Experimental Results of a LHC Type Cryogenic Vacuum System Subjected to an Electron Cloud

V. Baglin, B. Jenninger

CERN AT-VAC, Geneva

1. Introduction
   - LHC & Electron Cloud
   - LHC cryogenic vacuum system

2. Electron cloud in a cryogenic environment
   - COLDEX set up
   - Long term beam circulation
   - Condensed gas
   - Operating temperature / filling parameters / comparison with other detectors

3. Some implications to the LHC
   - Scrubbing period (pressure/heat load)
   - Cooling / filling schemes
   - Beam screens warming up against quench and end effects

4. Conclusions and future work

1. Introduction

1.1 LHC & Electron cloud

- Limit performances of PEP-II, KEK-B, SPS …
- In LHC, it will induce heat load and stimulated molecular desorption
- Vacuum chamber parameters : secondary electron yield, photon and electron reflectivity, photoelectron yield, vacuum chamber geometry …
- Beam structure : bunch spacing, bunch density, bunch length …

- COLDEX in SPS

Parameters	LHC	SPS	
Beam energy (GeV)	7 000	26	450
Bunch length (ns)	1	2.8	1.7
Revolution period (μs)	89	23	
Batch spacing (ns)	-	225	
Beam current (mA)	560	55 / 110 / 165 / 220	
Number of batches	-	1 / 2 / 3 / 4	
Number of bunches	2808	72 / 144 / 216 / 288	
Filling factor (%)	79	9 / 16 / 24 / 31	
Bunch current (protons/bunch)	$1.1\ 10^{11}$		
Bunch spacing (ns)	25		

1.1 LHC & Electron cloud (2) : budgets

- Electron cloud heat load budget :

  ~ 1.5 W/m at injection (450 GeV)
  ~ 1 W/m at collision (7 TeV)

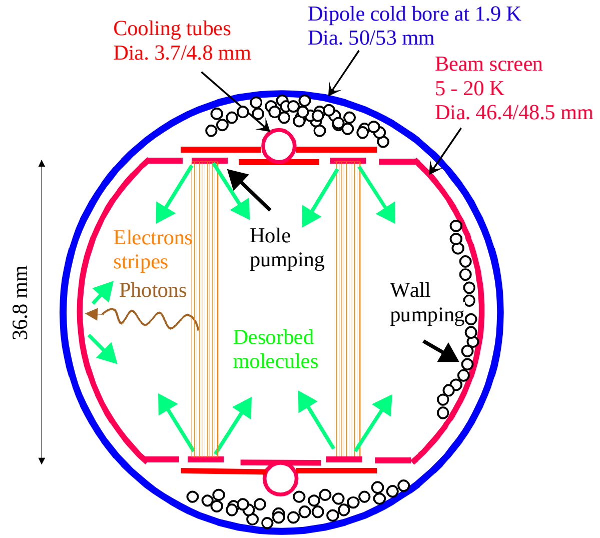
- Gas budget : (450 GeV dominated by Coulomb scattering, 7 TeV dominated by nuclear scattering)

  Scrubbing beams at injection : ~ 10^{-7} Torr H_2 eq.
  Physics beams : ~ 10^{-8} Torr H_2 eq.

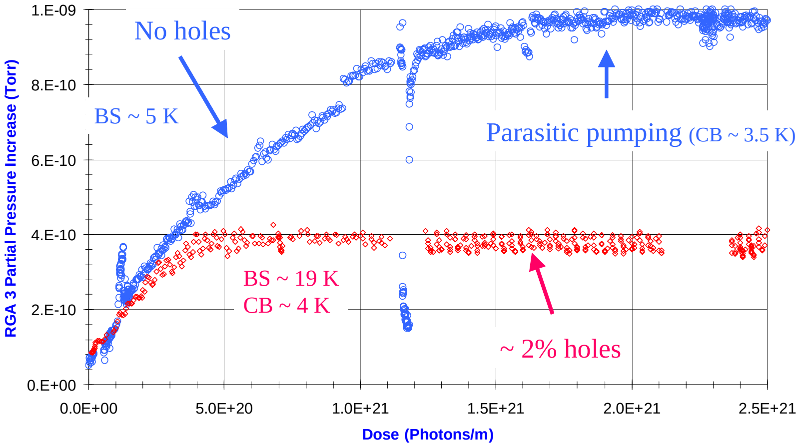
1.2 LHC cryogenic vacuum system

- Molecular desorption stimulated by photon, electron and ion bombardment
- Desorbed molecules are pumped on the beam vacuum chamber : **CLOSED geometry**

- Molecular physisorption onto cryogenic surfaces (weak binding energy)
- Molecules with a low recycling yield are first physisorbed onto the beam screen (BS) (CH_4, H_2O, CO, CO_2) and then onto the cold bore (CB)
- H_2 is physisorbed onto the CB



- The vacuum dynamic is characterised by :
  - pumping speed of slots, BS and CB
  - vapor pressure
  - primary and recycling desorption yields



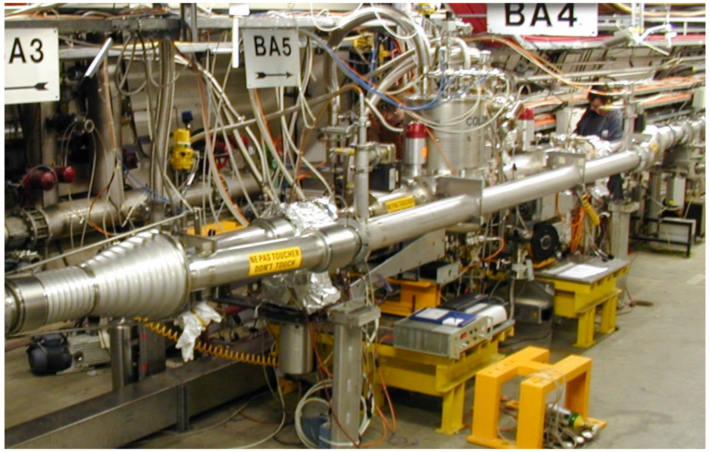
V. Baglin *et al.* EPAC 2000, COLDEX, EPA beam line SLF 92

