Preliminary Considerations for the LHeC Beam Vacuum System

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Main Topics

- **Introduction**
- **Beam Lifetime Considerations**
- **Synchrotron Radiation Issues**
- **Engineering and Pumping Considerations**
- **Closing Remarks**

Introduction
Accelerator vacuum requirements

- **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 [cont.]

- **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
  - Specific shielding against radiation to protect magnet coils

Beam Lifetime Considerations
Beam-Gas Scattering

- **Beam-gas scattering dominated by bremsstrahlung on the nuclei of gas molecules. Therefore, depends on:**
  - Partial pressure
  - Weight M of the gas species
  - Radiation length [g/cm^2]

Typical composition of photon-stimulated desorption: 75% H_2, 24% CO/CO_2, 1% CH_4

☞ Ar is 67 times more harmful than hydrogen (H_2)

☞ CO_2, CO and N_2 are about 30 times worst compared to hydrogen (H_2)

☞ CH_4 is 10 times worst

☞ **Pressure requirements are expected to be 10 times higher in the Ring-Ring option compared to the Linac-Ring option**

☞ Bake out shall be the baseline

Beam Lifetime considerations

Critical Energy of Photons

Desorption rate depends on critical energy of the synchrotron light

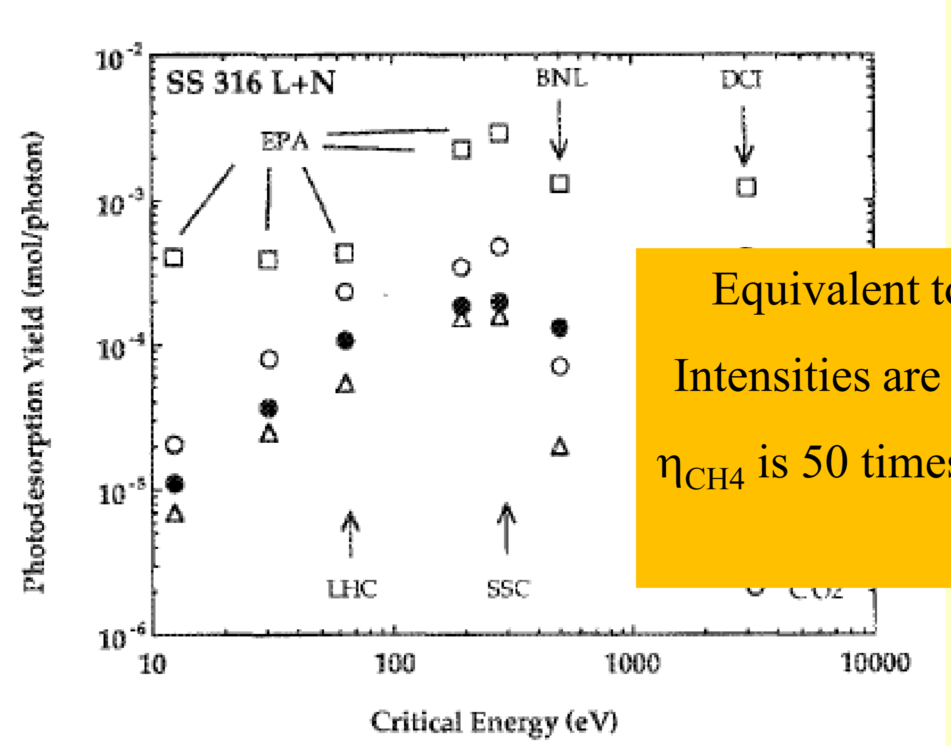
ε_c is the energy which divides in 2 the emitted power

