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

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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 …

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

• COLDEX in SPS
1.1 LHC & Electron cloud (2) : budgets

- Electron cloud heat load budget:
  
  \[ \text{\sim 1.5 W/m at injection (450 GeV)} \]
  \[ \text{\sim 1 W/m at collision (7 TeV)} \]

- Gas budget: (450 GeV dominated by Coulomb scattering, 7 TeV dominated by nuclear scattering)
  
  Scrubbing beams at injection: \( \sim 10^{-7} \text{Torr H}_2 \text{ eq.} \)
  Physics beams: \( \sim 10^{-8} \text{Torr H}_2 \text{ eq.} \)
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) (CH₄, H₂O, CO, CO₂) and then onto the **cold bore** (CB)
- H₂ 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

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ECLOUD 04, Napa CA, 19-23/04/04

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

Year 2002

- 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:

\[
\dot{Q} = m [h_{He}(T_{\text{down}}) - h_{He}(T_{\text{up}})]
\]

- **Typical data**:

![Graph showing temperature and flow measurements over time.]

- **COLDEX in SPS - 13-14/05/02**

- **Time (h)**: 20:00, 21:00, 22:00, 23:00, 0:00, 1:00, 2:00, 3:00, 4:00

- **Temperature (K)**: BS Flux (m3/h)

- **Q = 4.5 W/m**

- **Q_0 = 1.5 W/m**
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 $\Delta P = 5 \times 10^{-7}$ Torr (but a $\Delta P$ of $10^{-7}$ Torr was measured during the experiment !)
- Final $\Delta P = 7 \times 10^{-9}$ Torr
- A factor 70 reduction of total pressure : **Vacuum cleaning**

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

![Graph showing total pressure increase over SPS dose (A.h)]

**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: $\text{H}_2$ dominated turns to $\text{H}_2 + \text{CO}$

![Graph showing gas composition over SPS dose (A.h)]

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 \( \sim 1.1 \times 10^{11} \) protons/bunch, 95 % duty cycle

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

- Final heat load \( \sim 1.5 \) W/m

- \( HL = 1.9 \exp(-D/70) \)

- Electron dose \( \sim 20 \) mC/mm\(^2\) for estimated \( <85> \) eV

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

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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 an electron current associated with the pressures increase and heat loads :
  \[
  \Rightarrow \text{electron cloud in the SPS}
  \]
- Reduction of the electron activity : \( \frac{I_{\text{final}}}{I_{\text{initial}}} \approx 0.7 \)

- Assuming that above 150 V, all electrons are collected

  \[
  \langle E \rangle = \frac{I}{P}
  \]

  - Initially :
    \[
    \langle 75 \rangle \ \text{eV} \Leftrightarrow 1.9 \ \text{W/m}
    \]
  
  - Finally :
    \[
    \langle 95 \rangle \ \text{eV} \Leftrightarrow 1.6 \ \text{W/m}
    \]
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:

\[ \delta_{\text{max}} \approx 1.2 - 1.3 \]

Reasonable agreement between simulations and experiments

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Simulation with ( \delta_{\text{max}} = 1.3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat load</td>
<td>1.6 W/m</td>
</tr>
<tr>
<td>Current</td>
<td>17 mA/m</td>
</tr>
<tr>
<td>( \langle E \rangle )</td>
<td>85 eV</td>
</tr>
<tr>
<td>Fraction &gt;30 eV</td>
<td>n.a</td>
</tr>
<tr>
<td>Dose</td>
<td>\approx 20 mC/mm(^2)</td>
</tr>
<tr>
<td>( \delta_{\text{max}} )</td>
<td>1.1</td>
</tr>
</tbody>
</table>

V. Baglin et al. Chamonix 2001

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2.3 Condensed gas (1)

Scrubbing run 2002 : 20 A.h

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

Warming-up and beam circulation at RT for 4 h

- 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$_2$O has a $\delta_{max} \sim 1.9$ (on a baked surface)!!
2.3 Condensed gas (2)
MD during the year 2002 - 2003

- $5 \times 10^{15}$ CO/cm²: - Heat load increases < 0.2 W/m with 4 batches
  - $\eta' = 1 \times 10^{-1}$ CO/e⁻

- $15 \times 10^{15}$ CO₂/cm²: - Heat load increases < 0.1 W/m with 4 batches
  - $\eta' = 5 \times 10^{-2}$ CO₂/e⁻
  - cracking of CO₂ to CO and O₂

- $60 \times 10^{15}$ CO/cm²: - 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

![Graph showing heat load versus SPS dose for COLDEX and WAMPAC 3 at different temperatures](image)
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
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**

**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, $25 \times 10^{15}$ 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 $\sim 10^{-7}$ to $10^{-6}$ Torr
- A vacuum cleaning is observed at cryogenic temperature
- The dynamic pressure is initially dominated by $\text{H}_2$, then by $\text{H}_2$ and $\text{CO}$

- In the SPS, a significant heat load is observed at cryogenic temperature $: \sim 2\text{ W/m}$
- A conditioning is observed at cryogenic temperature (is $\delta_{\text{max}} \sim 1.2$-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

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