# Implications of the Electron Cloud on the Design of the LHC Vacuum System

**O. Gröbner**

**Credits :**

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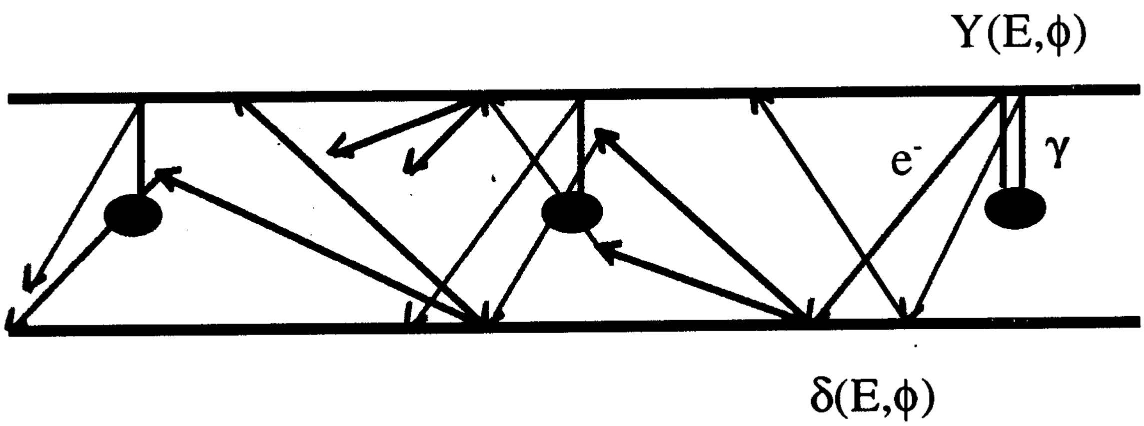
# Electron cloud generated heat load in the LHC beam screen



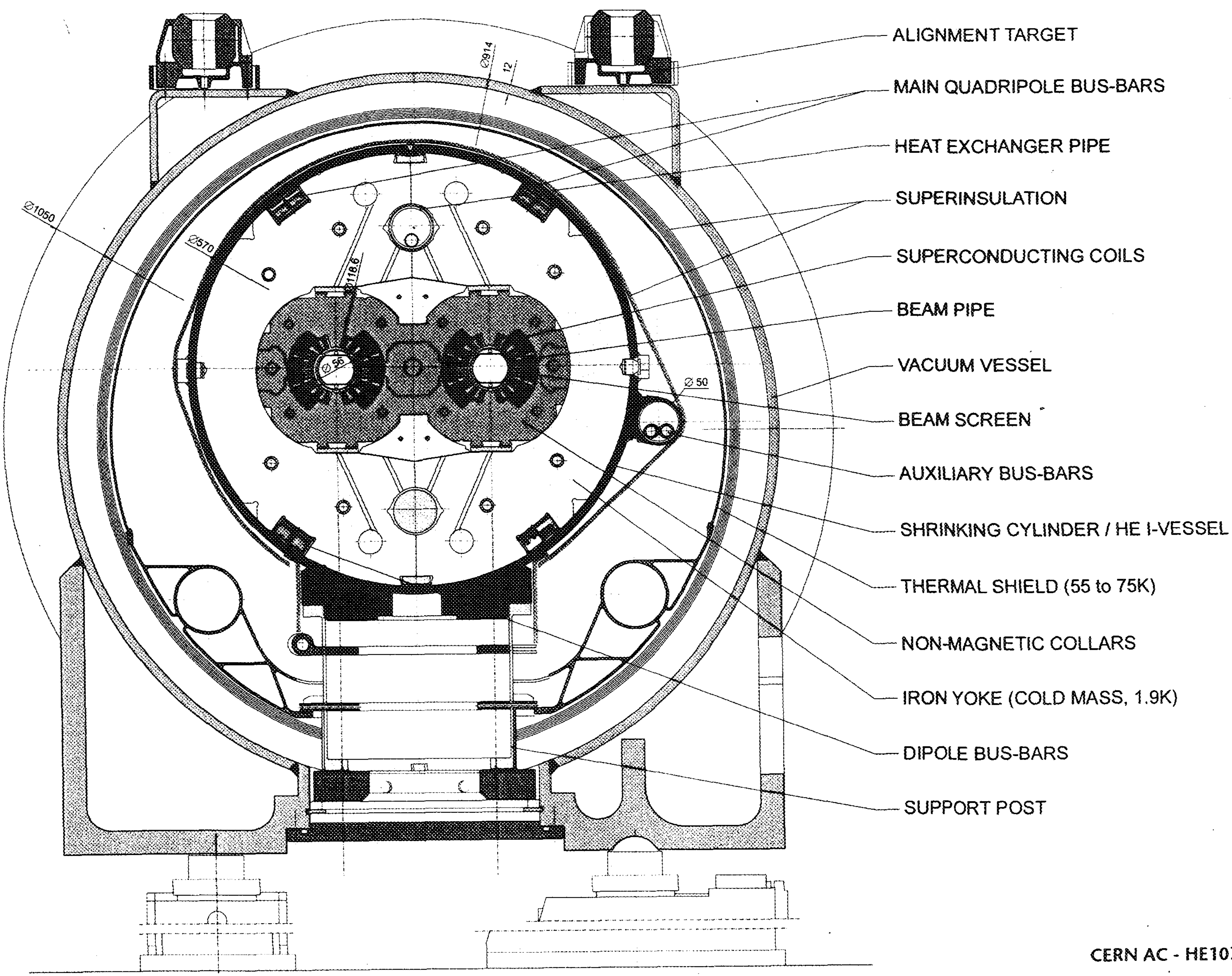

## Key parameters

- Synchrotron radiation intensity, $\gamma$
- $Y(E,\phi)$ photoelectric yield
- $\delta(E,\phi)$ secondary electron yield, $E_{max}$, $\delta_{max}$
- Energy distribution of secondary electrons
- Photon reflectivity (magnetic field)
- Beam screen shape and diameter
- Bunch intensity and spacing
- External fields (magnetic, electric, space charge)

## Gas load

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

# LHC DIPOLE : STANDARD CROSS-SECTION

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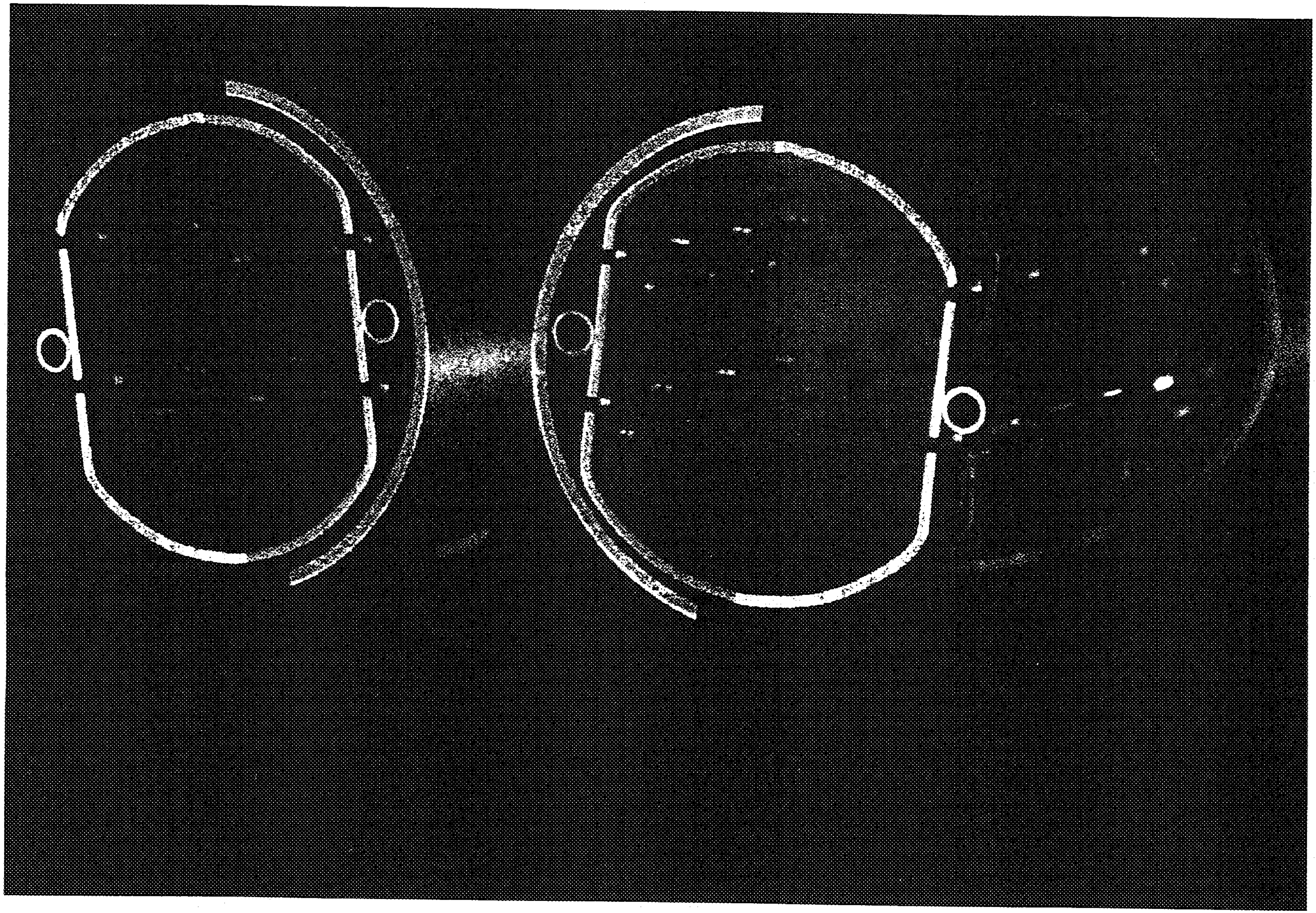
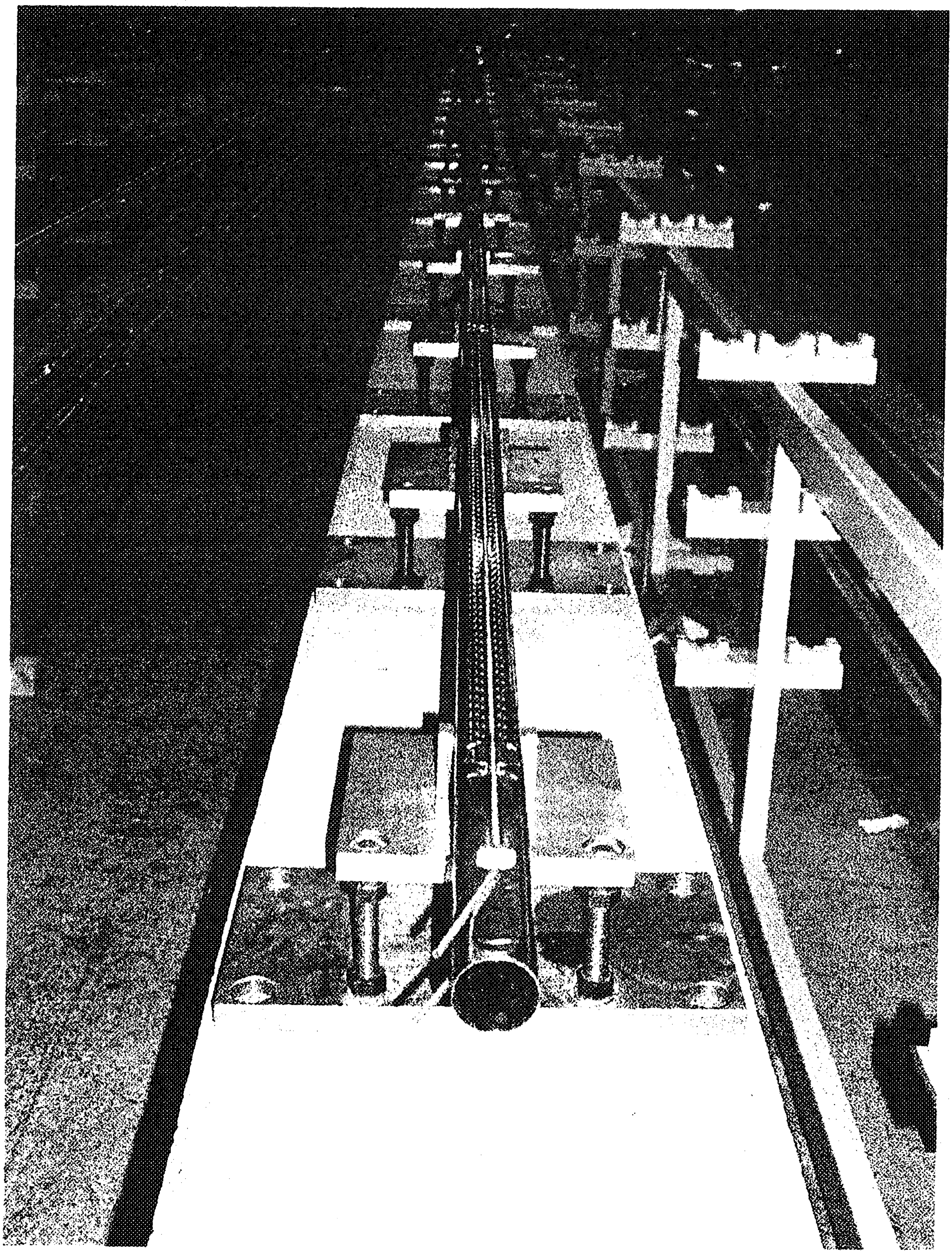
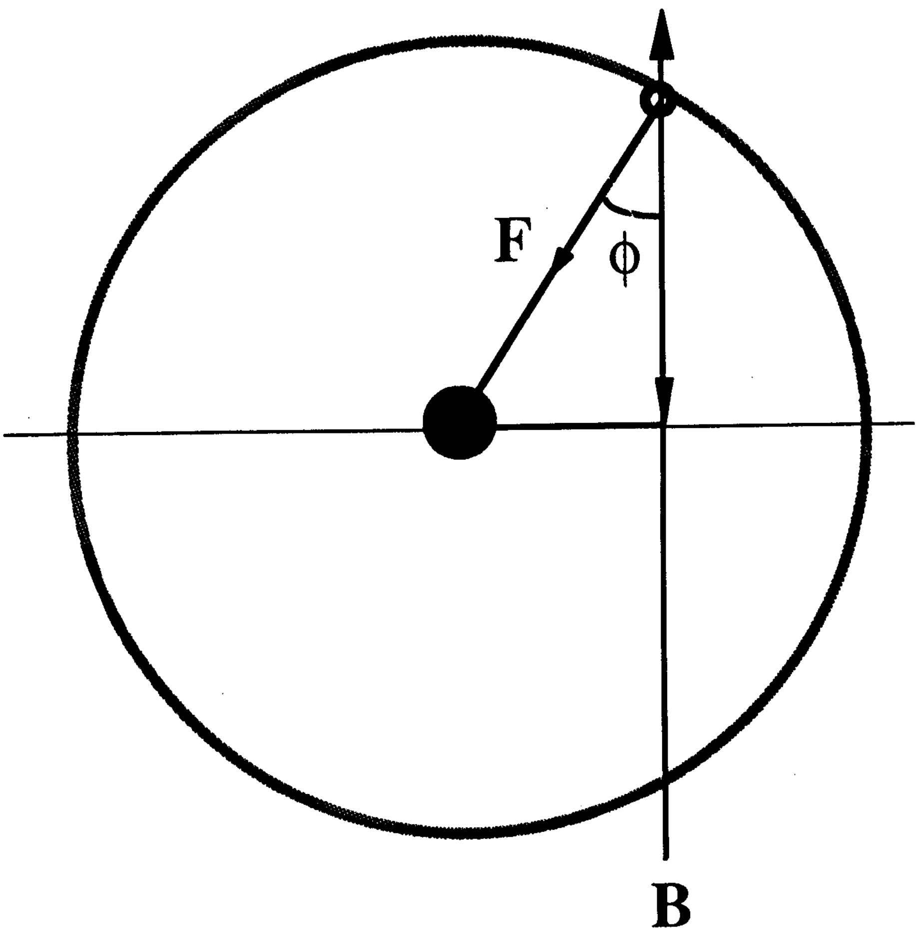




