Interaction between Beams and Vacuum System Walls.

R. Cimino,
LNF INFN, Frascati, Italy.
Interaction between Beams and Vacuum System Walls.

- Phenomenology:
  What happens to the Vacuum beam pipe in presence of the beam?
  - Synchrotron radiation: Heat Load, Photo-electrons and electron induced desorption
  - Ion induced desorption and associated instability.
  - Desorption yields and conditioning.
  - “Electron cloud” effects and associated instabilities
  - Additional materials ➔ Addendum

- Mitigation strategies
- Conclusion
One real example to see what the beam does to Vacuum:
8-10-2010

450 GeV – 150 ns bunch spacing: Merged vacuum @ LHC
Exotic Vacuum behavior @ LHC:

450 GeV – 150 ns bunch spacing: Merged vacuum
Easily solved: Installation of Solenoids
Solenoids have effect on pressure!!!

- **Beam Intensity**
  - Solenoid ON A4L1
  - Solenoid ON A4R1

Remove multipacting
Still primary electrons

After 20 min
\[ \Delta P \approx 7 \cdot 10^{-10} \]
Solenoids have effect on pressure!!!

Evidence for: e-Cloud Instabilities due to the interaction between beams and Vacuum system walls

Remove multipacting
Still primary electrons
Vacuum in new generation accelerators is much “more” than a technical issue!

- Let us see what may cause such beam and/or pressure instabilities.
- The case of the: LHC arcs
Cold Bore @ 1.9 K

Extreme High Static Vacuum (<< $10^{-13}$ Torr)
Need of a Beam Screen @ 5K < T < 20K to reduce heat load (SR, Eddy current, Impedance, etc…) on Cold bore for thermal load issues.
The Beam Screen is a complex technological product!

FUNCTION

- Reduce beam-induced cryogenic loads
- Increase development time of transverse resistive-wall instability
- Resist eddy-current forces at magnet quench
- Preserve field quality in magnet aperture
- Maintain good beam vacuum
- Limit development of electron cloud

PROCESS

- Limit residual heat load to cold mass
- Intercept synchrotron radiation
- Limit resistive wall impedance
- Structural material with high resistivity
- Low-permeability materials
- Provide pumping from shielded cold surface
- Limit reflectivity and SEY of beam screen surface

DESIGN FEATURE

- Low-conduction supports
- High-conductivity copper plating
- Cooling at low temperature
- Austenitic stainless steel structure
- Pumping slots
- Avoid temperatures favoring desorption of common gas species
- Sawtooth absorber
- Beam scrubbing

Cu layer

Pumping slots shields

Cooling tubes

“Saw teeth”
Let us see what happens during operation and beam passage to:

- The vacuum system
- The Beam screen Surface

T=0, without beam
Beam – Gas Interactions

The beam interacts with the residual gas:

\[ dl = -I \sigma n \, dx \]

\[ \frac{dI}{dt} = -I n v \sigma \]

This defines:

Vacuum Beam Life time \((\tau)\)

\[ I = I_o e^{-\frac{t}{\tau}} \]

\[ \tau = \frac{1}{n \sigma v} \]

For a vacuum system:

\[ \frac{1}{\tau} = \frac{1}{\tau_{H2}} + \frac{1}{\tau_{CH4}} + \frac{1}{\tau_{H2O}} + \frac{1}{\tau_{CO}} + \frac{1}{\tau_{CO2}} \]

The vacuum life time must be much larger (i.e. >> 24 h) than other life times such as e.g. the particle loss due to the collisions

Where:
- \(\sigma\) is the cross section i.e. the probability the beam interacts with the atoms of target
- \(I\) is the beam intensity
- \(n\) is the atomic density of a target of thickness \(dx\)
- \(v\) is the beam velocity
Ionisation cross section is a function of the speed & the charge of the projectile and of the nature of the residual gas.