2. Electron cloud in a cryogenic environment

2.1 COLDEX set-up (1)

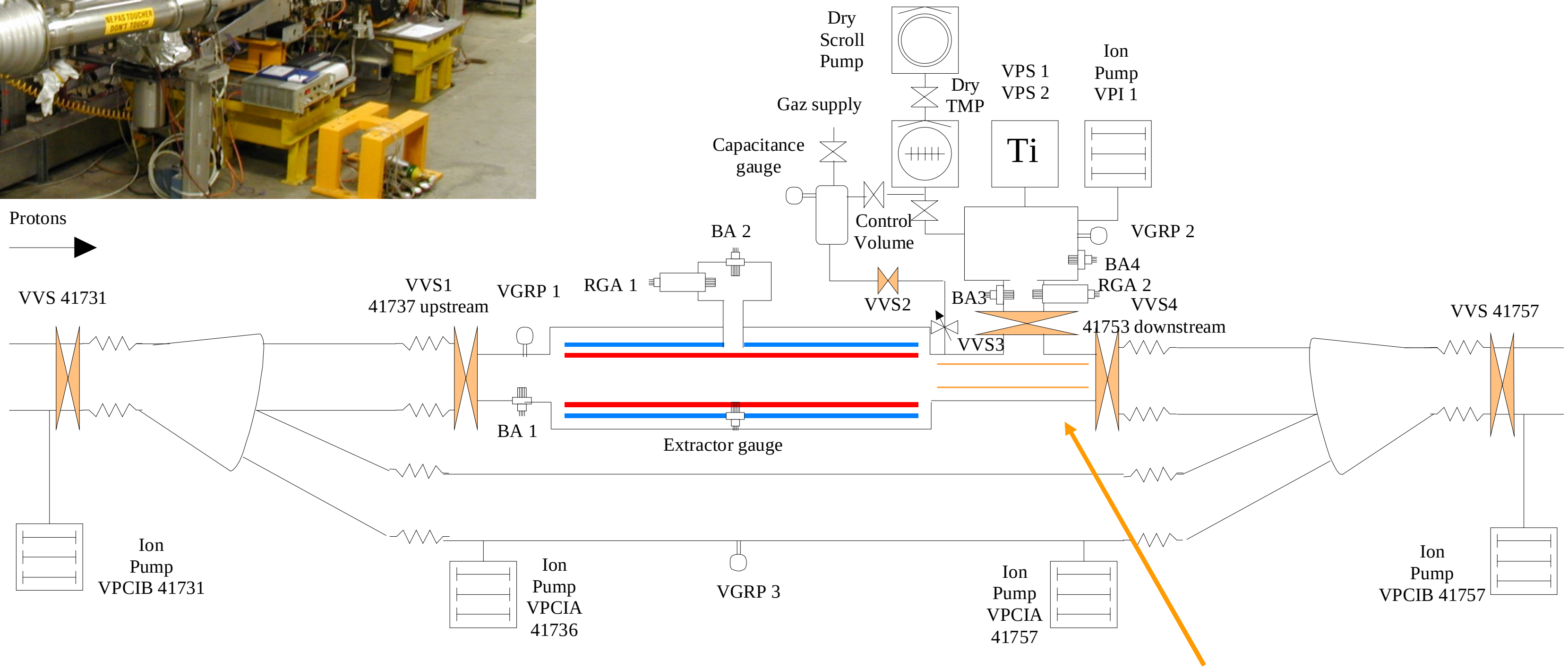
Field free region (SPS Long straight section 4), closed geometry, 2.2 m long

Pressure & gas composition measurements, heat load measurement (temperature, flow)



BS from 5 to 150 K

CB from 2 to 5 K



Wampac 3

2.1 COLDEX set-up (2) : types of beam screens

Year 2002

(8th EVC, Berlin, June 2003 - Vacuum 73 (2004) 201-206)

- OFE Cu, 2.2 m long, elliptic, H = 84 mm, V = 66 mm
- 1 % holes (7 mm diameter)
- Inserted cold warm transition (15 mΩ), stainless steel, 0.1 mm thick.
- Calibrated thermometer, anchoring < 0.6 K, linear flow meter
- Background : (1.5 +/- 0.4) W/m

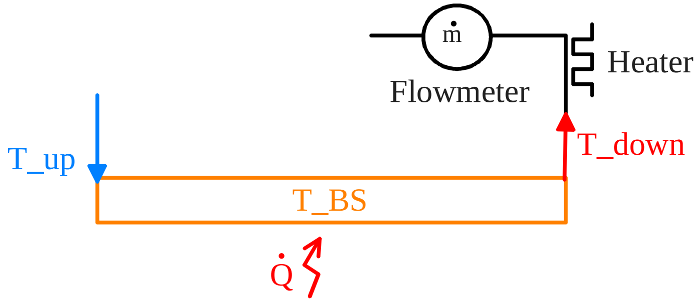
Year 2003

- OFE Cu, 2.2 m long, circular, D = 67 mm (was in EPA ring in 1999, dose of 10^{23} ph/m)
- 1 % slots (2 x 7.5 mm)
- Electron shield behind slots (L = 17.85 cm) to protect cold bore and measure current
- Thermalised cold warm transition with RF fingers. Cu coated stainless steel, 0.1 mm thick.
- In situ heat load calibration, ~ 100 mW/m is measurable
- Calibrated thermometer, anchoring ~ 3 K, calibrated flow meter
- Background : ~ 1.4 W/m

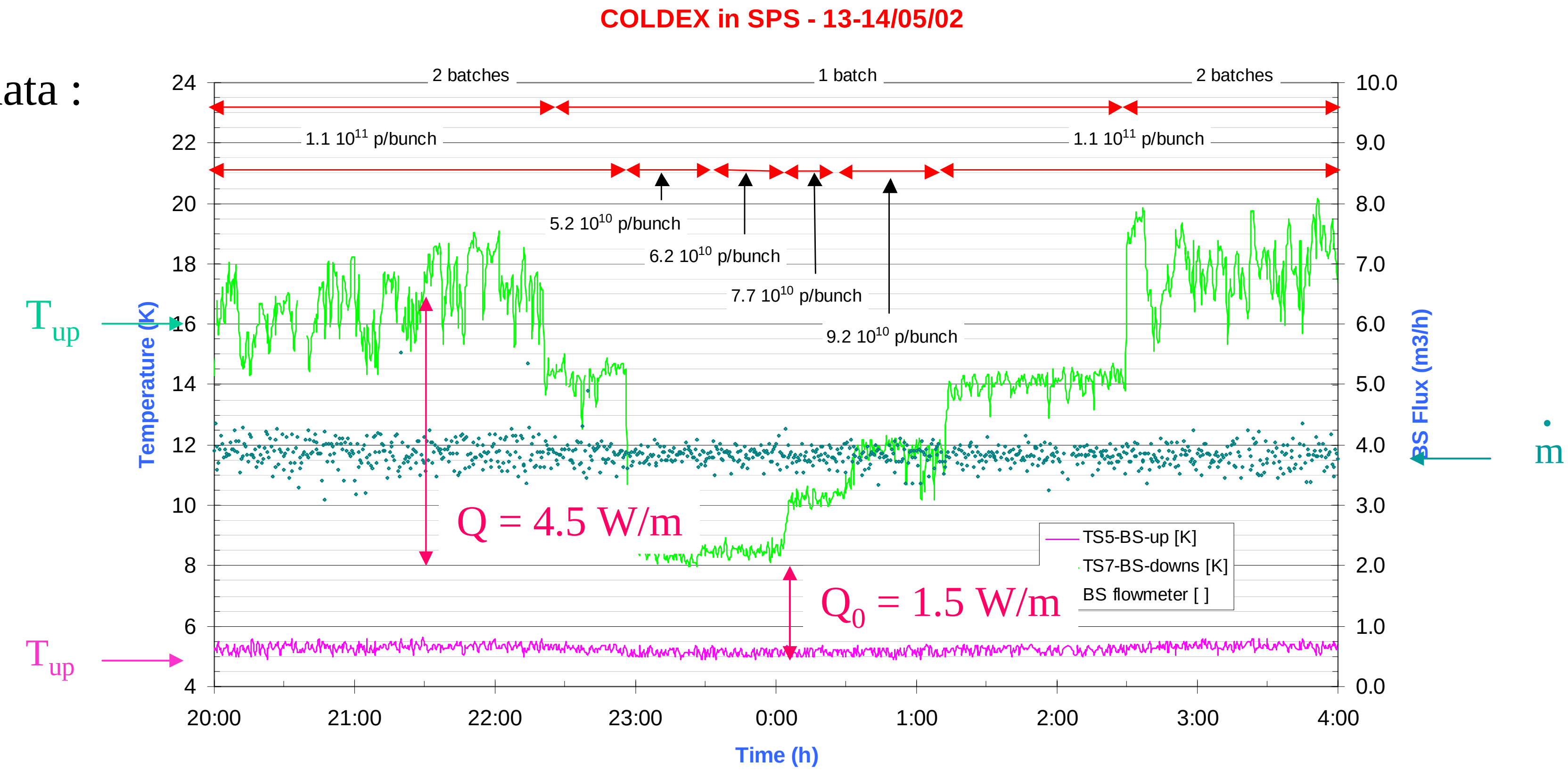
2.1 COLDEX set up (3) : heat load measurement

