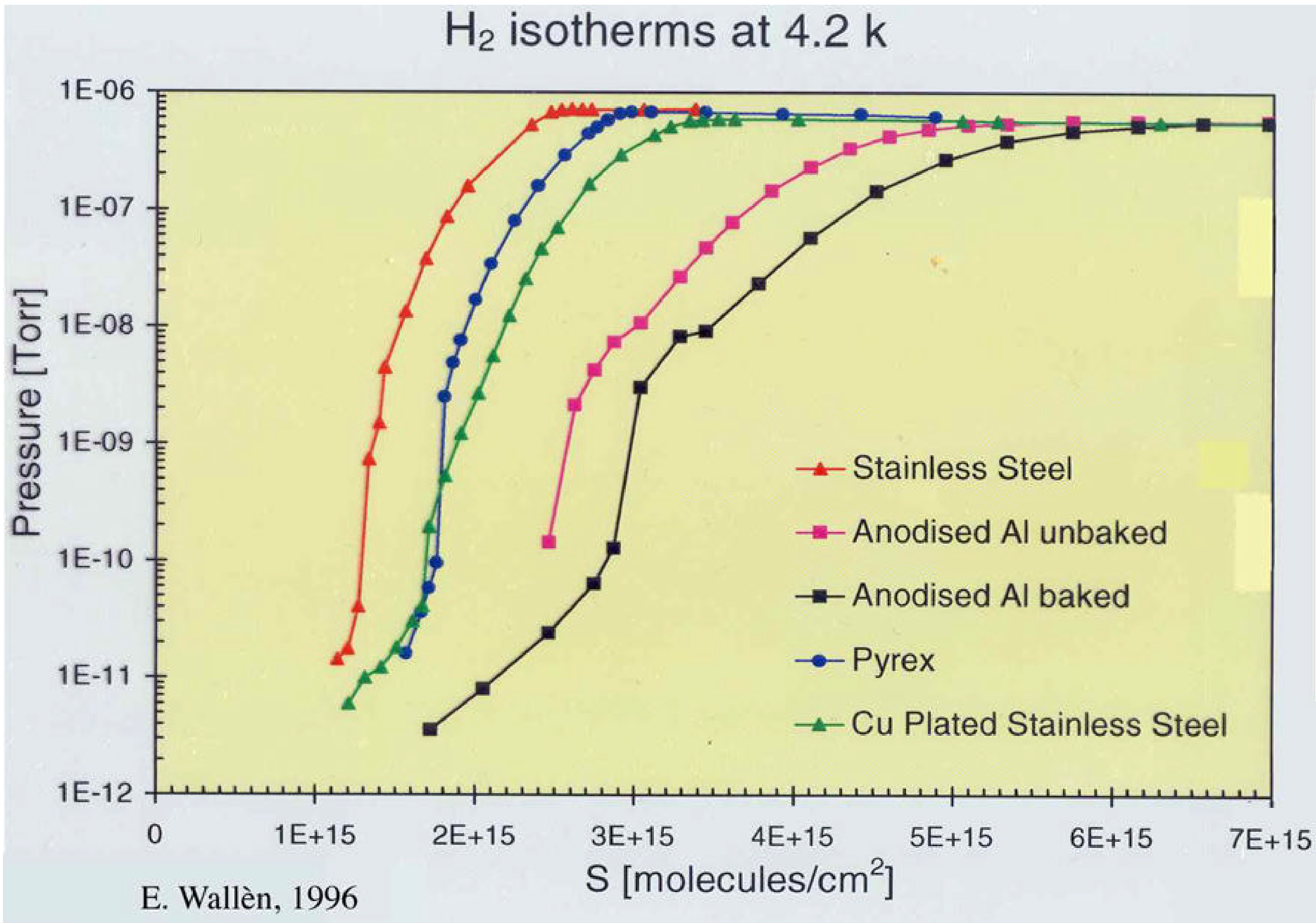


Hydrogen vapour pressure

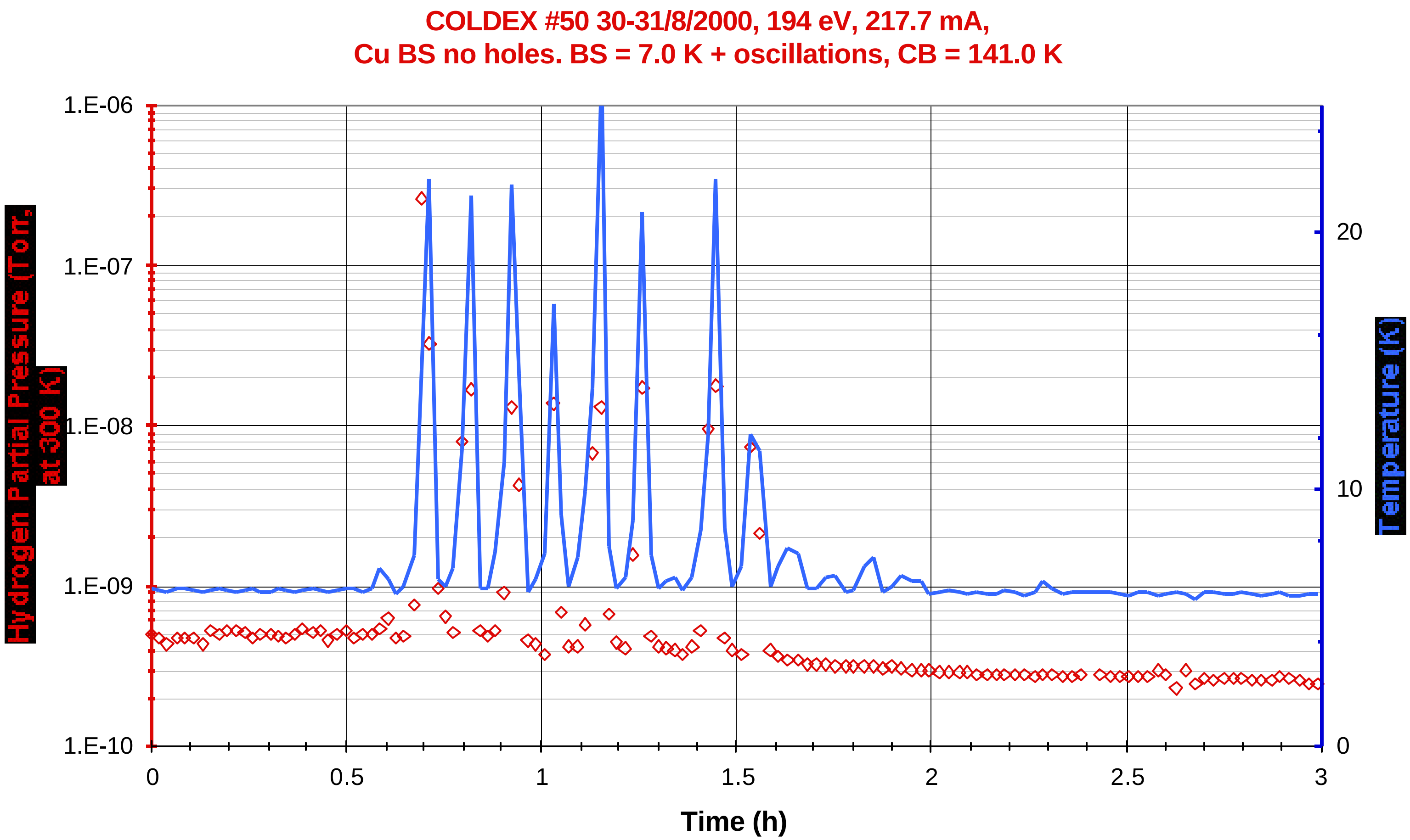


C. Benvenuti, R. Calder

Hydrogen vapour pressure



Effect of temperature variations on the pressure



Hydrogen vapour pressure due to room temperature radiation

For the LHC: the density limit of 10^{15} H_2 m^{-3} would correspond at 2.3 K to a limit pressure of

