Electron cloud mitigation with LASE technology

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on behalf of working team

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ICFA mini-Workshop on "Mitigation of Coherent Beam Instabilities in particle accelerators" MCBI 2019, 22-27 September 2019, Zermatt, Switzerland
Outline

• Introduction
• LASE as low SEY solution for e-cloud mitigation SEY measurements
• Surface resistance
• Vacuum properties
• Advantages over other passive mitigation methods
• Conclusions
Main mission of vacuum solution teams

• Develop solutions and technologies which should simultaneously meet specified parameters on
  ➢ Vacuum (thermal outgassing, particle induced desorption and pumping)
    ❖ Beam lifetime
    ❖ Fast ion instability in negatively charged machines
    ❖ Pressure instability in positively charged machines
    ❖ E-cloud and BIEM
  ➢ Photoelectron emission and secondary electron emission
    ❖ E-cloud and BIEM
  ➢ Surface resistance
    ❖ Beam impedance and energy spread

• Implementing these technologies and solutions in real machines
  o These solutions should be compatible with mechanical, cryogenics, magnets design and other specifications.
LASE as low SEY solution for e-cloud mitigation
Existing e-cloud mitigation methods

**By active means:**
- Weak solenoid field (10-20 G) along the vacuum chamber
- Biased clearing electrodes
- Charged particle beam train parameters
  - Bunch charge and sizes, distance between bunches

**Advantages:**
- Solenoids can be installed on existing facilities (if there is a space for them)
- Beam parameters have some flexibility

**Disadvantages:**
- Requires:
  - Controllers, Power supplies, Cables
  - Vacuum compatible electric feedthroughs
- Reduced flexibility with beam parameters
- Initial and operation cost should be considered

- I.e. should be avoided, if possible

**By passive means:**
- Low SEY material
- Low SEY coating (TiN, NEG, a-C, …)
- Mechanically grooved surface
- Rough surface (etching, anodasing, LASE)
- Permanent magnets (in KEK-B)
- Special shape of vacuum chamber
  - An antechamber allows reducing PEY

**Advantages:**
- No controllers, No power supplies, No cables
- Permanent magnets can be installed on existing facilities

**Disadvantages:**
- In-vacuum deposition or wet chemistry
- Difficult to apply on existing facilities
- Durations of surface treatments
- Initial cost should be considered

- I.e. preferable solution(s)
What is LASE?

- LASE – Laser Ablated Surface Engineering

- Nanostructuring of Material Surfaces by Laser Ablation is well established science and manufacturing (> 25 years of experience), see review papers:

Discovery of LASE for SEY mitigation

The new was applying LASE surfaces to suppress PEY/SEY and to solve the e-cloud problem.

Main result: SEY < 1 can be achieved on Cu, Al and stainless steel.


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Low SEY surfaces can be produced using various lasers with different wavelength, such as $\lambda=355$ nm and $\lambda=1064$ nm, different power, with a variety of other parameters.

• SEY reduction due to a superposition of
  • microstructure (groves)
  • sub-micron and nano-structures

Groves are main source of surface resistance.

R. Valizadeh, et al.
Produced and tested more than 120 different LASE samples

- With different laser parameters treated with the following lasers:
  - Nanosecond 355 nm
  - Nanosecond 1064 nm
  - Picosecond 355 nm
  - Picosecond 1064 nm

- In different atmospheres:
  - Air, vacuum, Ar, CH₄

- More than 60 samples have SEY_{max}<1
SPS liner as test sample has been laser treated:
- Two areas of 40 x 490 mm$^2$ with different LASE parameters
Electron cloud mitigation has been successfully demonstrated in particle accelerator for the first time.

SEY < 1 can be consistently achieved for practical implementations on technical surfaces.

The e-cloud induced by the SPS proton beam was suppressed as efficiently as by the a-C coating.

The results also show that the LASE induced structure are robust, highly reproducible and scalable.

• XRD of Cu laser ablated in Ar atmosphere
  ➢ LASE in Ar atmosphere inhibit the formation of oxide layer

• XRD of Cu ablated in Air
  ➢ LASE I air atmosphere results in a stable detectable by XRD oxide layer
The increase in SEY is attributed to the growth of hydrocarbon on the surface which also contribute to super hydrophobicity of laser ablated surfaces.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>as received</th>
<th>after acetone</th>
<th>ten months later</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_{\text{max}}$</td>
<td>0.92</td>
<td>1.03</td>
<td>1.15</td>
</tr>
<tr>
<td>$E_{\text{max}}$ (eV)</td>
<td>682</td>
<td>682</td>
<td>632</td>
</tr>
</tbody>
</table>

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Effect of acetone and ultrasonic bath on SEY