- Direct heat load measurement by the flow method, He at 1 bar :

$$\dot{Q} = \dot{m}\,[h_{He}(T\_down) - h_{He}(T\_up)]$$



- Typical data :



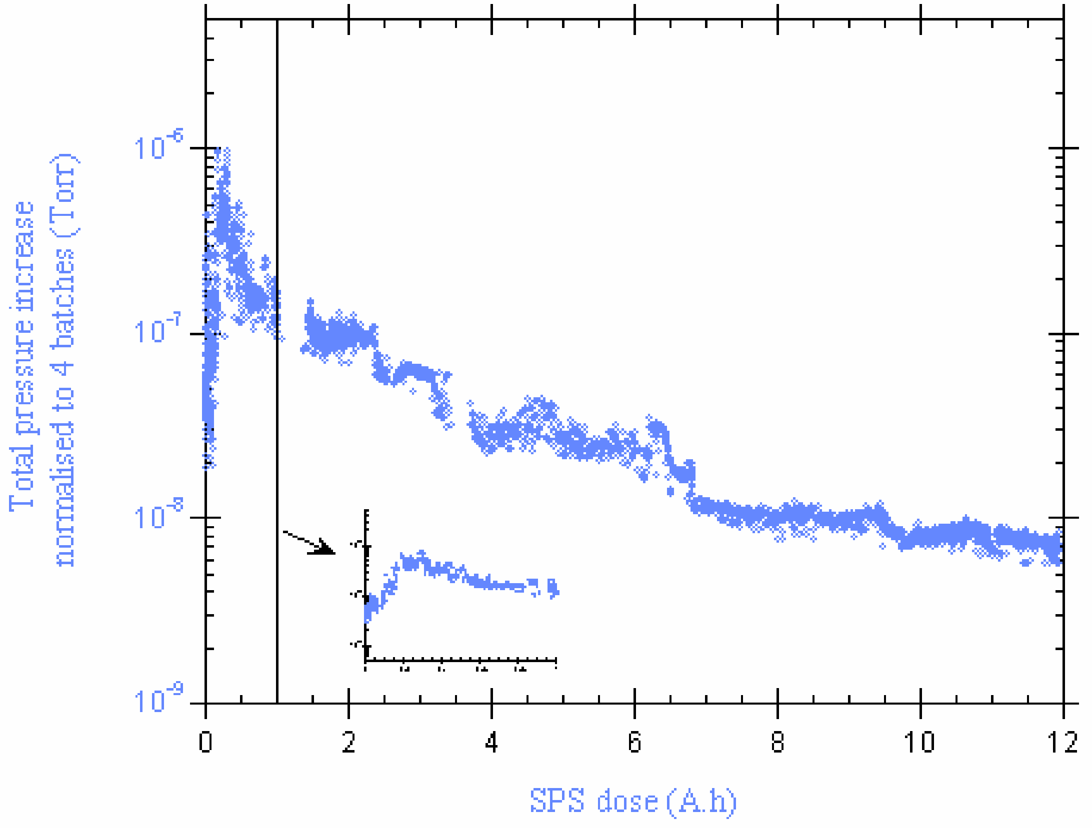
2.2 Long term beam circulation (1) : pressure increase

Scrubbing run 2003 : 12 A.h

Normalised to 4 batches with ~ 1.1 10^{11} protons/bunch, 95 % duty cycle

- Initial ΔP = 5 10^{-7} Torr (but a ΔP of 10^{-7} Torr was measured during the experiment !)
- Final ΔP = 7 10^{-9} Torr
- A factor 70 reduction of total pressure : **Vacuum cleaning**

