Vacuum aspects for an LHC upgrade

Oswald Gröbner
CERN ret.

Acknowledgments:

V. Baglin, N. Hilleret, M. Jimenez, J.M. Laurent, P. Strubin, F. Zimmermann

e-mail: Oswald.Grobner@wanadoo.fr
       Oswald.Groebner@chello.at
Synchrotron Radiation

\[ P(W/m) = 1.24 \cdot 10^3 \frac{E^4(\text{TeV}) \cdot I(A)}{\Box^2(m)} \]

Linear Photon flux \[ \Box(\text{photons/s/m}) = 7 \cdot 10^{19} \frac{E(\text{TeV}) \cdot I(A)}{\Box(m)} \]

Photon stimulated molecular desorption and photoelectron production

In present hadron machines the critical photon energy is very low (45 eV in LHC) and all power is contained easily in the beam pipe -> ‘self shielding’

When the critical energy exceeds ~20 keV, Compton scattered photons of the high energy end of the spectrum escape and irradiate machine components (e.g. sc coils). Shielding may become an issue in the future.
Desorption yield

Molecular desorption yield for H$_2$ and for CO as a function of the critical photon energy at room temperature and at 77 K.

Room temperature molecular desorption yields are approx. proportional to the critical photon energy and hence would scale as the third power of the beam energy.

At 77 K, the dependence on the critical photon energy seems to be weaker, approx. as the 2/3 power. Desorption yields in the cold part of the LHC would scale like the square of the beam energy.

Few data are available -> more R&D is needed
Synchrotron radiation induced pressure rise

The dynamic pressure rise should scale

Cold arcs \[ \Delta P_{\text{cold}} = E^3 I \]

Room temperature sections \[ \Delta P_{\text{warm}} = E^4 I \]

More recently, all room temperature sections will have getter coatings and will be baked

Conventional st707 NEG \(\rightarrow\) factor 10 better than baked stainless steel \(<10^{-5} \text{ molecules/photon}\)
(Figure provided by F. LePimpec)

Coatings with NEG-films provide a further improvement: \(\sim 10^{-6} \text{ molecules/photon}\)
Combines
\(\rightarrow\) low desorption rate & high pumping speed.
(C. Benvenuti et al. EVC-6)
Pressure increase by beam induced multipacting (BIM)

Electron stimulated gas desorption has been observed in many machines: first in the ISR in 1977 more recently in KEK-B, PEP-2, RHIC, SPS with LHC-type beams.

Gas load, $Q_{\text{cloud}}$, is directly related to the power deposited by the electrons, $P_{\text{lin}}$, to the molecular desorption yield, $\square_e$, and to the average energy of the electrons in the cloud, $E_{\text{cloud}}$:

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

The factor $k$ relates molecular density to pressure units.

Scrubbing can reduce the pressure rise by two processes:
- Reduction of the electron cloud power $P_{\text{lin}}$ i.e. reduction of secondary electron yield
- Reduction of the electron stimulated desorption yield $\square_e$ by surface clean-up (K. Kennedy, LBNL)
Primary ionisation of the residual gas

\( \sigma_p \) ionisation cross section of CO for the high energy protons, \( \sim 2 \times 10^{-22} \text{ m}^2 \)

Ion current to the wall (A m\(^{-1}\))

\[ I_p = \sigma_p \frac{P_{gas}}{kT} I_{beam} \]

For LHC-type beams H\(_2\) ions gain \( \sim 220 \text{ eV} \) and CO ions \( \sim 180 \text{ eV} \)

The heavier CO ions take \( \sim 1\) s to reach the wall (e.g., beam screen)
Thus ions have a ‘long’ memory

For the cold LHC, assuming a total CO pressure of \( 10^{-7} \text{ Pa} \)

\[ I_p < 50 \text{ nA/m} \]

Hence it represents an insignificant current and power load.
Primary ionisation responsible for ion induced pressure rise
Secondary ionisation of the residual gas

Electrons of the cloud can ionise the residual gas ->
   Ions go to the wall -> ion stimulated desorption
   Source of electrons
   Heat load
   Positive space charge can trap low energy electrons
The effect will be enhanced by beam induced pressure rise e.g. due to BIM

The analogous expressions for an ionisation vacuum gauge

\[ I^+ = s_i \cdot L_e \cdot P_g \cdot I_e \]

\( I^+ (A m^{-1}) \)  ion current to the wall,
\( s_i (m^{-1} Pa^{-1}) \)  specific ionisation of the residual gas,
\( L_e (m) \)  path length of electrons,
\( P_g (Pa) \)  residual pressure
\( I_e (A m^{-1}) \)  electron current of the cloud
Most electrons have near optimum energy (50–300 eV) for gas ionisation.