**Dipole beam screen for String2**

# Effect of the magnetic field in a dipole

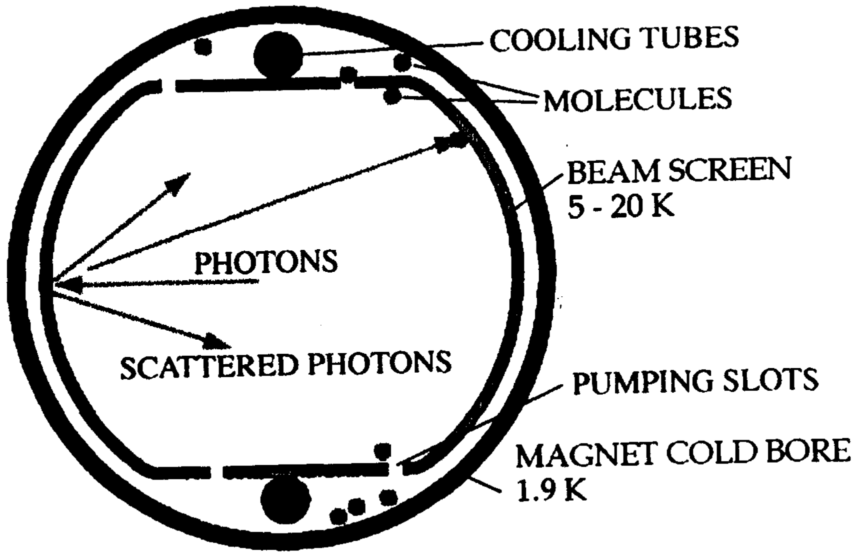



Averaged over $2\pi$, the projection of the kick in the direction of the magnetic field gives an energy transfer to the electrons which is 1/2 of the value in a field free region

The energy transfer perpendicular to the magnetic field is negligible -> the electron makes about 60 cyclotron periods during a bunch passage

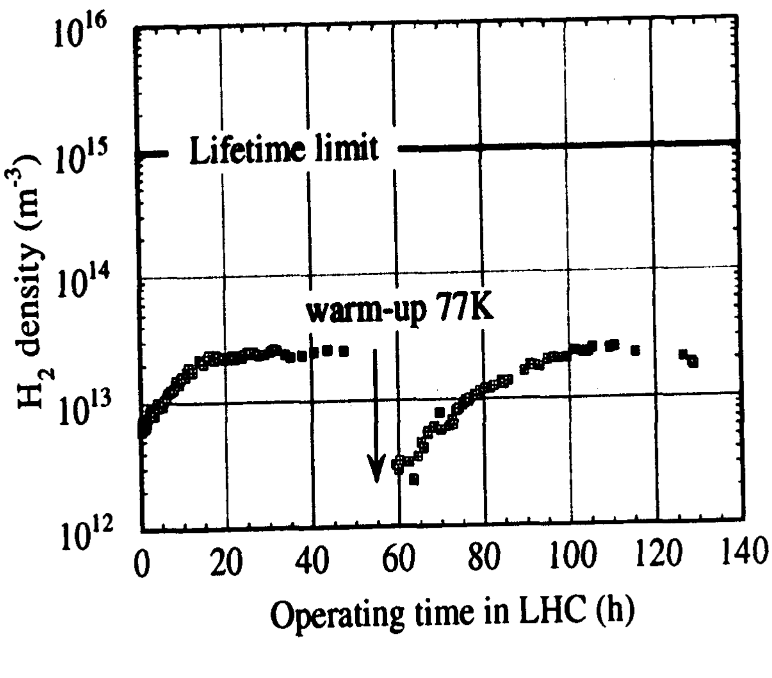
# LHC vacuum with synchrotron radiation.

Synchrotron radiation photons desorb strongly bound gas molecules which are cryosorbed and gradually accumulate on the cold beam screen.




Scattered/reflected photons re-desorb these molecules at a rate increasing with coverage, leading in turn to an increasing gas density (pressure).

The increase in pressure due to 'recycling' of molecules increases the probability for gas to escape through the pumping slots and to be permanently cryosorbed on the 1.9K cold bore. This effect stabilises the gas density in the beam pipe to a safe value.



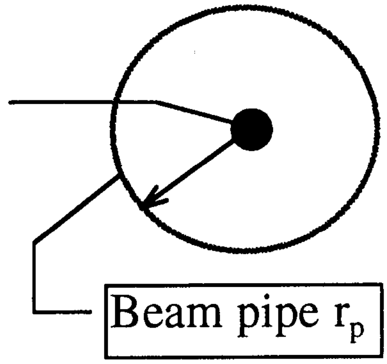

Without pumping holes, the beam screen would have to be warmed-up periodically to pump-out condensed gas.

Test run at INP in Novosibirsk, scaled to LHC parameters and for initial operation at ~1/10 of the nominal beam current illustrating the effect of recycling of gas and warming-up of the beam screen.

see PAC 97

# Some basic equations

$$E(r) = \frac{\lambda}{2\pi\varepsilon_o r} \quad \text{with} \quad \boxed{\lambda = \frac{e N_b}{c\tau}}$$




the momentum transfer

$$\Delta p = e E \tau = \frac{e^2 N_b}{2\pi\varepsilon_o c r}$$

hence independent of the bunch length

The velocity due to this momentum transfer is

$$\Delta v = \frac{\Delta p}{m} = \frac{e^2 N_b}{2\pi\varepsilon_o m c r} = 2c\, r_e \frac{N_b}{r}$$

introducing the classical electron radius

$$r_e = \frac{e^2}{4\pi\varepsilon_o mc^2} = 2.8\ 10^{-15}\ \mathrm{m}$$

The transit time condition requires

$$\frac{2r_p}{v} = t_{bb}$$

and introducing the distance between successive bunches

$$L_{bb} = c\, t_{bb}$$

gives a very simple relation

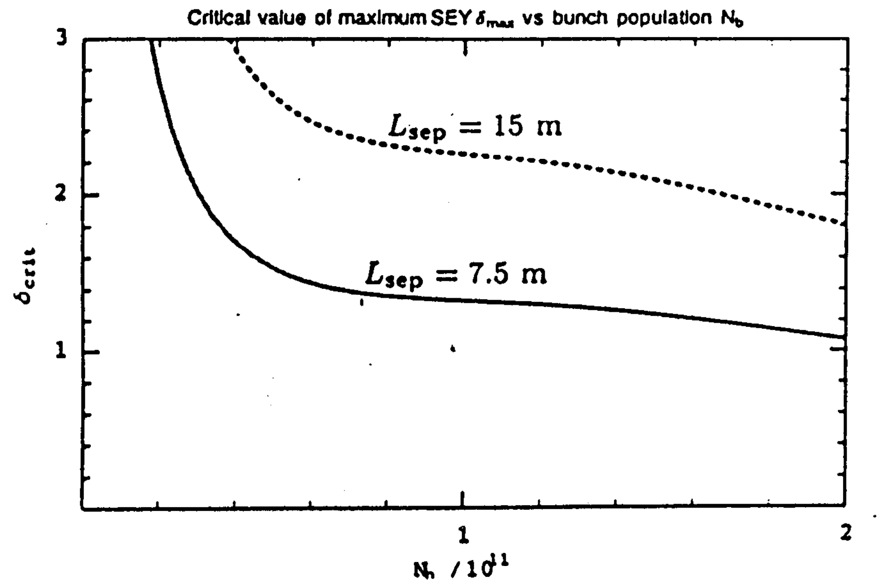
$$N_b = \frac{r_p^2}{r_e L_{bb}} \qquad (\sim \tfrac{1}{3} \text{ of LHC})$$

The energy resulting from the kick of a bunch is

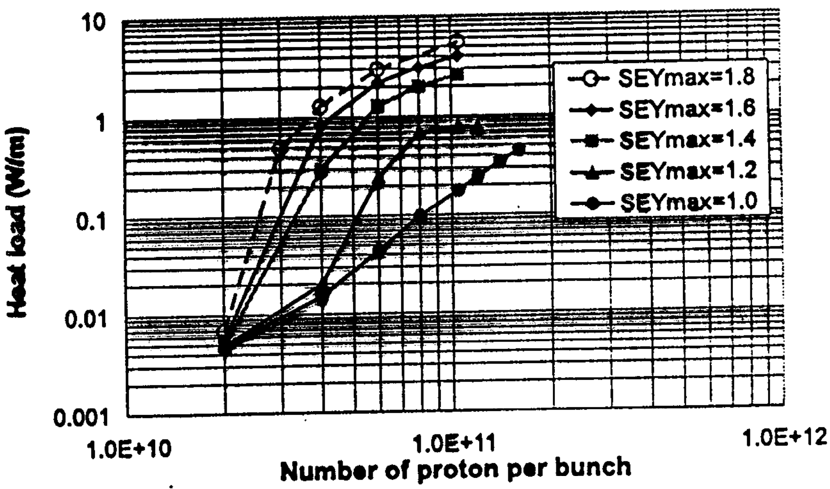
$$\Delta W = \frac{\Delta p^2}{2m}$$

or

$$\Delta W = 2\frac{mc^2}{e} r_e^2 \left(\frac{N_b}{r}\right)^2 \quad (eV)$$




LHC-PR 166




PAC-99

$\delta_{ye} = 0.2$
$R = 0.1$ → { 0.05 assumed for baseline, ribbed; 0.05 }

hence heatload should be reduced by a factor 8

INT experiment

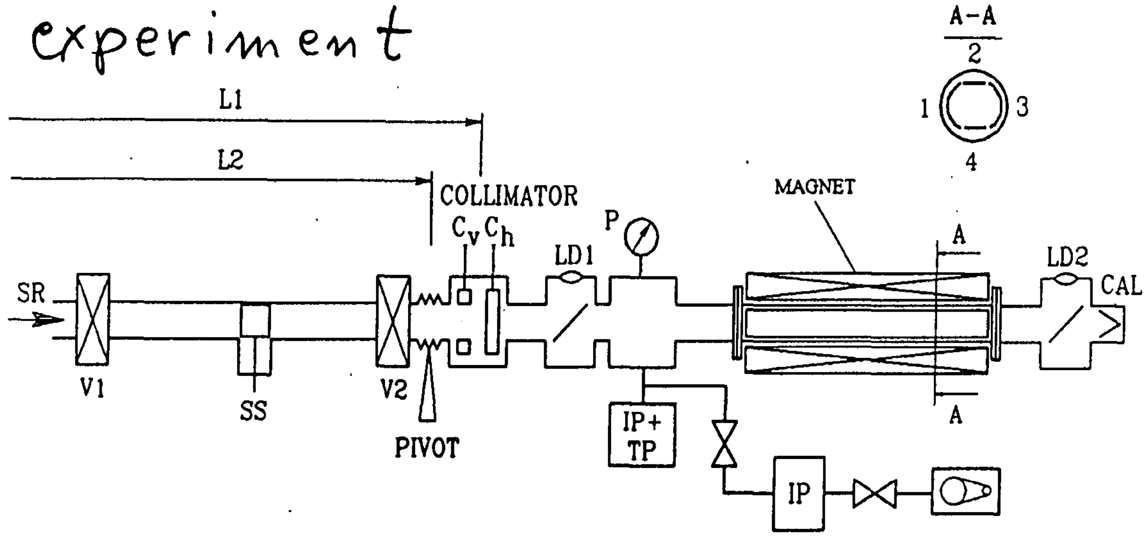



**Figure 2: Set-up for measurements of the photon reflectivity and azimuthal photoelectron distribution in a magnetic field.**

