Requirements from the Vacuum Systems
HE-LHC

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Main Topics

- **Introduction**
- **Machine parameters impacting vacuum performances**
- **Remedies to vacuum dynamic effects**
- **Gas load issue in cryogenic sections**
- **Closing Remarks**

Introduction
Accelerator vacuum requirements (1/3)

- **Particle beams are travelling under vacuum to reduce beam-gas interaction which is responsible for:**
  - Machine performance limitations
    - reduction of beam lifetime (nuclear scattering),
    - machine luminosity (multiple coulomb scattering),
    - intensity limitation by pressure instabilities (ionization) and
    - for positive beams only, electron (ionization) induced instabilities (beam blow up).
  - Heat load to the cryogenic system induced by the scatted protons/ions
  - Magnet quench i.e. a transition from the superconducting to the normal state.
    - heavy gases are the most dangerous because of their higher ionisation cross-sections.
- **Beam-gas scattering frequently induces background to the Detectors**
  - Non-captured particles which interact with the detectors
  - Nuclear cascade generated by the lost particles upstream the detectors.
- **Beam-gas scattering can be responsible for the increase of the radiations**
  - High dose rates could lead to material activation (personnel safety issues), premature degradation of tunnel infrastructures like cables and electronics
  - Higher probability of single events (induced by neutrons) which can destroy the electronics even in the service galleries

Introduction
Accelerator vacuum requirements (2/3)

- **Vacuum system shall obey to severe additional constraints which have to be considered at the design stage since retrofitting mitigation solutions is often impossible or very expensive**
  - Minimise beam impedance and HOM generation
  - Optimise beam aperture in particular in the magnets
  - Intercept heat loads (cryogenic machines)
    - Synchrotron radiation
    - Energy loss by nuclear scattering
    - Image currents
    - Energy dissipated during the development of electron clouds

Introduction
Accelerator vacuum requirements (3/3)

- **Pressures in the accelerator beam vacuum pipes are dominated by:**
  - Thermal outgassing - is not beam related, results from design, material and procedures (firing and bake-out)
  - Primary beam losses
    - Cryogenic sections are the more critical since not baked out and covered by condensed gassed BUT "protected" by the quench limit of the cryomagnets
  - Temperature of operation of the vacuum system is a determinant factor
  - Beam induced desorption effects dominates at high energies and high intensities
    - Effects linked to the bunched structure of beams
      - Electron cloud and Ion instability build-up
    - Effects linked to the total beam intensity
      - Primary beam losses induced desorption
      - Primary ionisation with circulating beams
      - Ions-induced positive space charge
      - Synchrotron radiation and photo-electrons induced desorption
    - Feedback effects
      - Secondary ionisation of residual gas by photo-electrons or electrons from the cloud

Machine parameters impacting vacuum performances
Synchrotron radiation

- **Synchrotron radiation power**
  - Factor 17.5 higher as compared to LHC
  - Must be extracted by the cryogenic system at higher temperatures thus requiring a beam screen (BS)

$$P[W/m] = 1.24 \times 10^3 \frac{E^4 I}{\rho^2}$$

- **Linear photon flux proton beam**
  - +30% of LHC nominal
  - 10 times more critical energy implies factor 3/4 in the photo-electron yield
  - Results in 4.5 times more photo-electrons stimulated desorption

$$\Gamma[photons/s/m] = 7 \times 10^{19} \frac{E\,I}{\rho}$$

- **Photon stimulated pressure rise**
  - At RT, the yield will be increased by 17.5 (NEG bring a factor 10 reduction, 10 for the critical energy and factor17.5 increase for E and I dependence)
  - At cold, the yield will be increased by 74 (10 for critical energy and 7.4 for E and I dependence)
    - Pumping speed i.e. number of holes in the beam screen shall be significantly increased!

$$\eta(576\,eV) \approx 10 \times \eta(44\,eV)$$

$$\Delta P \propto \eta(\varepsilon_c)\,E\,I$$

$$at\ RT:$$

$$\eta \propto \varepsilon_c \ and\ \varepsilon_c \propto E^3 \quad so\ \Delta P \propto E^4 I$$

$$at\ cold:$$

$$\eta \propto \varepsilon_c^{2/3} \ and\ \varepsilon_c \propto E^3 \quad so\ \Delta P \propto E^3 I$$