- The recycling effect is observed at the start of the electron desorption



BS = 13 K

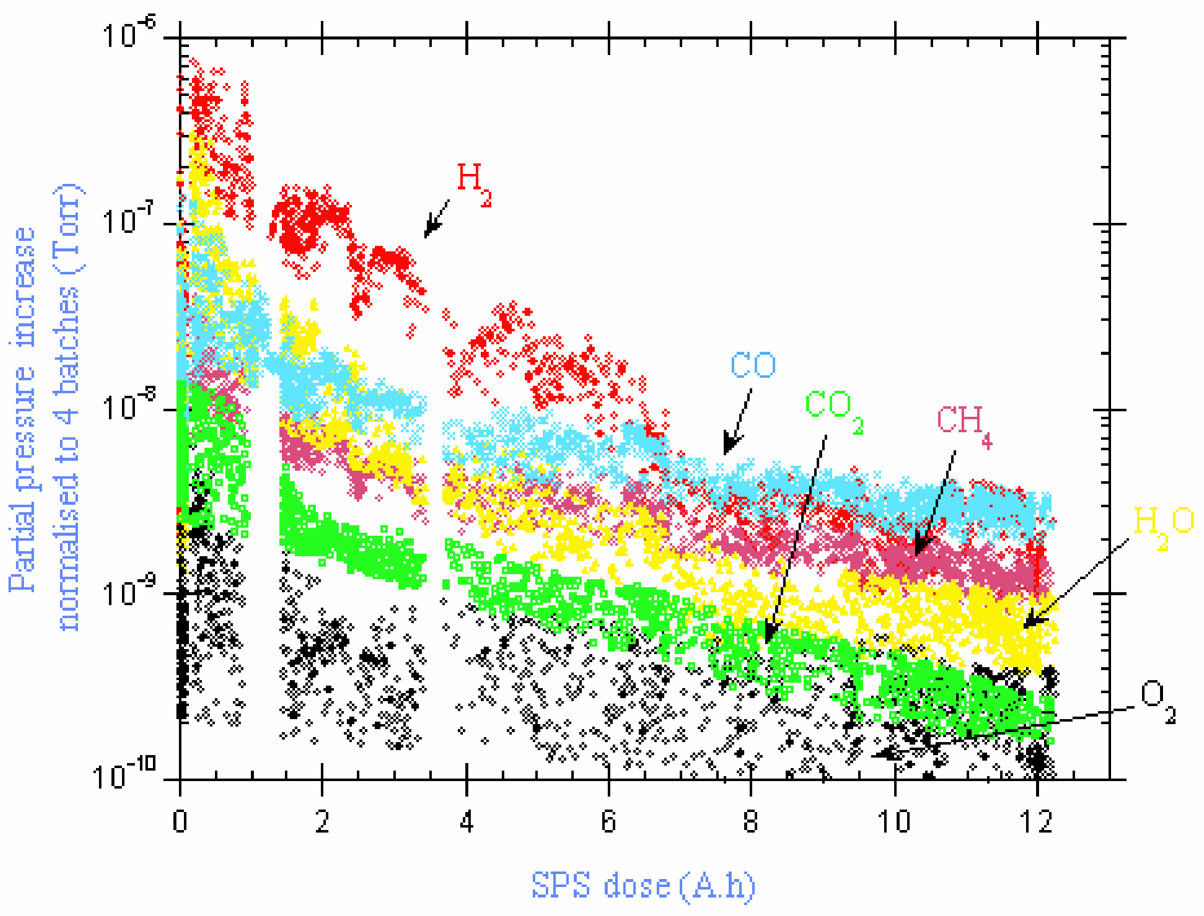
CB = 3 K

2.2 Long term beam circulation (2) : gas composition

Scrubbing run 2003 : 12 A.h

Normalised to 4 batches (0.2 A)

- Gas analysis : H_2 dominated turns to H_2 + CO



BS = 13 K

CB = 3 K

2.2 Long term beam circulation (3) : heat load

Scrubbing run 2003 : 12 A.h

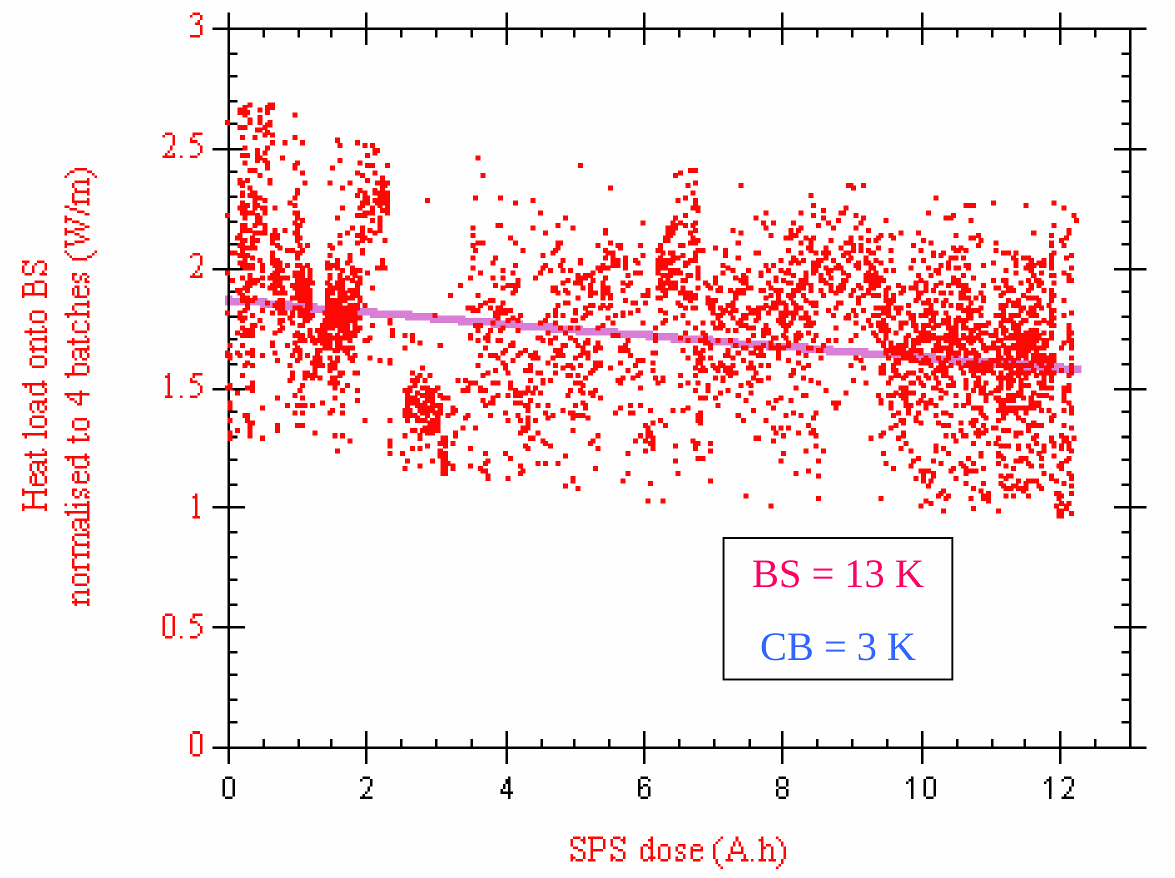
Normalised to 4 batches with ~ 1.1 10^{11} protons/bunch, 95 % duty cycle

- Heat load (HL) onto the BS is decreasing with electron dose : beam conditioning

- Final heat load ~ 1.5 W/m

- HL = 1.9 $\exp^{(-D/70)}$

- Electron dose ~ 20 mC/mm^2
for estimated <85> eV



- No heat load is dissipated onto the CB thanks to the electron shields

2.2 Long term beam circulation (4) : electron shield's electrode

Scrubbing run 2003 : Electrons collection up to 30 µA (*i.e.* 36 mA/m)

- Observation of a electron current associated with the pressures increase and heat loads :

  => electron cloud in the SPS
- Reduction of the electron activity : $I_{final} / I_{initial} \sim 0.7$