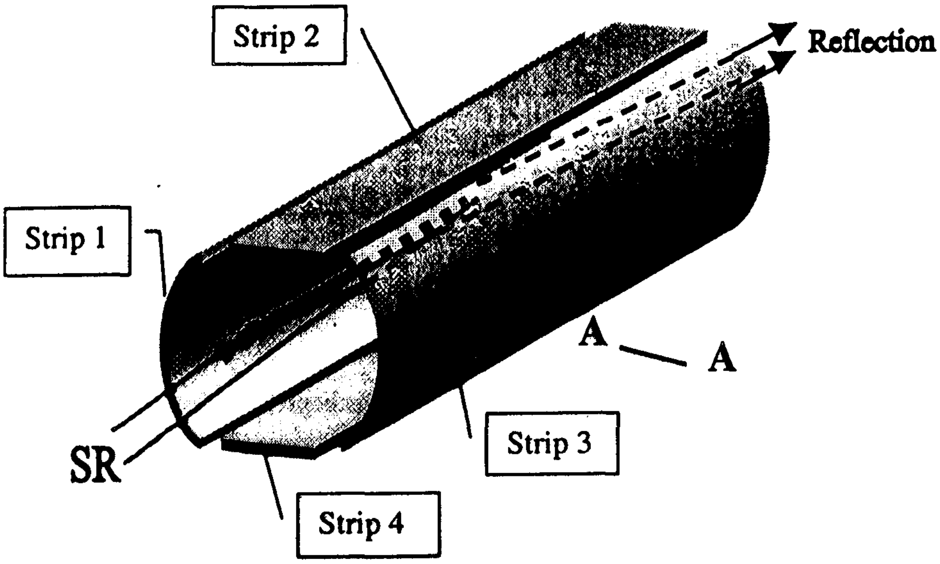
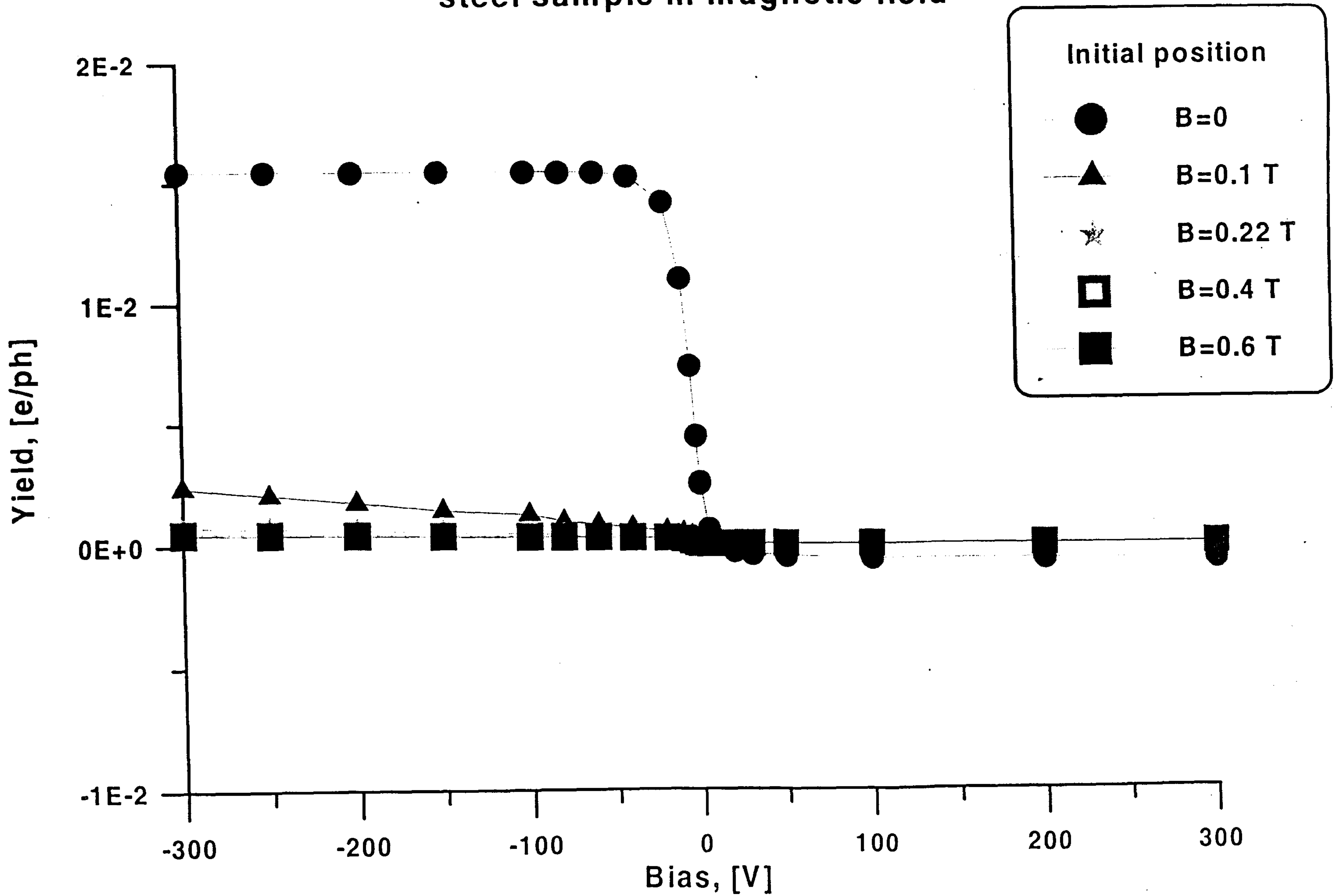



**Figure 3: ample configuration for experiments of the photon reflectivity and azimuthal photoelectron distribution in a magnetic field.**

| Sample | Critical Energy $E_c$ (eV) | Forward Scattered Reflection | | Diffuse Reflectivity $R_{dif}$ | Photon Adsorption $R_l$ | $\frac{R_{dif}}{R_l + R_{dif}}$ | Y (electron/ photon) |
|---|---|---|---|---|---|---|---|
| | | $R_e$ (by current) | $R_W$ (by power) | | | | |
| 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 |

EVC-6 Lyon Dec. 1999

Exp. 2.2. Photoelectron emission from copper laminated stainless steel sample in magnetic field



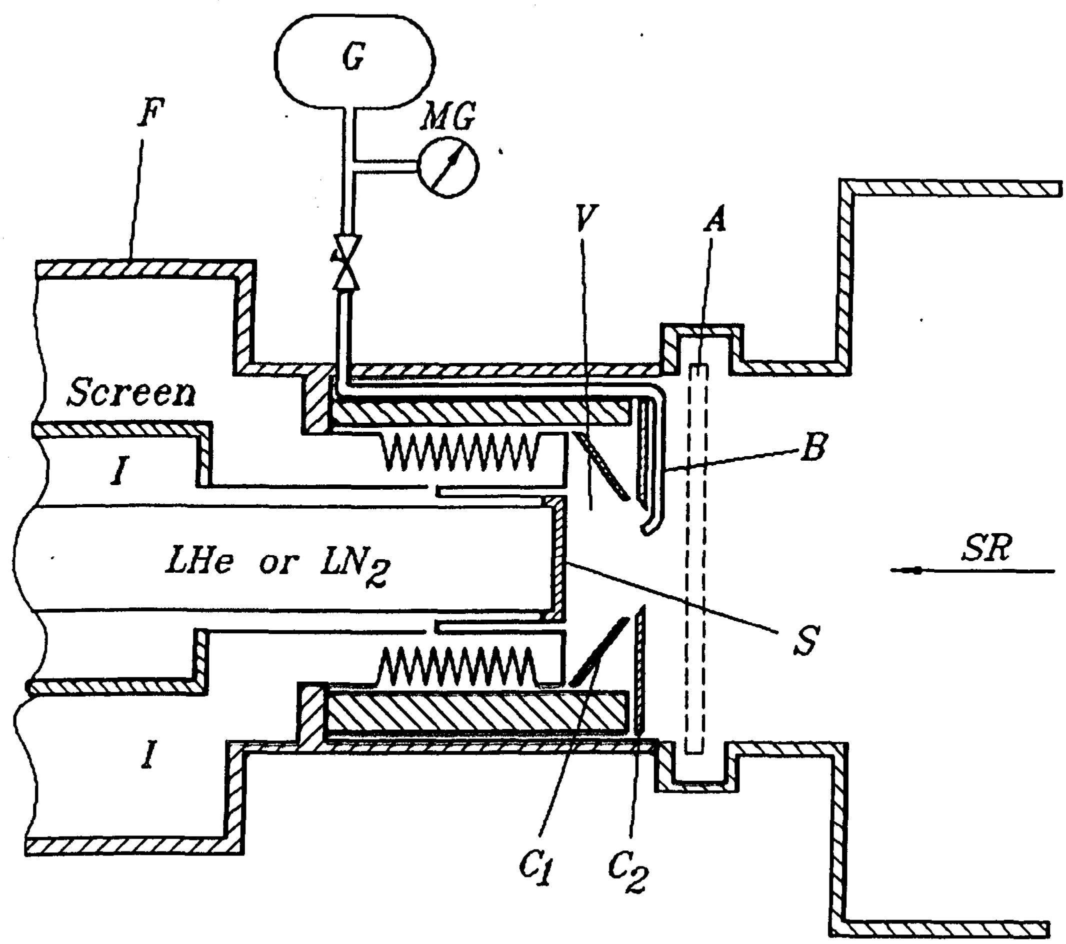
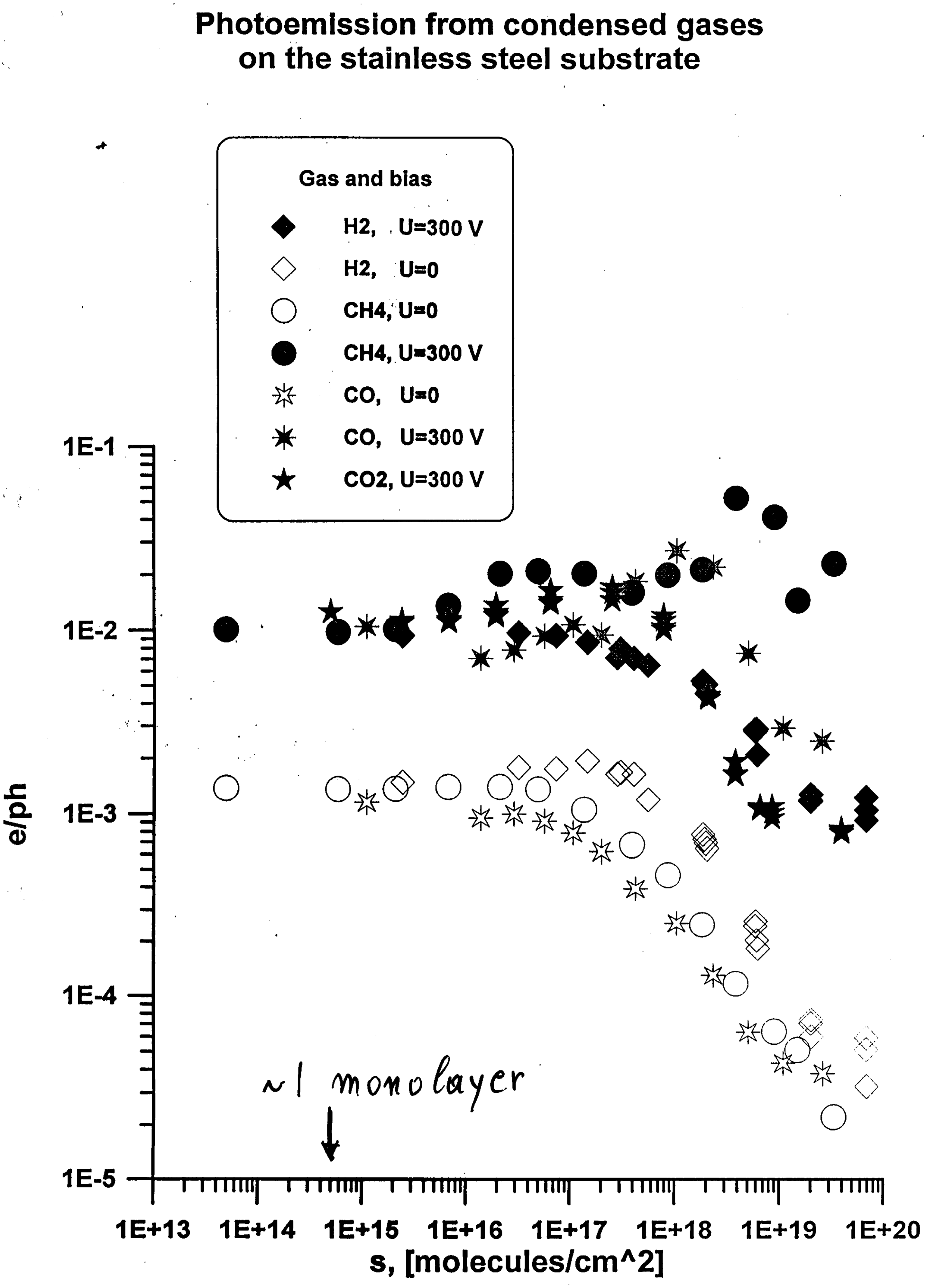
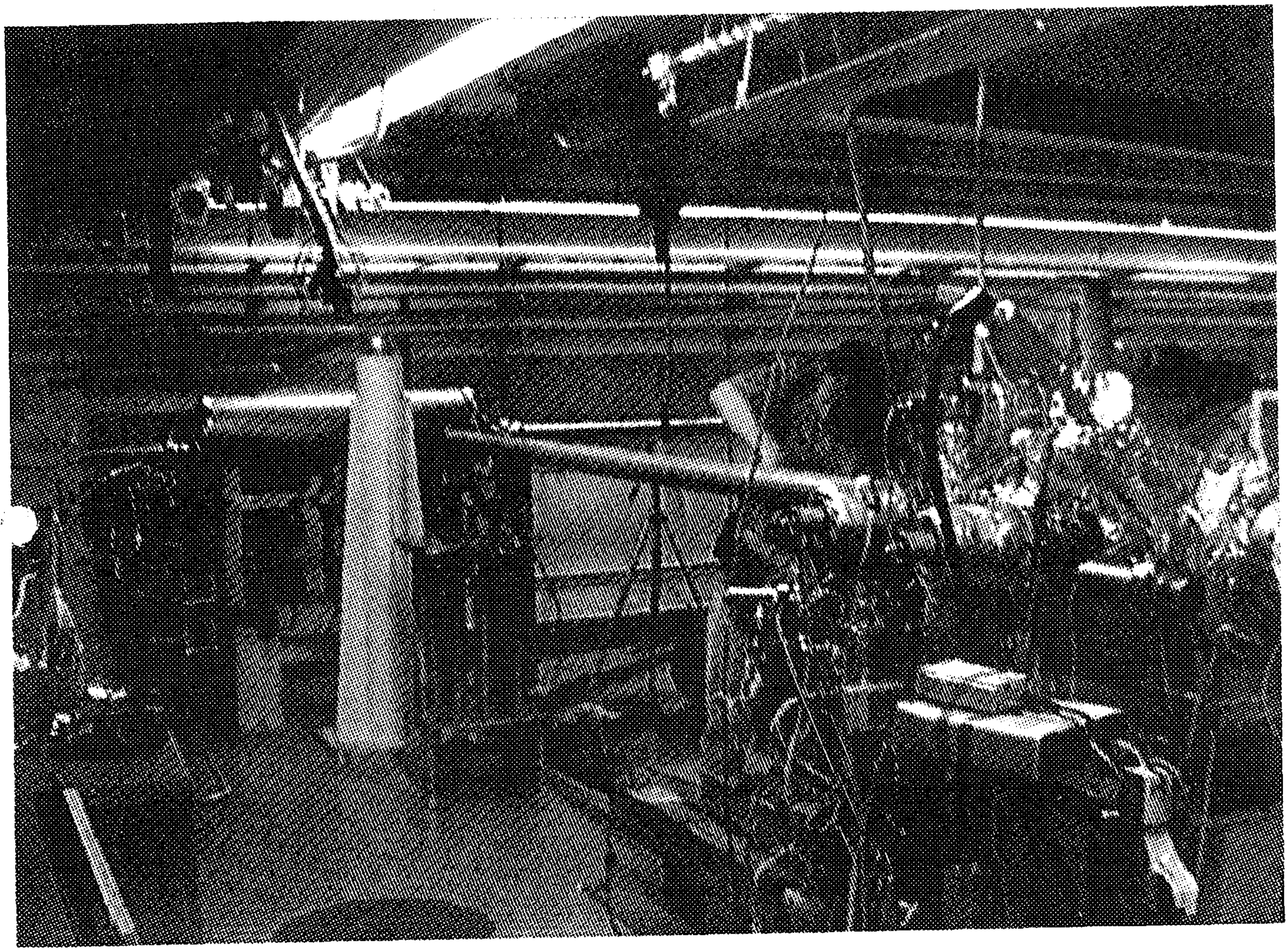
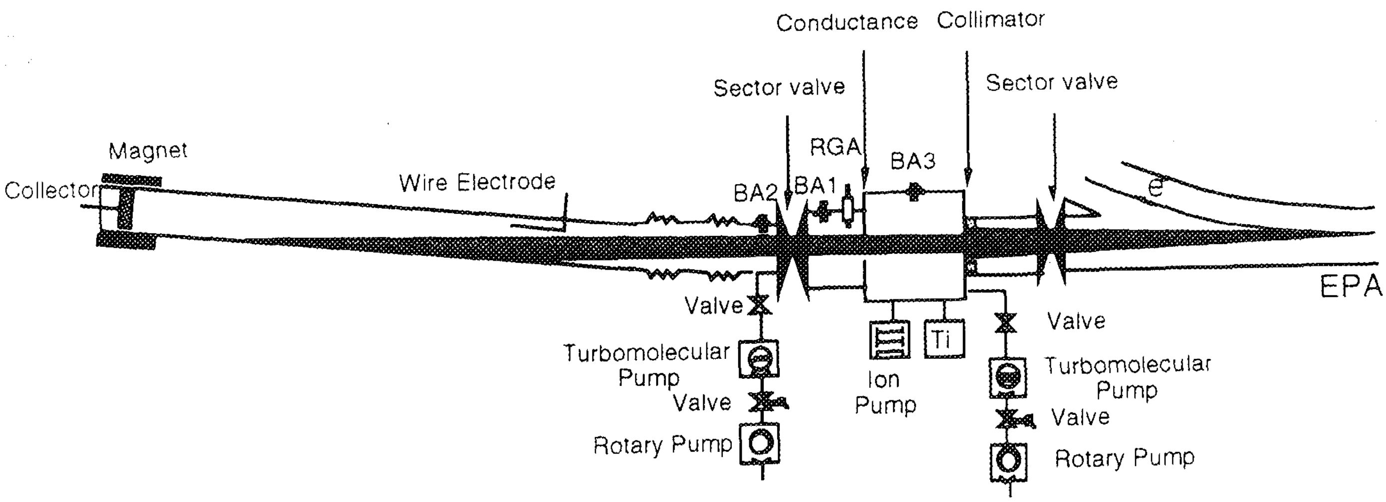