Machine parameters impacting vacuum performances
Energy and Total Intensity (1/2)

- **Energy (7 => 16.5 TeV)**
  - Is the dominant factor (power scaling) for SR power, photons and photo-electrons stimulated desorption
  - Higher energies implies higher bending magnetic fields and thus affects the design of the beam screen which shall stand magnetic quenches
- **Total Intensity**
  - Image current/Impedance
    - Smaller aperture would imply a ticker copper layer
      - Larger forces on to the beam screen in case of a quench
      - Mechanical stability still to be checked since increasing BS thickness will reduce aperture…
  - RF shielding
    - Engineering solutions exists and are applied in synchrotron rings

Machine parameters impacting vacuum performances
Energy and Total Intensity (2/2)

- **Intensity (factor 1.8 less compared to LHC)**
  - Is contributing linearly to all dynamic vacuum processes

  - Is the determinant factor for Ion induced instability which results from the Primary ionisation with circulating beams (σ and I dependant)
    - Circulating beams will ionise the residual gas molecules, then these ions will get accelerated by the beam potential and will impact the vacuum pipe walls inducing a local desorption
    - If the conductance/pumping speed are not adapted, a feedback effect would take place resulting in an exponential increase of the pressure
    - η is 10 times higher
    - *I* is 1.8 times smaller
    - σ does not vary significantly
    - S_{eff} will depend on Temperature and transparency of the BS

$$P(I) = \frac{P_0}{1 - \frac{\eta I}{\frac{e}{\sigma} S_{eff}}}$$

Machine parameters impacting vacuum performances
Bunch Population: Electron Cloud (1/3)

- **Bunch population (1.15 => 1.3 10^{11}p/bunch)**
  - Significant effect on the threshold and intensity of the electron cloud
  - Electron cloud is a limiting phenomenon since
    - Increasing the heat load to the cryogenic system: electron bombardment
    - Increasing the pressure and thus the background to Detectors: electron stimulated desorption
    - Interacts with beams and induces instabilities and blow-up

Machine parameters impacting vacuum performances
Bunch Population: Electron Cloud (2/3)

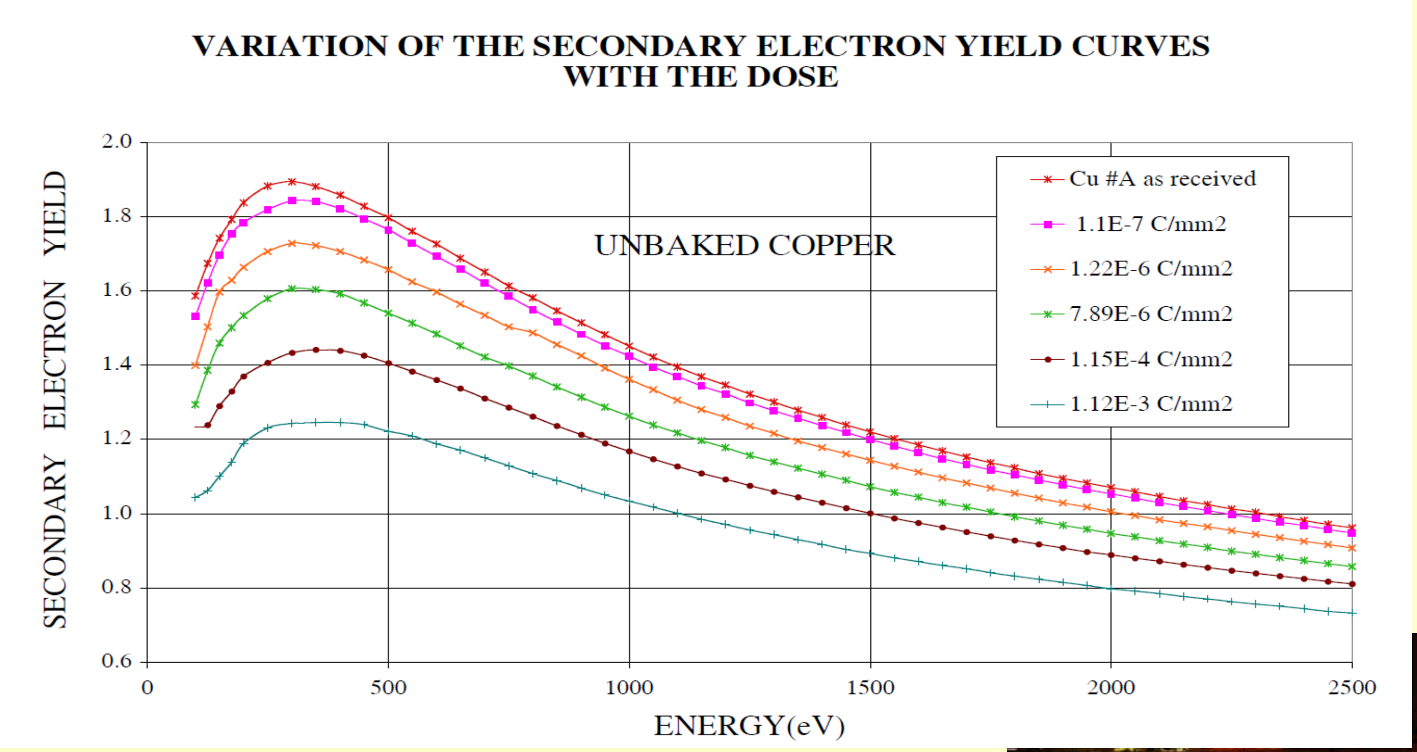
- **Stimulated outgassing gas load is given by:**