$P_{limit} = 2.4\ 10^{-10}$ Torr

LHC cold bore must be screened from synchrotron radiation to cryo-sorb a large coverage of hydrogen with a low vapour pressure

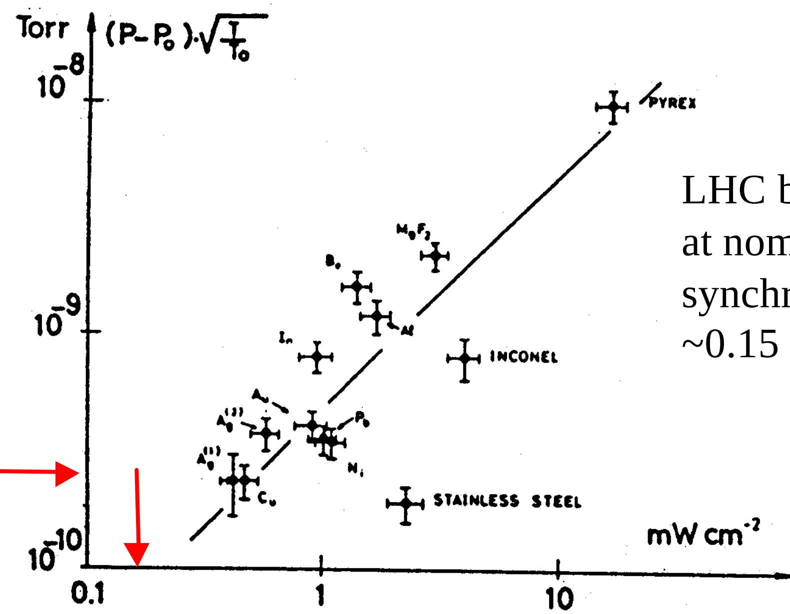
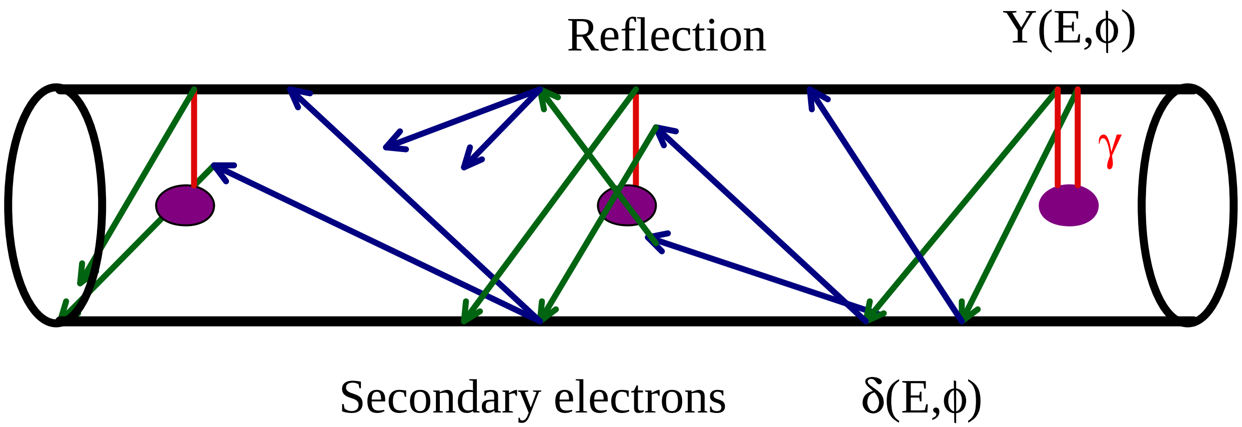


FIG. 14. Saturated vapor pressures of H_2 condensed on different cryosurfaces (at 2.3 K and fully exposed to radiation from 300 K) versus the radiation power absorbed. The line represents the best fit with slope 1 to plotted results.

LHC beam screen and at nominal conditions : synchrotron radiation -> ~0.15 mW/cm^2

C. Benvenuti, R. Calder, G. Passardi, J.Vac. Sci. Technol., Vol 13, No. 6, Nov./Dec. 1976, 1172

Electron cloud generated heat load and outgassing in the LHC beam screen



Key parameters
Synchrotron radiation intensity,
Y(E,φ) photoelectric yield
δ(E,φ) secondary electron yield, E_{max}, δ_{max}
Energy distribution of secondary electrons
Photon reflectivity (magnetic field)
Beam screen shape and diameter
Bunch intensity and spacing
External fields (magnetic, electric, space charge)

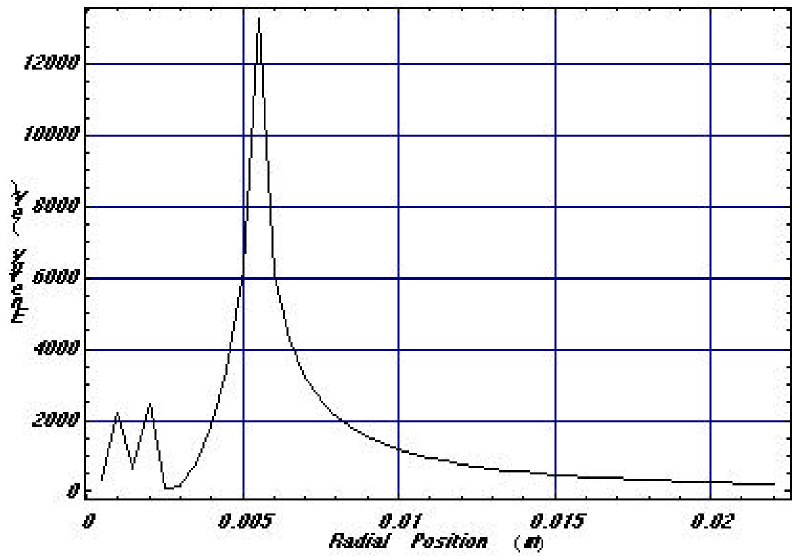
$$Q_{cloud} = k \frac{\eta_e P_{lin}}{< E_{cloud} >}$$

Outgassing:
k converts molecules to pressure
<Ecloud> average energy
η_e molecular desorption yield
P_{lin} *(W/m)* linear power deposition

Energy deposition by the electron cloud

- Beam induced power must be intercepted by the actively cooled beam screen

- Electron cloud effect
  - Beam blow-up
  - Multipacting -> BIM



Energy gain of electrons by the passage of an LHC bunch as a function of the radial position in the beam pipe.