Heavy gas must be avoided.
Ions interact with accelerator wall: Ion desorption yield

- Ionised gas will hit the Accelerator wall and induce ion desorption.
- Pressure and beam ion interaction will increase, increasing desorption
- Such a resonant phenomenon will cause Vacuum instability and there will be a critical beam current, at which the pressure increases to infinity.

Unbaked stainless steel

Varies with:
- the material,
- the ion energy
- and ion species

Several molecules can be desorbed per ion \(\rightarrow\) Sputtering
Ions interact with accelerator wall: Ion desorption yield. Conditioning and implantation

- In the LHC: the maximum flux is about $3 \times 10^8$ ions/(cm$^2$.s) i.e. a dose of $3 \times 10^{15}$ ions/(cm$^2$.year)

- In the LHC, there is no conditioning due to ion bombardment
Let us see what happens during operation and beam passage to:

- The vacuum system
- the Beam screen Surface

$T=0$, without beam
Synchrotron Radiation

- A charged particle which is accelerated produce radiation
- The power of the centripetal radiation is larger than the longitudinal radiation (factor $\gamma^2$)
- For a relativistic particle, the radiation is highly peaked (opening angle $\sim 1/\gamma$)

**Critical energy:** divide the power spectrum in two equals parts

$$\varepsilon_c = \frac{3}{2} \frac{hc}{2\pi} \frac{\gamma^3}{\rho}$$

Electrons: $\varepsilon_c [\text{eV}] = 2.21810^3 \frac{E[\text{GeV}]^3}{\rho[\text{m}]}$

Protons: $\varepsilon_c [\text{eV}] = 3.583510^{-7} \frac{E[\text{GeV}]^3}{\rho[\text{m}]}$
Synchrotron Radiation: $E_c = 44$ eV @ LHC

Time = 0

- The average power emitted by the beam per unit length is:
  
  For LHC: $P_{SR} = 0.17 \text{W/m/apert.}$

$$P_0 \propto \frac{E^4}{\rho^2} I \propto B^2 E^2 I$$
Photo-desorption:

SR & Surface Science

Radial Distance

CB

BS

Time = 2 ns

Fig. 6. Tentative Microscopic Model for PSD from OFHC Copper.

O. Gröbner et. al. EPAC 1992
Photo-desorption:

- The dynamic pressure decrease by several orders of magnitude with photon dose: “photon conditioning”
- The photon desorption yield is characterised by $\eta_{\text{photon}}$

Cu baked at 150°C

Time = 2 ns

See: talk from O. Malyshev
Photo-desorption at LT:

Initial yield, $\eta_0$, are smaller than at room temperature.

BUT at LT:

- presence of physisorbed molecule

V. Baglin et al., Vacuum 67 (2002) 421-428

V. Anashin et al., Vacuum 53 (1-2), 269, (1999)

Average removal coefficient (molecules/photon)

Average coverage (molecules/cm$^2$)

Time = 2 ns

See: talk from V. Baglin
Photons induce Heat load:

Time = 2 ns

<table>
<thead>
<tr>
<th>Parameters</th>
<th>LHC</th>
<th>H-L LHC</th>
</tr>
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<tbody>
<tr>
<td>c.m. Energy [TeV]</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Circumference C [km]</td>
<td>26.7</td>
<td></td>
</tr>
<tr>
<td>Dipole field [T]</td>
<td>8.33</td>
<td></td>
</tr>
<tr>
<td>Injection energy [TeV]</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>Peak luminosity [$10^{34} \text{cm}^{-2}\text{s}^{-1}$]</td>
<td>1.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Stored beam energy [GJ]</td>
<td>0.392</td>
<td>0.694</td>
</tr>
<tr>
<td>SR power per ring [MW]</td>
<td>0.0036</td>
<td>0.0073</td>
</tr>
<tr>
<td>Arc SR heat load [W/m/aperture]</td>
<td>0.17</td>
<td>0.33</td>
</tr>
<tr>
<td>Critical photon energy [keV]</td>
<td>0.044</td>
<td>4.3 (5.5)</td>
</tr>
</tbody>
</table>