CO $\sim 3 \left( m^{-1} Pa^{-1} \right)$

H$_2$ $\sim 1 \left( m^{-1} Pa^{-1} \right)$

The corresponding cross sections

- $\sigma_{s} \sim 1.2 \times 10^{-20}$ m$^2$ for CO
- $\sigma_{s} \sim 4.0 \times 10^{-21}$ m$^2$ for H$_2$

As it is done for the calibration of vacuum gauges, the path length of the electrons can be obtained from a measurement - e.g. at the SPS.
SPS Measurements

SPS measurements with a cold monitor (without magnetic field) reported to LHC MAC

(Figure provided by V. Baglin)

\[ I^\square (A m^{-1}) \sim 50 \text{ mA/m} \]
\[ I^+ (A m^{-1}) \sim 3 \text{ mA/m}, \]

normalised to nominal conditions, (1.1 \(10^{11}\) p/bunch, 25 ns bunch spacing and 4 batches) (V. Baglin)

\[ P_g (Pa) \sim 10^{-6}, \text{ taken as CO} \]

One obtains a path length for the electrons of \[ L_e (m) \sim 10^6 \text{ m} \]
**Ion space charge**

Since ions take of the order of $10^6$ s to reach the wall, they represent a space charge i.e.

An ion cloud of $i \sim 5 \times 10^{10}$ ions/m, or $\sim 4 \times 10^{12}$ ions/m$^3$

From this SPS measurement, the space charge of the cloud could be significant

$$U = \frac{e}{4\pi\varepsilon_0} i \sim 50 \text{ V}$$

One would expect that the ion cloud is neutralised.

Hence it could play an important role to trap a significant number of low energy electrons.

Time scale of $\mu$s is given by the slow ions.

Note: this ion cloud density would correspond to a room temperature pressure of $\sim 10$ nPa.

Since this effect is proportional to pressure, once a pressure rise has been initiated, it could stay for a long time -> depending on the pump down speed.
SPS measurements

Effect of Batch Spacing

Field free (COLDEX)

225 ns batch spacing

800 ns batch spacing

1050 ns batch spacing

2050 ns batch spacing

Preliminary results of the Scrubbing Run 2004

AB/AT Seminar, 22 July 2004
Survival of low energy electrons

Reflectivity of low energy electrons, which would be reflected several times from the wall of the beam duct before they are lost, is not in agreement with this long memory of the e-cloud.

Reflectivity of low energy electrons (blue curve) as a function of energy -> see CERN-AB-2004-012(ABP) by R. Cimino et al.

Required reflectivity (red) for electrons to decay by 1/e during the nominal batch spacing of 225 ns in the SPS beam pipe as a function of electron energy.

Only electrons with less than ~few eV would satisfy this condition.
Beam induced pressure instability

Conventional picture, without secondary ionisation:

Molecular desorption yield $\square$ (molecules/ion)
unit charge $e$, ionisation cross section $\square$

Critical current $(\square I)_{\text{crit}}$ defines the stable pressure range

$$P(I) = \frac{P_0}{1 \frac{\square I}{e^{/}} S_{\text{eff}}}$$

$S_{\text{eff}}$ is the effective linear pumping speed of the system.
For the LHC with a beam screen the minimum pumping is provided by the pumping holes
Beam pumping effect

Since the bombarding ions are taken from the residual gas, it would be more correct to express the net ion induced desorption as

\[(\square) \frac{I_b}{e}\]

where \(\square\) represents the probability that the incident ion is captured in the wall. A negative value of the net desorption yield would imply that the capture probability is larger than the desorption \(\rightarrow\) the beam acts as an ion pump.

For a commercial ion pump: \(\square \approx 0.1\)

For a real accelerator vacuum chamber it is probably even smaller.

Beam pumping has been observed as a ‘curiosity’.

Note: in all reports from the ISR we had assumed \(\square = 1\) and were surprised why we did not observe beam pumping systematically.
Desorption coefficients (molecules/ion)

Molecular desorption yields as a function of the ion energy for unbaked and baked stainless steel.

Net desorption yields since ions are taken from the gas phase.

Note: with $k=1$, most baked and well-cleaned systems should pump!
Ion impact energy at the collision point

Strong beam focusing gives increased ion energy the crossing points of the LHC

With the magnetic solenoid field of a detector magnet

\[ E_{ion} \approx \frac{e}{2m} B^2 r_{pipe}^2 \]

Energies become rather large and, with grazing incidence, could ultimately induce sputtering of wall material.