Figure 1. The experimental set-up on the synchrotron radiation beam line. *F* is the cryostat, *I* is the isolating vacuum, *V* is the experimental volume which can be separated from the beam line with the valve *A* shown in the closed position. The membrane gauge *MG* measures the gas pressure in the volume *G* which is injected via the pipe *B* and condensed onto the substrate *S* at cryogenic temperature. $C_1$ and $C_2$ are the insulated collector electrodes.



Photoemission from condensed gases
on the stainless steel substrate
Gas and bias
H2, U=300 V
H2, U=0
CH4, U=0
CH4, U=300 V
CO, U=0
CO, U=300 V
CO2, U=300 V
1E-1
1E-2
1E-3
1E-4
1E-5
e/ph
~1 monolayer
1E+13
1E+14
1E+15
1E+16
1E+17
1E+18
1E+19
1E+20
s, [molecules/cm^2]




Conductance
Collimator
Sector valve
Sector valve
Magnet
RGA
BA3
Collector
Wire Electrode
BA2
BA1
e
EPA
Valve
Turbomolecular Pump
Valve
Rotary Pump
Ion Pump
Ti
Valve
Turbomolecular Pump
Valve
Rotary Pump

# EPA photoelectrons Compilation

au 28/11/97

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

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

I photoyield current [A]
q = 1.602E-19 C

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

$F_{Collimator}$ = 46 % at 308 MeV
= 65 % at 500 MeV

$L_{Hit}$ = 3.414 m

$L_{Collected}$ = 0.500 m (computed)