$$\Theta\left[Gas\,load\right] = k\,\frac{\eta_e P_{lin}}{\left\langle E_{cloud}\right\rangle}$$

  - k converts from molecular densities to pressures
- **The gas load is decreased by two beam induced effects:**
  - Vacuum cleaning
    - Reduction of the stimulated desorption yields (η) ⇨ factor 10-100 reduction
  - Beam conditioning (or scrubbing)
    - Reduction of the secondary electron yield (SEY, δ) of the internal beam pipe wall
    - ⇨ Reduction from 2.1 down to 1.5 in the SPS after 4-5 days of beam scrubbing
- **Electron cloud considerations**
  - Number of protons/bunch decreased but still above the threshold (~3.10^{10} in SPS dipoles)
  - Number of bunches is decrease by factor 2 ⇨ bunch spacing decreases electron cloud (50 ns is 10 times smaller than 25 ns)
    - Trapping of electrons by space charge effects can compensate this effect
  - Bunch size is reduced increasing the beam potential which is an important factor for the Ecloud
    - Electrons receive a higher kick in energy

Machine parameters impacting vacuum performances
Bunch Population: Electron Cloud (3/3)

- **The dominant factors are:**
  - Energy of the primaries
  - SEY and reflectivity of the low energy electrons (<5 eV)
  - Energy of the primary electrons
  - Magnetic field: at 22 Tesla, the larmor radius is of μm for a 100 eV electron...



Machine parameters impacting vacuum performances Feedback Effects: Ecloud vs Ion instability

- **Ion induced pressure rise with electrons**
  - Secondary ionisation by an e-cloud can reduce the critical beam current and hence the vacuum stability
  - Ionisation cross section for low energy electrons is about two orders of magnitude larger than for high energy protons.
  - Assuming the SPS Ecloud intensity 0.05 A/m and the LHC total intensity 0.54 A, this effect will start dominating if the path of the electrons in the magnetic field exceed 0.1 m...
  - Ecloud can bring a good design for ion instability to an unstable regime!

$$P(I) = \frac{P_0 S_{eff} + \eta_e kT \frac{I_e}{e}}{S_{eff} - \frac{\eta I}{kT}\left(\sigma_p \frac{I_B}{e} + \sigma_s L_e \frac{I_e}{e}\right)}$$

L_e [electron path]

σ_p and σ_e : ionisation cross section of protons and electrons

Remedies to vacuum dynamic effects
Synchrotron radiation & Ion induced instability

- **Synchrotron radiation**
  - Induced heat load
    - BS are required to intercept the heat load at a higher temperature
    - Absorbers could be considered, depends on magnet strength/length
      - Their cooling shall be decoupled from the cooling of the BS to preserve the cooling capacity
  - Photo-electron yield shall be reduced by using a sawtooth structure
    - Normal incidence instead of grazing incidence
  - Photon and photo-electrons induced desorption
    - Will improve with time resulting from the vacuum cleaning effect (dose effect)
    - Low memory effect in case of venting to air
- **Ion induced instability**
  - Make a design which provides enough effective pumping speed (considering beam pipe conductance) as from day-one
  - Longitudinal conductance has a negligible effect
    - Cold bore pumping dominates
  - Operating temperature of the cryomagnets is a key factor