Instead of a pressure bump one could generate a ‘metal cloud’ or a ‘metal curtain’ if the sputtering yield is sufficiently large.
Vacuum stability in a cryogenic vacuum system

Molecules are cryo-pumped with high efficiency directly onto the cold bore. The pumping speed per unit length is

\[ S_{\text{eff}} = \frac{1}{4} v s F \]

with \( v \) the mean molecular velocity, \( s \) the sticking probability of molecules on the wall and \( F \) the surface area per unit length.

With the LHC beam pipe radius \( r_p \), the stability limit is

\[ (I)_{\text{crit}} = \frac{\sqrt{v s r_p e}}{2} \]

and for \( s \sim 1 \) the critical current will be of the order of kA.

However, this large stability limit is offset by two factors:
- The sticking probability is less than unity
- The molecular desorption yield, \( \Box \) for thick layers of condensed gas, specifically for \( \text{H}_2 \), which accumulates on a cold wall can become very large, up to \( 10^4 \) molecules per ion (Courtesy N. Hilleret et al.).
H$_2$ vapour pressure increase by exposure to thermal radiation

Results from ‘76 rediscovered in 90ies

This effect would make it impossible to pump H$_2$ on a ‘naked’ cold bore in LHC.

The limitations of cryo-pumps due to the exposure to environmental room temperature radiation and to the bombardment by beam induced energetic particles (photons, electrons, ions) must be taken into account.

Imposes -> LN$_2$ cooled baffles and the LHC beam screen. This requirement arises not only for heat load reasons but mainly to avoid re-desorption of molecules.
**Ion induced pressure rise with electron cloud**

The gas load per meter of vacuum system i.e., $PS_{\text{eff}}$ (Pa m$^3$ s$^{-1}$ m$^{-1}$), is the sum of:

- **Thermal outgassing**
  \[ P_{o}S_{\text{eff}} \]

- **Electron stimulated desorption**
  \[ \Box e kT \frac{I_{e}}{e} \]

- **Primary and secondary ion desorption**
  \[ \Box i \left( \Box p \frac{I_{B}}{e} + \Box s L_{e} \frac{I_{e}}{e} \right) \frac{P}{kT} \]

\[
PS_{\text{eff}} = P_{o}S_{\text{eff}} + \Box e kT \frac{I_{e}}{e} + \Box i \left( \Box p \frac{I_{B}}{e} + \Box s L_{e} \frac{I_{e}}{e} \right) \frac{P}{kT}
\]

Equilibrium gas density as a function of beam current

\[
P(I_{B}) = \frac{P_{o}S_{\text{eff}} + \Box e kT \frac{I_{e}}{e}}{S_{\text{eff}} \frac{\Box i}{kT} \left( \Box p \frac{I_{B}}{e} + \Box s L_{e} \frac{I_{e}}{e} \right)}
\]

Secondary ionisation by the e-cloud can reduce the critical beam current and hence the vacuum stability limit.
Secondary ionisation rate is pressure dependent, BIM can also trigger a pressure instability.
Quantitative estimate

Using the previously shown SPS measurements with cold monitor,

\[ T \sim 20 \text{K} \]
\[ \square_p \sim 2 \times 10^{-22} \text{ m}^2 \]
\[ \square_s \sim 1.2 \times 10^{-20} \text{ m}^2 \]
\[ I_e \sim 0.05 \text{ A/m}, \]
\[ I_B \sim 0.2 \text{ A} \]
\[ L_e \sim 10^6 \text{ m} \]

In the denominator, which determines vacuum stability

The first term
\[ \square_p I_B \frac{1}{e} \sim 2.5 \times 10^{-4} \text{ (m}^2 \text{ s}^{-1}) \]

While the second term
\[ \square_s L_e I_e \frac{1}{e} \sim 3.7 \times 10^3 \text{ (m}^2 \text{ s}^{-1}) \]
Conclusions

Dynamic vacuum issues should remain on the priority list of items to be studied.

Getter coated beam pipes in warm sections of LHC provides good safety margin.

Several design parameters are not well known e.g. ion induced desorption yields,…

Strong evidence that secondary ionisation of the residual gas is linked to e-cloud.

Interplay between ions and electrons may explain long memory effect observed.

More studies concerning link between e-cloud and ion induced vacuum stability.

Ions should be included in heat load budget -> calorimetric measurements.