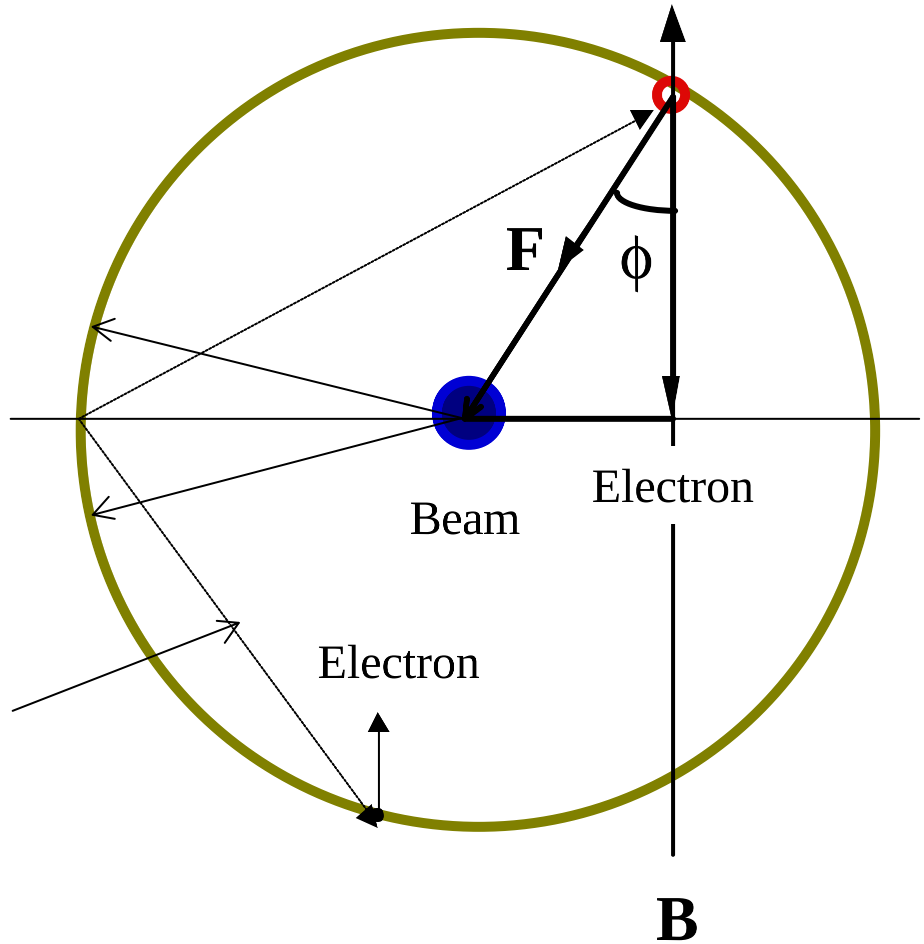
Effect of a dipole magnetic field

Cyclotron oscillations/bunch ~120
Cyclotron radius ~ 6 μm for 200 eV

F is the electric force excerted by the proton bunch. on the electron.

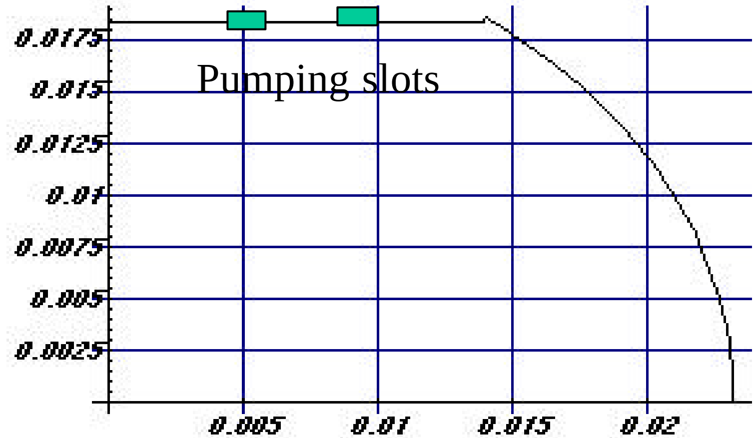
Primary SR photons strike in the median plane. Here photoelectrons are suppressed by the magnetic field.

Reflected/scattered photons reach top and bottom of the beam pipe
Low photon reflectivity is desirable to reduce the photoelectrons which can move freely along the field lines.

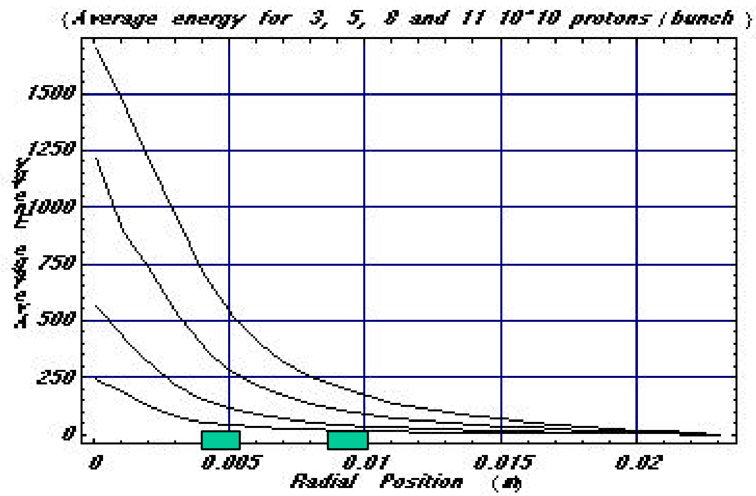


Electron cloud in a dipole magnetic field

LHC beam screen
(quadrant)



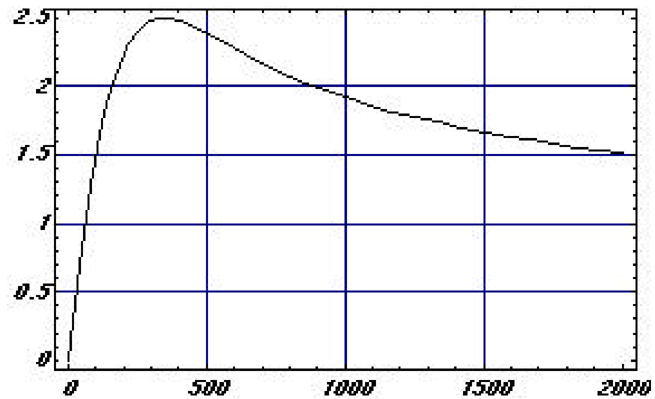
Average energy of the electrons as a function of the horizontal position from the beam in an LHC dipole.