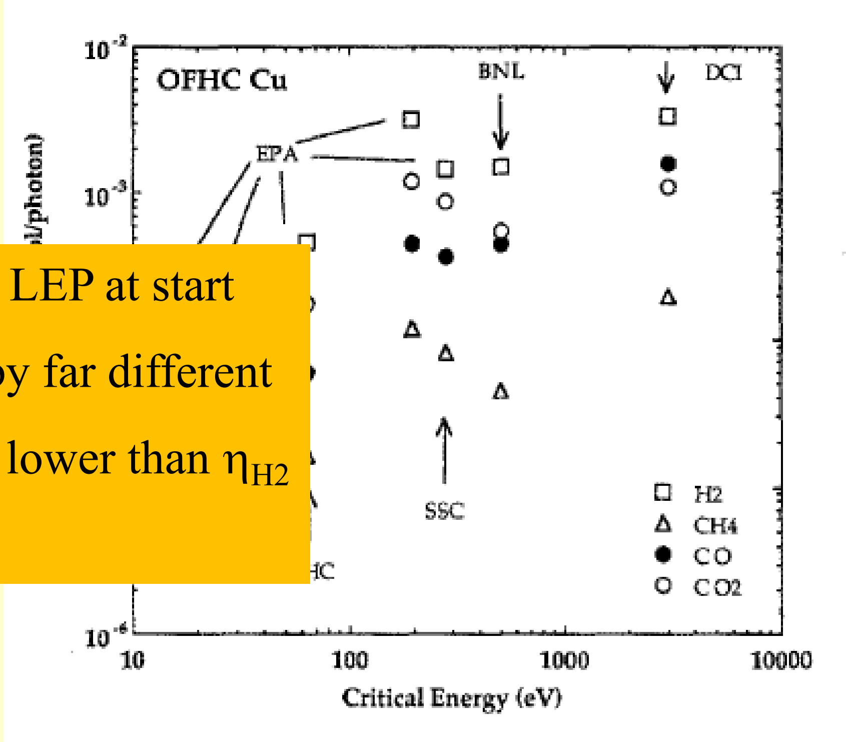
$$\varepsilon_c(eV) = \frac{3\cdot 10^{-7}}{R}\left(\frac{E_B}{E_o}\right)^3$$

E_o = 0.94 GeV for proton, $5\cdot 10^{-4}$ GeV for electron

E_B is the energy of the beam, R the bending radius

For most materials, desorption rates vary quasi linearly with critical energy





Equivalent to LEP at start

Intensities are by far different

η_{CH4} is 50 times lower than η_{H2}

Synchrotron Radiation
Photon-induced Outgassing

- **Synchrotron radiation power**
  - Is an issue for the heat load evacuation and scales: $P\,[W/m] = 1.24 \times 10^{3} \dfrac{E^{4} I}{\rho^{2}}$
    - linearly with I (mA)
    - Power of 4 for energy (GeV)
    - Inversely to power 2 of bending radius
- **Linear photon flux proton beam**
  - Scales linearly with energy and intensity and
  - Inversely with bending radius

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

- **Photon stimulated pressure rise**
  - At RT, scale:
    - Power of 4 of E and linearly with I
  - At cold, scale:
    - Power of 3 with E and linearly with I

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

$at\ RT$:

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

$at\ cold$:

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

Synchrotron Radiation
Photon-induced Outgassing [cont.]

- **Synchrotron radiation power**
  - Ring-Ring: 45 times higher than LEP
    ~180 times in by-passes
  - Linac-Ring: 10 times higher than LEP
    in bending sections/injection

$$P\,[W/m] = 1.24\times10^{3}\,\frac{E^{4} I}{\rho^{2}}$$

- **Linear photon flux proton beam**
  - Ring-Ring: 45 times higher than LEP
    ~45 times in by-passes
  - Linac-Ring: 5 times higher than LEP
    in bending sections/injection

$$\Gamma\,[photons\ /s/m] = 7\times10^{19}\,\frac{E\ I}{\rho}$$

- **Photon stimulated pressure rise**
  - Ring-Ring: 45 times higher than LEP

–

  - Linac-Ring: 30 times less than LEP

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

$at\ RT$:

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

$at\ cold$:

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

Synchrotron Radiation
Vacuum Cleaning

- **Vacuum Cleaning**
  - Characterize the reduction of the desorption yields (η) of a surface resulting from the bombardment of the surface by electrons, photons, ions.

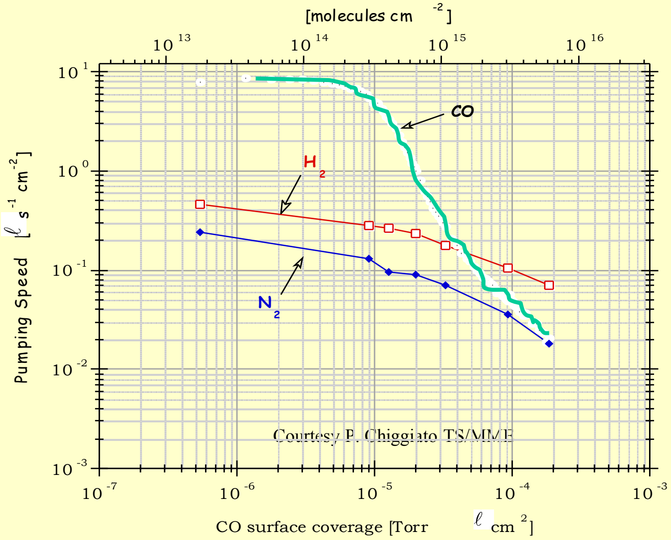
  ☞ η = Number of gas molecules desorbed from the surface/bulk by a primary electron, photon, ion.