$P_{TOT} \sim 3 \text{ GW}$

$P_{TOT} \sim 80 \text{ MW}$

Credits: R. Kersevan -- Beam Dynamics meets Vacuum, Collimations, and Surfaces 2017
Photon reflectivity:

Radial Distance

CB
BS

\[ \text{Time} = 2 \text{ ns} \]

PS: reflected photons do NOT induce HL.
See: R. Cimino V. Baglin and F. Schäfers PRL 2015


SR & Surface Science
Photon reflectivity: where photons go?

In the dipoles we are in presence of a strong Magnetic field

Photoelectrons contributing to e-cloud build-up mainly from scattered photons

Mainly electrons produced by photons absorbed on the top and bottom of beam screen can seed e-cloud build-up in dipoles and BS is optimized to reduce them.

PS: Reflected photons do NOT produce photoelectrons. See: R. Cimino V. Baglin and F. Schäfers PRL 2015
Photoemission: \((\text{vs. } h\nu, Q, E, T, B)\)


Produced \(e^-\) (PY): very important for single beam instabilities (K. Ohmi and F. Zimmermann PRL 2000)
Even in absence of SR:
\( e^- \) from ionization of residual gas... etc

Beam induced multipacting is observed in SPS where no \( e^- \) are photoemitted.
Beam induced el. acceleration

(F. Zimmermann)
At the moment of creation
After acceleration

at moment of creation
after bunch passage

Time = 10 ns

Energy (eV)
$e^-$ induced $e^-$ emission


Time = 15 ns

Surface Science: SEY
$e^-$ induced $e^-$ emission vs. E

Energy Distribution Curves as function of Ep


Time = 20 ns
e\textsuperscript{-} cloud Build-up

Radial Distance

Time structure vs. Simulations.

(F. Zimmermann)

Time = 25 ns

E- cloud simulation

Cas, Glumslöv, Sweden. 12 - 6 - 2017 R. Cimino
Radial Distance

**e⁻ induced heat load**

CB

BS

\[ p^+ \]

\[ p^- \]


**Simulation**

Time = 25 ns

*e⁻ cloud build up causes Heat load!*

CAS, Glumslöv, Sweden. 12 - 6 - 2017 R. Cimino
e⁻ induced gas desorption

Radial Distance

See: talk from O. Malyshev

Time = 25 ns

It is a beam/Vacuum issue!

Dynamic pressure increase !!!

Desorbed gas

Surface Science and simulation
Beam blow up

Time structure vs Simulations.

It affects beam quality!

Jean-Luc Vay
IPAC’2012

Time = 25 ns

E- cloud simulation

CAS, Glumslöv, Sweden. 12 - 6 - 2017   R. Cimino
Electron cloud in accelerators

• Phenomenology:
  What happens to the Vacuum beam pipe in presence of the beam? (LHC Example)

• Numerical model

• The Surface Science properties of relevance:
  ✓ SEY (Secondary Electron Yield);
  ✓ PY (Photo Yield);
  ✓ R (photon Reflectivity)

• Mitigation strategies

• Conclusion

R. Cimino and T. Demma
“Electron cloud in Accelerators”
Secondary Electron Yield (SEY)

three-step process:
- production of SEs at a depth $z$
- transport of the SE toward the surface
- emission of SE across the surface barrier

It depend on the surface type and condition: has a big impact to simulations (see calculation for LHC).