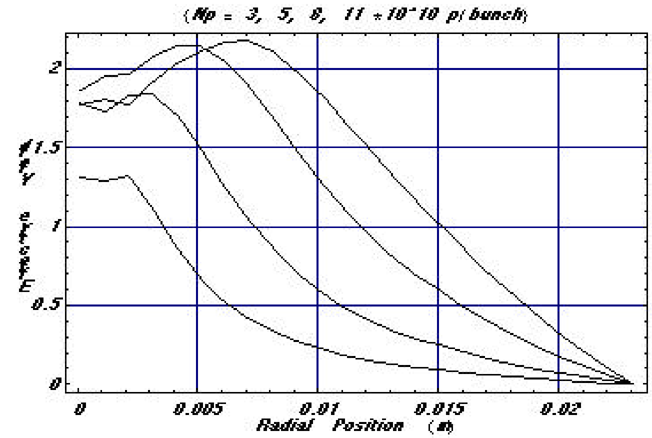


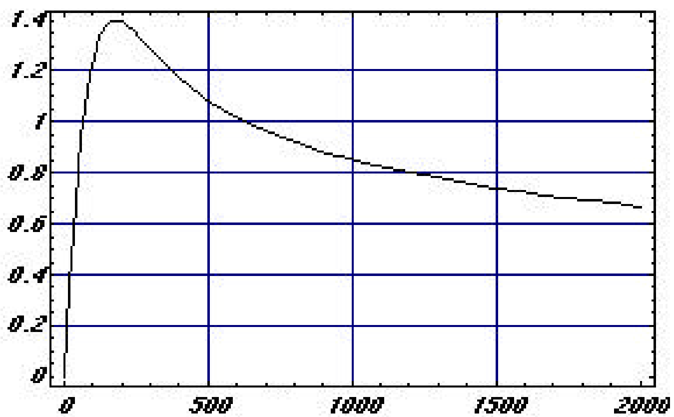
Beam scrubbing in a dipole field

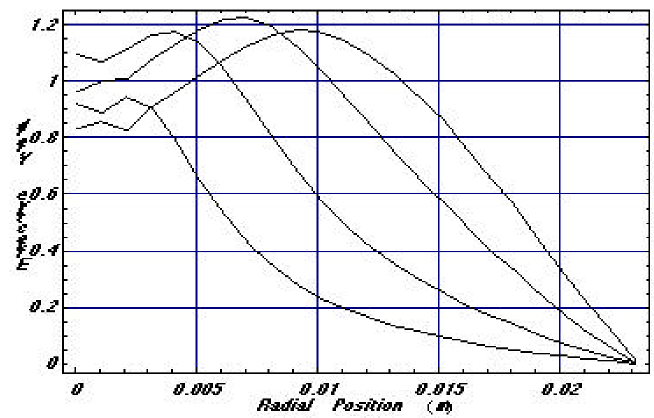
Secondary electron yield
Before and after scrubbing

Averaged yield vrs. Radial position
for different bunch intensities

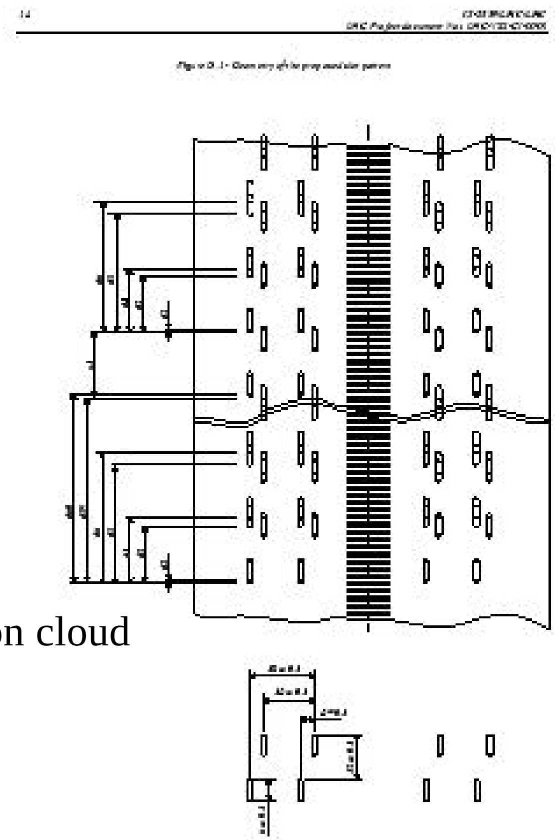








Beam screen pumping slot pattern



Power deposited on cold bore:
Inner row at 5 mm
Outer row at 9 mm from center line

60 slots/m with an average length of 8mm
Representing a transparency of ~ 0.48

At nominal beam parameters :
Inner row ~ 5%
Outer row ~ 2%
of the energy deposited uniformly by the electron cloud may be reach the cold bore.

Hence, for 0.5 W/m -> 35 mW/m

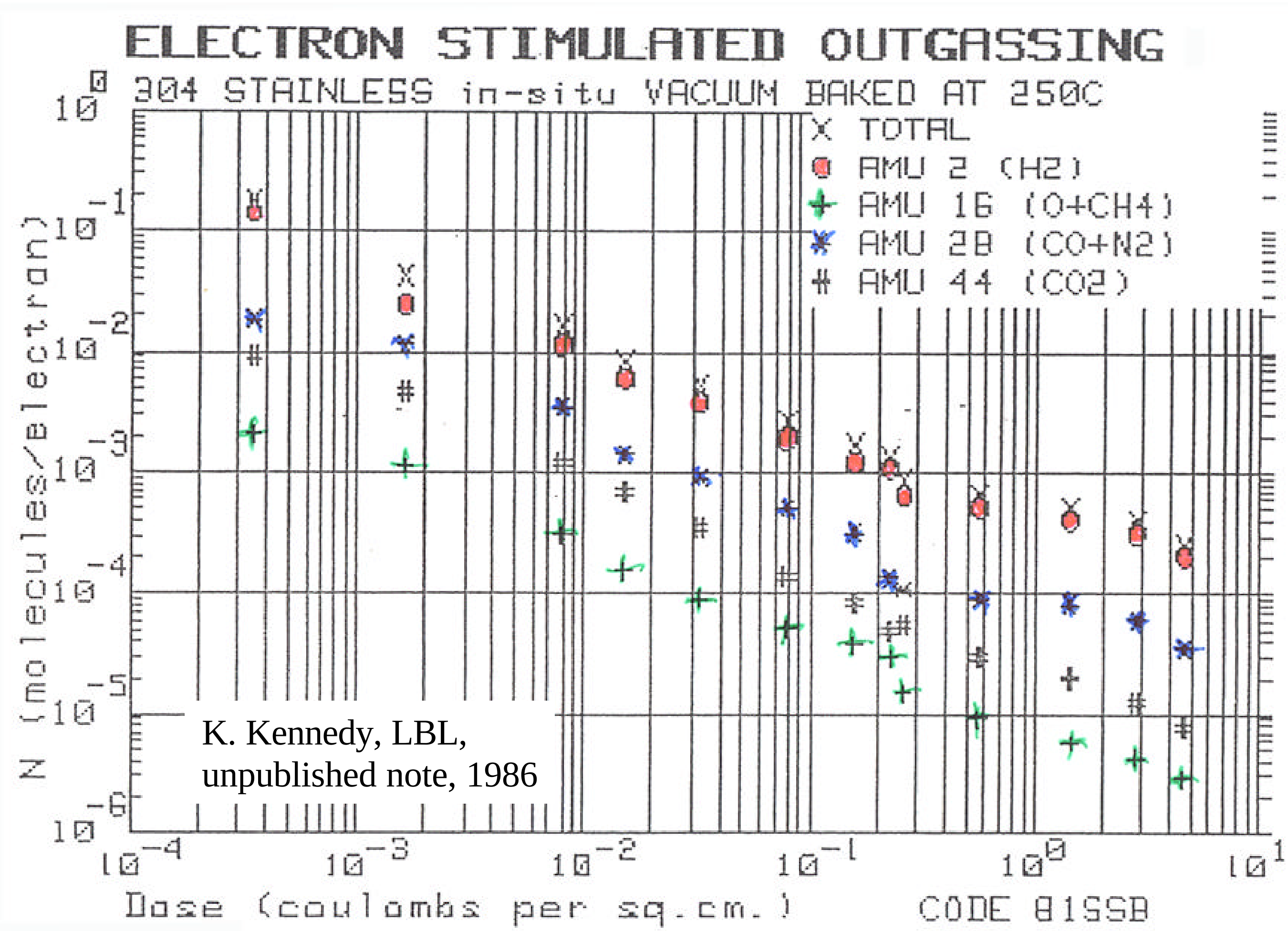
Beam Induced Multipacting (BIM)