- **Accelerator vacuum system can not be designed for nominal performances on "day 1", shall rely on:**
  - Vacuum cleaning
    - Reduction of the desorption yields (η) by photon, e- and ions bombardments

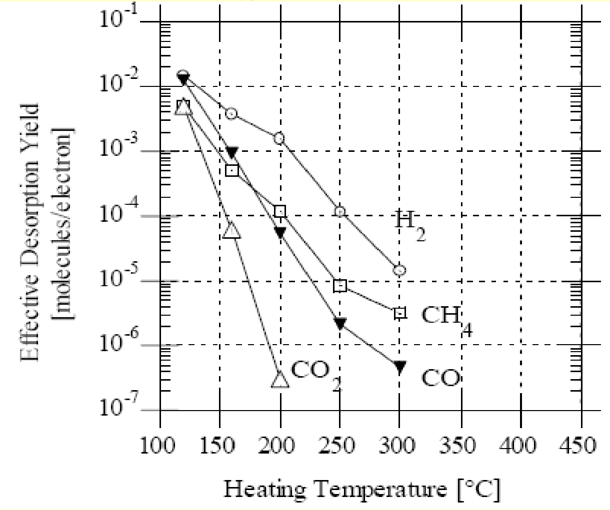
☞ **Necessitate accepting a shorter beam lifetime or reduced beam current during initial phase, about 500 h for LEP**
  - Could be significantly decreased by using NEG coatings

Synchrotron Radiation
NEG coatings: THE baseline…

Pumping Speed



ESD Yields



•C. Benvenuti *et al.* J.Vac.Sci.Technol A 16(1) 1998

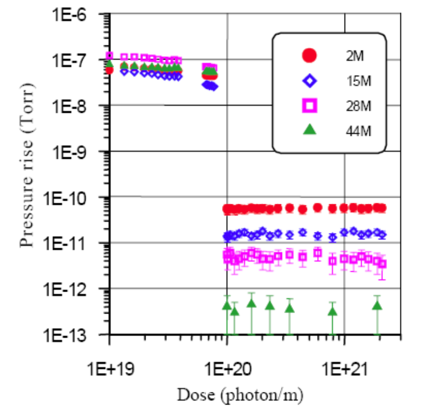


Figure 2: Pressure rise measured in the centre of the TiZrV coated test chamber before activation (<$1\cdot10^{20}$ photons/m) and after activation (>$1\cdot10^{20}$ photons/m).

PSD Yields

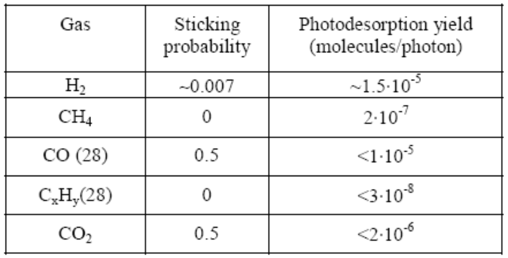
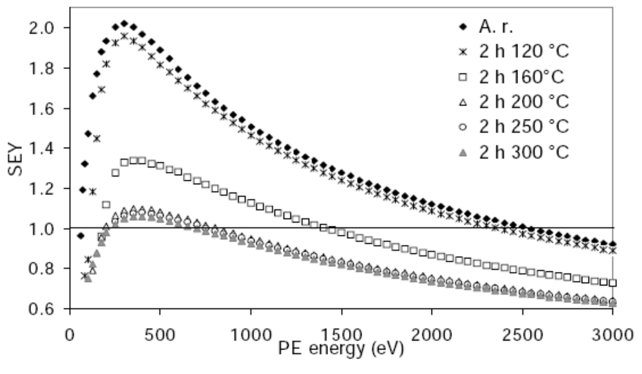