Need of “state of the art” Surface Science systems to study SEY

The XPS system

- Manipulator
- Faraday Cup
- Sample Prep. Chamber for reactions
- LEED + e⁻ gun
- Electron Analyser
- X-ray Lamp
- e⁻ gun

Addendum
Measure of Secondary e\textsuperscript{-} Yield: 2 methods

\[ \text{SEY} = \delta = \frac{I_{\text{out}}}{I_{\text{in}}} = \frac{I_{\text{gun}} - I_{\text{sample}}}{I_{\text{gun}}} \]

Addendum
2nd method: Measure of Secondary e⁻ Yield

- In a µ-metal chamber
- Sample manipulator (also at Low T)
- Sample well insulated (to measure small current $I_s$)
- A Faraday cup
- A Low energy electron gun

- e⁻ beam Stable between 30 - 500 eV
- Currents from few nA to µA (20µC/h/mm² - 20mC/h/mm²)
- Intense spot ($\phi < 0.5$ mm) with low background

$\text{SEY} = \delta = \frac{I_{\text{out}}}{I_{\text{in}}} = \frac{I_{\text{gun}} - I_{\text{sample}}}{I_{\text{gun}}}$
Measure of Secondary $e^-$ Yield: 2 methods

$$\text{SEY} = \delta = \frac{I_{\text{out}}}{I_{\text{in}}} = \frac{I_{\text{gun}} - I_{\text{sample}}}{I_{\text{gun}}}$$

### $I_{\text{out}}$ and $I_{\text{in}}$ (N. Hilleret)

**Advantages:**
- Simultaneously measure $\delta$ at each energy: very fast.
- Effective also for “dispersive samples” (i.e. Sponges)

**Disadvantages:**
- Gun far from the sample (difficult to control LE $e^-$)
- Big(er) spot and no LE-SEY
- Loose Normal emitted $e^-$

### $I_{\text{Sample}}$ and $I_{\text{in}}$

**Advantages:**
- Gun close to sample.
- Reduce noise for low current measurements (i.e. insulators)
- LE-SEY accessible!?!?

**Disadvantages:**
- Gun need to be very stable (takes time)
- More work (2 separate runs)
Measure of Secondary e⁻ Yield

\[ \text{SEY} = \delta = \frac{I_{\text{gun}} - I_{\text{sample}}}{I_{\text{gun}}} \]

At each Primary energy we measure \( I_{\text{gun}} \) (with the Faraday cup) and \( I_{\text{sample}} \).

- Each point in \( \delta \) is the integral of the energy distribution of the emitted electrons

Integrating the curves gives the Percentage of Secondaries and Reflected electrons.

To separate “true secondaries from “re-diffused electrons is arbitrary and has not been considered in this analysis.

We observe that the contribution to of the reflected electrons at very low primary energy is, in this material, very high.

Such Low energy part of SEY was, up to recently, somehow controversial.

Total secondary electron yield of Cu as a function of incident electron energy. 1. from the letter for fully scrubbed Cu ($T=10$ K). 2. Experimental data for bulk Cu after heating in vacuum (room temperature).


Other measurements reported the reflection coefficient of about 7% for incident electron energy below few electron volts for most pure metals.

See: R. Cimino et al. PR ST 18, 051002 (2015)
Addendum

Setting the energy scale.

Expected Setup limitations at Low energy

- Study in identical conditions (same geometry etc.) atomically clean (XPS) Cu obtained by cycles of Ar+ sputtering of the “as received” Cu.
- Compare it to “as received” Cu samples.
- “As received” is NOT a well defined chemical state!

See: R. Cimino et al. PR ST (2015)
“As received” vs. Clean Cu

R. Cimino et al.
PR ST (2015)

Primary Energy above $E_F$ (eV)

SEY

Cu OFHC "As Received"

Cu LHC "As Received"

Clean Polycrystalline Cu

R. Cimino et al.
PR ST (2015)
“As received” vs. Clean Cu

R. Cimino et al.
PR ST (2015)
Addendum

For the LHC: test HL simulations.