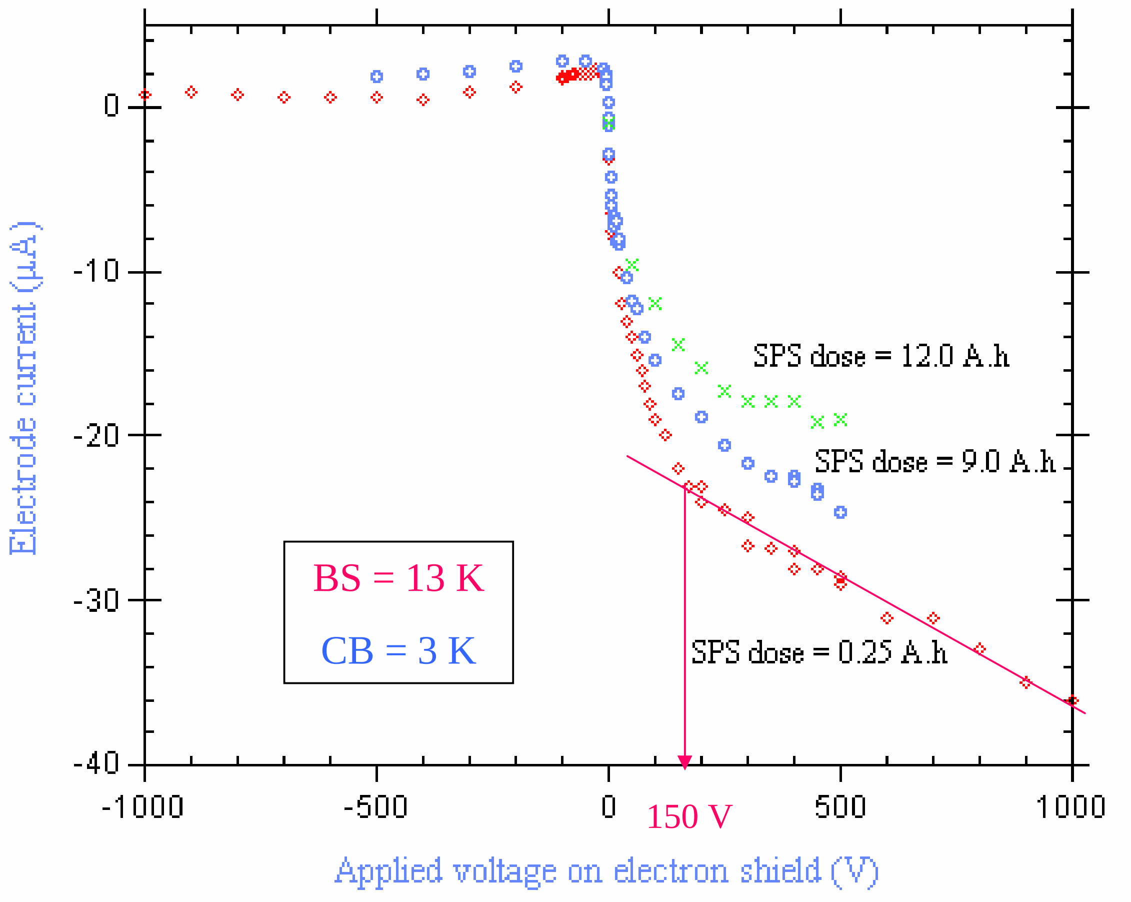
- Assuming that above 150 V, all electrons are collected

$$<E> = I/P$$

- Initially :

  <75> eV ⇔ 1.9 W/m
- Finally :

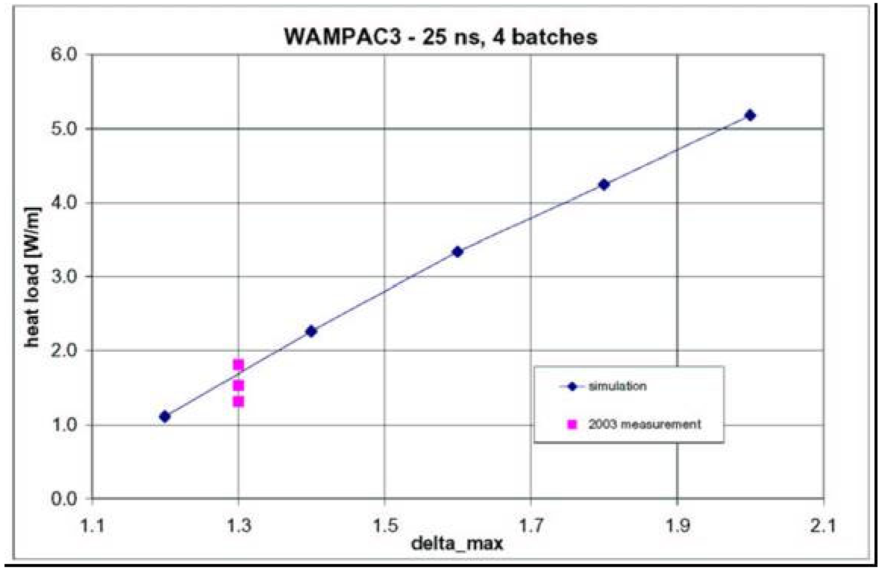
  <95> eV ⇔ 1.6 W/m



2.2 Long term beam circulation (5) : Comparison to ECLOUD simulations

Courtesy of D. Schulte and F. Zimmermann

The heat load observed in COLDEX and WAMPAC 3 during the 2003 scrubbing run is compatible with : δ_{max} ~ 1.2 - 1.3



Reasonable agreement between simulations and experiments

	Measurements	Simulation with δ_{max} = 1.3
Heat load	1.6 W/m	1.6 W/m
Current	17 mA/m	19 mA/m
<E>	85 eV	100 eV
Fraction >30 eV	n.a	~ 70 %
Dose	~ 20 mC/mm^2	10 mC/mm^2
δ_{max}	1.1	1.2