Remedies to vacuum dynamic effects
Temperature of operation of the cryogenic systems

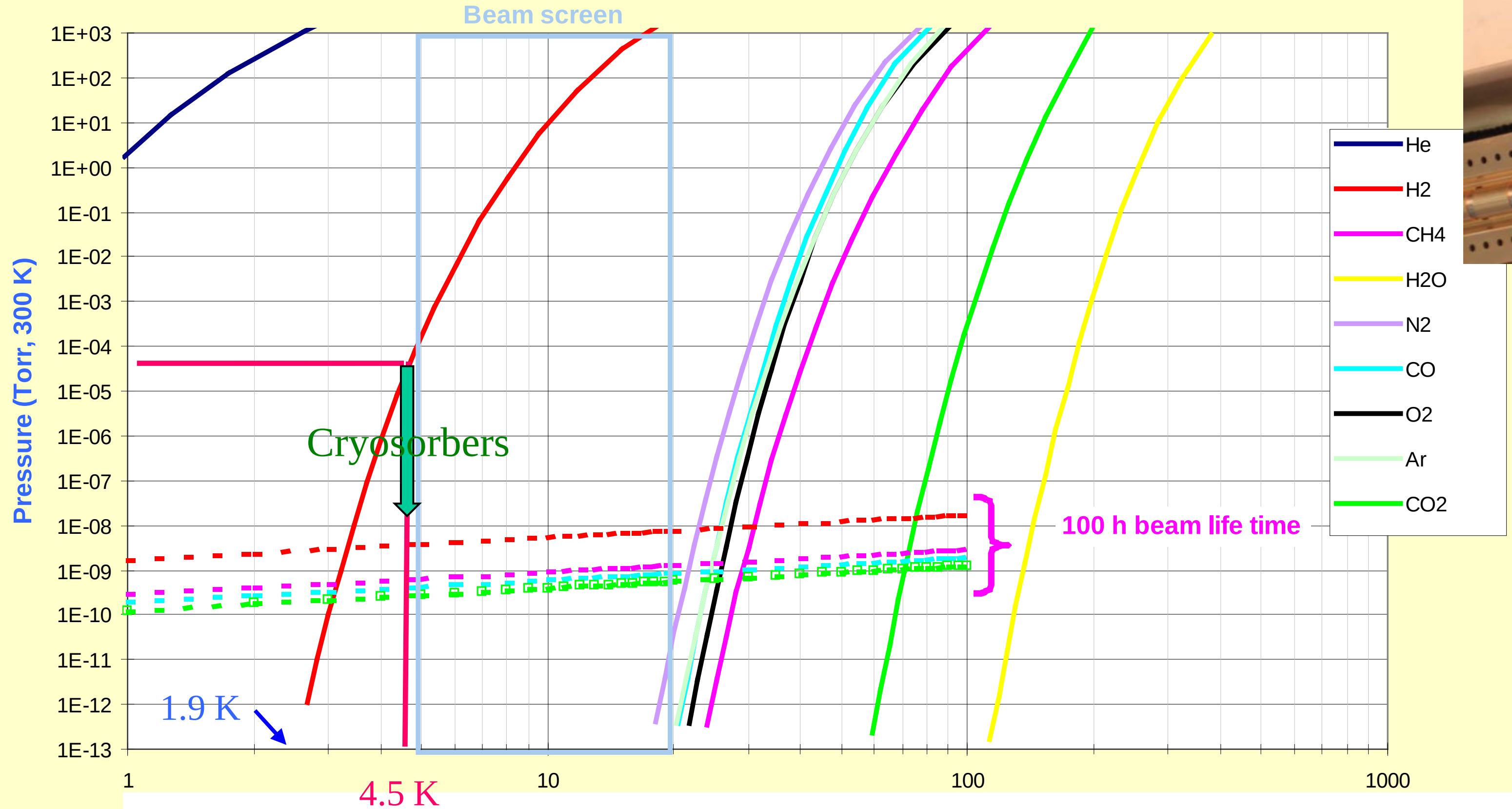
- **The pumping on cold bore / beam screen is dependant from:**
  - Mean molecular velocity [ν]
  - Sticking probability [s]
  - Surface area of pumping per unit of length of the beam pipe [F]