– Pressure Increase due to Multipacting

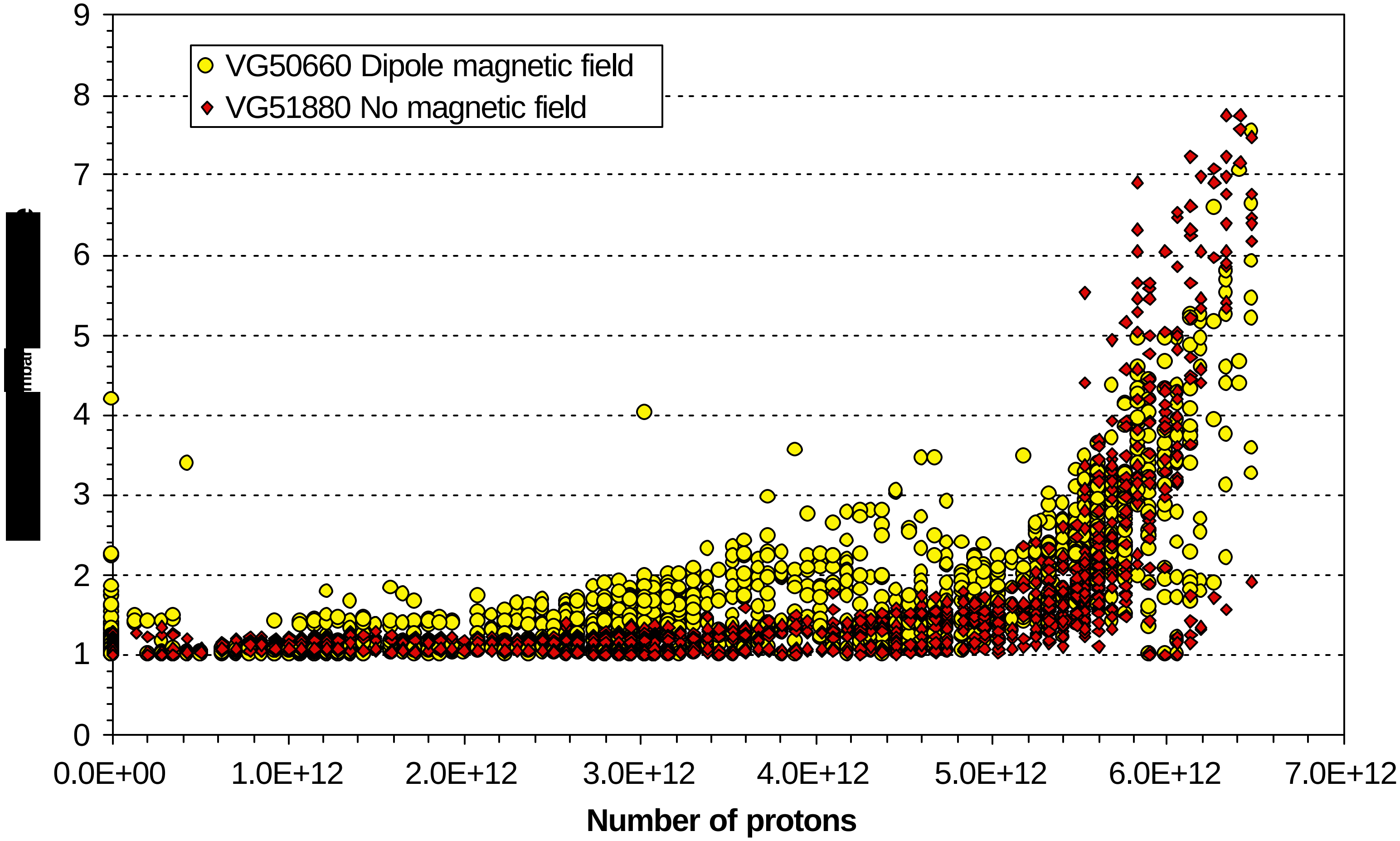
- Electron stimulated gas desorption has been observed in several machines : first in ISR in 1977 recently in KEK-B, PEP-2, SPS with LHC-type beams.
- Gas load, Q_{cloud} is directly related to the power deposited by the electrons, P_{lin}, to the molecular desorption yield,
- h_e and to the average energy of the electrons in the cloud, E_{cloud} .

$$Q_{cloud} = k \frac{h_e P_{lin}}{< E_{cloud} >}$$

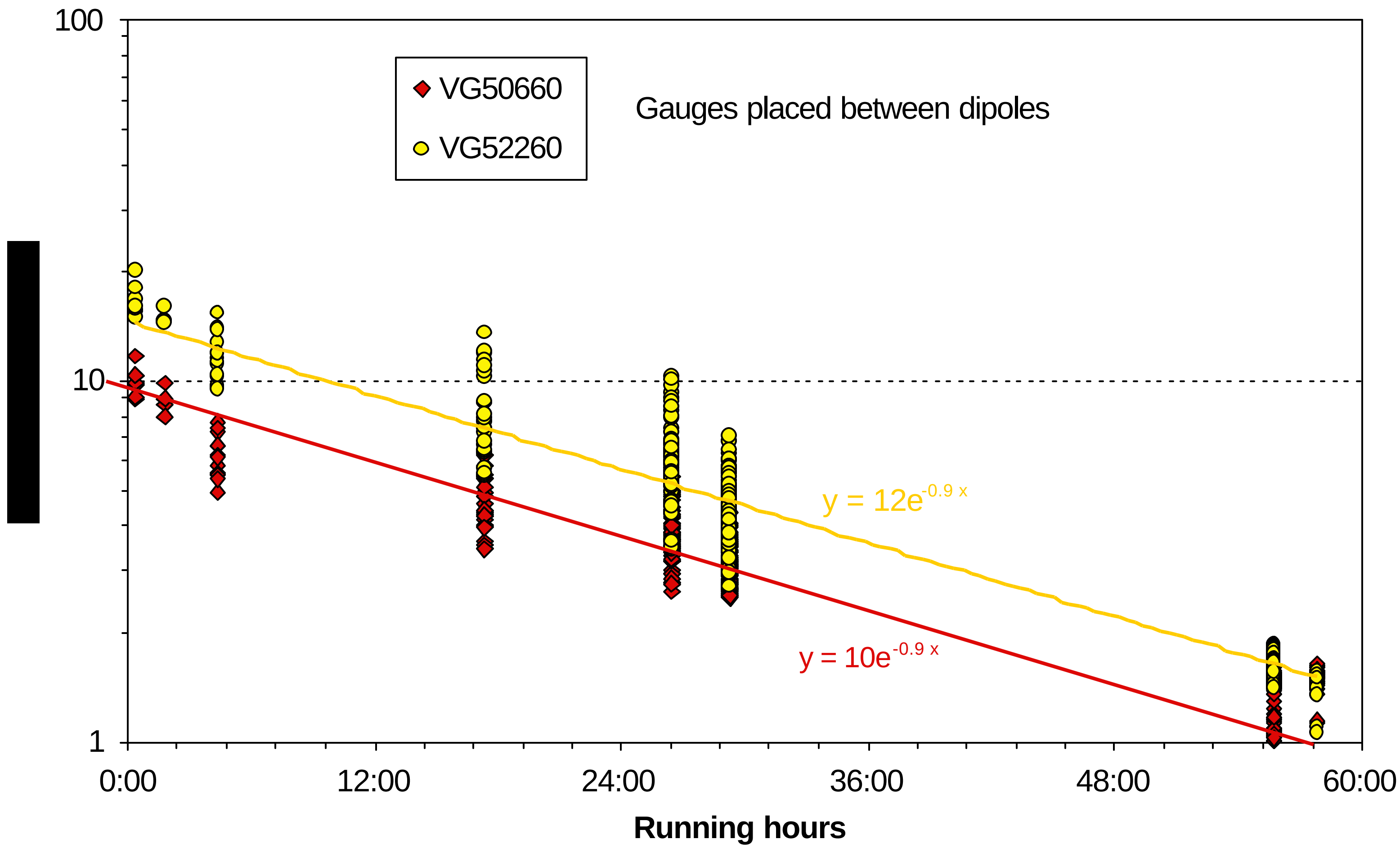
Electron stimulated molecular desorption