- LASE surface is clean (no vacuum cleaning required)
- but in case of contamination after treatment they may require cleaning

The increase in SEY can be attributed to two factors:
- Loss of particulate as can be seen on the foil left behind after ultrasonic bath cleaning
- Built up of hydrocarbon on the surface after solvent cleaning
Impact of LASE e-cloud mitigation on other systems

- LASE
  - SEY: $\delta_{\text{max}} < 0.6$
- PEY ? (scaled with SEY?)
- Vacuum
  - Bakeout
  - Thermal outgassing
  - PSD, ESD and ISD
- Beam wakefield impedance
  - Surface resistance
- UFO
  - Particle generation
- Cryogenic vacuum system
  - Effect of cryosorbed gas on PEY, SEY, PSD, ESD, ISD
Surface resistance
In our earlier results:

- $\delta_{\text{max}} < 1$ can has been achieved on Cu, Al and stainless steel.

- However, main question we had to ourselves and being asked by other colleagues:

  How 100-$\mu$m deep groves affect surface resistance?
Surface resistance measurements: method

- The cavity geometry consists of two parts:
  - a body of the cavity
  - a planar sample,
  - separated by an air gap.
- Contactless
- RF chokes in order to keep the RF power within the cavity
- Operating in $\text{TM}_{010}$ mode, has circular H field distribution hence induces radial current.
- The surface resistance of the sample $R_{\text{sam}}$ can be calculated for known
  - test cavity surface resistances $R_{\text{cav}}$
  - measured $Q_0$,
- The magnetic field distribution in the cavity was calculated using CST Microwave Studio.
  - For our cavity, $G = 235\ \Omega$,
  - for a case using perfect electric conductor (PEC) boundary conditions, the field ratios are $p_c = 0.625$ and $p_s = 0.375$. 

\[
R_{\text{sam}} = \frac{GQ_0^{-1} - R_{\text{cav}}}{p_c} \frac{p_s}{p_s}
\]
**Surface resistance measurements**

1\textsuperscript{st} cavity – directionally averaged $R_s$

Test cavities (3.9 and 7.8 GHz):
- The simulation results obtained with Microwave Studio
- Fabricated from Al.
- 3 choke cavity operating in TM$_{010}$ mode, has circular H field distribution hence induces radial current.
- Half pill box cavity operating in TM$_{110}$ mode, has strong transverse H field hence induces axial electric current

**Samples:**
- 100 mm $\times$ 100 mm laser treated copper surface

2\textsuperscript{nd} cavity – $R_s$ measurements along a selected direction
Following low SEY studies

- Emphasis on physics:
  - How and why SEY is reduced on LASE surfaces
  - Further reduce SEY
  - Reduce surface resistance
  - Reduce particulate generation
  - Measure vacuum properties

LASE: A role of laser scan speed on copper samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Scan speed [mm/s]</th>
<th>Groove depth [μm]</th>
<th>$R_s$ [Ω] 0°</th>
<th>$R_s$ [Ω] 45°</th>
<th>$R_s$ [Ω] 90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>untreated</td>
<td>-</td>
<td>0.033</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a)</td>
<td>180</td>
<td>8</td>
<td>0.078</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>(b)</td>
<td>120</td>
<td>20</td>
<td>0.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(c)</td>
<td>90</td>
<td>35</td>
<td>0.14</td>
<td>0.15</td>
<td>0.19</td>
</tr>
<tr>
<td>(d)</td>
<td>60</td>
<td>60</td>
<td></td>
<td></td>
<td>0.20</td>
</tr>
<tr>
<td>(e)</td>
<td>30</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Treatment of copper using a $\lambda = 355$ nm laser resulted in creation of three different scales structures as presented:

- microstructure grooves ranging from 8 to 100 $\mu$m deep,
- coral-like submicron particles superimposed on the grooves which is made of agglomeration of
- nano-spheres
Calculated and measured $R_s$ at frequency $f=7.8$ GHz