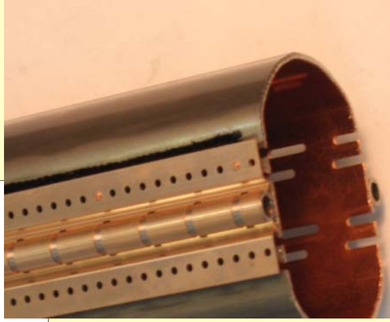
$$S_{eff} = 1/4\, \upsilon\, s\, F$$

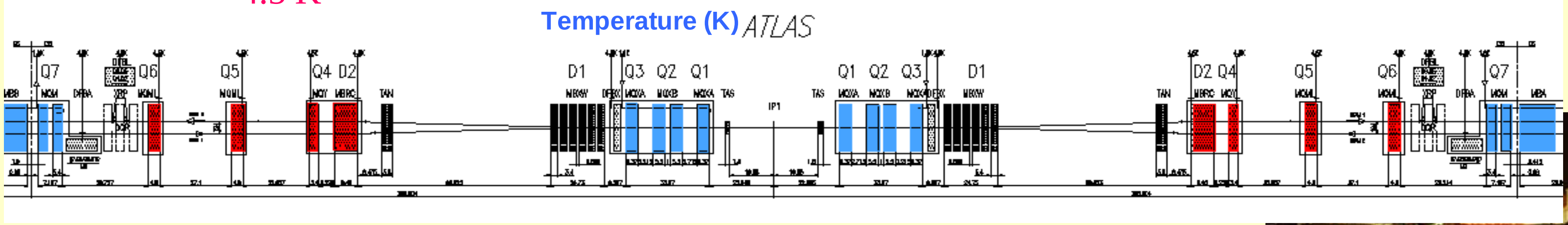
  - The increase of the magnet operating temperature will:
    - Keep the pumping speed constant as [F] does no vary
    - Decrease the pumping capacity as [s] will decrease
  - To compensate:
    - The transparency of the beam screen shall be increased
      - Since the aim is to reduce the magnet aperture, the % of hole will also increase
      - HOM effects ?
    - If T_{op} is higher than 3 K, cryosorbers will be required and shall be "thermalised" by the cold bore (not by the beam screen)
    - If pumping capacity is limited, regenerations will be required BUT in this case the magnet will have to be warmed-up instead of the beam screens
      - Permanent turbomolecular pumping of the beam vacuum will then be needed...

Remedies to vacuum dynamic effects
Adsorption isotherms

Saturated vapour pressure from Honig and Hook (1960)