V. Baglin *et al.* Chamonix 2001

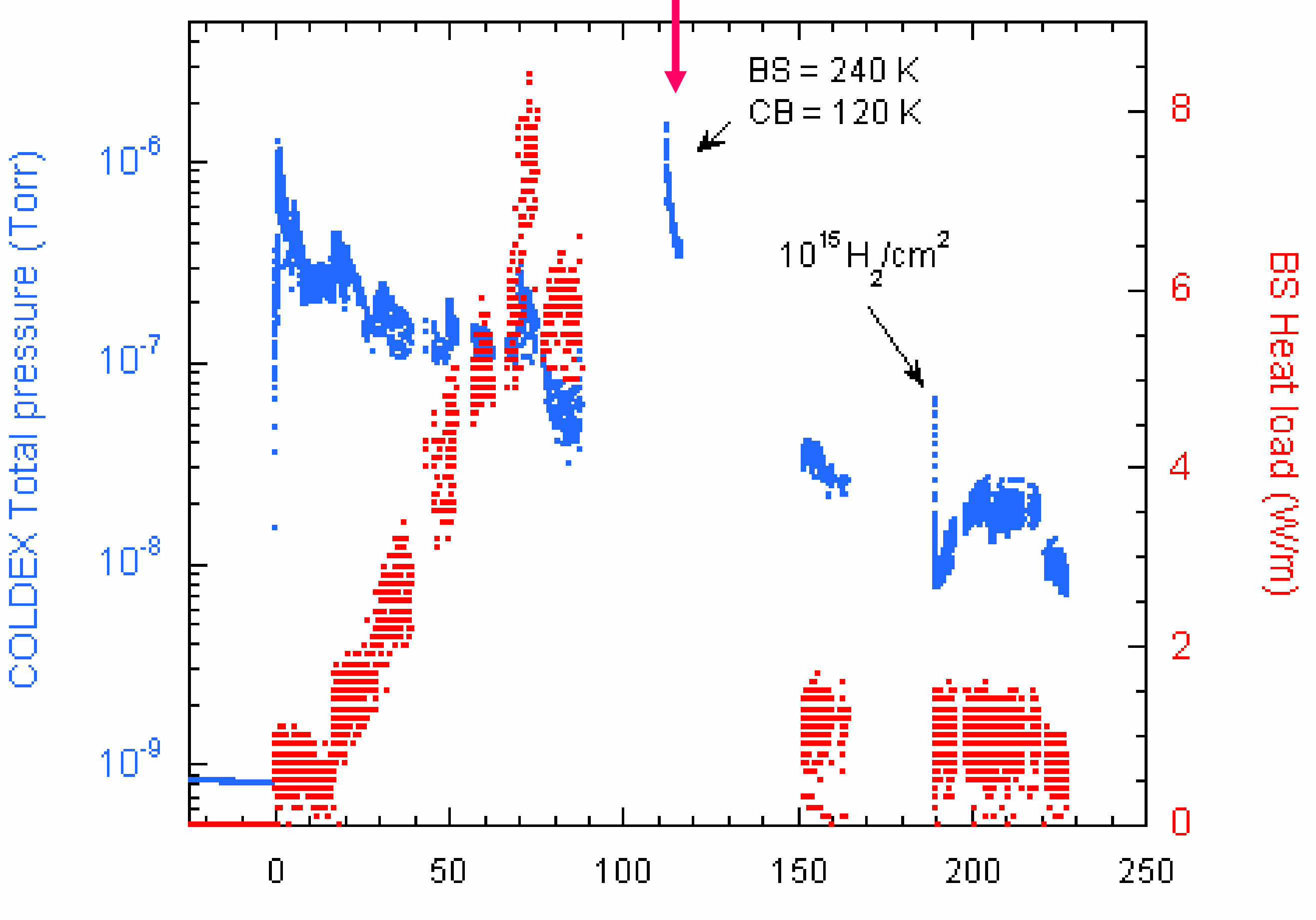
2.3 Condensed gas (1)

Scrubbing run 2002 : 20 A.h

Raw data : 2 batches with ~ 1.1 10^{11} protons/bunch, 95 % duty cycle

- Initial $\Delta P = 10^{-6}$ Torr : large desorption of gas
- Heat load on the BS increases with time
- Heat load on the BS decreases after warming-up and beam circulation at ~ RT
- Presence of condensed gas induces large heat load
- Ex : 30 monolayers of H_2O has a δ_{max} ~ 1.9 (on a baked surface)!!

Warming-up and
beam circulation at RT for 4 h



BS and CB increase to 20 K

BS ~ 10 K, CB ~ 4.2 K

2.3 Condensed gas (2)

MD during the year 2002 - 2003

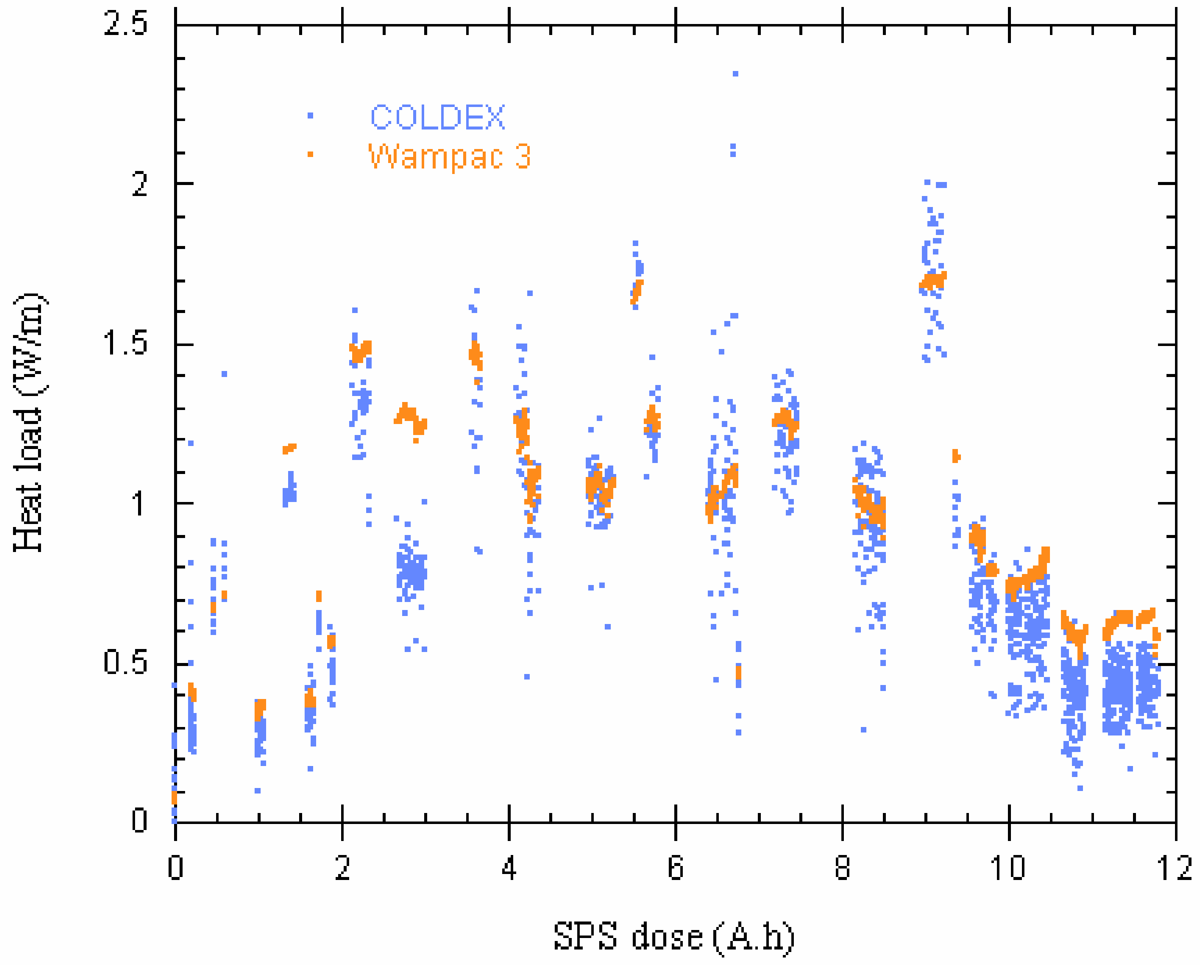
- 5 10^{15} CO/cm^2 : - Heat load increases < 0.2 W/m with 4 batches
  - $\eta' = 1\ 10^{-1}$ CO/e^-

- 15 10^{15} CO_2/cm^2 : - Heat load increases < 0.1 W/m with 4 batches
  - $\eta' = 5\ 10^{-2}$ CO_2/e^-
  - cracking of CO_2 to CO and O_2

- 60 10^{15} CO/cm^2 : - Heat load increases to ~ 5 W/m with only 1 batch !