Beam Induced Multipacting
with an LHC-type beam in the SPS

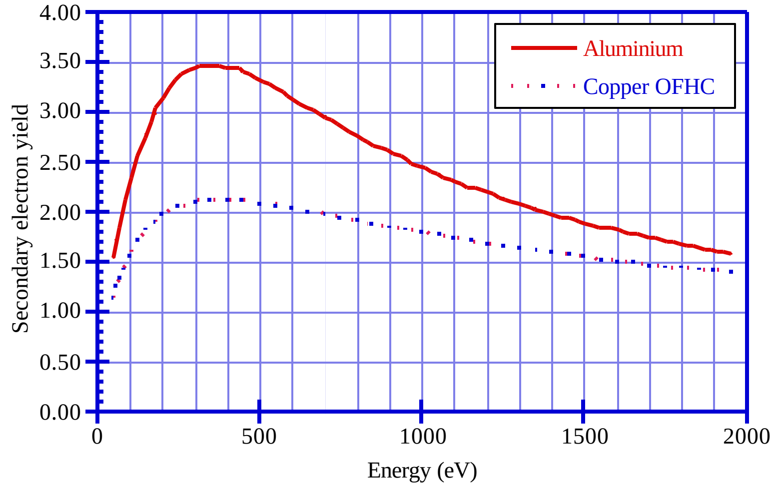


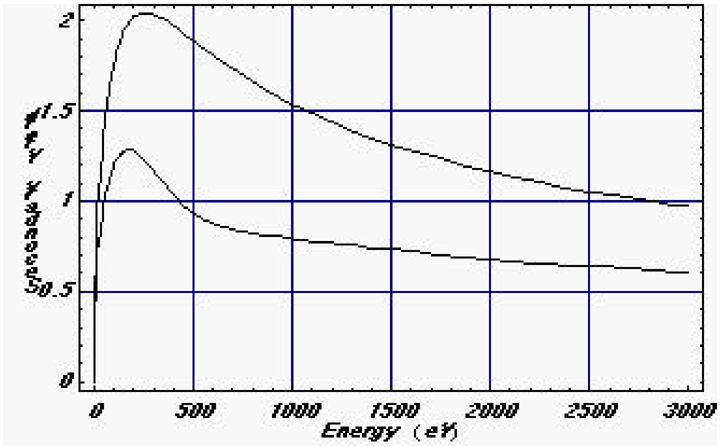
Reduction of BIM in the SPS with running time



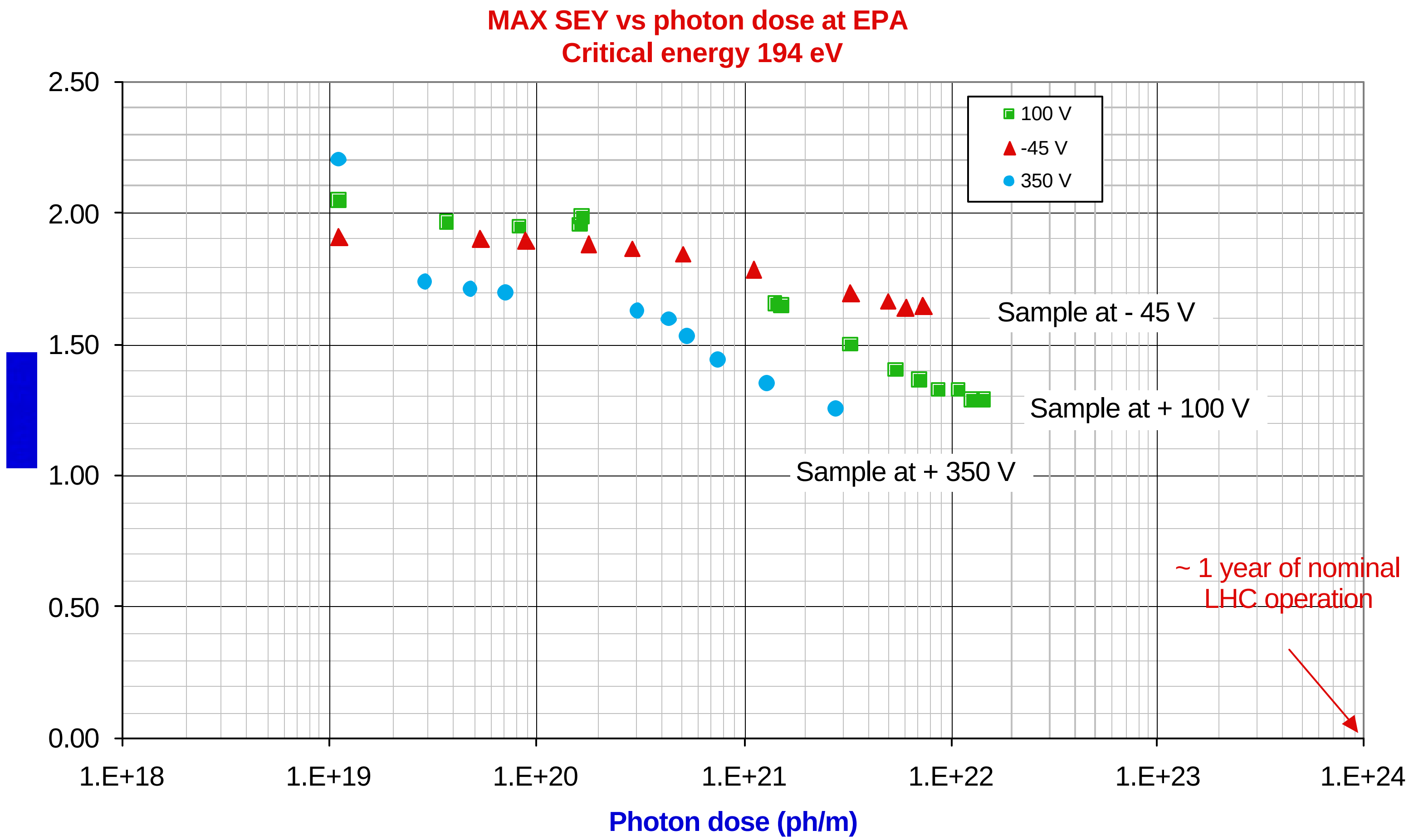
Secondary electron yield

- Secondary electron yield of technical copper and aluminium surfaces
- Due to dosing with electrons and photons, the yield decreases to between 1 to 1.4
- Secondary electron yield for Cu, initial values and after a photon dose of 1.5 10^{20} photons/m at 194 eV critical energy.
- E_{max} and δ_{max} are input for simulation