R. Cimino et al. PR ST (2015)
For the LHC: test HL simulations.

\[ R = \delta(0) = 0.8 \]

in all cases

R. Cimino et al. PR ST (2015)
For the LHC: test HL simulations.

R. Cimino et al. PR ST (2015)
Electron cloud in accelerators

- Phenomenology:
  What happens to the Vacuum beam pipe in presence of the beam? (LHC Example)

- Numerical model

- The Surface Science properties of relevance:
  - SEY (Secondary Electron Yield);
  - PY (Photo Yield);
  - R (photon Reflectivity)

- Mitigation strategies

- Conclusion

R. Cimino and T. Demma
“Electron cloud in Accelerators”
Why?

• Not only to study the input parameters used in simulations of multipacting and e-cloud build-ups, related instabilities

• But also to simulate and prevent single bunch instabilities just connected to the mere existence of a certain density of e- in the accelerator chambers.

(K. Ohmi and F. Zimmermann PRL 2000)
Experimental set up to measure R & PY @ BESSY II - Optic Beamline and Reflectometer


See: Eliana La Francesca @ FCC Week 2017, Berlin
Reflectivity and PY Measurements

- Photon Energy range $35\div1800$ eV
- Beam height $h=0.3$ mm
- Incident Beam measurement
- GaAsP Photodiodes (4x4mm) (1.2*4mm)
- Incidence angle 0.25, 0.5 deg
- Reflectivity measurement

Photo Yield:
$\text{PY} = \frac{N_e}{N_\gamma}$

See: Eliana La Francesca @ FCC Week 2017, Berlin
Specular Reflectivity VS Photon energy

At high energy reflectivity is significantly enhanced

At grazing incidence angle, contaminants are influencing Cu Reflectivity

See: Eliana La Francesca @ FCC Week 2017, Berlin
Total Reflectivity VS Specular Reflectivity

Sample | Specular Reflectivity | Total Reflectivity
---|---|---
Cu 1A | 0.61 | 0.73
Cu 1A + CC | 0.78 | 0.90

Scattered photons goes top & bottom

See: Eliana La Francesca @ FCC Week 2017, Berlin
Photo Yield VS Incidence angle

Preliminary Results:
- little dependence on roughness
- Carbon coating seems to reduce PY

Sample | Cu 1A ($R_a=10$ nm) Max value | Cu 2A ($R_a=30$ nm) Max value
---|---|---
Cu | 0.47 | 0.46
Cu + CC | 0.23 | 0.15

See: Eliana La Francesca @ FCC Week 2017, Berlin
Electron cloud in accelerators

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  ✓ R (photon Reflectivity)

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R. Cimino and T. Demma
“Electron cloud in Accelerators”
Towards mitigation Strategies….

- We measure and feed material parameters (R, PY, and SEY) into simulations.
- Understand their profound nature to:
  - Optimize chemical (mech.) processes to reduce their detrimental influence on beam.
  - Search for new material / coatings with intrinsically “good” parameters.

**XPS**

**SEY**

**SR Reflectivity and PY (@BESSY-II)**

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CAS, Glumslöv, Sweden. 12 - 6 - 2017  R. Cimino
Most of the existing and planned accelerator machines base the reaching of their design parameters to the capability of obtaining walls with a SEY $\sim 1.3$ or below!

**Mitigation Strategies**

- External solenoid field
- Electrodes in the lattice
- Surface Scrubbing (or conditioning)
- Intrinsically low SEY material
- Geometrical modifications
<table>
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<tr>
<th>External solenoid field.</th>
<th>Not always possible…</th>
</tr>
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<td>If possible… (Impedance, costs.)</td>
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<td>Scrubbing (or conditioning)</td>
<td>-Efficiency (time &amp; final SEY)…</td>
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<td>Intrinsically low SEY material</td>
<td>Stability and material choice…</td>
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<tr>
<td>Geometrical modifications</td>
<td>Impedance. Space, Machining costs.</td>
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Scrubbing (or conditioning)

Intrinsically low SEY material

Geometrical modifications

External solenoid field.