2.4 Operating temperature : heat load at RT versus 15 and 50 K
Raw data of scrubbing run 2003 and MD

- As far as no gas are condensed onto the BS, the heat load at 15 – 50 K and RT are similar
  => the conditioning rate is almost temperature independent



COLDEX

BS at 13 K,
CB at 3 K

WAMPAC 3
at RT

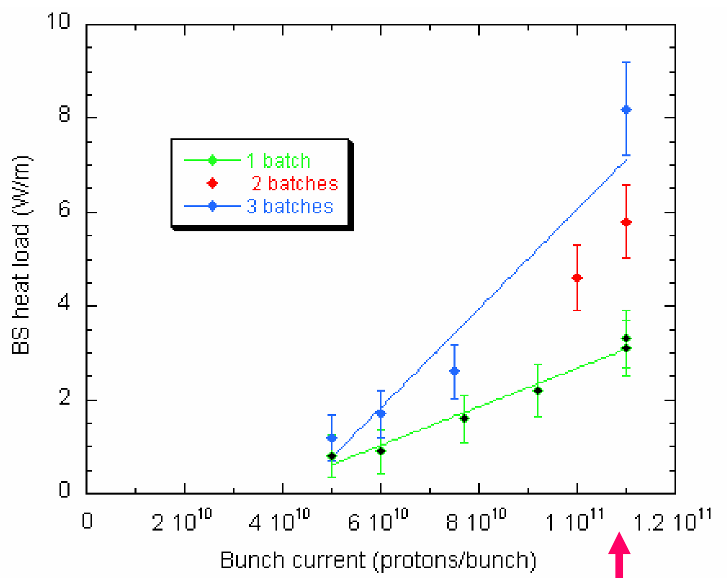
2.5 Filling parameters :
75 ns bunch separation
A single MD in 2003

- Preliminary result indicates a reduction of the dissipated heat load by at least a factor 2
- More studies this year

Effect of number of batches and bunch current
During scrubbing run 2002
consecutives batches separated by 225 ns, 95 % duty cycle, 2.8 ns bunch length

- At nominal bunch current : heat load proportional to the number of batches *i.e.* few bunches are required to equilibrate the electron cloud

- Threshold at 4 10^{10} protons/bunch



BS and CB increase to 20 K.
Measured from 50 to 75 h

Nominal

2.5 Comparison with other detectors located in SPS

2002 : WAMPAC 1

2003 : WAMPAC 3, COLDEX, pick up calorimeter, cold & room temperature strip detectors

- All raw data were normalised to 4 batches in the SPS (0.22 A) assuming proportionality to the beam current

- Detectors which measure electron activity have a mean electron energy which is used to compute the heat load.
(pick-up : 100 eV , strip detector : 180 eV in field free and 300 eV in dipole field)

- After 2 A.h in the SPS and up to the maximum dose achieved so far :
  - All detectors, with the exception of the strip detector in field free, follows the same linear trend *i.e.* a decrease of 25 to 30 mW per A.h
  - But the level of the dissipated power varies, probably as a function of chamber diameter

3. Some implications to the LHC

3.1 Scrubbing period (1) : heat load

- Conditioning exist ONLY when an electron cloud is present
- Dedicated period are required to perform the conditioning
- Conditioning shall be performed at injection (~ 1.5 W/m available)
- Conditioning might be "lost", "over-conditioning" would be helpful
- Rough estimate :

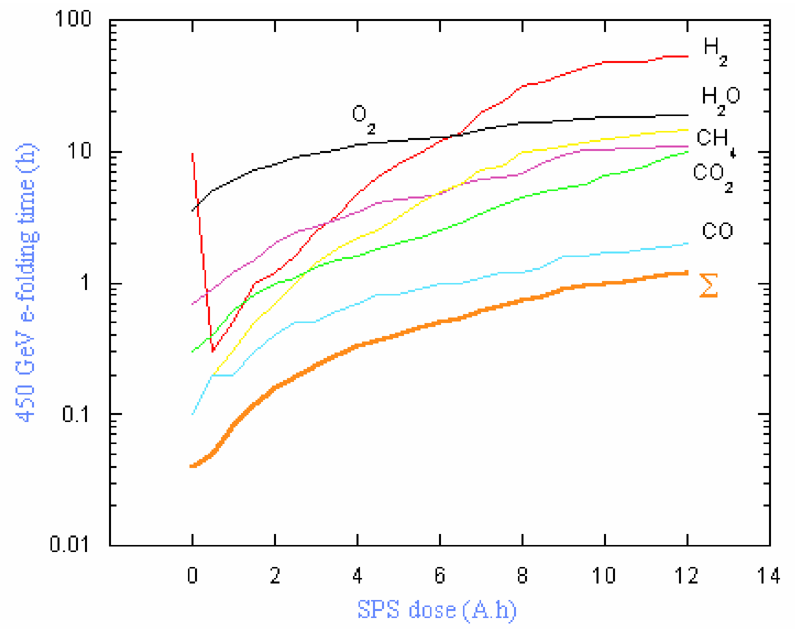
Based on the previous fit, HL = 1.9 $\exp^{(-D/70)}$, and assuming that ~ 1.5 W/m could be dissipated onto the BS, a dose of 200 A.h would be required to reduce the dissipated heat load at nominal current to ~ 1 W/m

3.1 Scrubbing period (2) : vacuum pressure

Scrubbing run 2003 : 12 A.h, normalised to 4 batches (0.2 A)