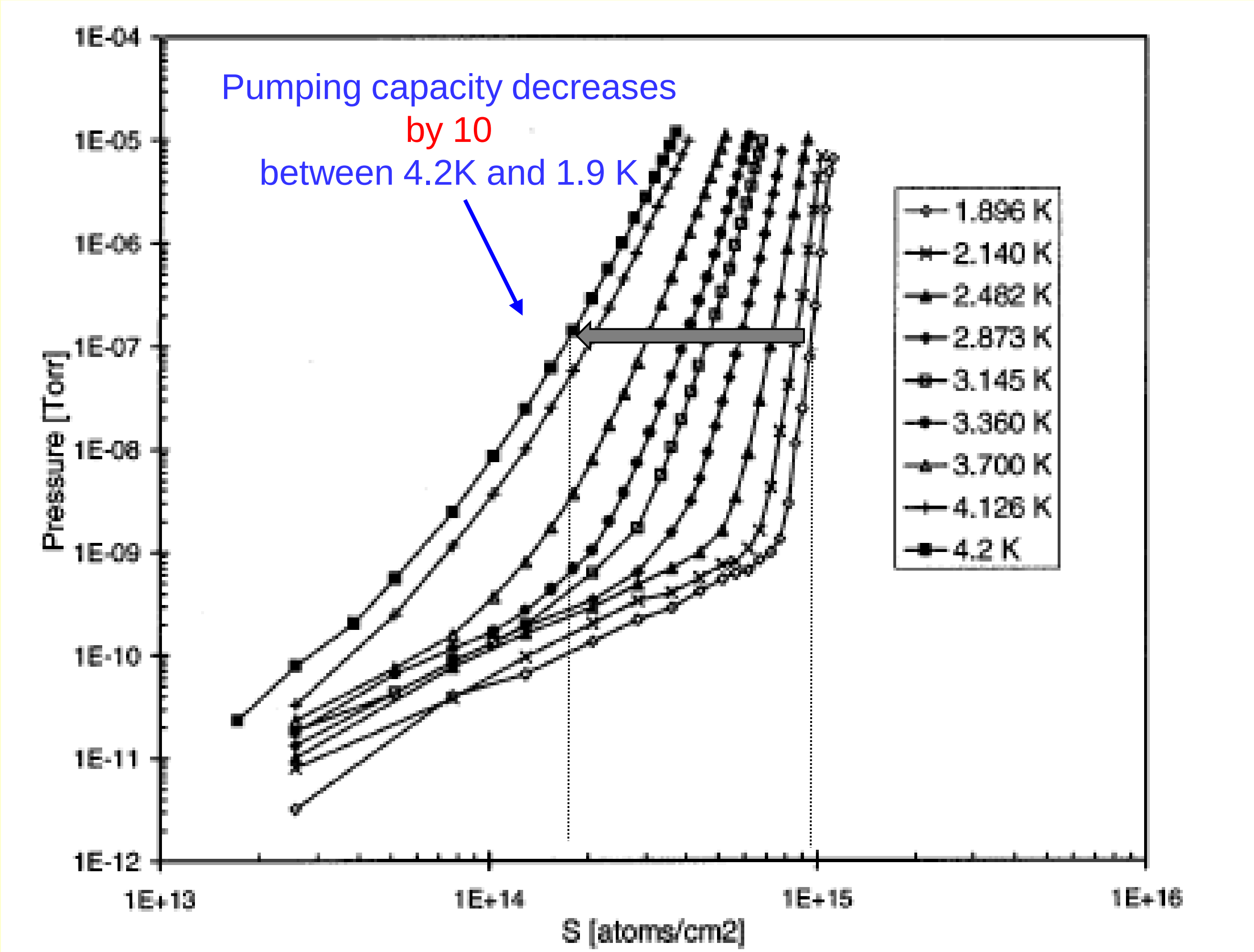






Remedies to vacuum dynamic effects
Pumping capacity

He adsorption isotherms on stainless steel (similar for H)



Remedies to vacuum dynamic effects
Electron Cloud mitigation (1/3)

- **Active solutions: clearing electrodes**
  - No threshold efficiency
  - No lifetime issues
  - Can suppress also the surviving electrons
    - Low-energy electrons surviving gaps between bunches
  - Does not degrade in case of venting to air
  - Similar efficiency at cryogenic temperatures

  BUT
  - Shall be in the vertical plane in dipoles since electrons are confined in 2 (3) strips in the vertical plane
  - Shall be large enough to cover the spacing of the vertical strips which varies with bunch intensity
  - Can be placed behind the pumping holes of the BS
  - Results in an aperture reduction

Remedies to vacuum dynamic effects
Electron Cloud mitigation (2/3)

- **Passive solutions: coatings**
  - NEG coatings (SEY=1.1 after activation)
    - Needs a bake out. Solution validated in many accelerators
    - Improvements ongoing to achieve low-temperature NEG activation coatings (120-140 °C), compatible with their use in RT magnets and Detectors
  - a-C (graphite) coatings (SEY<1)
    - Looks promising, lifetime being evaluated
    - SEY could be further decreased by a combination of geometrical surface effects (rougthness)
      - Impedance effects to be evaluated
    - Higher outgassing rates but could be decreased with a low-temperature bake out (<120°C)
    - Ongoing studies for its qualification at cryogenic temperatures
      - Will help with background to Detectors
      - Could provide more pumping capacity for hydrogen (cryosorber material)
      - Thick gas coverage could modify the SEY
  - Other types of coating could be considered for SEY>1.5: TiN

Remedies to vacuum dynamic effects
Electron Cloud mitigation (3/3)

- **Scrubbing effect**
  - Efficient only up to the bunch intensity used during the scrubbing periods
  - Detectors can not take any data during the scrubbing run since saturated by the beam-gas scattering
  - Little experience of its efficiency on surfaces at cryogenic temperatures
    - Measurements show that condensed gasses significantly modify the “apparent” SEY

Gas load issue in cryogenic sections
Beam Screen /Cold Bore Recycling

- **Thick coverage of beam screens (BS) and cold bore (CB) by atoms/molecules desorbed directly (beam losses) and indirectly (photons, electrons and ions) could lead to pressure oscillation and vacuum instabilities.**