R = reflection

# RIBBED COPPER SURFACE FOR LHC BEAM SCREEN

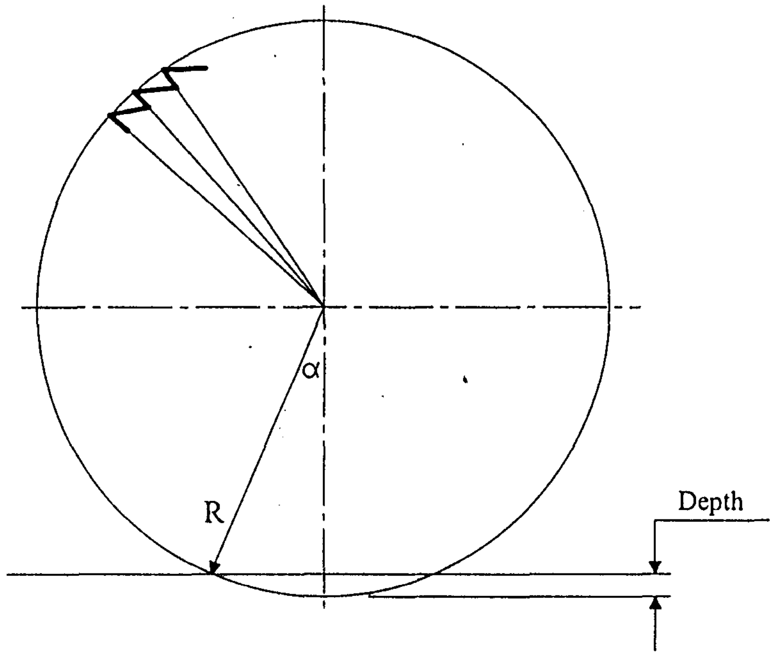



Figure 1

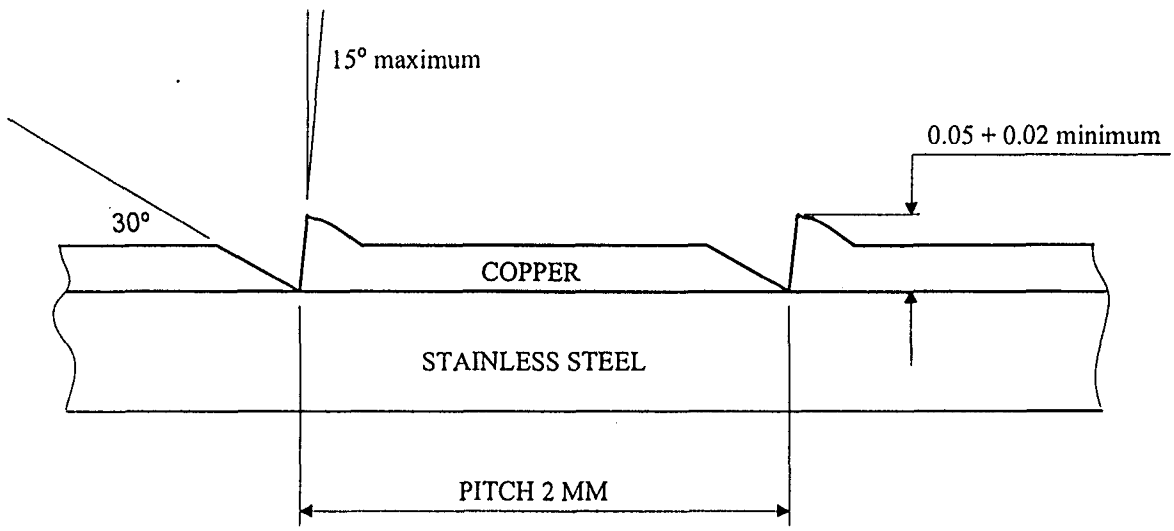



Figure 2

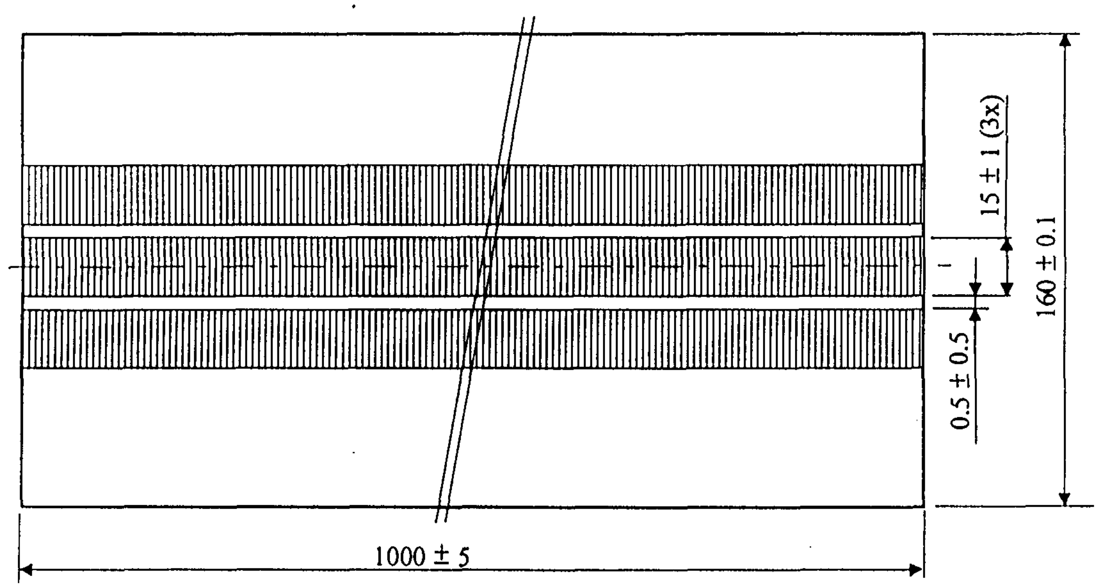


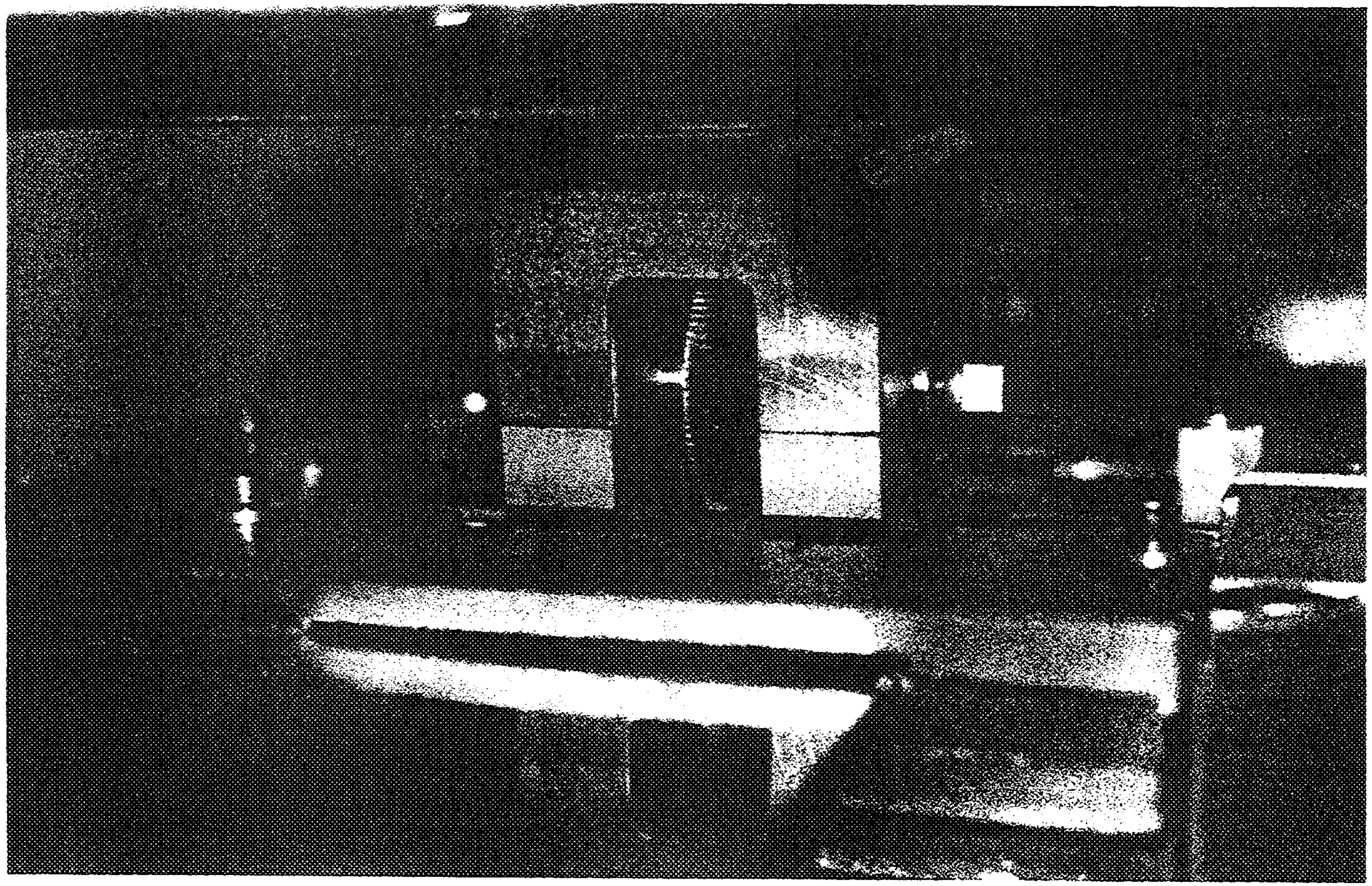

Figure 3


N. Kos
02 - 09 - 98

Ian Collins LHC/VAC

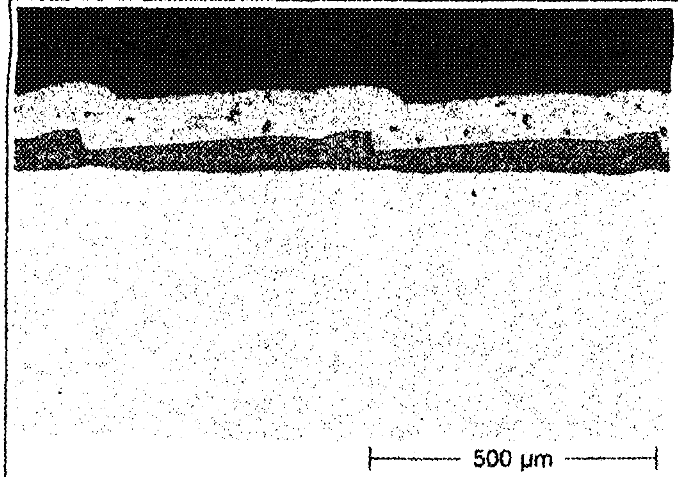
LHCMAC #8

Heraeus



W. C. Heraeus GmbH & Co. KG

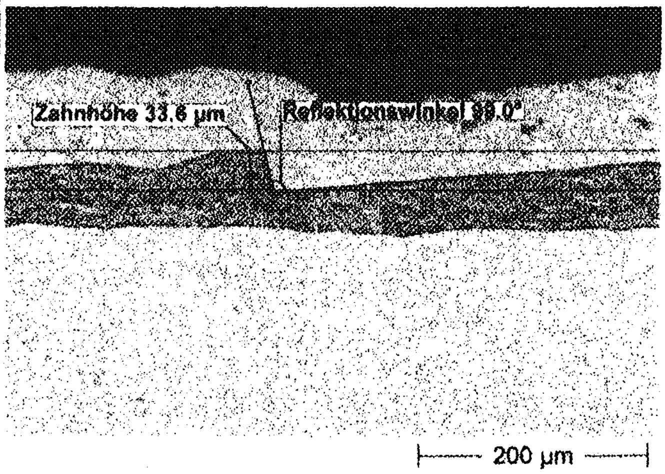
| | | |
|---|---|---|
| Heraeus<br>WCH-GBM-TCS<br>Hellenkamp<br>Tel.: 06181/35-493<br>Fax. 06181/35-5318 | Material: Stahl - Cu Band<br>Allgemeines: CERN - Profilierungsversuch<br>Ätzmittel: Au-Ätzmittel | **Metallographie**<br>P00361<br>22.06.1999<br>135 80 008<br>H.Eisentraut |