<table>
<thead>
<tr>
<th>Sample</th>
<th>Scan speed [mm/s]</th>
<th>Groove depth for LASE (Roughness for untreated metals) [μm]</th>
<th>$R_s$ [Ω] measured with a 7.8-GHz cavity</th>
<th>$R_s$ [Ω] calc with formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>untreated</td>
<td>0.4</td>
<td>0.028</td>
<td>0.029</td>
</tr>
<tr>
<td>(a)</td>
<td>180</td>
<td>8</td>
<td>0.078</td>
<td>0.046</td>
</tr>
<tr>
<td>(b)</td>
<td>120</td>
<td>20</td>
<td>0.13</td>
<td>0.046</td>
</tr>
<tr>
<td>(c)</td>
<td>90</td>
<td>35</td>
<td>0.14</td>
<td>0.046</td>
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<td>(d)</td>
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<td>60</td>
<td>–</td>
<td>0.046</td>
</tr>
<tr>
<td>(e)</td>
<td>30</td>
<td>100</td>
<td>–</td>
<td>0.046</td>
</tr>
<tr>
<td>Al</td>
<td>untreated</td>
<td>0.4</td>
<td>0.034</td>
<td>0.034</td>
</tr>
<tr>
<td>Nb</td>
<td>untreated</td>
<td>1.0</td>
<td>0.071</td>
<td>0.080</td>
</tr>
<tr>
<td>SS</td>
<td>untreated</td>
<td>1.4</td>
<td>0.17</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Hammerstad and Bekkadal formula: 

$$ R_s = \sqrt{\frac{\mu \omega}{2 \sigma}} \left( 1 + \frac{2}{\pi} \arctan \left( 0.7 \frac{\mu \omega \sigma R_Q^2}{R_s} \right) \right); $$
Dielectric Resonator – Surface Resistance Measurement in ALBA (Barcelona)

- Brass cylinder
- Samples replace upper and lower plates
- Operating in the $\text{TE}_{011}$ mode
  - Insensitive to electrical contacts to the metallic enclosure
  - Rutile
  - Resonance frequency at 77 K is 8.0 GHz
- The unloaded Q-factor is given by

\[
\frac{1}{Q_0} = \sum_i \frac{R_{Si}}{G_i} + p \cdot \tan(\delta)
\]

$R_{Si} = \text{Surface resistance}$  
$p = \text{Filling factor}$  
$G_i = \text{Geometrical factor}$  
$\tan(\delta) = \text{Loss factor}$
SEY and surface resistance of LASE treated copper

<table>
<thead>
<tr>
<th>Sample</th>
<th>Material</th>
<th>λ (nm)</th>
<th>Average Power (W)</th>
<th>Pulse length (ns)</th>
<th>Frequency (KHz)</th>
<th>Pitch (μm)</th>
<th>Beam size (μm)</th>
<th>Power per pulse (μJ)</th>
<th>Fluence per pulse (J.cm⁻²)</th>
<th>Speed (mms⁻¹)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Cu</td>
<td>1063</td>
<td>30</td>
<td>0.15</td>
<td>600</td>
<td>10</td>
<td>15</td>
<td>50</td>
<td>28</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>Cu</td>
<td>1063</td>
<td>20</td>
<td>2</td>
<td>40</td>
<td>50</td>
<td>15</td>
<td>500</td>
<td>280</td>
<td>40</td>
</tr>
<tr>
<td>6</td>
<td>Cu</td>
<td>1063</td>
<td>20</td>
<td>2</td>
<td>40</td>
<td>10</td>
<td>15</td>
<td>500</td>
<td>280</td>
<td>40</td>
</tr>
<tr>
<td>7</td>
<td>Cu</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Sample 1  | Sample 4  | Sample 6  | Untreated       |
R_{SRT} [mΩ] | 25.527    | 24.940    | 25.100          | 26.035         |

R_{S77K} [mΩ] | 10.792 | 9.814 | 9.697 | 10.709

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SEY and surface resistance of LASE treated copper

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</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Cu</td>
<td>1063</td>
<td>30</td>
<td>0.15</td>
<td>600</td>
<td>10</td>
<td>15</td>
<td>50</td>
<td>28</td>
<td>40</td>
</tr>
<tr>
<td>8</td>
<td>Cu</td>
<td>1063</td>
<td>30</td>
<td>0.15</td>
<td>600</td>
<td>5</td>
<td>15</td>
<td>50</td>
<td>28</td>
<td>40</td>
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An $R_s$ increase of 14% for SEY of 1.1 and 60% for SEY of 0.8
• An open question:
  • $R_s$ as a function of temperature down to 4 K
    • To be addressed in future
  • A dedicated facility in ASTeC is under development
    • Planar samples could be studied in a few months
    • Tubular sample can be considered later
LASE vacuum properties
LASE: thermal outgassing

- Sample:
  - a 100-mm diam. disk (copper gasket)
  - After LASE
- No difference in outgassing detected in a vacuum chamber without and with a sample
Samples were tested after a bakeout to 200°C for 24 h:

- **316LN stainless steel flanges DN40:**
  - LASE treated in: 30 W, 600 KHz, 0.1 ns, 40 mm/s, 10 µm
  - Untreated

- **Cu blank gaskets Ø48 mm:**
  - LASE-1 treated in: 20 W, 60 KHz, 2 ns, 40 mm/s, 10 µm
  - LASE-2 treated in: 30 W, 40 KHz, 2 ns, 40 mm/s, 10 µm
  - Untreated (2 samples)