Reduction of the secondary electron yield by photon scrubbing



V. Baglin, LHC-VAC

Compilation of photoelectric yields and of photon reflectivities

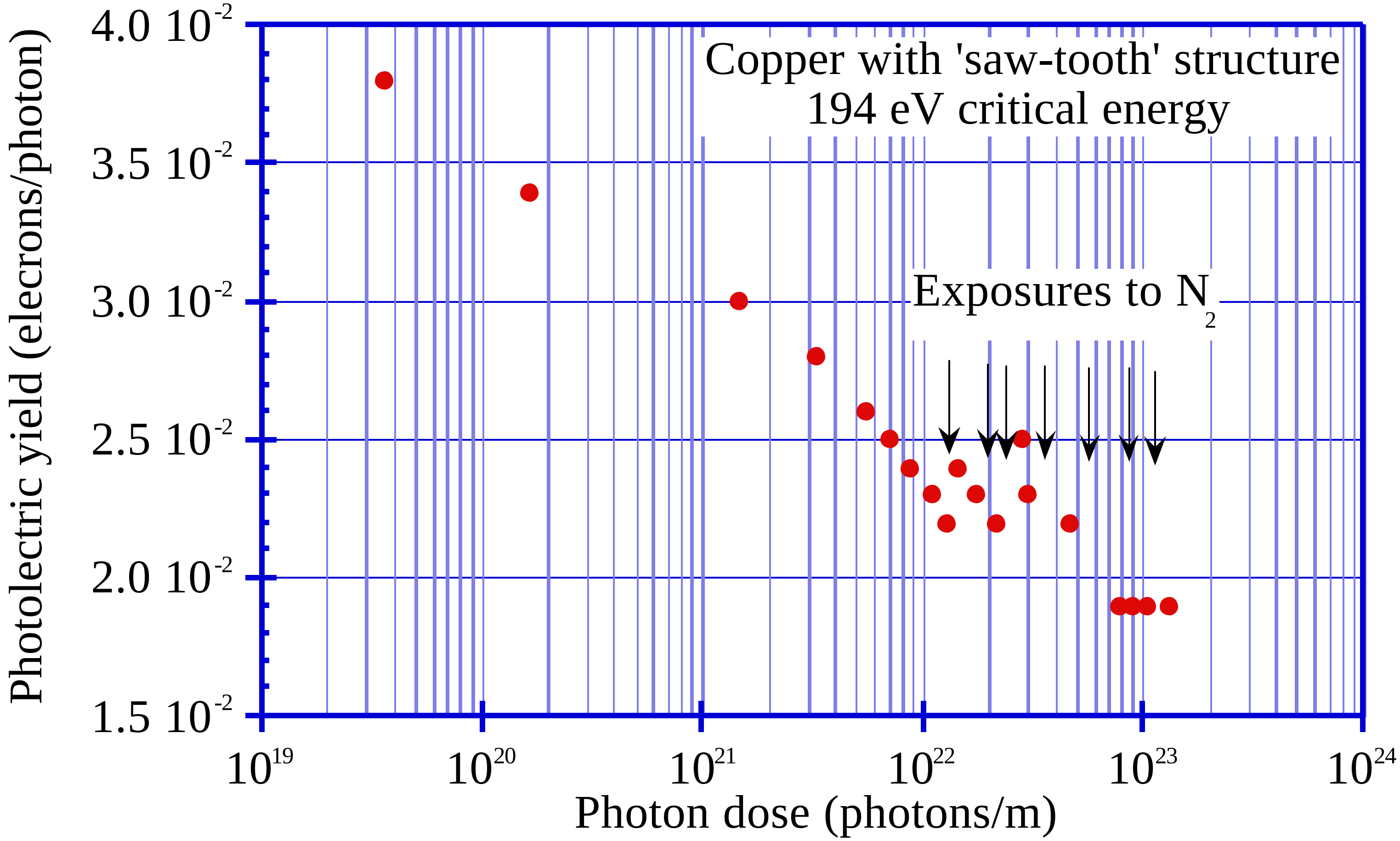
$$Y^{*}\,[\text{e.photon}^{-1}] = \frac{I/q}{\dot{\Gamma}\; F_{Collimator}\,(1-R)}\,\frac{L_{Hit}}{L_{Collected}}$$

$$\dot{\Gamma}\;[\text{photons.s}^{-1}] = 1.0029\;10^{15}\; I_{Beam}\,[\text{mA}]\; E_{Beam}\,[\text{GeV}]$$

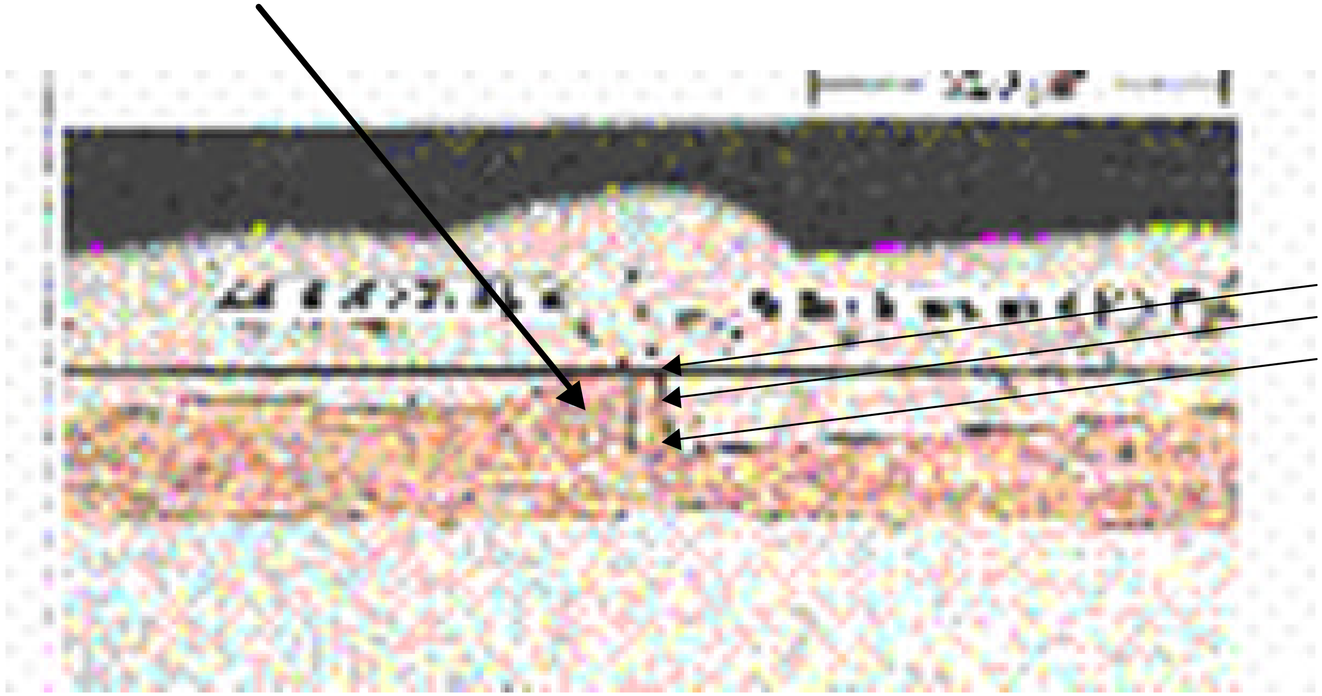
			308 MeV		500 MeV	
Date	Tube	status	R (%)	Y*(e/ph)	R (%)	Y*(e/Ph)
7/2/97	Cu roll bonded	Unbaked	80.9	0.114	77	0.318
8/28/97	Cu electroplated	Unbaked	5	0.084	6.9	0.078
9/17/97	Cu roll bonded air baked	Unbaked	21.7	0.096	18.2	0.180
11/13/97	Cu "macro" ribbed	Unbaked	1.8	0.053	-	-
11/14/97		150, 9 hours	1.3	0.053	1.2	0.052
11/17/97		150, 24 hours	1.3	0.040	1.2	0.040
11/18/97	Ti Zr	Unbaked	20.3	0.055	17.1	0.078
11/19/97		120, 12 hours	19.5	0.048	16.7	0.072
11/20/97		250, 9 hours	19.9	0.026	17.4	0.040
11/25/97		350, 10 hours	20.6	0.015	16.9	0.028
11/28/97		350, 10 h after saturation with 5E15 CO/cm2	20.7	0.016	-	-
12/1/99	Cu colaminated sawtooth	Unbaked	-	0.029	6	0.038