906P0467

Probe vom 17.06.99 - Links

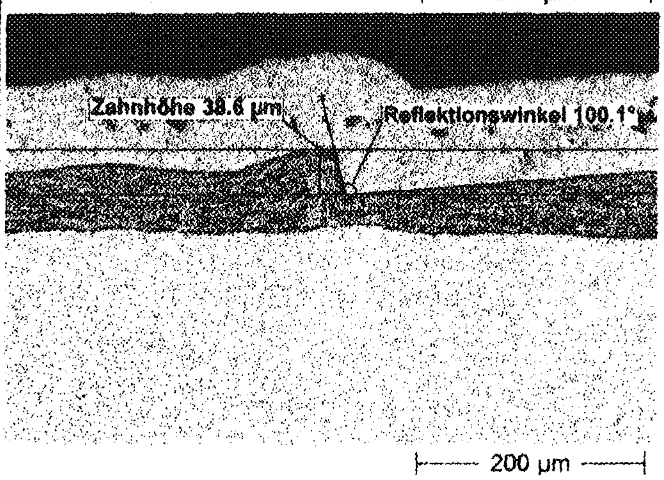
100 : 1




906P0468

Probe vom 17.06.99 - Links

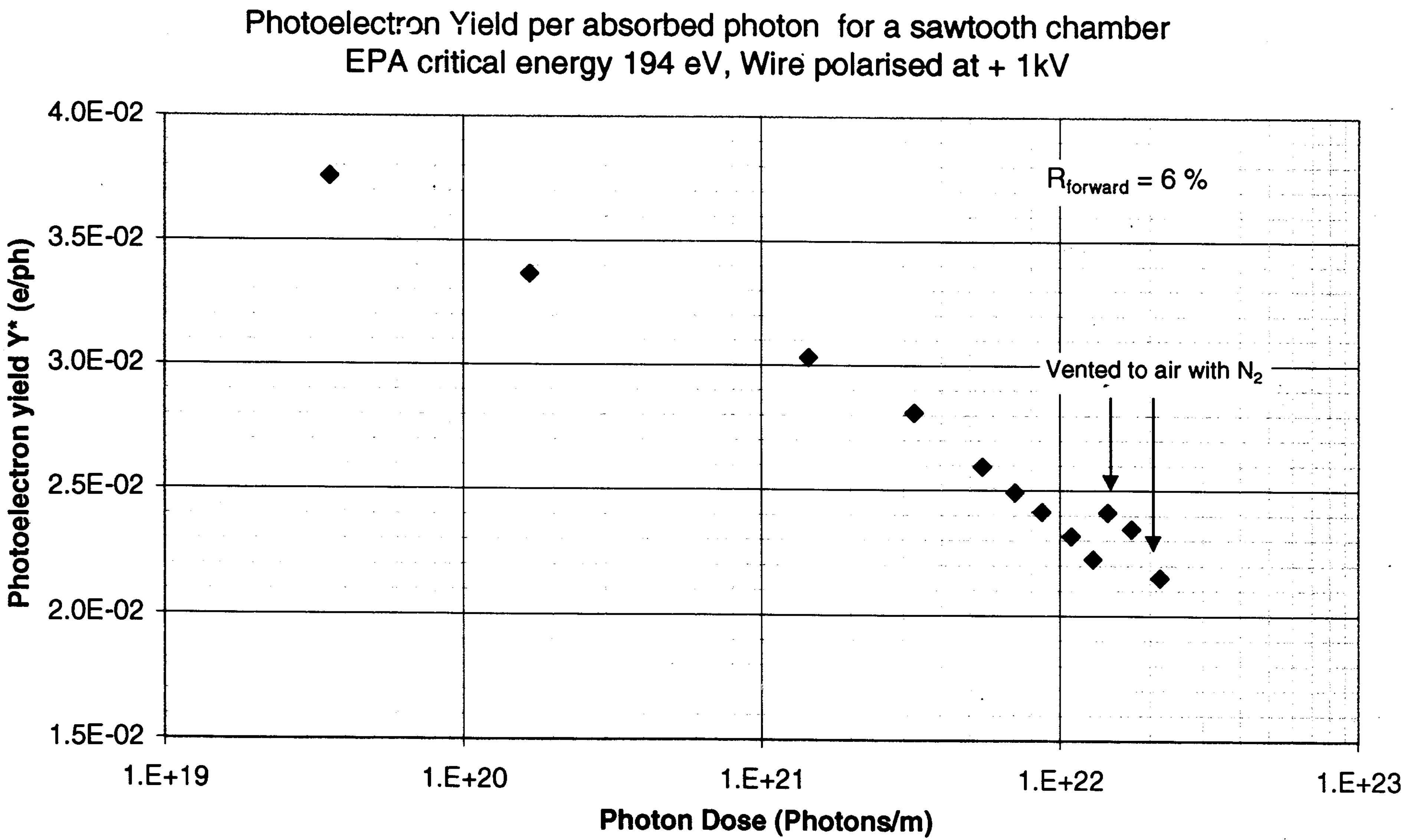
200 : 1




906P0471

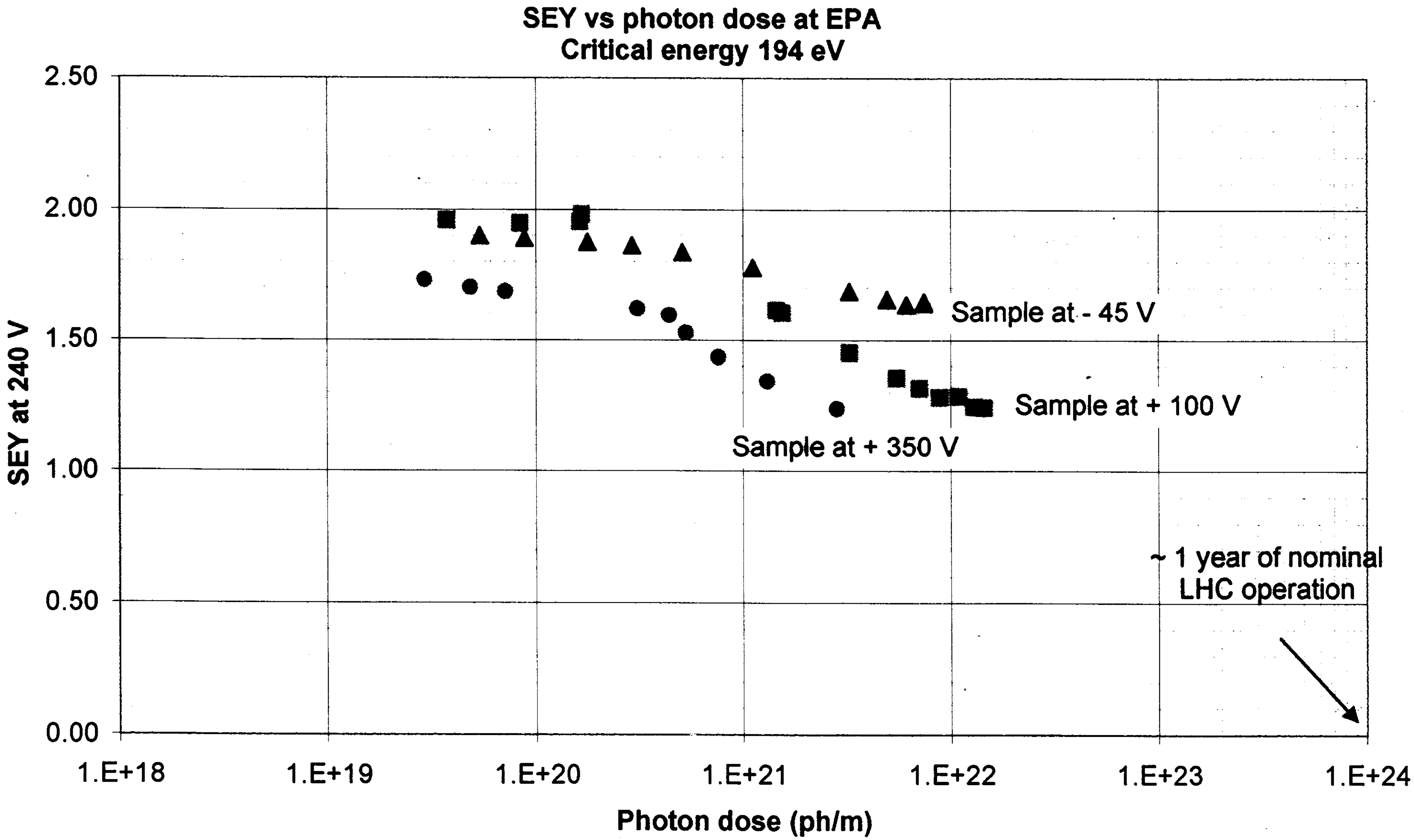
Probe vom 17.06.99 - Links

200 : 1

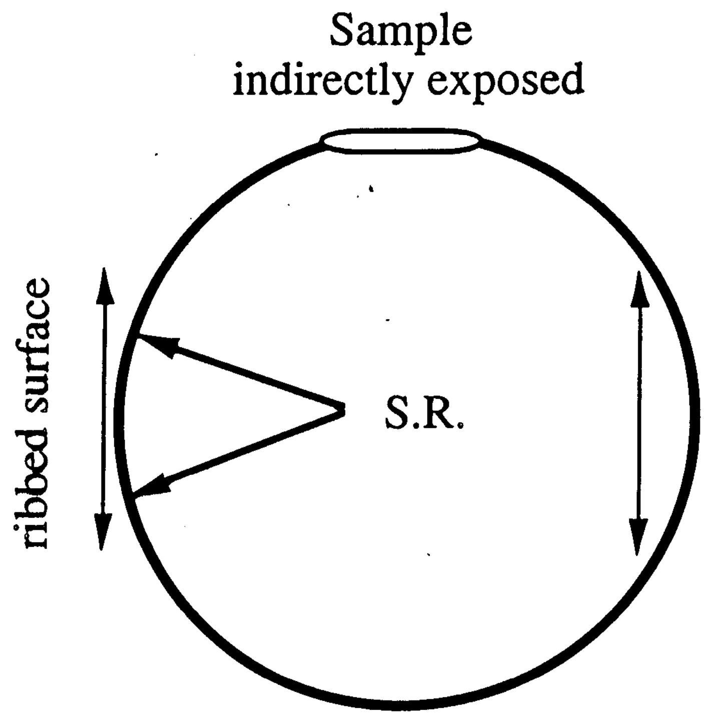





V. Baglin et al.


SEY vs photon dose at EPA
Critical energy 194 eV
SEY at 240 V
2.50
2.00
1.50
1.00
0.50
0.00
1.E+18
1.E+19
1.E+20
1.E+21
1.E+22
1.E+23
1.E+24
Photon dose (ph/m)
Sample at - 45 V
Sample at + 100 V
Sample at + 350 V
~ 1 year of nominal
LHC operation

## Beam scrubbing time for the LHC arc scaled from EPA test




S.R. hits the copper test chamber along a ribbed surface

SEY as a function of the photon dose (indirectly exposed sample with bias)

Scrubbing effect scales with the specific surface area : factor ~ 2 less for the beam screen.

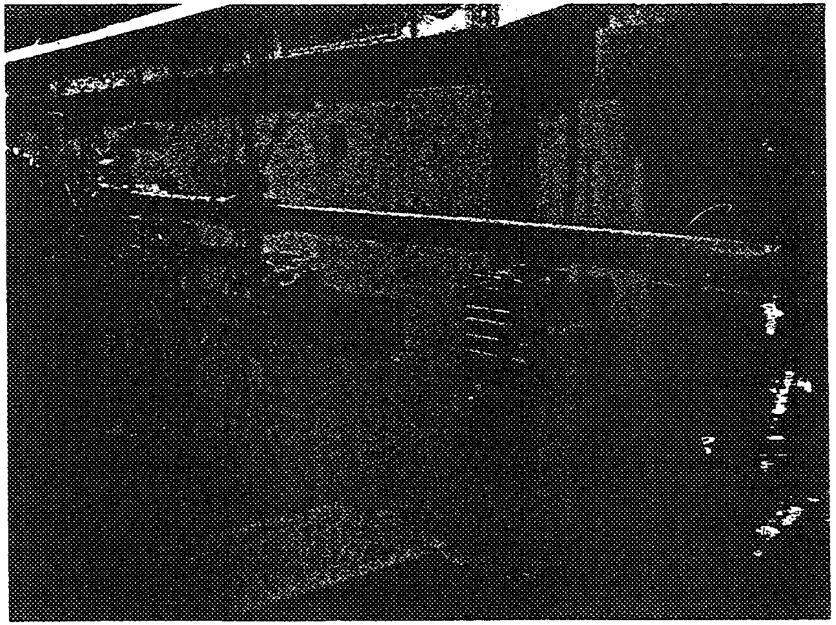
The sample bias simulates the average electron energy for the cloud. However, the biased sample may collect more photo-electrons than a grounded surface.

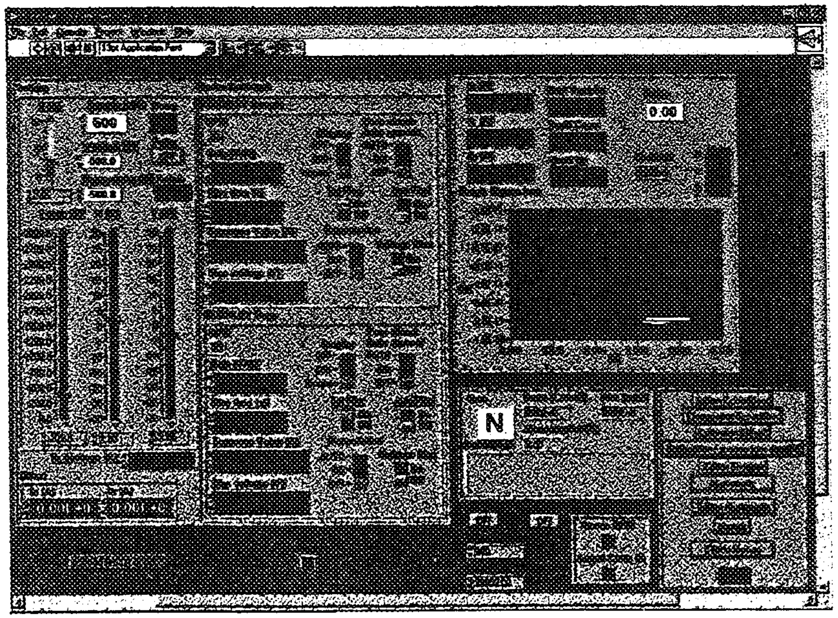
At 350 V bias the clean-up is ~5 times faster as compared to 100 V.

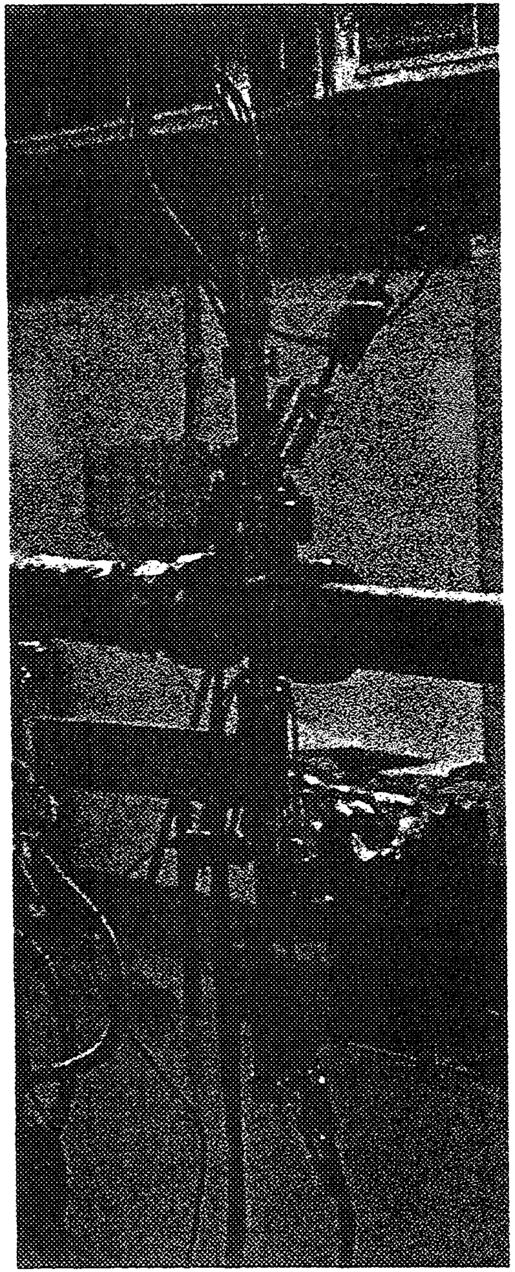
**$10^{22}$ photons/m in EPA equivalent to ~ 7 Ah in LHC.**

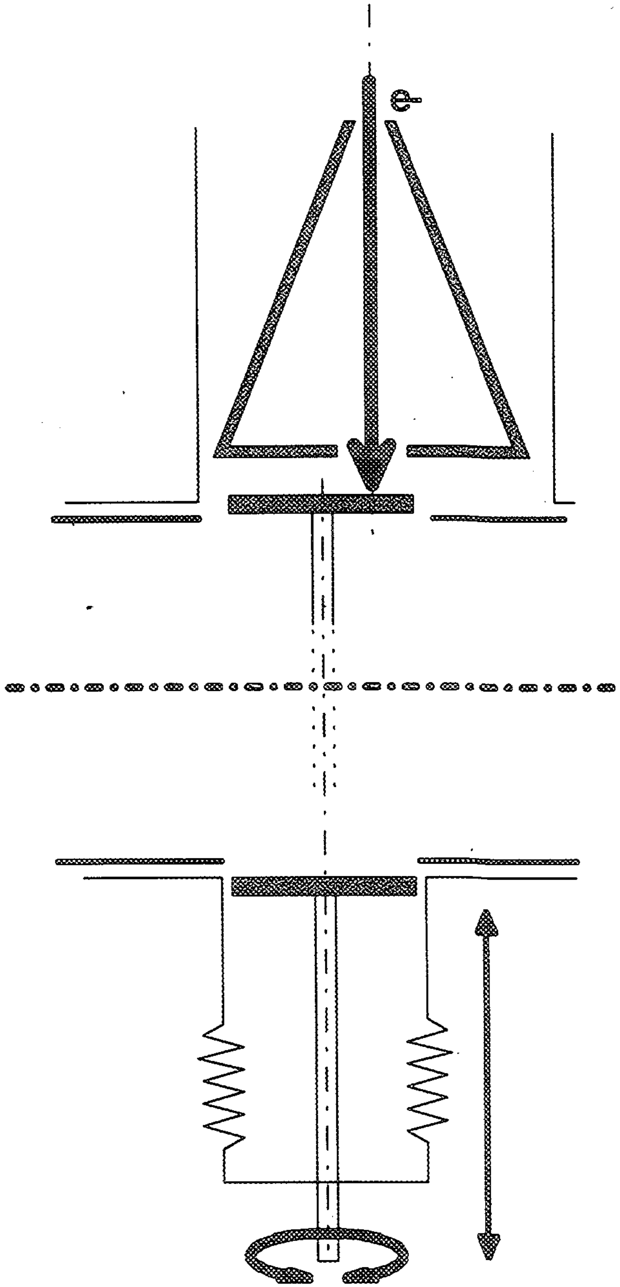
## Installation in EPA (11$^{th}$ of october 1999)