Table 2: Summary of results from the activated test chamber

Gas	Sticking probability	Photodesorption yield (molecules/photon)
H_2	~0.007	~$1.5\cdot10^{-5}$
CH_4	0	$2\cdot10^{-7}$
CO (28)	0.5	<$1\cdot10^{-5}$
C_xH_y(28)	0	<$3\cdot10^{-8}$
CO_2	0.5	<$2\cdot10^{-6}$

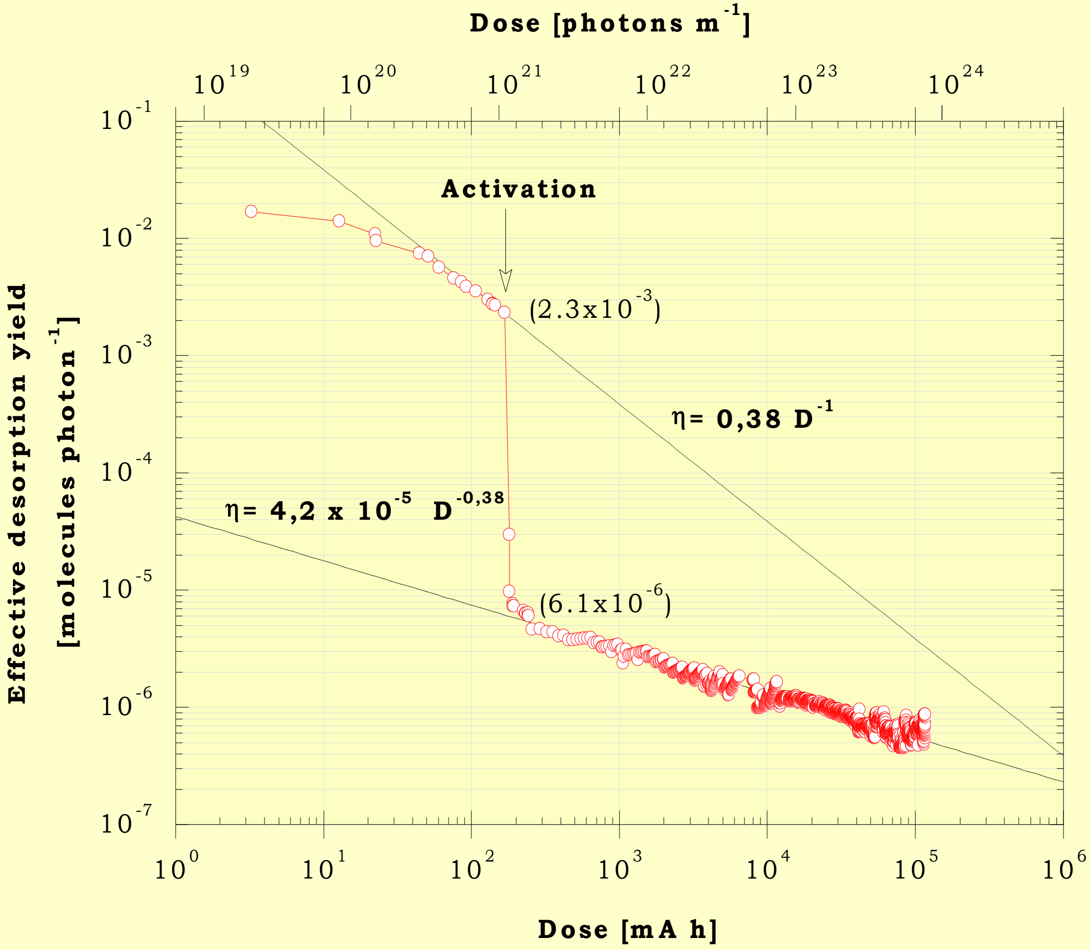
Secondary Electron Yield



C. Scheuerlein *et al.* Appl.Surf.Sci 172(2001)

…being successfully used in SR facilities

Synchrotron Radiation
NEG coatings: THE baseline… [cont.]