I beam current, R forward reflectivity of photons
Fcoll = 0.46 at 308 MeV and 0.65 at 500 MeV due to photon collimation
Lhit = 3.414 m, Lcollected = 0.5 m calculated

Reduction of photoelectric yield by photon scrubbing



“Saw-tooth” surface inprinted into Cu layer



Grazing angle of incidence of photons in the LHC arc: 2 to 3 mrad

Experimental setup in INP

Set-up to measure the distribution of reflected
Photons as well as photo electron production
from a test beam screen
In the presence of a magnetic dipole field

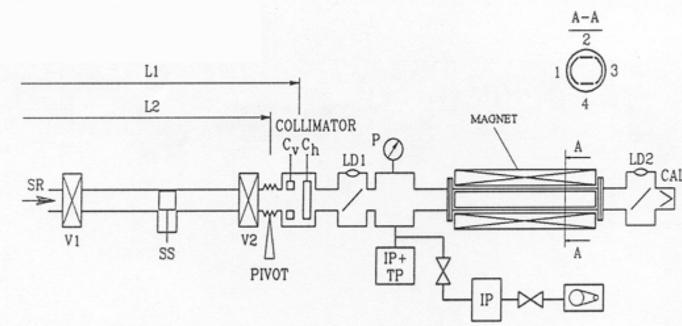


Figure 2: Set-up for measurements of the photon reflectivity and azimuthal photoelectron distribution in a magnetic field.

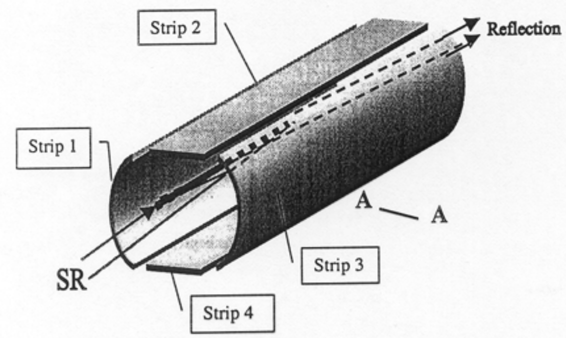


Figure 3: ample configuration for experiments of the photon reflectivity and azimuthal photoelectron distribution in a magnetic field.

Sample	Critical Energy E_c (eV)	Forward Scattered Reflection: R_e (by current)	Forward Scattered Reflection: R_W (by power)	Diffuse Reflectivity R_{dif}	Photon Adsorption R_l	$\frac{R_{dif}}{R_l + R_{dif}}$	Y (electron/ photon)
Smooth surface	20	0.67	—	0.04	0.29	0.13	0.03
Saw–tooth surface	49	0.035	—	0.22	0.74	0.23	0.049
	246	0.026	0.03	0.185	0.79	0.19	0.063

Reduction of the secondary electron yield by beam scrubbing in LHC

Required scrubbing time $$t = \frac{2p\, r_p\, D}{e\, Rg\, G}$$

D scrubbing dose [C/m^2]

r_p beam pipe radius

e unit charge

R photon reflectivity, (in magnetic field)

g photoelectric yield

Γ linear photon flux

Scrubbing dose for d_{max} <1.5 measured: 300 C m^{-2}

(N. Hilleret, B. Henrist)

LHC beam screen (ribbed wall and air baked copper):

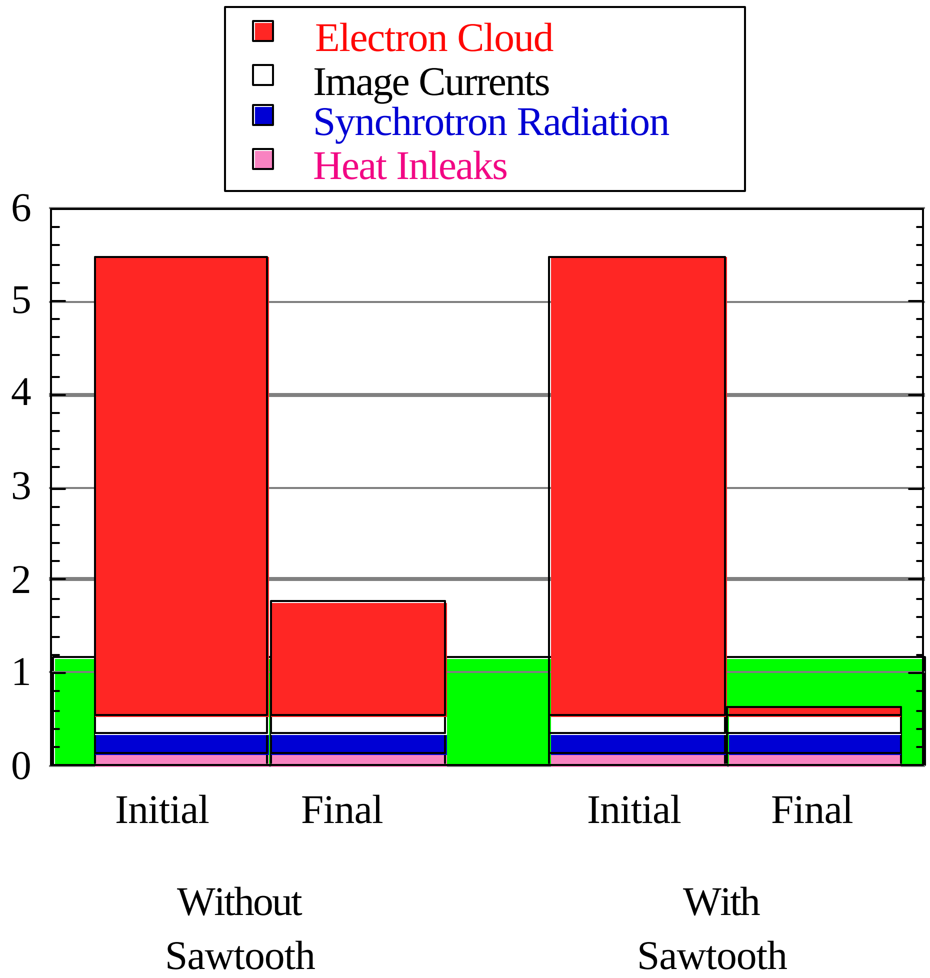
R ~ 0.02 and g ~ 0.1

Γ ~ 10^{17} photons s^{-1} m^{-1} nominal flux

time ~ 360 h, or few hours without magnetic field.

Question: Is this estimation in line with experience from existing e+ storage rings (KEK b-factory, PEP-2)?

Nominal heat loads on LHC beam screen



Summary for LHC

- Design of the LHC vacuum system is strongly influenced by s.r. effects.
- Primary and secondary desorption effects
- Total quantity of desorbed gas -> saturated vapour pressure
- Physisorbed gas molecules must be screened from effects of the beam (s.r. but also (photo-)electrons and ions)
- Temperature fluctuations of cryosorbing surfaces (beam screen) must be avoided or minimised
- Secondary desorption -> re-distribution of cryosorbed gas and important transient effects.
- S.R. produces large number of photoelectrons -> e-cloud effects.