- **$E_{e-} = 500$ eV**
Electron Stimulated Desorption (ESD) from LASE

Main results:

- Copper sample with LASE demonstrated lower ESD yields than untreated sample.
- ESD for 316LN stainless steel with LASE is comparable with an untreated sample.
PSD experiment in KARA as a part of EuroCirCol WP4:

- 2 m long porotype of the FCC-hh vacuum chamber
- A tube in two halves, treated area of each half is 2 m x 20 mm.
- Laser 1064 nm.
- PSD measurements at room temperature
• Particle counts
  • Measurements taken with 0.5 bar of filtered N₂ onto a sample 50 mm away from the sample
  • The measurements taken for 1 min, the counts were averaged over 3 measurements
  • The detector could measure particles up to 25 microns
  • Largest particle size measured was 1 micron
  • Polished and untreated samples were used as reference

➢ Clear specification required on tolerable number and size of microparticles (per 1 m of beam pipe)
**Summary: Impact of LASE e-cloud mitigation on other systems**

<table>
<thead>
<tr>
<th>LASE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SEY</td>
<td>$\delta_{\text{max}} &lt; 0.6$</td>
</tr>
<tr>
<td>PEY</td>
<td>PEY? (scaled with SEY?) (R. Cimino’s team - INFN)</td>
</tr>
<tr>
<td>Vacuum</td>
<td></td>
</tr>
<tr>
<td>Thermal outgassing</td>
<td>Low</td>
</tr>
<tr>
<td>PSD</td>
<td>To be studied (KARA experiment)</td>
</tr>
<tr>
<td>ESD</td>
<td>Much lower than for untreated Cu, comparable to untreated stainless steel</td>
</tr>
<tr>
<td>Bakeout/activation temperature</td>
<td>Can be baked to 150 – 300 °C</td>
</tr>
</tbody>
</table>
| Cryogenic vacuum system | Ongoing studies in INFN (R. Cimino’s team)  
Ongoing studies in ASTeC |
| Beam wakefield impedance | No visible difference from Cu at 8 GHz  
Low $R_s$ LASE surface development in ASTeC |
| UFO | Particulate generation measurements and control (LASE parameters, gas flow, cleaning, etc.) |
Advantages over other passive mitigation methods

- There is no need for vacuum or clean room facilities
  - Reduced cost
- The laser is capable of fabricating the desired micro/nanostructure in a single step process.
  - Processing time
- Surface engineering is performed through a beam of light and, thus, contactless
  - No contamination from the tools or the process materials
- The process is applicable to the surfaces of any 3D object
  - i.e. inner walls of vacuum chambers
- It is possible to lase in many different environments, such as gases, liquids, or in a vacuum
  - i.e. controlling surface composition (oxides, nitrides, carbonises…) and surface formation
Technology for in-situ LASE treatment

Cable Drum

Cable Guide / Drive Mechanism

Mole Assembly

Crawler Assembly

Cable support

LHC Magnets

Revolving mirror

Piezo pusher

Laser focusing mechanism

Crawler centralising wheels

Piezo pusher pad

Axial cam

Mirror housing (rotates)

Mirror housing bearings

Gear drive

Electric motor

Tension spring connection

Laser fibre termination housing (fixed)

Laser optics housing (moves axially)

The mirror optics housing moves axially as the mirror rotates to maintain laser focus on the flat sections of beam pipe.
• There is a large number of LASE treatment parameters
  • Some of them lead to reducing down to $\delta < 0.6$
  • Some of above has no impact (or small increase in) the RF surface resistance at 8 GHz
    • $\delta_{\text{max}}$ and $R_s$ specifications (tolerable level) required
  • No vacuum problems at room temperature
    • Cryogenic studies are ongoing
• The LASE technique can be applied to existing vacuum surfaces where the improvement has to be done \textit{in-situ} with minimum disturbance to the beam line.
• \textbf{LASE can be done} in air (or selected gas) at atmospheric pressure; therefore the actual cost of the mitigation is considerably lower, a fraction of the existing mitigation processes.
• The process is also readily scalable to large areas.
Collaboration Team

- Dr Oleg Malyshev
- Dr Reza Valizadeh
- Adrian Hannah
- James Conlon
- Taaj Sian
- Patrick Krkotic
- Prof M. Pont
- Dr Phillippe Goudket
- Dr J.M O’Callaghan
- Jennifer Much

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- Dr Mike Cropper (Loughborough)
- Dr David Whitehead (Manchester)
- Dr Jonthan Smith (Tech X)
- Dr Paul Apte (Rideo)