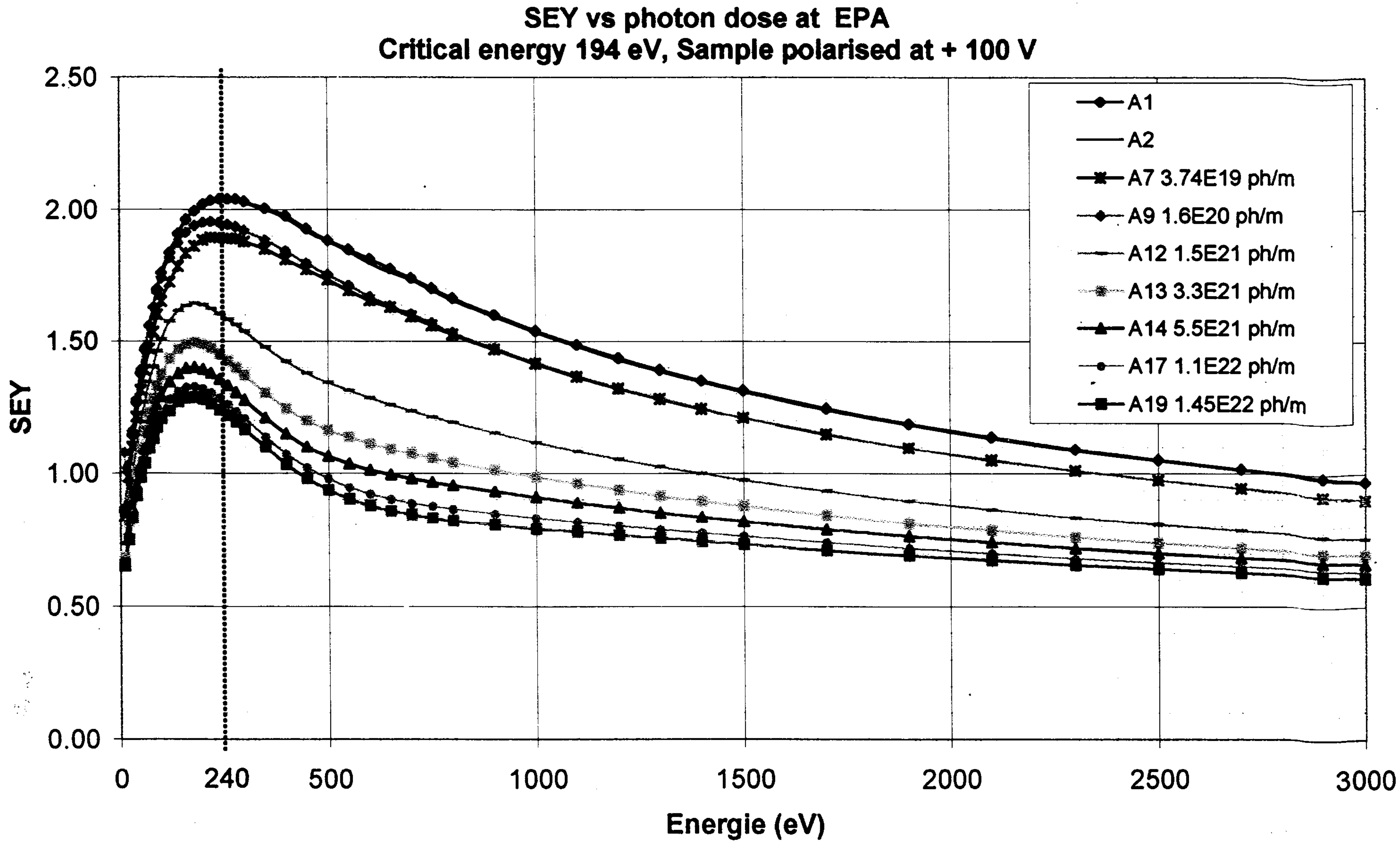
Movable sample holder (remotly controlled by labview)











SEY vs photon dose at EPA
Critical energy 194 eV, Sample polarised at + 100 V
SEY
Energie (eV)
2.50
2.00
1.50
1.00
0.50
0.00
0
240
500
1000
1500
2000
2500
3000
A1
A2
A7 3.74E19 ph/m
A9 1.6E20 ph/m
A12 1.5E21 ph/m
A13 3.3E21 ph/m
A14 5.5E21 ph/m
A17 1.1E22 ph/m
A19 1.45E22 ph/m

## Estimated nominal and ultimate heat loads due to electron cloud on the dipole beam screen

(Simulations by F. Zimmermann)

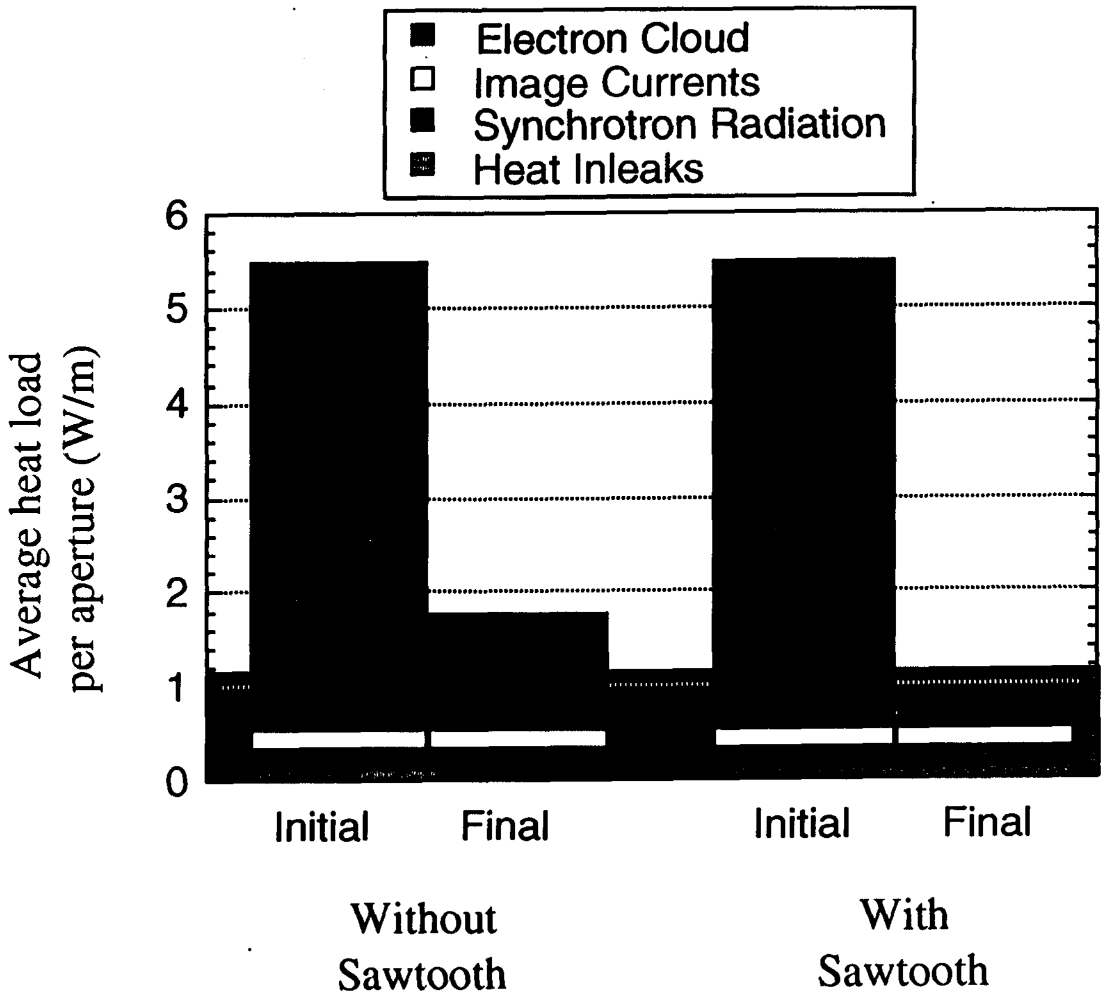
| | Without Saw-tooth | | With Sawtooth | |
|---|---|---|---|---|
| Parameter | Initial | Final | Initial | Final |
| Reflectivity, R | 1.0 | 1.0 | 0.1 | 0.1 |
| Photoelectron yield, Y | 0.2 | 0.1 | 0.05 | 0.025 |
| Secondary electron yield maximum, $\delta_m$ | 2.3 | 1.1 | 2.3 | 1.1 |
| $E_{max}$ (eV) | 300 | 450 | 300 | 450 |
| Nominal Heat load, P (W/m) | 5.0 | 1.5 | 5.0 | 0.045 |
| Ultimate Heat load, P (W/m) | 7.6 | 3.4 | 7.6 | 0.120 |

$$P_{final} = R \cdot P_o(\delta_m) \cdot Y$$

$$for\ \delta < \delta_{crit}$$

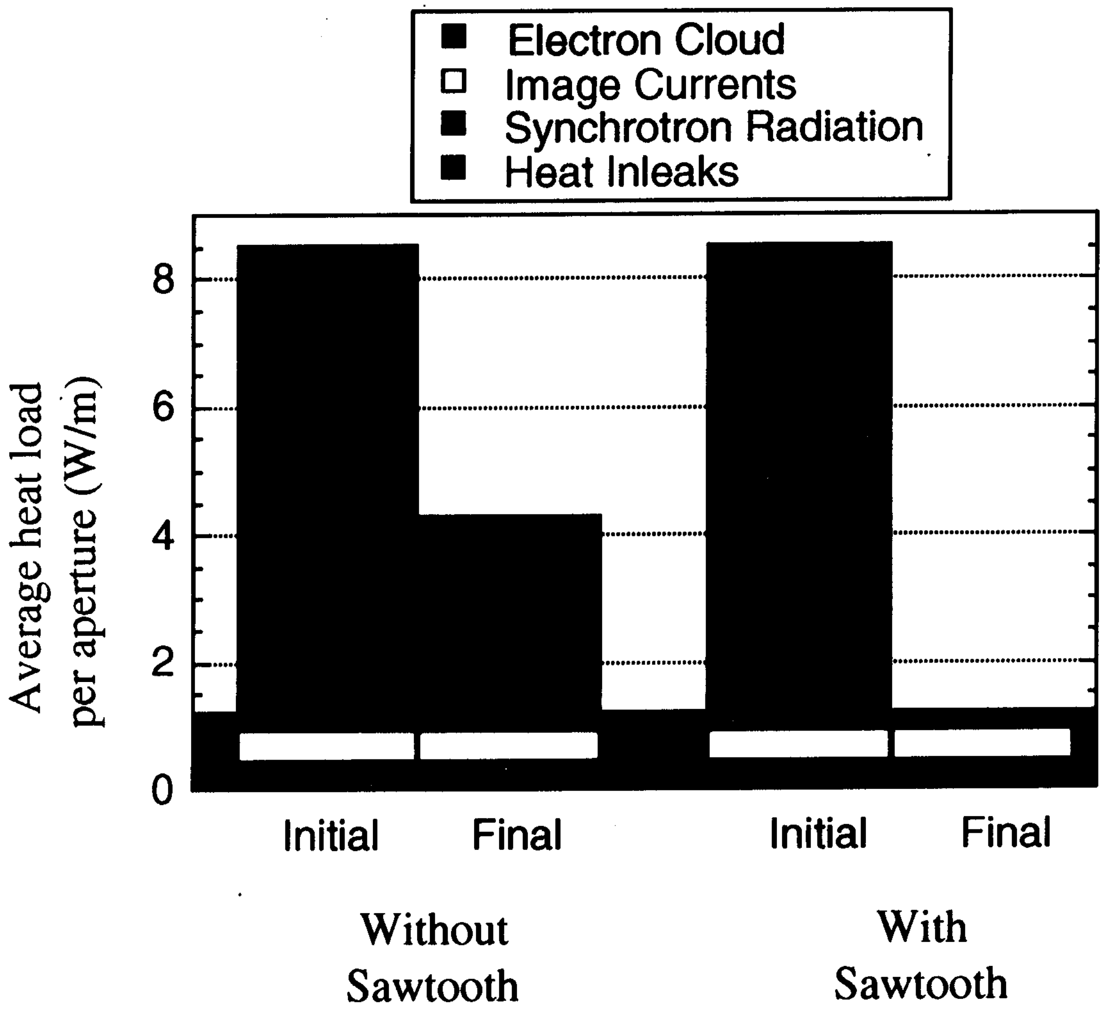
## Estimated heat loads per aperture at 4.6-20K for nominal operation (0.56A)