- **In practice, should not become a limiting factor since:**
  - Thick coverage in BS
    - BS can be recycled by heating up to 80 K
    - Gas will be “flashed” towards the cold bore through the BS pumping holes
    - Conditions can be met during short LHC Technical Stop (2-3 days)
  - Thick coverage of CB
    - CB can be recycled by warming-up to 80 K
    - Gas is pumped away using mobile turbomolecular pumps
    - Conditions met once per year during the LHC Technical Stop (Christmas)

Closing Remarks
Start-up with beams

- **Start-up scenario**
  - Accelerator vacuum system can not be designed for nominal performances on day-one, often
    - Rely on vacuum cleaning (reduction of the desorption yields by photon, e-, ions bombardments)
    - Rely on beam scrubbing (reduction of the secondary electron yields)

  - With bunched beams, two options
    - Nominal number of bunches and progressive increase of the intensity per bunch
      - Allows to benefit from vacuum cleaning effects and therefore the effects linked to the bunched structure of beams (electron cloud and ion instability) are less limiting since stimulated desorption coefficients (η) have decreased with time/dose (photons)
        - » Areas with two circulating beams will behave differently...
    - Nominal intensity per bunch and progressive increase of the number of bunches
      - Allows for higher luminosities with lower machine optimisation but all effects linked to the bunched structure of beams (electron cloud and ion instability) will be at their maximum

Closing Remarks
Observations from other accelerators: LHC vs SPS

- **Effects linked to the bunched structure of beams (electron cloud and ion induced instability) are hard limits for performances of accelerators. Alternative solutions can be found to allow running up to nominal/ultimate performances but always by compromising on other aspects**
  - SPS requires a Scrubbing Run (3-5 days) to be able to operate nominal LHC beams with limited electron cloud and acceptable pressure rise. This Run relies on:
    - The reduction of SEY by electron bombardment: dose effect
    - The low stimulated desorption yields: avoid as much as possible venting of vacuum sectors
  - LHC (will) require a both a vacuum cleaning and scrubbing period BUT with larger constraints since background to the experiments, induced heat load to cryogenics and cryomagnet quench limits (beam-gas scattering) prevent operation with large electron cloud which should have lead to a faster vacuum cleaning and beam scrubbing

Closing Remarks
Preliminary consideration for HE-LHC (1/2)

- **Considering what was observed in other accelerator, HE-LHC shall go for more conservative design: Effects linked to the bunched structure of beams shall be mitigated as from the design**
  - Will help to reduce to the minimum the background to Detectors
  - Will help in case the beam scrubbing of cryo surfaces and cold/warm transitions is slower than initially considered
  - Will help in case the accumulation of the low energy electrons with high reflectivity (survivals) compensate the reduction of the secondary electron yield (SEY)
    - Beam scrubbing no longer help, photo-electrons production will dominate (design issue i.e. will not be significantly improving with time/dose)
    - At the moment, no evidence of this phenomenon as can not be observed in SPS, tentative to study it at RHIC did not go to the end.
    - Have evidence for the long survival time of the very low energy electrons (< 5eV)

Closing Remarks
Preliminary consideration for HE-LHC (2/2)

- **Vacuum system shall be designed to**
  - Be stable on day-one against ion-instability
  - Reduce the number of photo-electrons
  - Rely on vacuum cleaning (decrease of η_{ph}/η_{e-}) for gas desorption stimulated by SR and photo-electrons
  - Implies the use of a beam screen but as compared to LHC, the following issues must be looked at:
    - More pumping speed is required: more pumping slots
    - Mechanical constraints: deformation with quench, impedance and HOMs
  - Cooling capillaries at BS to thermalise it between 40-60 K
  - Cryosorbers are required if the cryomagnets are operated above 3 K
  - Clearing electrodes in dipoles behind the BS and attached to the cooling capillaries to suppress electron cloud, alternatively:
    - Proceed to a coating of quads and cold/warm transitions of standalone cryomagnets
    - Use solenoids (3-5 mT) to mitigate electron cloud build up in vacuum instrumentation ports and interconnecting pieces which can not be coated
  - Long straight sections at RT should be baked and use NEG coatings
    - Alternatively, install solenoid if coating is not feasible