PSD at ESRF

Some evidences exist that a large part of the remaining desorption after activation could be due to a small fraction of the photons flux striking outside the chamber

CH_4 desorption yield reduced by a factor of at least 200 after activation, no Kr degassing detected

Courtesy of
P. Chiggiato

Synchrotron Radiation
Engineering Issues

- **Power deposition**
  - 50% of the radiation power hitting the vacuum chamber is absorbed in the aluminum chamber
  - Remainder 50% (high-energy part of the spectrum) escape into the tunnel and creates severe problems:
    - Degradation of organic material and electronics due to high dose rates
    - Formation of ozone and nitric acid could lead to severe corrosion problems in particular with aluminum material
- **Lead Shielding**
  - Lead shielding of 3 to 8 mm soldered directly on the vacuum chamber were used at LEP
    - Higher SR flux could require more thickness, calculations still to be done.
- **Heat load extraction**
  - Evacuation of SR induced heat load on vacuum pipe wall and on lead shielding is a critical issue which need to be studied
    - Bad experience in LEP, lead was melted
- **Material fatigue**
  - The induced stress (Ring-Ring option) resulting from the much higher intensity as compared to LEP shall be evaluated.

Engineering and Pumping Considerations
Materials

- **Aluminum extruded beam pipes are often used since**
  - Cheap and easy to extrude complex shapes
  - High thermal conductivity, optimum for cooling issues

☞ **Is a limitation for:**
  - Bake out temperature and NEG coatings activation
  - Reliability of vacuum interconnection based on aluminum flanges is a concern at high temperature (>150°C)
  - Corrosion problems
  - Larger thickness in particular if bake out is required

- **Stainless steel**
  - Is more difficult and costly to machine and shaped
  - Has poor heat conductivity

☞ **But have higher resistance to corrosion and more reliable vacuum connections**

Engineering and Pumping Considerations
Pumping Scheme

- **Pumping scheme based in both cases on:**
  - Mobile turbomolecular pumping stations for roughing
  - UHV shall be ensured by NEG coatings…
    - ☞ Sublimation pumps could be an alternative at some locations

…combined with ion pumps

- ☞ Pumping of noble gasses and methane

- Use of superconducting RF structures and magnets imply Cold/Warm transitions
  - Will need special attention in particular if using NEG coatings

Engineering and Pumping Considerations
Ring-Ring versus Linac-Ring

- **Vacuum design**
  - Easier for Ring-Ring since more space available around the beam pipes
    - Much tight tolerances for the design of the Linac-Ring beam pipes
- **Vacuum stability**
  - Easier to ensure with the Linac-Ring
    - Less SR and limited to the bending sections
- **Integration of vacuum pumps & instrumentation**
  - Easier for Ring-Ring since more space available around the beam pipes
    - Space limitation introduce by the presence of the LHC
    - By-pass around CMS shall be dismountable
      - Shall use extensively NEG coatings + bake out to recover the required operating pressure and avoid having to go through vacuum cleaning process
- **Maintenance of the vacuum system**
  - Simpler for the Linac-Ring since the accelerator is independent from the LHC
    - Ring-Ring will induce constraints to the LHC and vice-versa

Closing Remarks
Aspects to be addressed in details

- **Vacuum requirements**
  - Linac-Ring versus Ring-Ring Options
- **Vacuum stability (Synchrotron radiation and photon-induced desorption)**
  - Linac-Ring option versus Ring-Ring options
- **General description of the vacuum system**
  - Specificities of the Linac-Ring option
    - Impact on design and vacuum stability
  - Specificities of the Ring-Ring option
    - Impact on design and vacuum stability
- **Vacuum systems**
  - Vacuum pumping
    - Discrete versus distributed
    - Cold/Warm configurations with Linac-Ring option
  - Vacuum Diagnostics
  - Vacuum Sectorisation – Sector valves
    - Cold/Warm configurations with Linac-Ring option

Closing Remarks
Aspects to be addressed in details [cont.]

- **Vacuum engineering issues**
  - HOM and Impedance implications
    - SR facilities design instead of simple LEP design(?)
  - Bake-out of vacuum system
    - Activation of NEG coatings
  - Heat loads induced by synchrotron radiation
  - Shielding issues
    - Heat load evacuation
  - Bellows and fla
  - Corrosion issue
- **Experimental a**
  - SR induced pres
  - Heat load evacuation if using photon absorbers
    - Photo-electrons generation

Unexpected SR heat loads
  Orbit displacements
  Adjustments of quadrupoles and wiggler magnets

Were degrading LEP performances by inducing leaks

- **Technical challenges**
  - Vacuum stability of Experimental areas – long distances without pumping
- **Integration constraints at Injection and Extractions**