If possible… (Impedance, costs.)

-Efficiency (time & final SEY)…

Stability and material choice…

Impedance. Space, Machining costs.

Not always possible…
SOLENOID EFFECTS ON AN ELECTRON CLOUD

L. Wang, BNL, Upton, NY 11973, USA
S. Kurokawa, H. Fukuma, S.S. Win, Tsukuba, KEK, Japan
A. Chao, SLAC, Menlo Park, California, USA

No field

60 Gauss solenoid field

Adopted solution for SuperKEK bellows

Figure 2: Electron orbit (top row), energy at the wall (middle row), and electron-cloud distribution (bottom row) with 0 G (left column) and 60G (right column) solenoid fields in the SNS’s accumulator drift region
Scrubbing (or conditioning)

- Efficiency (time & final SEY)...

Intrinsically low SEY material

- Stability and material choice...

Geometrical modifications

- Impedance. Space, Machining costs.

Electrodes in the lattice.

If possible... (Impedance, costs.)

External solenoid field.

Not always possible...
Electrodes at DAΦNE

Electrodes at DAΦNE

(a) Evolution of the averaged cloud density for different values of the electrode voltage. (b) e− cloud density at the end of the bunch train.

Scrubbing (or conditioning)

- Efficiency (time & final SEY)...

External solenoid field.

Not always possible...

Electrodes in the lattice.

If possible… (Impedance, costs.)

Intrinsically low SEY material

Stability and material choice…

Geometrical modifications

Impedance. Space, Machining costs.
The Beam “scrubbing” effect is the ability of a surface to reduce its SEY after e⁻ bombardment.

from LHC PR 472 (Aug. 2001):

“...Although the phenomenon of conditioning has been obtained reproducibly on many samples, the exact mechanism leading to this effect is not properly understood. This is of course not a comfortable situation as the LHC operation at nominal intensities relies on this effect...”

X-ray photoelectron spectroscopy

KE = hv - BE - ϕ

ϕ: work function
BE: binding energy
KE: kinetic energy

C1s

hv = 400 eV
FWHM = 250 meV

hv = 1253.6 eV
FWHM = 0.95 eV

binding energy (eV)
XPS spectroscopy of technical samples

Metal (Rb)

3d\textsubscript{3/2} and 3d\textsubscript{5/2}

binding energy (eV)
XPS spectroscopy of technical samples

Addendum

oxygen

metal

M-O

binding energy (eV)
XPS spectroscopy of technical samples

Addendum

oxygen

metal

hydrogen

carbon

binding energy (eV)

binding energy (eV)

C-C $sp^3$

C-H

M

M-O

binding energy (eV)

binding energy (eV)
XPS spectroscopy of technical samples
Addendum

XPS spectroscopy of technical samples

binding energy (eV)

M-O

metal

oxygen

carbon

hydrogen

125 123 121 119 117 115 113 111

binding energy (eV)

290 288 286 284 282

binding energy (eV)

M

C-C sp

C-H

C-O-C

C-C sp

Cls
Addendum

XPS spectroscopy of technical samples

- Oxygen
- Carbon
- Hydrogen
- Metal

Binding energy (eV)

M-O

M

C=C sp²
C-H
C-O-C
C=O

290 288 286 284 282

binding energy (eV)
XPS spectroscopy of technical samples

Addendum

CAS, Glumslöv, Sweden. 12 - 6 - 2017    R. Cimino
SEY and XPS are directly related
e^- beam induced surface reactions


Cu-O dissociation → O₂

CO → CO₂

oxide reduction

C-H dissociation → H₂

C-O dissociation

C film growth

the contribution of all electron-induced surface reaction reduces δ_max from 2.2 to 1.1
co-laminated Cu for LHC beam screen

R. Cimino et al. PRL 109 064801 (2012)

\[ \delta_{\text{max}} \]

- Energy (EV)
- Dose (C/mm\(^2\))

\( E_{\text{after}} 10^{-2} \text{C/mm}^2 \) @ 200 eV
co-laminated Cu for LHC beam screen

R. Cimino et al. PRL 109 064801 (2012)
optimize the “scrubbing” process @ LHC with beam parameters enhancing the presence, in the cloud, of higher energy el.