Installed cooling capacity = 1.17 W/m

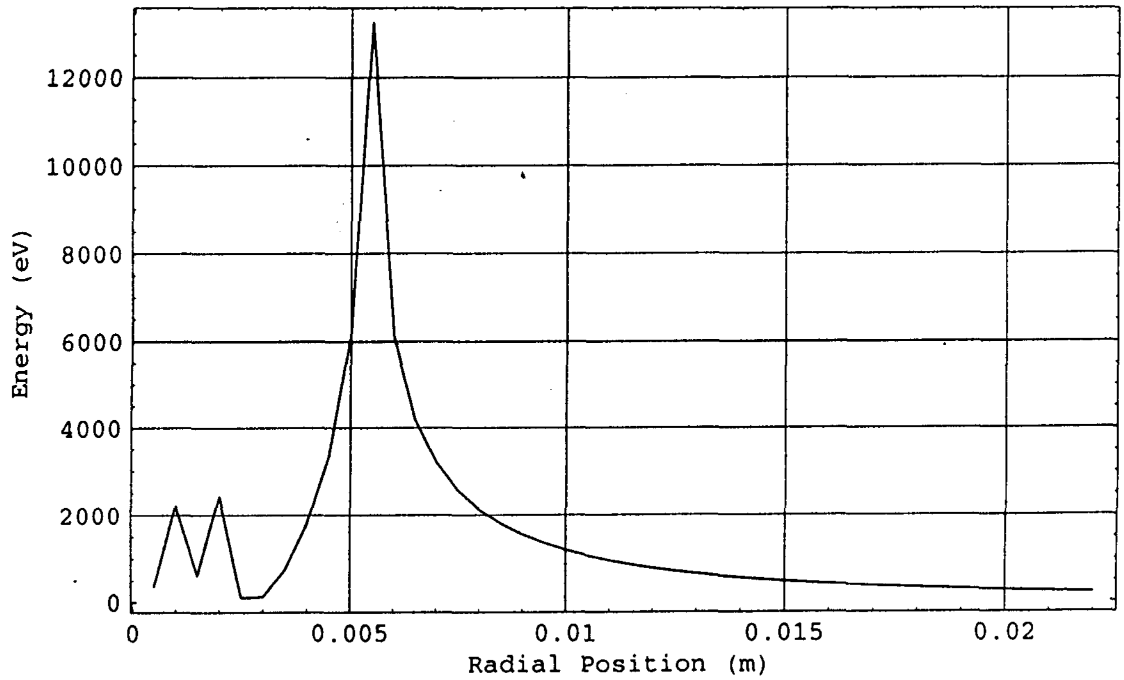


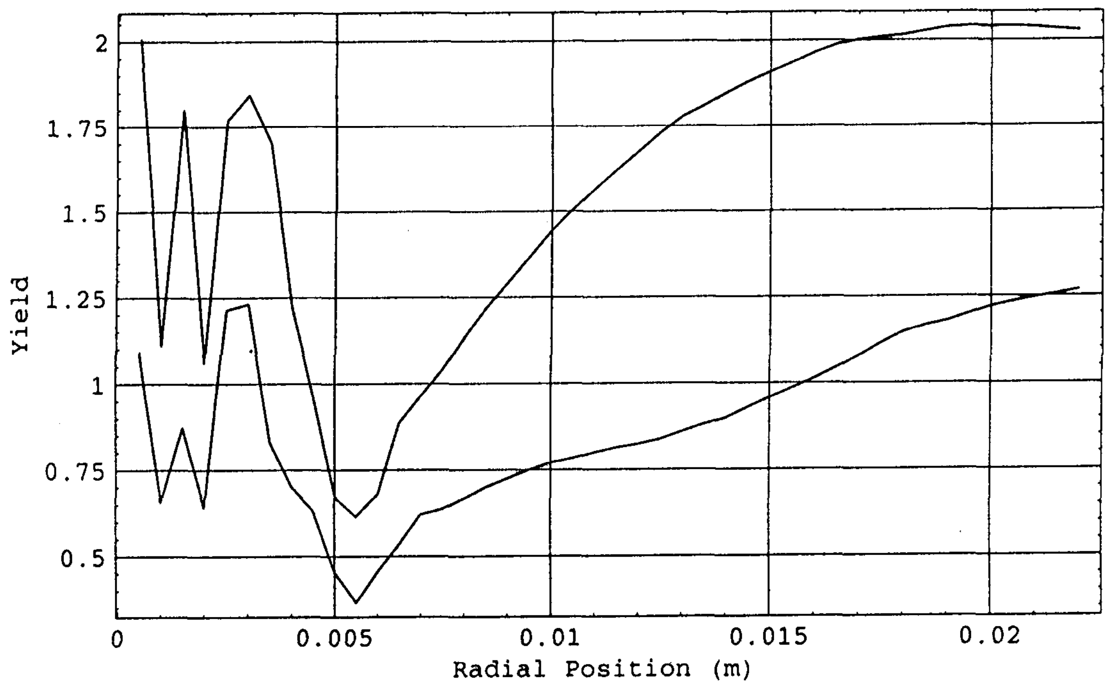
# Estimated heat loads per aperture at 4.6-20K for ultimate operation (0.85A)

Installed cooling capacity = 1.17 W/m



# Electron energy and secondary electron yield vrs. radial position at nominal LHC conditions

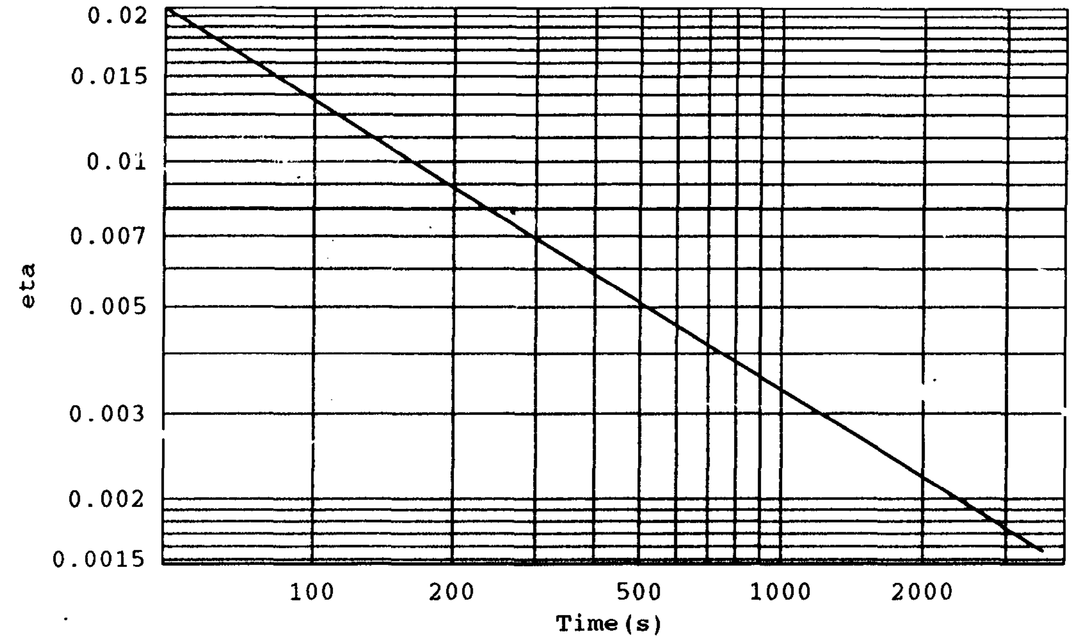


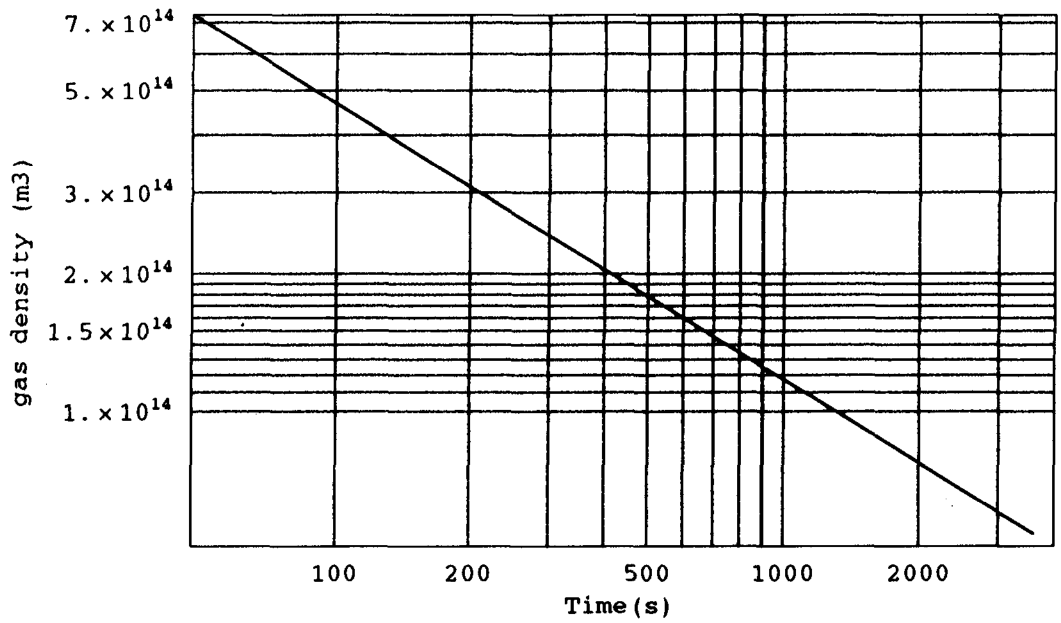

Secondary electron yield before and after photon scrubbing

# Electron Cloud Scrubbing in LHC

Linear power density: 0.5 W/m

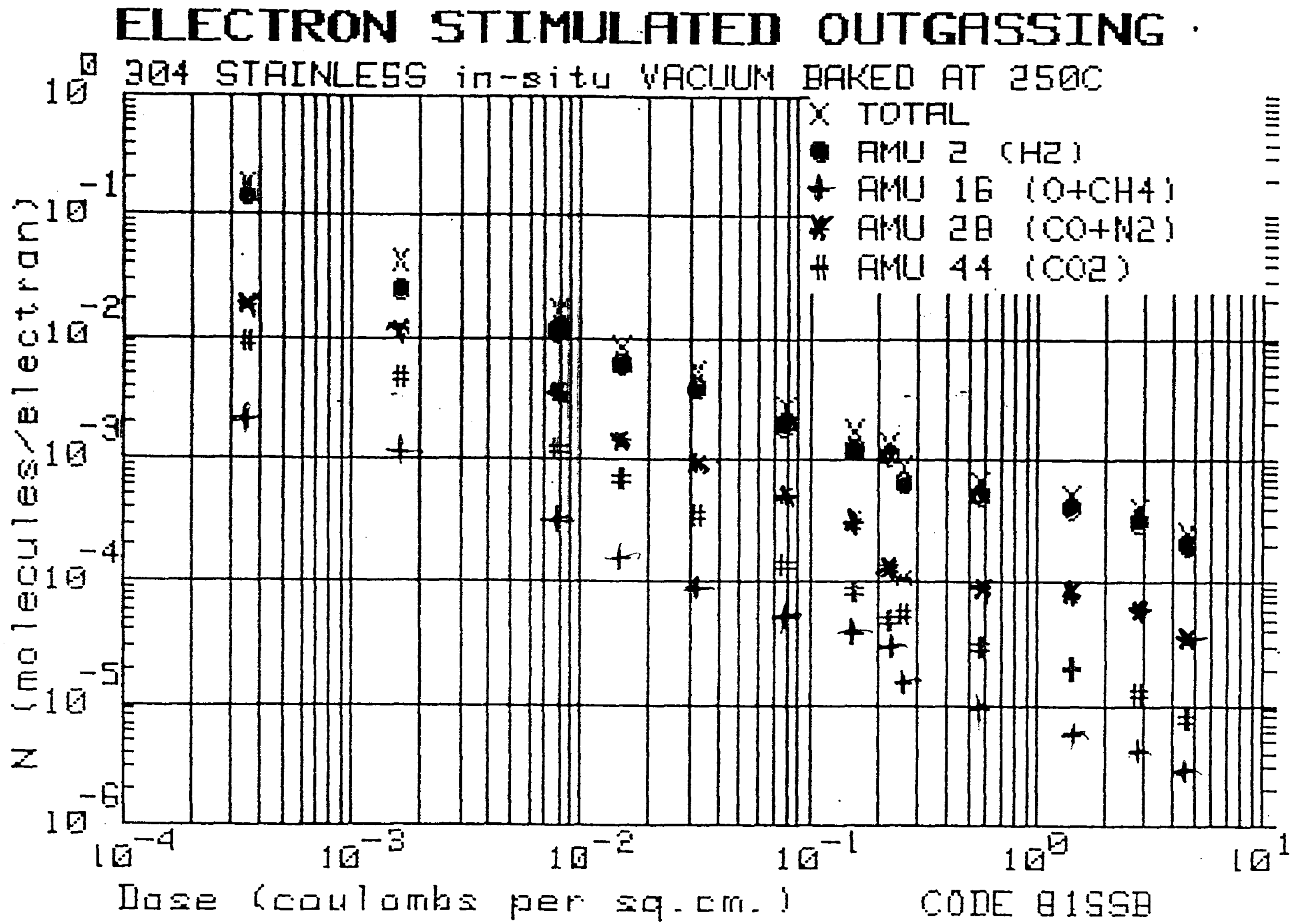



Electron stimulated desorption yield vrs. scrubbing time (s)




Electron cloud induced pressure rise vrs. time (s)

Lifetime limit density corresponds to $10^{15}$ molecules/$m^3$




K. Kennedy
LBL, 1986
unpublished Note

Fig 10

O. Gröbner, LHC-VAC 10. Feb. 2000

# LHC Beam Screen Scrubbing Scenario

## I Photon scrubbing

First year operation at 7 TeV with ~ 1/5 $I_{nominal}$ and below the cooling power limit.

compatible with dynamic vacuum pressure.

scrubbing time => 70 h

Subsequent years : with nominal beam current use gaps in bunch trains to avoid multipacting and to stay within the cooling power limit.

scrubbing time => reduced prop. with beam current

## II Electron scrubbing

Beam current limited by cooling power (0.5 W/m).

scrubbing dose ~ $10^{-3}$ C/mm$^2$ within < 1 hour

dynamic pressure rise remains below the lifetime limit and well below the magnet quench limit.

-> Electron scrubbing can be used to recondition a limited part of the machine in a shortest time. It may be done at injection energy but requires control of the beam.

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## CONCLUSIONS/SUMMARY

LHC will depend on beam conditioning to operate with nominal beams :

**dynamic pressure** due to photon induced desorption (1/10 to 1/5 of nominal currents during first year)

**e-Cloud effects** (heat load) -> ~1/3 of nominal current during ~ 7Ah to reduce SEY < critical value of 1.3

Budget for beam screen cooling ~1W/m (two beams) is adequate for conditioning

Final heat load proportional to PEY -> suppression by dipole/quadrupole magnetic field : straight sections dominate

perp. photon incidence by saw tooth structure -> low reflectivity, PEY

Special surface coating/treatment to reduce conditioning time without photons in long straights/experimental vacuum chambers.

## Future validations

1) Photon scrubbing with a cryogenic system : -> COLDEX with EPA beams and in the SPS

2) SPS provides LHC type beams (but without synchrotron radiation) for multipacting studies (beam blow up, bunch trains, electron-conditioning, ...)

3) Special coatings/surface treatments to reduce conditioning time (dose, memory effect, ...)

4) Comparison between different machines which have shown/not shown e-Cloud effects

5) Fine tune, bench mark existing simulation codes beam pipe radius, pumping slots in beam screen