- Minimise radiation level, coulomb scattering and nuclear scattering

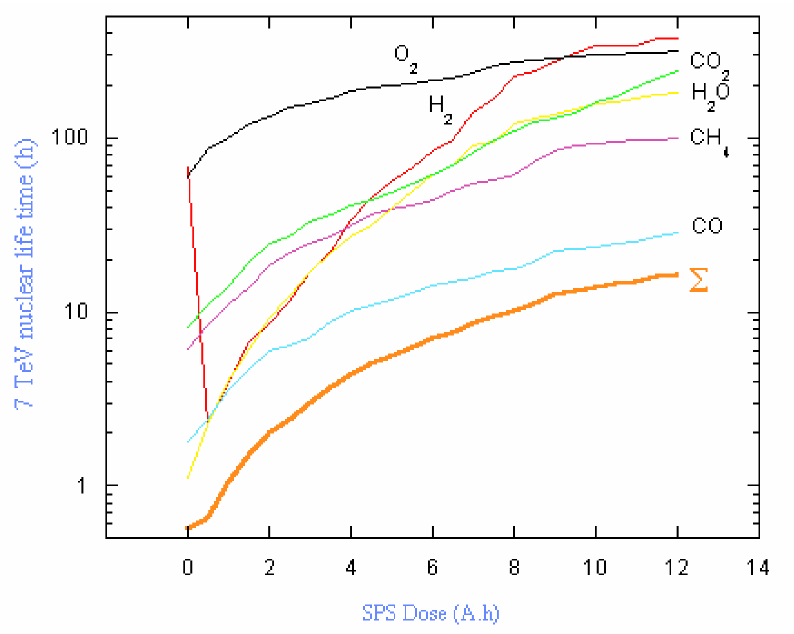
Coulomb scattering at 450 GeV



BS = 13 K

CB = 3 K

Nuclear scattering at 7 TeV



For LHC physics runs :
- emittance rise time ~ 15 - 20 h
- nuclear life time ~ 100 h (with 0.6 A)

Extrapolation to early LHC physics with electron cloud:

Need to control and decrease the electron cloud power to < 1 W/m

i.e. operate with less than 0.2 A

3.2 Cooling / filling schemes
During LHC operation

- Minimise the amount of condensed gas onto the BS by an appropriate cooling scheme

- Minimise the amount of dissipated heat load (vacuum conditioning, 75 ns bunch spacing, filling pattern, satellite bunch or other means to clear the electron cloud …?)

- Maximise the conditioning efficiency : high energy electrons are more efficient than low energy electrons. Use preferentially large bunch current.

3.3 Beam screen warming up against quench and end effects

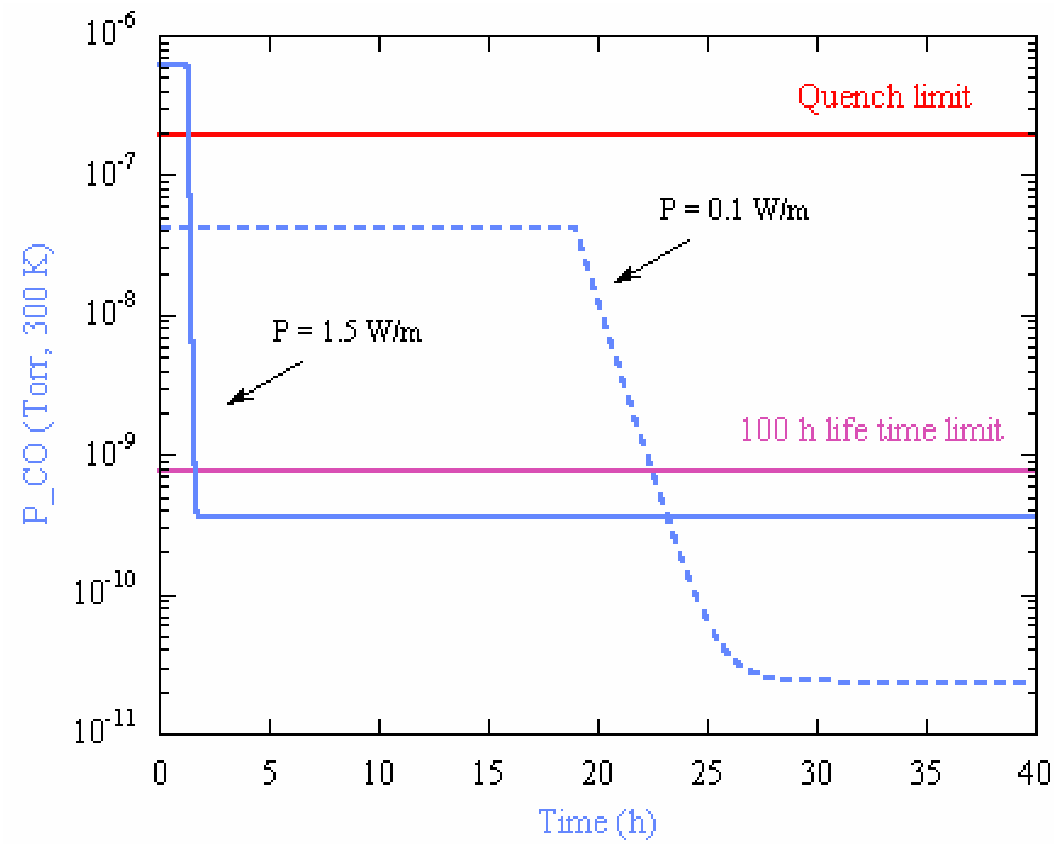
Example : consequences of a magnet quench.

Condensed CO onto the BS over 2 m, 25 10^{15} CO/cm^2,

heat load onto the BS due to electron cloud : 0.1 and 1.5 W/m, 100 eV electron energy

- Above quench limit for 1 h with 1.5 W/m
  => risk of quench
- Below quench limit for 20 h with 0.1 W/m
  => lower beam current

flushing of CO via BS heating will improve the situation (heaters)



Simulation with :

BS = 15 K

CB = 1.9 K

4. Conclusions & future work

- In the SPS, the electron cloud stimulates molecular desorption ~ 10^{-7} to 10^{-6} Torr
- A vacuum cleaning is observed at cryogenic temperature
- The dynamic pressure is initially dominated by H_2, then by H_2 and CO

- In the SPS, a significant heat load is observed at cryogenic temperature : ~ 2 W/m
- A conditioning is observed at cryogenic temperature (is δ_{max} ~ 1.2-1.3 in COLDEX ?)
- BUT , for LHC, other means to reduce the electron cloud shall be studied and be validated in existing machines

- COLDEX observations are in a rather good agreement with the ECLOUD code

- Thick layers of condensed gas induce large heat load (up to 8 W/m) and vacuum transients which have consequences onto the LHC design and operation

- More laboratory and machine data related to beam conditioning and condensed gases are required to benchmark the codes and predict more accurately the LHC behaviour

- The operation with the LHC requires a deep understanding of the electron cloud phenomena to control the radiation level, the emittance blow up and the vacuum life times

Acknowledgments

CERN-AB

For the SPS LHC-type beam and the theoretical support to the understanding of the Electron cloud : G. Arduini, P. Collier, the SPS and PS operators, F. Ruggiero, F. Zimmermann, D. Schulte.

CERN-AT

N. Delruelle, O. Drouyer, D. Legrand, O. Pirrotte.

My colleagues from the vacuum group for their support and their stimulating discussions, specially :

J. Arnold, J-C. Billy, R. Cimino, R. Gavaggio, N. Hilleret, B. Jenninger, M. Jimenez, G. Mathis, P. Strubin, B. Versolatto, K. Weiss, R. Wintzer.

CERN-TS

J. Ramillon