Give a more reliable estimate of the needed scrubbing time.

R. Cimino et al. PRL 109 064801 (2012)
Beam scrubbing effect with photon

![Graph showing beam scrubbing effect with photon]

**OFE Colaminated Copper**

- As received surface; $\text{PY} = 0.103$
  (dose $<$ 1 min. LHC operation)
- After $\sim$ 1 day LHC operation; $\text{PY} = 0.063$

Scrubbing (or conditioning)

- Efficiency (time & final SEY)…

Electrodes in the lattice.

- If possible… (Impedance, costs.)

External solenoid field.

- Not always possible…

Stability and material choice…

Intrinsically low SEY material

Impedance. Space, Machining costs.

Geometrical modifications
C films on polycrystalline Cu

a-C films
magnetron sputtering @ RT
p(Ar) = 10^{-2} mbar  \Delta t = 2\text{min}

C film thickness 2-3 nm

C films on polycrystalline Cu

the graphitization of the C films corresponds to a lower SEY

a-C bases its stability on its low reactivity

If condensed gas is physi-sorbed on a cold the surface the resulting SEY will be the one of the contaminant layer.

Argon on Clean Cu sample at 10 K

(see M. Angelucci et al: EuroCirCol coll and @ Beam Dynamics meets Vacuum, Collimations, and Surfaces 2017)
If annealing (@ ~ 200 °C) is possible: TiZrV


- A. r.
- 2 h 120 °C
- 2 h 160 °C
- 2 h 200 °C
- 2 h 250 °C
- 2 h 300 °C

Activated NEG: it pumps, low SEY, stable: ideal mitigator

... If Resistive Wall Impedance is acceptable.
Scrubbing (or conditioning)

Intrinsically low SEY material

Electrodes in the lattice.

External solenoid field.

Not always possible…

If possible… (Impedance, costs.)

-Efficiency (time & final SEY)…

Stability and material choice…

Impedance. Space, Machining costs.

Geometrical modifications
Geometrical Mitigation:

$\delta_0 = 1.8$

$\delta_0 = 1.0$

Impedance?

$\text{d_{max}} < 0.8 \ldots$

Impedance enhancement factor

(Code: Finite Element Method, PAC07 THPAS067, L Wang)

\[
\frac{Z_{\text{grooved surface}}}{Z_{\text{smooth surface}}} = \frac{H^2 ds}{H_0^2 W}
\]

*The total impedance enhancement* = \( \eta^* \) percentage of grooved surface

\[ p = 1.25\text{mm (period)} \]
\[ d = 2.5\text{mm (depth)} \]
\[ t = 0.125\text{mm (thickness)} \]

\[ = 1.64 \]

\[ p = 1.25\text{mm} \]
\[ d = 2.5\text{mm} \]
\[ t = 0.25\text{mm} \]

\[ = 1.42 \]
micro/nano geometrical effects

laser treatment for e-cloud mitigation

Investigation at STFC includes:
• Laser scan speed
• Laser wavelength


See also: 185. I. Montero et al., in Proc. E CLOUD’12, CERN-2013-002
Conclusion

- The beam interact with the accelerator wall and the accelerator wall interact with the beam.
- Electron-Cloud is and will be an important issue in circular accelerators in years to come!
- Numerical simulations are able to predict observed effects.
- Mitigation techniques are developing.
- Synergic efforts, dedicated Surface, Material and Vacuum science laboratories are required to reach desired performances.
- Still a lot of interesting R&D!
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And all the e-cloud which community